50 years Westerbork Radio Observatory

A Continuing Journey to Discoveries and Innovations

Richard Strom,
Arnold van Ardenne,
Steve Torchinsky (Eds.)

ASTRON
Netherlands Institute for Radio Astronomy

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A CONTINUING JOURNEY TO DISCOVERIES AND INNOVATIONS

Dedicated to the Memory of Ger de Bruyn

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Westerbork Radio Observatory

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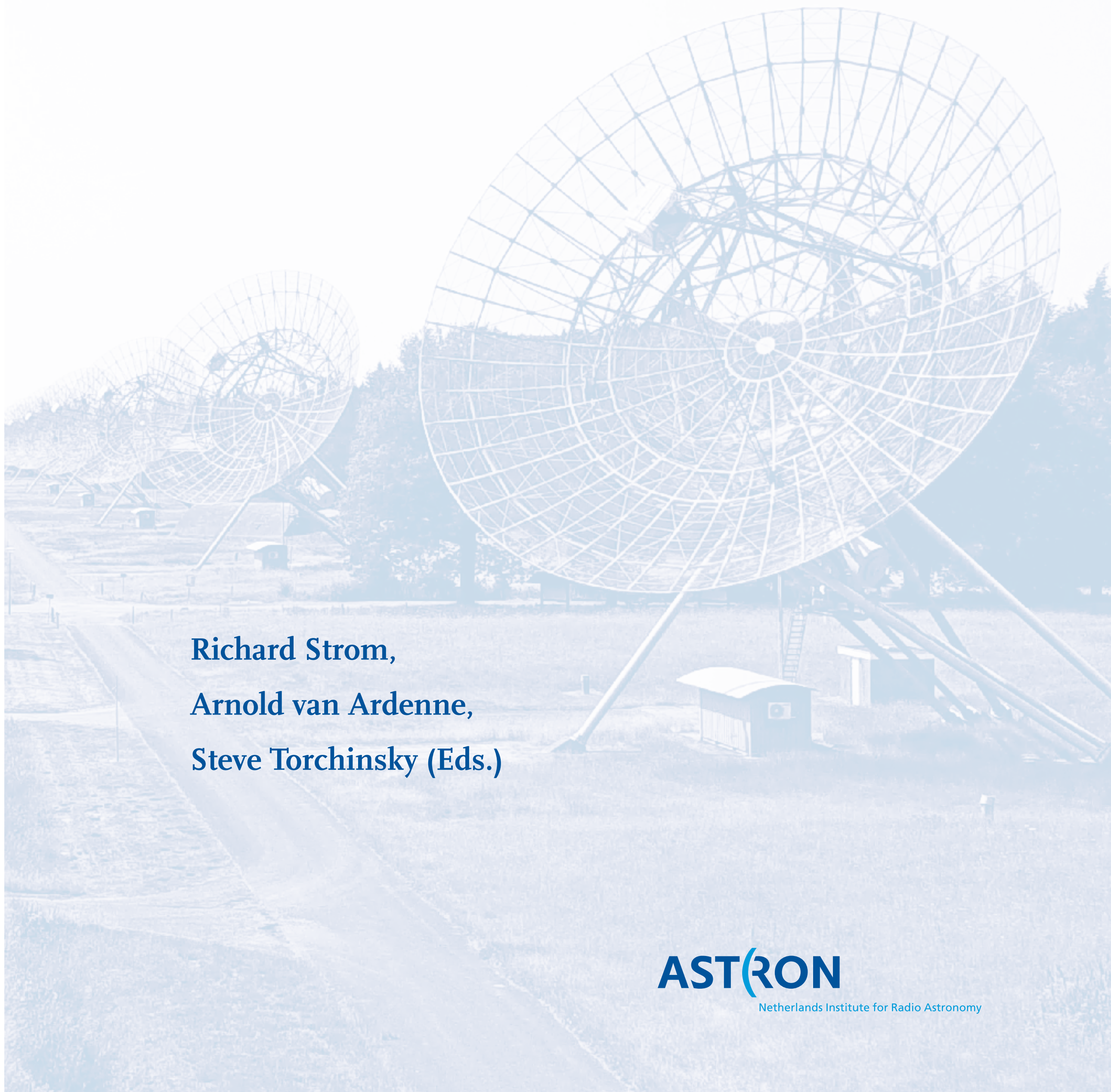

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ASTRON
Netherlands Institute for Radio Astronomy

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ASTRON is the Netherlands Institute for Radio Astronomy. We observe and investigate the signals that the Universe emits at radio wavelengths. Our mission is to make discoveries in radio astronomy happen. ASTRON is an institute of the Netherlands Organisation for Scientific Research (NWO).

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Preface

In September 2018 we celebrate fifty years since the completion of the Westerbork Synthesis Radio Telescope (WSRT). In 1968 it hailed a new era of astronomy, joining the One-Mile Telescope located at Cambridge UK, exploring the new technique of dish-based interferometry. Over its lifetime, WSRT has been used for a wide range of high-resolution centimetre wave radio astronomy, from studying our solar system to probing galaxies at the edge of the Universe.

A clear theme emerges from this retrospective. The continuing success of this instrument relies on the extensive teamwork of scientists and engineers. Right from the start, this team delivered the WSRT with a clear vision to provide the Netherlands, and the wider international astronomical community, with a telescope of exceptional dynamic range and stability of operations. Throughout its 50-year lifetime, the WSRT has continually evolved, driven by this ongoing engineering-science interlink, testing and maturing novel concepts to deliver world-class capabilities. Moreover, the longevity of the WSRT as a system, underpinned by the collaborative esprit de corps, demonstrates not only the instrument's performance, but also the high level of expertise passed on through generations of astronomers and engineers.

This collection of papers on the WSRT's history, discoveries, current and future promise provides a fitting tribute to the ambitious engineers and scientists of the 1960's who brought this array to the Dutch and international landscape.

WSRT can lay claim to its place in the history of the advancement of scientific knowledge. Teams of Dutch and international astronomers have made remarkable breakthroughs in science, stretching the capabilities of this telescope. A few highlights include the detection and confirmation of dark matter in spiral and dwarf galaxies, the millisecond pulsar in the constellation Vulpecula, the discovery of giant and double-double morphology radio galaxies, and the first map of the radiation belts of Jupiter together with the Pioneer flyby of 1973. Many significant discoveries of WSRT are described in detail throughout this book.

Looking back

From today's viewpoint, we can conclude that fifty years has been a long time in terms of astronomy development: Contemporary telescopes benefit from the massive developments in electronic technologies compared to those of the era when the WSRT was conceived. The WSRT infrastructure, i.e. the dish array itself, stands as a solid and enduring foundation, proving highly adaptable to new innovations through its lifetime.

Given the cost of a new telescope in 2018 can far exceed any one country's budget, it is insightful to review how the WSRT came to exist: After the completion of the Dwingeloo 25m single dish radio telescope in 1956, astronomers in the Netherlands, and neighbours Belgium and Luxembourg, looked towards the next step. The Benelux Cross Antenna Project was a proposal to build a pair of parabolic cylinders. Unfortunately, this project did not come to fruition, but it was the catalyst for what came soon afterwards. With the emergence of a new technique for radio astronomy, and the energy of a remarkable Dutch leader, the astronomer Jan Oort, the ambition for the WSRT was born.

In the late 1950s, aperture Synthesis imaging was developed by the group led by Martin Ryle at Cambridge University. The establishment of this significant technique, since adapted for medical and other devices, culminated in Martin Ryle and Tony Hewish receiving the Nobel Prize (1974). The Cambridge group designed and built the 'One-Mile' telescope array at Mullard Radio Astronomy Observatory near Cambridge, using the newly available 'powerful' computers able to deal with the computationally intensive Fourier transform inversions necessary for aperture synthesis.

It was Professor Oort (Leiden University) who drove the effort to build the WSRT, realizing the potential of radio interferometry. Oort's primary scientific driver was to study cosmology through studies of extragalactic radio galaxies, a topic that had become particularly divisive with the 'static universe' interpretations of the earliest, shallow radio source surveys. From the outset, the design for the WSRT was for twelve 25 m telescopes on an east-west baseline, extending over 1.5 km. Construction began in 1966/67. The first telescope was in place by August 1967, and the twelfth before the end of 1968. As detailed in this volume, and in the 25-year anniversary volume* the WSRT was significantly upgraded between 1975-1980 with the addition of two movable dishes, extending the array to baselines up to 2.7 km. In the early 1980s, new digital back end systems utilizing the major leaps in processing technologies greatly increased the processed data rates, allowing astronomers to observe increasingly wider bandwidths and at finer resolution.

As a National Facility, the WSRT is a common-user instrument, and like the majority of such astronomical facilities, it is made available to the whole community on a free-to-use basis. This has ensured fair access to the very best science proposals. WSRT data remains the property of the science team for 18 months to allow for analysis and publication. After this period, it is considered public and is freely shared for others to use in their research.

* *The Westerbork Observatory, Continuing Adventure in Radio Astronomy, Eds E. Raimond, R. Genee, Astroph.&Space Sc. Library, Vol 207, 1996,Kluwer ISBN0-2973-4150-3*

WSRT today and future

After its major upgrade in 2000, the WSRT contributed to key HI science and surveys, one of a small number of major radio interferometers operating in the cm-wavelength regime, e.g. the Karl G Jansky Very Large Array (VLA), One Mile (UK) and the Australia Telescope Compact Array (ATCA). The WSRT has one feature that sets it apart from most other radio telescopes with equatorial mounted dishes, whereas most other telescopes have an alt-azimuth mount design. The equatorial mount requires steering (movement) on only one axis to track an object on the sky. Compared to alt-azimuth designs, the WSRT's receivers remain stationary with respect to the sky during an observation - this is particularly powerful when dealing with polarisation observations, and moreover allows the relatively simple implementation of a receiver in the aperture plane, i.e. an *aperture plane phased array*.

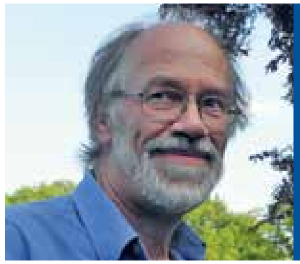
The emergence of the global collaboration to realize the Square Kilometre Array (SKA) in the early 2000's drove novel technology research. Whilst ASTRON commenced the development of phased array feeds/receivers (PAFs) as a potential technology for SKA, it became clear that this would also be an upgrade path for the WSRT. In this way the WSRT provided a vibrant platform with which to explore enabling technologies and industrial partnerships towards the future, including LOFAR and SKA. Thus, in 2015, twelve of WSRT's dishes were removed from operations whilst the PAF-based system upgrades are installed. The other two dishes remained productive operating within the European VLBI Network (EVN) and doing other research (e.g. for Galileo calibration), utilizing the Multi-Frequency Front End system (MFFE, 120 MHz to 8.3 GHz).

Today ASTRON is in the final phase of commissioning this PAF-based system, termed the APERture Tile In Focus, as described in more detail in this volume. Now named "Apertif", this system encompasses a 4-year upgrade that completely re-equips the backend and processing systems of the WSRT. WSRT-Apertif will be one of only two arrays in the world with the phased array feed systems (PAF). The other, ASKAP (the Australian SKA pathfinder), will be the southern hemisphere 'sister' telescope. It is notable that the WSRT has the largest raw collecting area, a factor that may well prove invaluable for the calibration of these complex systems. Notably the design of the two PAF systems (WSRT and ASKAP) are similar in concept but differ in implementation such that these will inform the community as we look to future upgrades. This future may include the adoption of PAFs for SKA as it matures in the next decade beyond its initial build design ("SKA phase 1").

With Apertif, WSRT stands ready to map the medium-deep view of the Universe in hydrogen at 21 cm, providing legacy surveys for researchers of the future. This Apertif system also offers a powerful way to monitor the transient sky, opening up the systematic detection of extreme-power and rare events.

In terms of field-of-view and sensitivity, the compatibility of WSRT with ASTRON's LOw Frequency Aperture Array's (LOFAR), gives the astronomical community a unique pair of instruments to explore the northern sky. ASTRON together with its partners will ensure these deliver the science to establish the important legacy surveys for the 2020's. WSRT together with ASKAP will map the sky providing the primary solution (called the *sky model*) to be used for SKA. In conclusion I would like to thank the authors and editors for their contributions to this anniversary volume. On behalf of the entire community, I acknowledge the support from the Netherlands Organisation for Scientific Research (NWO) of ASTRON, the WSRT and the user community over the last fifty years of exploration and discovery, and look to many more years to come.

Carole Jackson
General & Scientific Director
ASTRON 2018



A.G. (Ger) de Bruyn,

13 July 1948 – 9 July 2017

The idea of putting together this book on the accomplishments of the WSRT since it was put into operation in late 1969 was enthusiastically embraced by Ger de Bruyn a few years ago. Having been part of at least 40 years of WSRT operation, development and science, he had a good overview of whom to ask to contribute and on what topics to focus for a book that would in a factual, educational and entertaining way convey the story of engineers and scientists working together to make and keep the WSRT the successful instrument it has been since it conception. It is therefore extra sad that Ger died so suddenly in 2017 and was not able to see the making of this book through to the end. The editors and contributors would therefore like to dedicate this book not only to almost 50 years of WSRT operation, development and science, but also to Ger's career in radio astronomy which has been so closely tied to the WSRT for the last four decades.

Ger studied astronomy at the University of Leiden and received his doctorate in 1976 on a thesis entitled "Radio investigations of active spiral and Seyfert galaxies" under the supervision of Prof. Harry van der Laan. His thesis research was based on early radio continuum observations with the WSRT. Before joining the scientific staff at ASTRON (the Netherlands Institute for Radio Astronomy) in 1978, he spent two years at the Carnegie Institute/Hale Observatory in Pasadena as a Carnegie Fellow, where he used the Hale Observatory facilities to obtain optical spectra of many active galaxies of the kind he studied for his thesis.

Back in the Netherlands, he devoted most of his attention to using the WSRT at its limits to address a broad range of scientific questions. This was possible due to his excellent and ever-increasing understanding of synthesis imaging, including all the subtle effects of the earth's troposphere and ionosphere, the telescopes, the receivers, the backend and the correlator. Ger's drive to get the most out of the telescope made him famous amongst his peers, and for several decades Ger and his technical colleagues at ASTRON continually pushed the telescope to its limits by coupling forefront scientific research to creative and clever methods for processing the data. This led to the introduction of the so-called redundancy calibration, making use of the regular layout of the antennas of the WSRT. The redundancy calibration has made it possible to reach record dynamic-range radio images with this telescope.

Over the years the frequency coverage of the WSRT was expanded to both higher and lower frequencies, and Ger and his colleagues and students made enormous progress, especially at the lowest frequencies. An attempt to find signs of very distant neutral-hydrogen objects led to the discovery of very complex polarized emission from the galaxy. Follow-up research has shown that this complexity is pervasive in our Galaxy. To study these structures in detail, Ger and his colleagues and students introduced a new technique, rotation measure synthesis, which brings out these complex structures in all their detail and is a powerful tool for its interpretation.
In the late nineties the Westerbork array was used to image the radio emission of the entire northern sky at low frequency (327 MHz), and Ger played a pivotal role in the planning, calibration and analysis of this survey, the Westerbork Northern Sky Survey WENSS. The catalogues and images of this survey are a great asset for the general astronomical community and are widely used.

Some twenty years ago the idea was worked out that it should be possible to measure the extremely weak signal of neutral hydrogen in the early universe once it is heated by the first generation of stars. Ger was intimately involved in this effort. This turned out to be one of the prime motivations to build the Low Frequency Array LOFAR, designed by ASTRON engineers and realized about ten years ago. Ger, his colleagues and students prepared carefully to use LOFAR to detect the neutral-hydrogen signatures in the early universe. Efforts to detect these signatures are well underway through improved understanding of the telescope and the complexity of removing all effects from unassociated radio emission, including the effects of radio interference and the ever-changing ionosphere, which greatly affect the precision of these measurements. While shifting his interest to LOFAR Ger remained connected to the WSRT and continued to participate in discussions about the WSRT's future

Ger will always be remembered as a very creative, stimulating, knowledgeable, but most importantly friendly and generous colleague, focusing all attention on everyone and everything except himself. An important part of his scientific heritage is a large number of students, postdocs and senior researchers who continue to contribute to radio astronomy in the way he used to.

Thijs van der Hulst

Summary

This book describes a 50-year journey of the Westerbork radio telescopes. The journey is filled with scientific discoveries and new astronomical insights that have provided new knowledge about the Universe. This book is also about the context in which this research was made possible and therefore it is also about the *non-astronomical discoveries* such as the contribution to wireless communication ("WiFi").

Such a journey is only possible in an environment where excellent teams of engineers and scientists are capable of translating state-of-the-art technologies into the instrumental dreams of the astronomers.

In this book, the people involved and witnesses of the journey report their personal experience and views. Of course, many others have made a contribution, and whilst they may not have a mention in this book, it would not have been possible without them. Here we acknowledge the contributions of all the support staff, observers and technicians, many of whom were pioneers working 24/7 shifts.

The book starts with the earliest history of the relatively young branch of astronomy that is now called radio astronomy. The Netherlands commenced organized research from the early 1950s, notably led by giants such as Jan Oort and other visionaries, along with government and business support. The construction of the then world's largest movable 25 metre radio telescope in Dwingeloo, was a turning point as a first instrument dedicated to research. This book is about Jan Oort's next "natural" step, namely the set of 14 (initially 12) 25-metre radio telescopes in Westerbork distributed over a distance of 2.7 km capable of detecting 100 times more detail of radio sources with a much greater sensitivity than the single Dwingeloo dish. The picture (left) from 1966 shows the telescope construction in progress, looking from the west (bottom) to the east in the distance. The assembly hall is clearly visible in the

middle. A special chapter in this book discusses the special design features of the telescopes that, from 1968 on, provided the community with so much good science.

In the first ten years, the telescope was developed to be able to observe 24/7. Part of this development included moving the Leiden-based Laboratory to (now) ASTRON in Dwingeloo, eventually including the entire computational and support systems. This centralisation at ASTRON significantly shortened the production time for observing results: the quality of the instrument could ultimately be assessed instantaneously and possible improvements could be applied immediately. It was also possible to use the instrument as one large telescope in an international network of other telescopes. This enabled joint and simultaneous observations. This so-called Very Long Baseline Interferometry (VLBI) ultimately resulted in the establishment of the JIVE (Joint Institute for VLBI)-ERIC (European Research Infrastructure Consortium) in Dwingeloo. Also in this phase, the basis was laid for making observations in the time domain, in combination with the "traditional" imaging technique for which the telescope was originally built.

After the first ten years of fantastic discoveries, including detecting giant radio sources that are many times larger than the full moon, a phase of greater competition with other international telescopes followed. In particular with the American Very Large Array, now known as Karl G. Jansky VLA – named after the first discoverer of radio waves from the Universe in 1933. The picture below shows the Westerbork Synthesis Radio Telescope, named after the underlying observation technique, in the early nineties in full operation. In the upper right corner the two distant telescopes can still be seen.

As a result of constant investments by the Netherlands towards state-of-the-art telescope instrumentation, signal and data processing techniques and training (including international exchange and cooperation with, among others, universities and industry), a solid foundation was laid for modern world-class radio astronomy.

By making use of special properties of the telescope, such as the fact that the distance between the telescopes could be very accurately recorded, great successes followed. This feature and the huge stability of the instrument led to sky images of unsurpassed accuracy and "depth". The latter relates to the possibility of being able to observe very strong radio sources simultaneously with sources that are more than a million times weaker, in the same "radio" image. This feature improved our calibration techniques and progressed hand-in-hand with a deep understanding of the underlying mathematical-physical generic instrumental description. Without this and further developments, LOFAR and the international SKA project would not have been possible in a meaningful way. This also applies to Apertif, the new Westerbork observing system that was "invented" in the Netherlands. Using the accumulated knowledge and skills

and the use of intense computer and data processing techniques, the whole system works as a "radio" camera to instantaneously observe a much larger field of view.

This book will take you on a journey that shows how all this became possible. En route important side roads have been taken, leading to broad social applications. I invite you to come along on this journey, to wonder about the destinations and to enjoy the anecdotes along the way that are naturally part of this type of endeavor.

On behalf of the editors,
Arnold van Ardenne

Samenvatting

Dit boek beschrijft een reis van 50 jaar met de Westerbork radiotelescopen. De reis is gevuld met wetenschappelijke ontdekkingen en nieuwe sterrenkundige inzichten die steeds weer nieuwe onderzoeken over het heelal mogelijk hebben gemaakt. Het gaat ook over de context waarin dit mogelijk werd gemaakt en daardoor ook over bijzondere niet-sterrenkundige ontdekkingen zoals de bijdrage aan draadloze communicatie ("WiFi").

Zo'n reis is alleen mogelijk in een omgeving waarin excellente wetenschappers samenwerken met top-ingenieurs die de laatste stand van de techniek kunnen vertalen in de instrumentele dromen van de sterrenkundigen.

In dit boek zijn betrokkenen en getuigen van die reis aan het woord die vanuit hun persoonlijke beleving en kijk op zaken verslag doen. Natuurlijk hebben ook vele anderen een bijdrage geleverd. Zij konden weliswaar geen plaats in dit boek krijgen maar zonder hen zou dit verslag niet mogelijk zijn geweest. Te denken valt aan de ondersteunende staf, de waarnemers die als echte pioniers in het prille begin 24/7 diensten moesten draaien, de vele technici etc.

Het boek begint met de vroegste geschiedenis van de relatief jonge tak van sterrenkunde die nu radiosterrenkunde wordt genoemd. Nederland begon daarmee middels georganiseerd onderzoek vanaf begin jaren '50, vooral door grootheden als Jan Oort en andere visionairs waaronder overheid en bedrijfsleven. Na de bouw van de toen grootste beweegbare 25 meter radiotelescoop ter wereld in Dwingeloo, kwam een instrument beschikbaar waarmee het onderzoeksgebied écht op gang kwam. Dit boek gaat over Jan Oort's volgende "natuurlijke" stap, namelijk de rij van 14 (aanvankelijk 12) 25meter radiotelescopen in Westerbork over een afstand van 2,7 km die 100 keer meer detail van radiobronnen kan waarnemen met daarbij een veel grotere gevoeligheid. Het plaatje hiernaast uit 1966 toont de vroege stand van de constructie fase van de telescopen kijkend vanuit het westen (beneden) naar het oosten in de verte. In het midden is

duidelijk de assemblagehal zichtbaar. Er is een speciaal hoofdstuk in het boek opgenomen dat ingaat op de bijzondere constructie van de telescopen die vanaf 1968 de gemeenschap zoveel goede wetenschap heeft opgeleverd.

In de eerste tien jaar werd de telescoop uitgebouwd tot een compleet waarneeminstrument dat 24/7 waarnemingen kon doen. Daartoe werd het Laboratorium van Leiden naar (nu) ASTRON in Dwingeloo verplaatst en uiteindelijk werd ook het hele rekenintensieve proces van het maken van de hemelafbeeldingen overgeplaatst. Door deze verkorte cyclus kon de kwaliteit van het instrument uiteindelijk instantaan worden beoordeeld en eventuele verbeteringen direct worden aangebracht. Ook werd het mogelijk om het instrument als geheel in te zetten als één grote telescoop in een internationaal netwerk van andere telescopen. Zodoende konden gezamenlijk en tegelijkertijd waarnemingen worden gedaan. Deze zogenaamde Very Long Baseline Interferometry (VLBI) heeft uiteindelijk uitgemond in de vestiging van de JIVE (Joint Institute for VLBI)-ERIC(European Research Infrastructure Consortium) in Dwingeloo. In deze fase werd ook de grondslag gelegd voor het doen van waarnemingen in het tijddomein e.e.a. in combinatie met de "traditionele" beeldvorming techniek waarvoor de telescoop aanvankelijk was gebouwd.

Na de eerste tien jaar van fantastische ontdekkingen zoals reuze-radiobronnen die vele malen groter zijn dan de volle maan, volgde een fase van grotere concurrentie met andere internationale telescopen. Met name met de Amerikaanse Very Large Array, nu de Karl G. Jansky VLA genoemd - naar de eerste ontdekker van radiostraling uit het heelal in 1933. Het plaatje hieronder toont de Westerbork Synthese Radio Telescoop, zogenoemd naar de onderliggende waarneemtechniek, begin jaren negentig in vol bedrijf. In de rechterbovenhoek zijn nog vaag de twee verre telescopen zijn te zien. De gehele "basislijn" is daarmee 2,7km geworden.

Door in Nederland voortdurend te investeren in state-of-the-art telescoop instrumentatie, signaal- en data-verwerkingstechnieken en opleiding (waaronder internationale uitwisseling en samenwerking met onder meer universiteiten en bedrijfsleven), kon een stevige grondslag worden gelegd voor de moderne radiosterrenkunde van wereldfaam.

Door gebruik te maken van bijzondere eigenschappen van de telescoop, zoals het feit dat de afstand tussen de telescopen heel precies was vastgelegd en meerdere malen voorkomt, kwamen grote successen voort. Deze eigenschap en de enorme stabiliteit van het instrument, leidde tot hemelafbeeldingen van extreme nauwkeurigheid en "diepte". Dat laatste heeft betrekking op de mogelijkheid heel sterke radiobronnen te kunnen waarnemen tegelijkertijd met bronnen die meer dan een miljoen keer zwakker zijn, in hetzelfde "radio"-beeld. Deze verbeterde calibratie-techniek ging hand in hand met een diep begrip van de onderliggende wiskundig-fysische generieke instrumentele beschrijving. Zonder deze en verdere ontwikkelingen zouden LOFAR en het

internationale SKA-project niet zinvol mogelijk zijn geweest. Dat geldt ook voor Apertif, het nieuwe Westerbork waarneemsysteem dat in Nederland werd "uitgevonden". Met gebruikmaking van de opgebouwde kennis en kunde en de inzet van intense computer- en data-verwerkingstechnieken werkt het geheel als een "radio"camera die een veel groter beeldveld kan waarnemen.

Dit boek neemt u mee op een reis die laat zien hoe dit alles mogelijk werd en waarbij en-passant ook belangrijke zijwegen werden bewandeld leidend tot brede maatschappelijke toepasingen. Ik nodig u van harte uit op deze reis mee te gaan en u te verwonderen over de reisdoelen en om te genieten van de anekdotes onderweg die natuurlijk altijd met dit soort grootse inspanningen gepaard gaan.

Namens de redactie,
Arnold van Ardenne

Contents

Chapter 1 Historical introduction

Richard Strom*

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From the English longbows at the battle of Crécy (1346) to Winston Churchill's world war I mobilized cannon (its true identity hidden behind the pseudonym "[water] tank"), warfare has always pushed technological innovation to new fronts. The second world war (WWII) was no exception. It gave us technology ranging from the dynamo-powered flashlight (a Philips invention) to jet engines, and space-capable rockets (Germany's V2), not to mention (in a completely different realm) the mass production of Penicillin. In fact, it could be argued that WWII inventions marked the inception of the modern technological era[1].

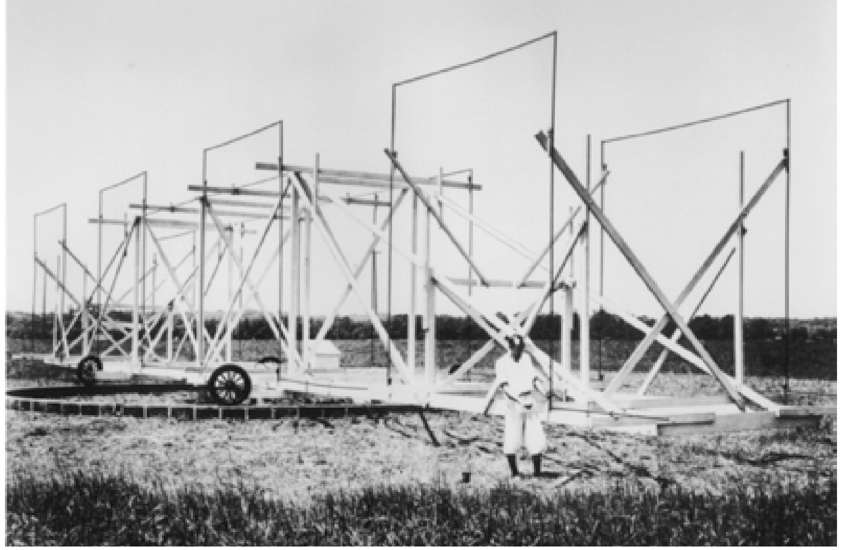
In the field of electronics, the war led to innovations such as radio navigation, aircraft landing systems, and radar. It was these developments which were to have a revolutionary impact on astronomy, initially in Britain, Australia and the United States. But the story begins in the US, with the electronics of the 1920s and '30s.

Figure 1. Karl G. Jansky (c. 1933)

Around 1930, there was increasing interest in the use of radio frequencies for communication. One of the main players, the Bell Telephone Laboratories in New Jersey, asked their research engineer, Karl Jansky (Figure 1), to investigate the interference environment in the "short-wave" band around 20 MHz. (In today's radio astronomy, this would be considered a long wavelength). In particular, Jansky was to look at frequency bands where naturally-occurring radio waves were weak, since this background radiation would be a limiting factor in determining whether faint communication signals could be detected at large distances. Jansky constructed an antenna (Figure 2) suitable for scanning the horizon at about 15 m wavelength. The working of his instrument has been thoroughly described in several publications (Kraus, 1981).

1 see for example on Wikipedia: https://en.wikipedia.org/wiki/Technology_during_World_War_II

Figure 2. Jansky antenna (c. 1930)



Jansky was both a good radio engineer, and a careful scientist. He detected "static" from local and distant thunder storms, as expected. He also found atmospherics from unknown sources, including one type which was always present, and followed a consistent daily pattern. It eventually became clear that the diurnal cycle adhered to timing, not of 24^h duration, but lasting 23^h56^m: The temporal pattern was sidereal, not solar. The most intense radio static came from the direction of the stellar constellation Sagittarius, which was interesting as it is the location of the center of the Milky Way. The nature of the radiation – the process by which it was produced – was a complete mystery. The Galaxy we see consists of stars and glowing gas clouds. Could the radio waves also have their origin in stars? Since the sun is a star, one might expect a radio signal to reach us from the sun, but in fact, none of the antenna records showed a hint of solar radio emission.

Figure 3. Grote Reber (c. 1960)

Having completed his investigation of radio static, Bell Laboratories assigned Jansky to other research, and the detection of extraterrestrial radio emission was not followed up. Although there were several proposals to continue studies of radio emission from space, none of them received funding. At the height of the great depression, this may not have been too surprising. The field was open to anyone with time, a large space (Jansky's antenna spanned some 30 m), an interest in radio equipment and a bit of money. In Wheaton, Illinois, there was such a person: Grote Reber (Figure 3). He had the discipline of an engineer, and the curiosity of a scientist. The backyard of his mother's house (also his residence) was just large enough for his project: The construction of a 9 m parabolic reflector and its supporting struts. He had studied radio engineering and electronics, and was a keen "ham" (radio amateur: callsign – W9GFZ). In his spare time, Reber constructed a steel reflector which could be steered in elevation. It was a meridian-transit radio telescope (Figure 4).

Figure 4. Reber 9-m antenna in Wheaton, Illinois (c. 1938)

With his instrument (and after overcoming initial difficulties), Reber was eventually able to confirm the existence of Jansky's radio emission from the Milky Way, and began making the first maps of the radio sky at declinations >-45°. His first astronomical publication on radio emission appeared in June of 1940. Reber continued his measurements throughout the war. With the 1940 publication, the story takes an unexpected twist.

Prof. Jan Oort (Figure 5) of Leiden University Observatory was keenly interested in understanding our Galaxy, having studied it for nearly 20 years. From the motions of stars near the sun, Oort had shown how the kinematics could be unraveled. What one really needed, however, was information on the motion of stars near the galactic center, but obtaining this seemed all but impossible. Research in the 1930s had shown that the disk of the Milky Way is filled with dust particles which obscure its more distant reaches, and in particular mask the vital center, around which everything spins. Seeing through this dusty fog seemed impossible. An important clue to overcoming the obstacle was contained, surprisingly, in Reber's article, but it would only reach Oort by a circuitous path.

Figure 5. Jan Oort (c. 1935)

In May 1940, the Netherlands was invaded by Germany, and a number of American publishers, with postal delivery in Europe uncertain, suspended the dispatch of their periodicals. By the autumn, Oort expressed his concern about the

Figure 6. Herre Rinia

delayed deliveries to his former colleague Bart Bok (then working in America), who looked into the matter. An agreement was reached which would ensure that scientific publications (like important astronomical journals) would reach the major European institutions despite the war. By December, the June issue with Reber's article had reached Oort. There are several facts which indicate that the information about radio emission from the Galaxy had an immediate impact. Oort sent the article to H. Rinia (Figure 6), a senior Philips engineer who had done some consulting work for Leiden Observatory. In his reaction, Rinia notes that the radio waves will penetrate atmospheric clouds as well, making observations of galaxies at radio wavelengths possible, even from the cloudy Dutch environment.

There was another indication that the research on radio emission from the Milky Way had significant impact in the Netherlands. At the time, there was a popular Dutch astronomy magazine called *Hemel en Dampkring* (Sky and Atmosphere), rather similar to America's *Sky and Telescope*. Within a couple of months, a summary of the Reber article was published by D. Koelbloed (an Amsterdam astronomer, who never did any research in the radio field). Oort had close contacts with *Hemel en Dampkring* 's editor, the astronomer J.J. Raimond. It seems fairly likely that Oort had something to do with the appearance of an article on the topic of radio astronomy.

After this flurry of activity and interest in the possibilities offered by radio research of galaxies, several years of relative silence follow. While the trigger had been Reber's 1940 article, it is unclear to what extent Dutch astronomers might have been aware of Jansky's work, most of which had been published in engineering journals. There are hints in a 1977 interview that Oort might have heard of it before 1940. He spent most of 1939 visiting astronomers in the U.S., and Jansky's discovery might well have come up in discussions. There is, however, no hard evidence that Oort was aware of it, and it seems that if he was, it had not made much of an impression on him.

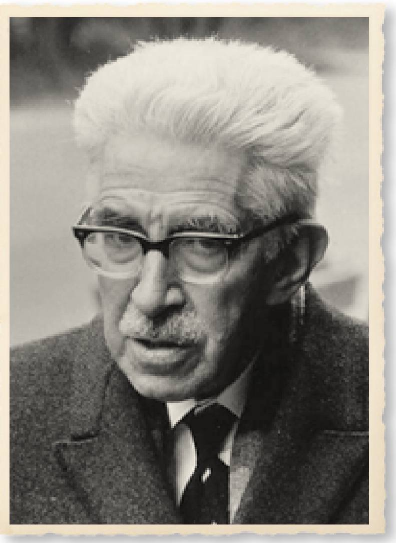


Figure 7. Marcel Minnaert (1967)

In 1941, not long after Reber's article had caused some commotion amongst Dutch astronomers, Marcel Minnaert (Figure 7), the director of Utrecht Observatory, organized the first national astronomy conference (NAC). There is a remarkable photograph of the participants (Figure 8), noteworthy because it includes many of the people involved in this early interest in radio astronomy (and almost as notable because the original is in color). There is also a program

Figure 8. 1941 NAC participants: Oort (far left), Minnaert (3rd from left), Houtgast (back centre, with beard), Van de Hulst (front centre, in shirt sleeves), Koelbloed (far right)

which lists the talks given during NAC 1941. Not a single one is related to radio emission, but this absence is probably not too surprising. No one present would have had much knowledge of the radio technique, whatever their interest might have been (though Koelbloed might have given a brief summary).

Here the matter rested for most of the war years. Oort did pursue the problem of interstellar dust, its production and destruction. He got Henk van de Hulst (Figure 9), then a student of Minnaert, to participate in this research, and to that end he arranged an extended visit to Leiden in the first quarter of 1944. Minnaert, who was politically left wing, was taken hostage, as were other prominent Dutch citizens, from 1942 to 1944. Oort left Leiden for most of the war years, to avoid a similar fate. From his undercover address he would regularly cycle the 100+ km to Leiden, to keep contact with colleagues and astronomy. He kept busy researching a planned book on the Galaxy, a work which never saw the light of day. One can only imagine that sometime, while thinking of the book, the possible use of radio astronomy in galaxy studies may have occurred to him.

Figure 9. Henk van de Hulst

In the planning for Van de Hulst's 1944 visit, no mention is made of radio. It only comes up after the visit has already begun. In Van de Hulst's own words, "In the spring

Figure 10. 1944 Leiden colloquium: Van de Hulst speaking, Oort far left (from 1957 film)

of 1944 Oort said to me: 'We should have a colloquium on the paper by Reber. Would you like to study it? And, by the way, radio astronomy can really become very important if there were at least one line in the radio spectrum.' " That line was, of course, the 21 cm HI transition, the likely detection of which was predicted by Van de Hulst at the April meeting.

The 1944 colloquium (Figure 10) in Leiden had as its title, *Radiogolven uit het Wereldruim* (Radio waves from space), and Oort had arranged for two speakers to discuss Reber's results. Cornelis Bakker (a physicist with the Philips NatLab., Figure 11) reviewed radio technique. Van de Hulst considered the origin of continuum radio emission, then possible lines: Recombination, and that of neutral hydrogen at 21 cm.

The existence of a hyperfine transition in atomic hydrogen was already known, but its physical properties were rather uncertain. Moreover, the conditions in interstellar space were unclear. The line might appear in absorption or in emission. On top of that, the hydrogen might all be in molecular form (H_2), rendering it undetectable by radio. In view of all these uncertainties, Van de Hulst was cautious in what he said.

Oort, never one to let things stagnate, wrote Bakker just four days after the Leiden Colloquium, thanking him for his contribution, but also asking whether Philips could build a receiver for the radio antenna reflector which was already taking shape in his mind. In his reply Bakker said that while there was interest at Philips, little could be done before the end of the war.

Figure 11. Cornelis Bakker (1959)

What was needed to look for the 21 cm HI line? The antenna, which was only the most visible component required (it is pictured in Figure 4), would in Oort's original plan be constructed by the Observatory workshop. He may have reasoned that if Reber could construct a 10 m dish with his own labor and funding, then the Observatory would surely be able to build something larger using its manpower, and public funding. This was rather optimistic, and a year later he was in contact with a civil engineering firm. Oort may not have realized that it would be almost as difficult to acquire a sufficiently low-noise receiver: 21 cm was an extremely short wavelength at the time. Bakker indicated that Philips could build low-noise amplifiers only for wavelengths of 30 cm and longer. Finally, there was the problem of finding an excellent radio engineer, as Reber had strongly advised in correspondence.

Despite the challenges, Oort and others began serious efforts to carry out radio astronomical research from the Netherlands. In 1946 or 1947, Ir A. H. de Voogt (Figure 12), head of the Post Office Radio Division, appropriated a number of abandoned German Würzburg radar dishes and set up the country's first radio astronomy observatory near Kootwijk. He, Minnaert and Jaap Houtgast (Figure 13) helped form a workgroup to study the ionosphere and radio emission from the sun. By 1947, Oort was also involved in the discussions.

Figure 12. A.H. de Voogt (c. 1947)

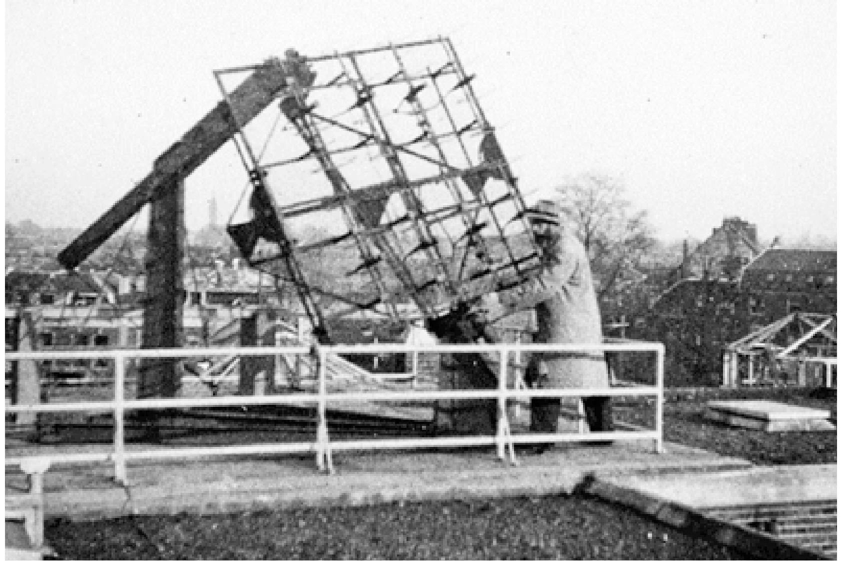


Figure 13. Jaap Houtgast with radar antenna for solar observations (Utrecht, Dec. 1947)

Figure 14. Cornelis Gorter (portrait by Harm Kamerlingh Onnes)

Figure 15. Kootwijk Würzburg 7.5-m radar antenna, observed HI, 1951

The Leiden physicist Cornelis Gorter (Figure 14), who had done laboratory experiments with microwaves, was also interested in detecting the 21 cm line, and apparently began an independent project in 1946. By 1948 he had an engineering student from Delft, H. Hoo, working on the problem. Meanwhile, De Voogt had suggested that Oort might use one of the Würzburg antennas (Figure 15) for the 21 cm line search, and the Gorter and Oort efforts were merged. Oort and Minnaert set up a Foundation for Radio Astronomy (Figure 16), which included representatives from Philips, the Meteorological Institute (KNMI) and the Post Office, and Hoo became its first employee.

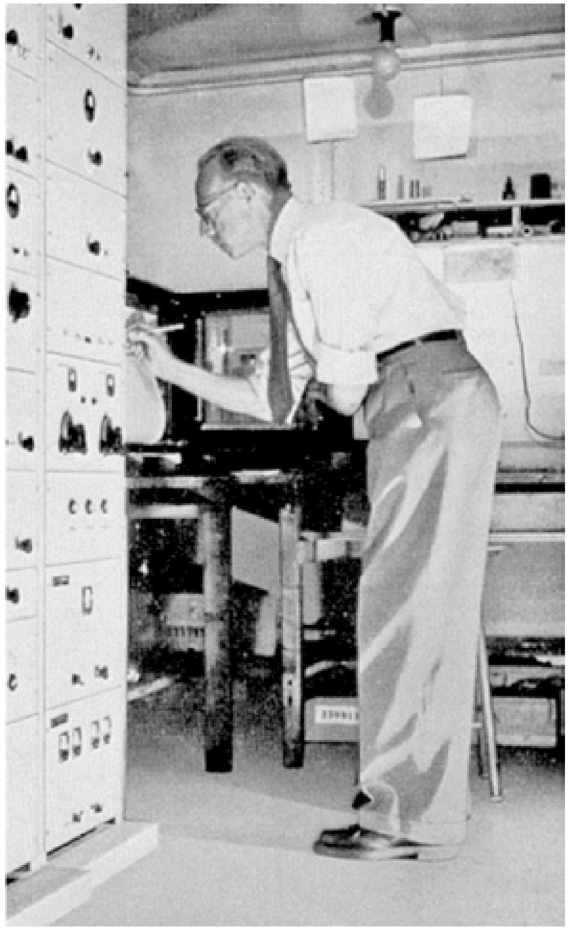
Figure 16. First Board of SRZM (1949). Top (l. – r.), Minnaert (vice chairman), Oort (chairman), Houtgast (secretary), Van de Hulst. Bottom (l. – r.), Frans Stumpers and Rinia (both Philips NatLab), Vening Meinesz and Jan Veldkamp (both KNMI), De Voogt (PTT)

By 1949 test observations were being made on the borrowed Würzburg at Kootwijk using Gorter's amplifier. Progress was steady, but slow. Then, on 10 March 1950, disaster struck. A fire destroyed the receiver hut and all the equipment. Some personal items were also lost. The total loss was estimated at 8000 guilders, about 50% of the annual budget, and nothing was insured. Fortunately, no one was hurt, but Gorter's amplifier and a new Brown recorder worth 3500 guilders had to be written off.

Meanwhile, across the pond... By 1950, another team was also looking for the line. Harold Ewen and Edward Purcell (Figure 17) at Harvard had heard about Van de Hulst's prediction at a conference in 1949. Both had radar experience and came up with a simple solution to the antenna problem: A horn. Their equipment was similar to that of the Dutch, based upon a super heterodyne receiver, with one important innovation. Frequency switching was used to remove amplifier drift. In addition, certain electronic components in Ewen's possession

Figure 17. Harold Ewen and Edward Purcell, 1956

Figure 18.
C.A. (Lex) Muller in the Kootwijk Würzburg receiver room (c. 1954)



were probably of higher quality. The line was detected on Easter weekend, 1951. *Finally, Dutch success just weeks later...* With the newly employed engineer Lex Muller (Figure 18), the Dutch team detected the line just 6 weeks after Ewen and Purcell, and both results were published simultaneously. For Ewen it meant the completion of his Ph. D. thesis. He and Purcell did not follow up their detection. For Oort and his team, it was only the beginning of systematic studies, first of the Milky Way, and later of other galaxies.

While the Foundation was occupied with its effort to detect the HI line, planning also continued with the intention to construct a 25 m class radio telescope to investigate the characteristics of atomic hydrogen in the Milky Way. Once the line had been detected, some of the manpower could be switched to the 25 m effort. Observations with the 7.5 m Würzburg at Kootwijk continued, and a survey of the visible sky was made in 1952-1953. The data were reduced and interpreted under Van de Hulst's guidance with the help of several students, and in collaboration with Muller and Oort (1954). By 1951, the 25 m antenna

Figure 19. Queen Juliana and Prof. Oort, opening of Dwingeloo 25-m Telescope, 1956

project was contracted to the civil engineering firm Werkspoor, and at the end of 1953 a site had been chosen near the village of Dwingeloo. Construction began in 1954, and the Dwingeloo Telescope was opened by Her Majesty Queen Juliana in April, 1956 (Figure 19).

Oort once again used a two-track approach by starting the next large telescope project during the latter stages of its predecessor, in this case, the Dwingeloo Telescope. Always aware that angular resolution at radio wavelengths, around 1 arcmin, would usually be inferior to that of optical telescopes, where 1 arcsec was possible, the plan would be to build an array of some 5 km overall size, in collaboration with Belgium and Luxembourg. The array would be in the form of a cross (or T), building on several successful radio telescopes in Australia, Canada and the US. It became the Benelux Cross Antenna Project (BCAP), to be constructed near the Belgian/Dutch border. The details of the project are described by E. Raimond. In the end, Belgium withdrew from the project, and it was modified, to become the WSRT.

Chapter 2

Concept, Design and Metrology of the WSRT Antennas

Jaap Baars*

1. Enter the BCAP/WSRT Project

In the spring of 1963, shortly before my physics graduation at the TU Delft, I applied for a job with the Benelux Cross Antenna Project (BCAP) at Leiden Observatory. The project was somewhat in disarray. Belgium had announced its withdrawal, and a significantly cheaper, and hence smaller, instrument was to be defined. With the successful demonstration of earth-rotation-synthesis by Ryle's group in Cambridge, the "Cross" was being reduced to a "Line" and Jan Högbom, Lex Muller and Ben Hooghoudt were trying to find the best array layout fitting the budget. They did not need me for that, but offered me to join the receiver development group. That was not what I wanted and with Prof. Oort's help I landed a junior research position at NRAO in Green Bank.

Upon my return in the fall of 1966 the telescope had been fully defined and I was given the job of assistant to Ben Hooghoudt, who was Project Manager for the civil works and the mechanical, electrical and control section of the Project. Soon I was spending most of my time at the site in Westerbork, where a lot of different activities were carried out. I was given the task overseeing and coordinating the large amount of metrology activities, and to assure that the contractor would satisfy the specifications. Hooghoudt involved me increasingly in the management of the project.

2. Specifications of the Westerbork Synthesis Radio Telescope (WSRT)

The original WSRT consists of 10 polar mounted reflector antennas of 25 m diameter, placed at an interval of 144 m along an East-West baseline and a 300 m long rail track at the eastern end that carries two more mobile antennas. The signals from the two mobile elements are combined ("correlated") with each of the 10 fixed antennas to provide 20 interferometers of different baseline length. During 12 hours observation the projection of the baselines on the sky rotates, providing data in the orthogonal coordinate. Four different positions of the mobile antennas "synthesise" a fully covered telescope of 1600 m diameter. It yields an angular resolution of 25 arcseconds at 21 cm wavelength. The observing process is slow, but it allows the creation of a large "synthesis telescope" at affordable cost.

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For the proper operation of a synthesis telescope it is important that the positions of the element antennas with respect to each other are accurately known at all times during the long observing time. The same is true for the time differentials that the received signals encounter on their path from the antenna through receiver electronics and cables to the correlator. In an ideal situation, these data are known and stable over the time of observation. This requirement may extend over several days as the mobile antennas occupy different positions on the track.

One way to accommodate deviations from this requirement is to determine the instrumental parameters from an observation of a cosmic radio source with a precise celestial position and sufficient intensity. This is called "calibration" of the interferometer. In the early sixties, not many such sources were available. Also, calibration takes away observing time from the object of interest and requires additional computation in real time. Synthesis is inherently computation intensive and computer power in those days was limited (the IBM 360 only became available in the mid sixties).

The decision was made to realise the synthesis telescope with a geometrical, mechanical and electronic precision and stability that would enable observations without the need for detailed calibration and correction of the data. The major specifications can be summarised as follows:
- baseline: East-West to < 1 arcsecond, straight and flat to <1 mm
- antenna position: < 1 mm in all three coordinates
- antenna internal dimensions and axis perpendicularity to < 1 mm and <5 arcsec
- reflector precision 5 mm rms for almost perfect performance at 20 cm wavelength
- a high symmetry in all system parts influencing phase stability.

3. Metrology methods and equipment

3.1. Baseline and antenna position

The E-W baseline was established by three concrete pillars at both ends and at the mid-point of the baseline. At the nominal position of each antenna, 144 m apart, a pillar with adjustable marker was aligned to the established E-M-W line. Dr. G. van Herk, a seasoned astrometrist of Leiden Observatory who had spent long periods in his younger years on the equator at a high site in Kenya measuring star positions was assisted by several colleagues to perform the measurements. Van Herk preferred drizzly weather because of the more stable atmosphere. He withstood the rain by cutting some holes for his arms and head in a huge plastic garbage bag, which we then pulled over his head at the start of the shift. He established the azimuth and declination of the baseline to exactly 90 and 0 degrees, respectively with an uncertainty of 0.5 arcsec. Later astronomical calibration confirmed the azimuth within the error and indicated a declination of -0.6 arcsec. The position of the markers at the antenna position was determined with an accuracy of 0.1-0.3 mm. Standard geodetic methods were used to position the antenna with respect to these markers. Radio astronomical checks found a few antennas to deviate by 2-3 mm, the remaining were within the measurement error of 0.5 mm.

3.2. Assembly of the antenna structures

A large temperature controlled assembly hall was erected at the site in which templates were placed to aid in the welding and assembly of the major sections of the antenna. These are sketched in Figure 1 and the hall is shown in Figure 2. A challenge was the realisation of better than 1 mm precision in the important dimensions within the antenna structure and amongst the 12 antennas, while allowing "standard" workshop procedures as far as possible. The shop fabrication produced parts that could be transported to the site. The biggest pieces were the gear racks that came by ship to about 10 km from the site and needed special road transfer for the last leg. The polar axis house and declination cradle (see Figure 1) were welded in templates with a carefully controlled procedure, continuously checked by measurements. The same expert welders worked on this during the entire production. They assured identical dimensions among the 12 antennas. The orthogonality of polar and declination axes is better than 0.2 mm and 3 arcsec.

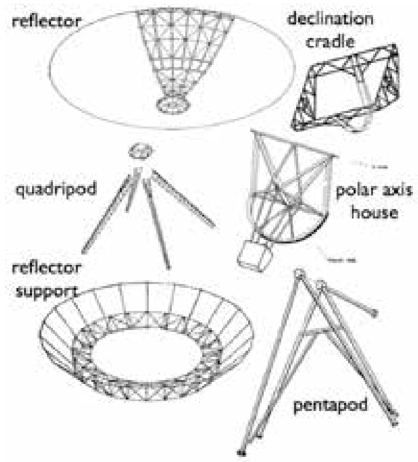


Figure 1. Exploded view of the major antenna sections. Polar axis house and declination cradle are welded in accurate templates.

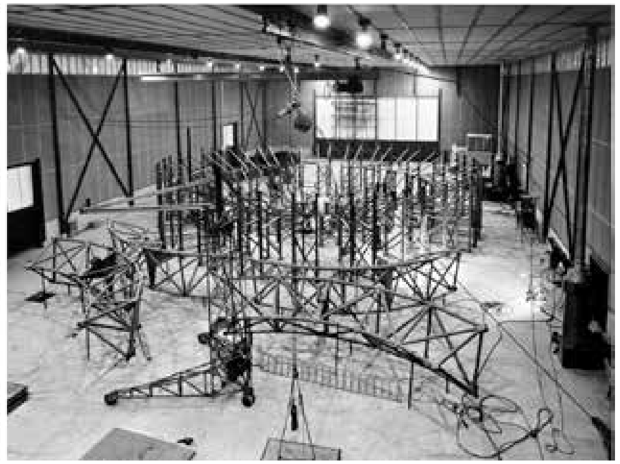
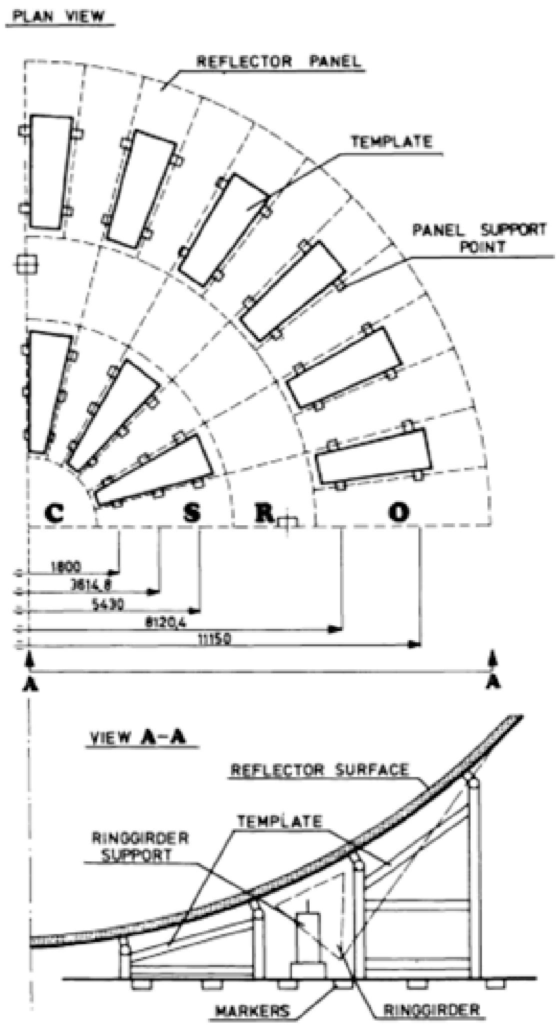


Figure 2. Assembly hall with template for reflector assembly in background. Shop fabricated ring girder sections are visible in the foreground. The temperature-stable hall is 60 x 30 m.

The assembly of the reflector was the most time consuming and labour intensive activity. Mr. A. Bijloo of Wilton-Feijenoord developed the template layout and the assembly and measurement procedure. As shown in Figure 2, the template consists of 72 vertical steel frames that carry the support pins on which the reflector surface panels will be laid out (Figure 3). There are 48 panels in

Figure 3. Layout of the template for the reflector. Note the support column for the ring girder inside the template.



the outer and 24 in the inner ring. Within the template there are 4 support columns that mimic the four corners of the declination cradle, to which the ring girder of the reflector is attached. The ring girder is welded complete from the four sections delivered from the factory.

The support pins on the template frames are adjusted to the required position by optical means as illustrated in Figure 4. A levelling instrument determines the correct height with respect to a calibration pillar and the radial coordinate is set with the aid of an optical plumb line to markers on the floor. Note that no angle measurements are involved in this scheme. The position of the support pins is precise to a few tenths of a millimetre. For this tedious and difficult work Bijloo had the assistance of the twin-brothers Bakker, who later became a

Figure 4. Schematic of determining the precise position of the panel support pin.

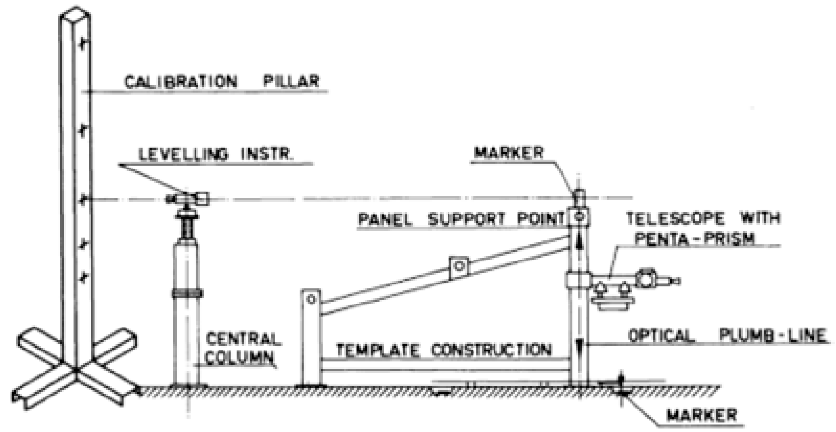
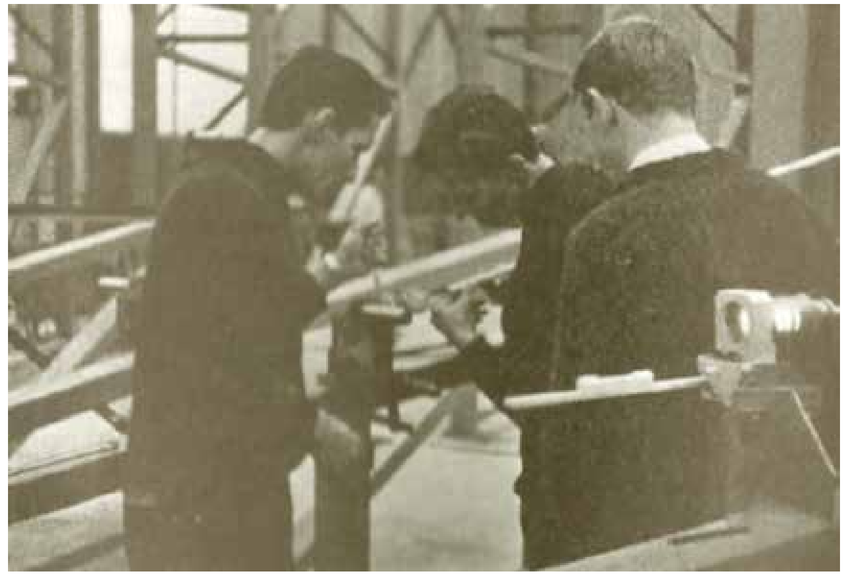


Figure 5. The twin-brothers Martin and Jaap Bakker adjusting a support pin. The author observes and documents the readings.



staple of the mechanical workshop in Dwingeloo. They formed a remarkable team. Once Bijloo described to them the need for a tool to simplify the work. They listened, nodded, and without exchanging a word each went to a different machine or bench. After an hour they produced the tool consisting of several parts that fitted together perfectly. Figure 5 shows them at work while I record their measurements on paper.

3.3. Assemble reflectors

The reflector panels, each a stiff steel frame of parabolic shape with a stainless steel surface mesh bonded by epoxy resin, were laid out on the support pins. The same measurement method was used to check the height of the surface in

The 1968 Building Site

Jan Buiter, Roelof Kiers

Quoting from Anke den Duyn's* text in the ASTRON JIVE Daily Image, the shortest story of the beginning of WSRT is as follows: *At the silent places on Earth, where astronomers look back in time with advanced technology, various historical timelines may intersect. In 1964, an icon of radio astronomy was put on the map by means of a thin red line, crossing out camp "Schattenberg". It was the first uncontroversial use of this small piece of land for several decades. More than ten years earlier, in March 1951, the ship "Kota Inten" had brought the first KNIL soldiers and their families from the tropical Molucca Islands to the chilly Netherlands just before Indonesia as former Dutch colony won its independence. They were accommodated into the former transit camp Westerbork now renamed Schattenberg.*

In 1966 about two years after breaking soil for the building of the WSRT the situation was as shown in the picture. With the assembly hall in the foreground between the yet unfinished telescopes RT1 and RT2 and the foundations of RT0 in the near foreground, it also shows in the background the Schattenberg camp which was in the slow process of being dismantled.

In fact, as the WSRT building evolved and started to do its earliest operations in 1968, a few hundred men, women and children were still living on the site watching the machine of the future being built. Co-existence evolved smoothly while the relocation progressed. The first engineers, observers, and operators on site fondly remember the Moluccan specialties kindly offered to them by their neighbours during 24/7 observing duties! They included Jan Buiter, one of the early Dwingeloo engineers involved in the construction, and observers/operators Sip Sijtsma and Kees Brouwer, and later Roelof Kiers who joined in 1970. Sip SIjtsma remained in Westerbork while the other three joined the lab in Dwingeloo and continued working for ASTRON until their retirement.

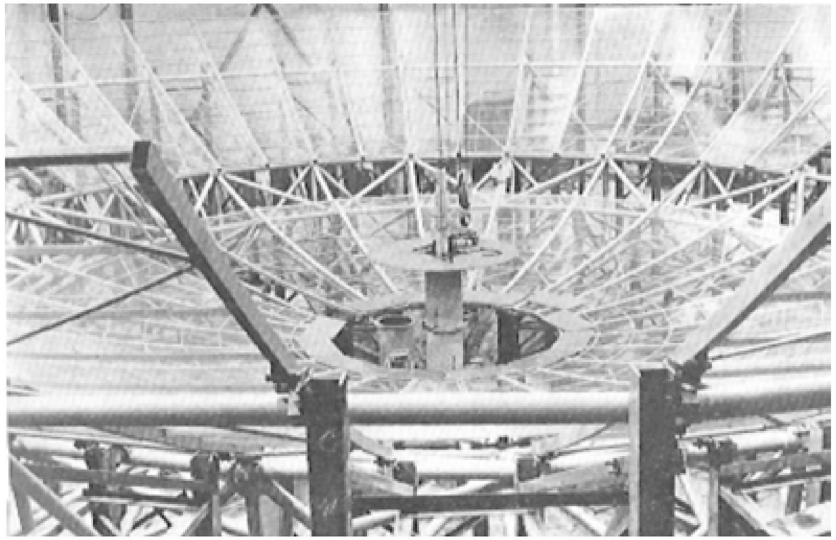
* Anke den Duyn is author of the book "Het logboek" which appeared in 2014 and translated as "The Journal" in 2016 (ISBN 978 90 822 3961 4)

order to correct imperfections in the panel with spacers. Once the panels were properly positioned they were bolted together to form the final surface. The panels provide the required stiffness; no further support structure is needed for the inner panel ring. The outside ring is supported by radial beams connected by a hoop at a radius of 10 m (Figures 1 and 6).

The connection of the reflector with the ring girder is highly original and simple. At each connection point there is a socket on the ring girder and the panel has a downward pin that protrudes into the socket with plenty of lateral tolerance to accommodate for standard manufacturing tolerances during welding of the ring girder in the shop. The space between pin and socket is filled with epoxy resin. A stress free connection is formed thereby without any influence on the reflector. This innovative solution has endured 50 years without any noticeable degradation! Unfortunately the epoxy bonding of the panels broke after about 8 years and was solved by fixing the mesh to the frame with thousands of screws (see insert by Wout Beerekamp). The method was later applied at other telescopes and with the improved precautions, proved successful.

The completed reflector surface contour was measured at about 250 points on the surface to check the overall parabolic shape. These measurements indicated some small systematic deviations, mainly in the outer panel ring, that could be decreased by changes in the order of bolting the panels. The average surface error of the antennas is 1.5 mm rms which is a factor three better than the specification. The very low surface error was achieved thanks to the high precision of the individual panels, and also to the corrections applied during the carefully measured assembly procedure.

Figure 6. A partially assembled reflector in the template. The uncovered ring girder is visible in the upper part. The hoop and the outer panel are seen in the foreground.



A further test was done to measure gravitational deformation. By lifting the reflector off the template so that it was supported only on the four support pillars of the ring girder, the gravitational deformation in zenith position was determined. It turned out to be about half the predicted value from the structural analysis, making the careful assembly all the more valuable. The result was that the telescope could be used with high efficiency at 6 cm wavelength.

4. Conclusion

Looking back 50 years I find it remarkable that all involved maintained a dedication to achieving the best possible precision in a repetitive process of assembling 12 antennas over a period of close to two years. Not much exciting happened on site, so we all took a brake when the huge crane appeared to assemble two antennas within three days. We had a really scary moment during the hoisting of the first reflector. A manoeuvre had been worked out to use two relatively small cranes, one of which was already in continuous use on site. Early in the hoisting with both cranes moving the reflector between them the load balance got skewed and a cable broke. With great luck we managed to lower the dish to the ground without damage. The rest of the hoists were performed with one huge crane with a double boom. It was expensive but it worked flawlessly.

One can ask whether the very tight tolerances applied to about every aspect of the WSRT, not only the baseline and antennas but also the electronic and cable system, weren't a bit of overkill. In the current situation of abundant computing power one might not be so demanding about mechanical tolerances. I have asked a few colleagues of the early days this question and their answer is "no, it wasn't overkill!" The high precision and, perhaps more important, the very high stability of the baseline while tracking enabled 12-hour observations without interruption for calibration. It helped the commissioning enormously and good quality maps were obtained from the beginning.

I conclude that we did not waste our time during the construction period. I add that it was also a period of satisfying work with excellent collaboration between observatory staff and contractors. The leadership of Ben Hooghoudt was stern but fair and he ensured that the relationship between customer and contractor did not become too cosy.

Chapter 3.1 From Design to Observations

Wim Brouw*

1. International

Designing and building the Westerbork Synthesis Radio Telescope was from the beginning an international affair. Not only within the three countries of the Benelux cooperation, but, due to the local lack of more than rudimentary knowledge about interferometry, by inviting specialists from abroad to become part, or even lead the design group.

Engineers from Australia and the US spent one or two years in Leiden at the Benelux Cross Antenna Project group, to share their knowledge. Thanks to the extensive connections of Jan Oort, and the fame of the Dutch astronomical community in general, there was no lack of people willing to come to Leiden!

This open attitude continued after the inauguration of the telescope. The National Foundation for Radio Astronomy (NFRA, now known as ASTRON) became the centre for radio astronomy in the Netherlands, or arguably of Europe, especially after the BCAP group joined the NFRA, as did the solar radio astronomy group from Utrecht University.

Open skies, where anybody could propose an observing project judged purely by its scientific merit, was the standard, although it was always recommended to collaborate with somebody in The Netherlands. The calibration knowledge of the NFRA staff was extremely important to help with the data reduction, which was only possible with specialised software for specific computers. There was no such thing as general hardware and software across computers from different makes. Even magnetic tapes, the output medium of choice, had different hardware specifications for different computer brands.

The fact that the WSRT was the first openly available multi-pixel radio camera made it attractive to a new generation of young astronomers to come and work in The Netherlands. They came to "learn the trade," but also generated new ideas. Both Dutch and foreign staff became in later years directors of new large radio telescopes.

In the same open atmosphere Dutch staff, notably software staff, spent one or more years at telescopes built overseas to help get their software up and run-

* Kapteyn Astronomical Institute, University of Groningen and ASTRON, The Netherlands

ning. The Fleurs Radio Synthesis Telescope (Australia) and the Very Large Array (USA) are examples. With this network, it became also feasible to exchange staff, both scientific and technical, on a regular basis between the several Radio Astronomical Institutes in the world.

The many new astronomical discoveries after the opening of the new window on the universe, made it clear that for the best interpretation of the new data, access to northern hemisphere observatories at wavelengths other than in the radio domain was important. Again cooperation started abroad, and the Netherlands, largely through the NFRA, became part of the optical UK/NL/ES "Roque de los Muchachos" observatory in the Canaries, and the sub-mm James Clark Maxwell Telescope with UK (and later Canada) on Hawaii. Cooperation with European Space Agency related groups, and involvement in several satellite programmes, opened the IR, γ-ray, X-ray and UV part of the spectrum

2. From analogue to digital

The WSRT was designed in the mid-nineteen sixties and built in 1965-1970. General purpose digital computers were slowly becoming available. The University Computer Centres had their high-end digital computers (16 kop/s, 64 kbyte memory), and process computers

Leiden University had a large university computer. It was programmed to reduce the data from raw WSRT interferometry correlations to make images. It was done mainly in machine code for efficiency reasons. Groningen had a

Figure 1: The correction for the direction dependent time delay for each element telescope was done by a series of switchable cable lengths per telescope, stored in the basement of the WSRT control building. Each telescope had a set of cables, totalling 1500 m in total, and switchable increments of 10 m (around 30 ns), at the intermediate frequency of 30 MHz) (E. Raimond, 1974)

different make of computer which could not run the same software. Converting it was too expensive. At the WSRT site a process computer was used to read a programme schedule and send data to the telescope steering units, and the receiver control units. In 1970 the steering of the individual telescopes was done by an analogue system (originally used for a 3-D lathe). The essential delay system to get the sky data in phase at the different telescopes was done by switch-

Staatsbezoek?

Richard Strom

It must have been in the early months of 1977 that most of us first heard the news. The radio observatories would receive a special visitor in June: The president of Suriname. As head of state, his host in the Netherlands would be none other than the Queen. Of course, H.M. Juliana had visited the observatories before – she was there to open the WSRT in 1970. In any event, preparations were made, and naturally there would be a welcoming ceremony for SRZM's[1] two guests. What more appropriate way to greet them than by having two children present flower bouquets? The children would be chosen from the families of Foundation employees, but how to select them? The only fair way was by lottery, and so a draw was organized. The winners were the oldest daughter of Dan Harris, and the son of Richard Strom (looking back on it, this outcome was pretty unlikely – one might say almost astronomically improbable! Both Dan and Richard were members of the Astronomy Group, the smallest department in the Foundation at the time). Perhaps there was a certain accidental logic to having a visitor from afar be greeted by children from another continent. Just imagine, the rare opportunity to welcome two heads of state – it was truly a moment for both youngsters to look forward to!

Preparations for the state visit ("staatsbezoek") continued through the spring. President Ferrier would be in the Netherlands from 1-4 June. The visit to the observatories was at his express request. From 1959 to 1965 he had been an advisor to the Dutch Ministry of Education, Arts and Sciences, and had close contact with Prof. Oort, who then led the effort to construct the Benelux Cross Antenna, the forerunner of the WSRT. Then, as unexpectedly as it began, preparation for the visit came to an abrupt end. On 23 May, four young members of the South Moluccan community stormed an elementary school in Bovensmilde, taking children and teachers hostage. At the same time, a train was hijacked near De Punt. Bovensmilde is barely 10 km from the radio observatories, and De Punt is also in Drenthe Province. The president's trip was postponed while the country's attention focused on the disturbing events which unfolded over the following weeks. Eventually, the state visit was rescheduled for the fall, but the president never travelled to Dwingeloo. In September legal proceedings against the hijackers began in the provincial capital Assen, making a trip to Drenthe inappropriate.
And so, the Harris and Strom children never had a chance to greet two heads of state.

1 SRZM: Stichting Radio-straling van Zon en Melkweg (the Netherlands Foundation for Radio Astronomy (NFRA))

A Thousand words on early Phase Control

Johan Hamaker

In the beginning
I joined the project housed in a side building of the venerable Leiden Observatory to find some ten engineers and technicians who were enthusiastically developing the electronics for this new world wonder: Phase Control of the WSRT.

Without any quantitative experience, the one thing we clearly understood was that stability of the entire system was the key to success. The phase, associated with signal delays and path lengths, was recognized as the most critical parameter.

The high-frequency cables
For our microwave signals we need coaxial cables. These are hollow tubes with a metal wire in the centre that is kept in place by plastic spacers. Nearly all the cable volume is filled with gas. Unlike the rest of the electronic circuitry, we have no control over the environment of the cables. They are subject to large temperature variations on various time scales. These cables are a soft spot in the system. 1,5 km of metal expands by about 15 mm for every degree Celsius. How does this change for a buried cable? What about the dielectric? These and other things were not known because manufacturers have no interest whatsoever in phase.

The WSRT telescopes are used in pairs. For errors over which one has no control, we may rely on symmetry. If the same effect occurs in both members of a pair it cancels out. This has been a leading principle in the entire design of the WSRT. Brute-force application of this principle to the cables means that all must be made equally long, regardless of the physical distance to be bridged. This is all one can do because we cannot be sure that the environment will behave symmetrically. It doubles the total length and hence the price of the cable system.

The cable track on the telescopes poses special difficulties. Flexible jumpers must be inserted to cross the rotation axes, both for the electric signals and for the filling gas. Their installation, to be done under primitive circumstances, proved to be very labour-intensive. Fortunately, astronomy in those days had access to a pool of volunteer student labour that could be mobilised at short notice. Peter Katgert and Rudolf le Poole delayed their education at Leiden University by three months to complete the job!

The phase calibration system
Looking back half a century it is hard to justify the twenty or so man-years expended in developing a system that could calibrate interferometer phases over 1,5 km with an accuracy below one millimetre (some 1:2 000 000). The choice to do this reflects both our lack of understanding in those days of the many tricks of the interferometry trade and the generosity of our funding!

Calibration is a two-step process. 1) Establish a primary phase standard to each telescope. 2) Compare the astronomical signal paths in the interferometers against this standard and correct the former accordingly (in the computer).

This simple and ultra-sensitive leak detector for the pressurized cables consists of a few jam jars connected by some piping. Gas passing in either direction between two connected pieces of cable bubbles through the silicon oil in the jars. The number of bubbles reflects the gas flow and hence the differential pressure between the two sides. A steady flow betrays a leak.

For the primary standard we send a signal up a reference cable and observe a reflection from the far end. An electronic marker (a modulation) distinguishes this particular reflection from other, spurious ones that inevitably occur along the way. The returning signal is about a millionth of that transmitted, so a monochromatic wave generator is needed that must be very carefully filtered to prevent leakage into the astronomy channels.

From the reference cables a small signal is injected into the astronomy channels where it is processed as if it came from an astronomical source. Modulation serves once more to separate the two kinds of signals.

The grand finale: Triumph and oblivion
In early 1973 the system was tested in its entirety. Surprisingly, the reference cables showed pronounced diurnal variations with temperature; no two of them were the same. Only the cable tracts on the telescopes could be responsible, but the matter was left for later investigation. Later it became clear that traces of water cycling between fluid and vapour states must be the culprit and the management of the cable gas was revised.

Known sources ('calibrators') were observed with the correcting system active, leaving the effects of telescope geometries as the only known errors. A mathematical model of these effects fitted to the observations showed a very good match. Even misalignments of the polar axes and the effect of thermal dilatation of the movable telescope carriages were recognisable.

This great success notwithstanding, the system was never promoted to operational status. Over the long period of its development we had learnt enough to judge that the benefits would not justify the operational costs, let alone the effort of duplicating it for the additional wavelength ranges foreseen for the WSRT. Within a decade our decision was vindicated by the invention of "self-calibration". This revolutionary technique reduced most earlier calibration methods to primitive relics from the dark ages.

ing in and out pieces of delay cables (see Figure 1). The correlations between the signals was also done in an analogue correlator. 80 complex channels were available: 4 polarisations between the 2 movable and the 10 fixed telescopes. The correlations were organised in series of about 8 s per 10 s measurement, converted from analogue to digital values, and finally written to magnetic tape (128 kbyte per inch). The tapes were transported, after data verification, to Leiden by train which was a swift and reliable and broadband connection!

A lot of thought went into the format of the data output. This hierarchical format, which started with single frequency, 80 channel observations, continued to serve well after new observing modes were added such as mosaicking, multi-sources, multi-frequencies, millions of channels, and the format always remained backward compatible!

At the Central Computing Institute of Leiden University, the data were flagged, checked, calibrated and converted into images. Both the raw data and the images were catalogued on magnetic tape. This catalogue could be queried to find earlier observations, and to avoid duplication. The knowledge about data formats, databases, catalogues and search engines was later used in the JCMT and La Palma observatories. Tapes with maps were distributed to observers, together with plots made on a line plotter (see Figure 2) for astrophysical interpretation.

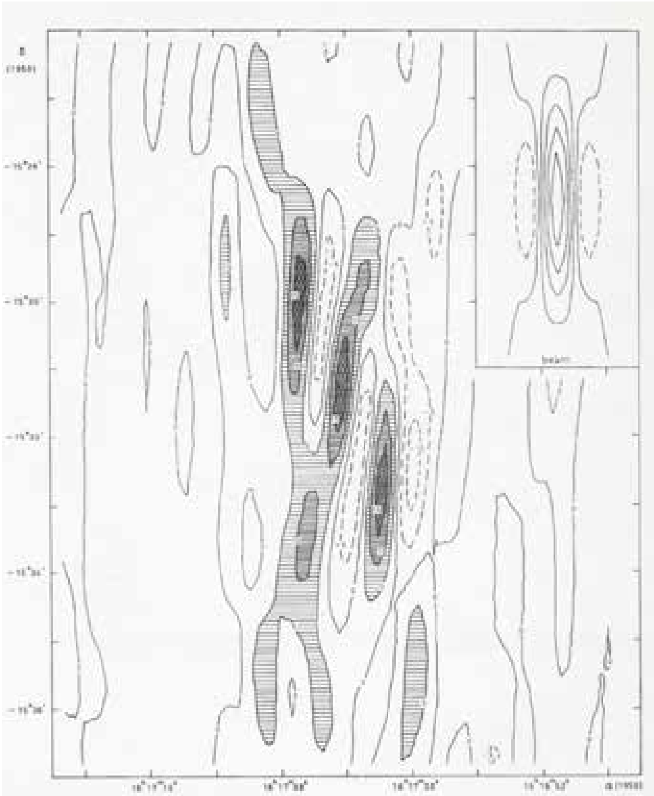


Figure 2: One of the first results of the new telescope was the observation of the X-ray source SCO-X1. It was resolved into 3 separate sources (a central variable source and 2 outlying sources). (J.H. Oort, Jaarboek ZWO 1970)

Clean was developed by Jan Högbom, an NFRA staff member, and source finding procedures were developed in Leiden. In Groningen, new display hardware and methods became available. Also, a large set of image handling routines were developed by students with the aid of the staff. This became the Gipsy system which is still available!

With the further advent of image handling and display facilities, often for digitized optical images, a standard exchange method was needed. Flexible Image Transport System (FITS) was designed in cooperation between ASTRON and NRAO, and this is also still in use today, including in areas outside astronomy! HI line work was one of the design goals of the WSRT. It was the idea to extend the imaging of our own galaxy done by the Dwingeloo telescope to that of external galaxies. Observations were done in a new mode of the analogue correlator: 2*5 interferometers, with 8 complex narrow channels each. Developments in the chip design and industry made it possible to start working on an extended digital correlator. Special chips were designed and manufactured, and in 1976 a digital lag correlator with 2560 complex spectral channels became operational. With the advent of cooled frontends, HI observations of external galaxies became a large market.

Sensitivity resolution requirements for line observations meant we needed more telescopes. Two more were built on the existing array, doubling the number of correlations. Later they were used to double the length of the longest baseline by moving them to a newly built rail 1500 m away (see Figure 3). The initial idea to move them by helicopter was not possible, and a special road was built.

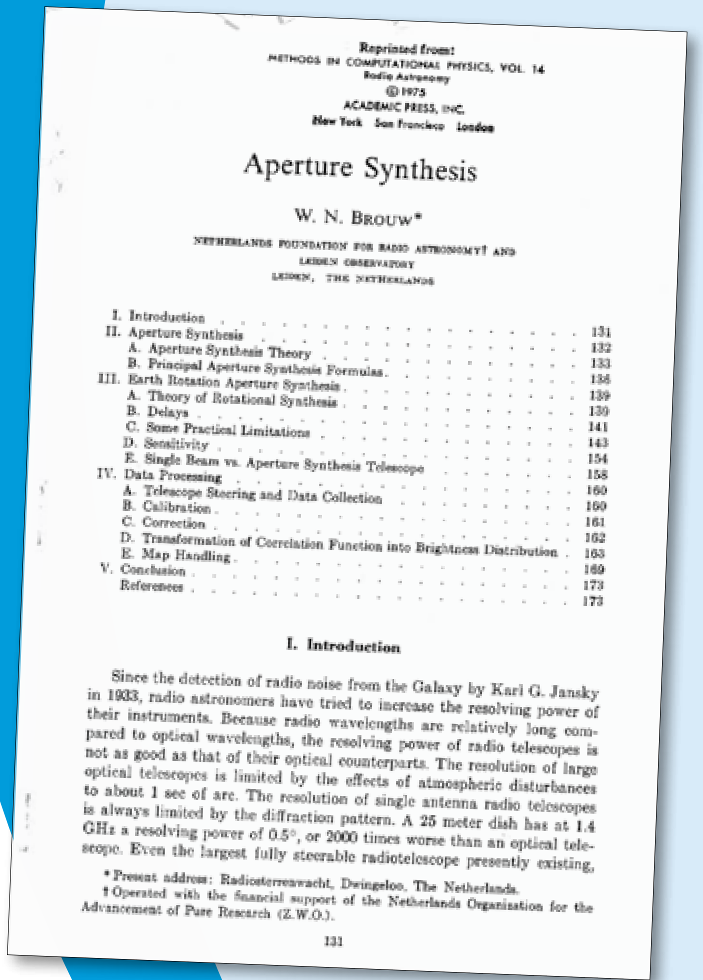
The digital receiver development did not stop here. A broadband digital continuum receiver was built, and a line backend with an order of magnitude more

Figure 3: At the end of the 1970s 2 telescopes were added on the existing track to the original 10+2 telescopes. After they were used to get a higher sensitivity, especially for HI line observations, they were moved to a newly built track 1500 m to the East of the existing telescope. A temporary road and bridge were built to get the 50 ton telescopes to their new position. (H.J. Stiepel)

The Last Word on Aperture Synthesis

Jan Noordam, Arnold van Ardenne

The book that was given us to read when first entering ASTRON as new electronics/physics recruits in 1975, was Wim Brouw's highly spirited 1971 PhD thesis work called *"Data Processing for the Westerbork Synthesis Radio Telescope."* It was firmly believed to be the obvious start for understanding Radio Astronomy besides, of course, the famous book by John D. Kraus "Radio Astronomy" published in 1966. Taken together this mighty canvas was supposed to strongly underpin our level of understanding such that a quick start could be made. The fact that we were given the opportunity to orient ourselves for some month as "trainees" (albeit not known by that name then), was greatly appreciated and an example we always tried to induce in later newcomers to the field.



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Aperture Synthesis

W. N. Brouw*

NETHERLANDS FOUNDATION FOR RADIO ASTRONOMY† AND
LEIDEN OBSERVATORY
LEIDEN, THE NETHERLANDS

I. Introduction

Since the detection of radio noise from the Galaxy by Karl G. Jansky in 1933, radio astronomers have tried to increase the resolving power of their instruments. Because radio wavelengths are relatively long compared to optical wavelengths, the resolving power of radio telescopes is not as good as that of their optical counterparts. The resolution of large optical telescopes is limited by the effects of atmospheric disturbances to about 1 sec of arc. The resolution of single antenna radio telescopes is always limited by the diffraction pattern. A 25 meter dish has at 1.4 GHz a resolving power of 0.5°, or 2000 times worse than an optical telescope. Even the largest fully steerable radiotelescope presently existing,

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† Operated with the financial support of the Netherlands Organisation for the Advancement of Pure Research (Z.W.O.).

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However, the final word on Aperture Synthesis by "the Master" was written in an account of over 40 pages, with no pictures in a lesser known book published in 1975. It shaped the WSRT, and the early VLA for that matter.

On the left is a copy of the first page which gives some clue to the where's and what's. It is remarkable to find that many issues that are keeping us busy today were already mentioned by Wim Brouw, based on the early experience with the WSRT synthesis processing and observations.

channels came later. The chips developed for the WSRT correlator were also used in receivers in telescopes abroad.

The extra telescopes, the need for higher pointing precision, including corrections for atmospheric refraction, necessitated also the replacing of the analogue steering of the telescope. Each telescope got a micro-processor, and a separate real-time process computer took over the role of sending commands to these microprocessors. In addition, a monitor system was included. The knowledge acquired by these changes was later used at the ATNF telescope in Australia.

At this point, the 5 operators needed for 24/7 supervision of the system were moved onto a normal 40-hour work week. A set of punch cards could operate the telescope for a number of days. Errors in the system were captured and sent by mobile phone (the old fashioned walky-talky variety) to an operator/technician on duty, who could look at some data or go to the telescope.

The large correlators required more and more of the processing power of central computers. Research was done to replace some of the processing with optical processing. E.g. the 2-D Fourier Transform necessary to convert the raw correlations into an image could be done with a lens and a laser: A lens is, in fact, a Fourier Transformer. Although some results were obtained, it became clear that on the one hand the lower precision and dynamic range were not acceptable, while on the other hand the development of digital computers went faster than the building of specialized hardware.

One of the results of the intimate knowledge of the internals of the Leiden Computer, was the first city wide network of terminals connected to a central computer. Institutes could use these special terminals to calculate with an interactive language, and with A Programming Language (APL). Later, Groningen and Dwingeloo were connected as well.

3. The broader field

Radio interferometers on the unstable surface of the Earth, at the bottom of the atmosphere, are limited in the dynamic range and positional accuracy they can reach. At the inauguration of the WSRT, with relatively low sensitivity, the attainable precision of about 20 dB, and 1% was sufficient. However, with the higher sensitivity, the longer baseline (see Figure 4), and higher frequency, these effects became more and more a hindrance to very high precision observations.

The use of self-calibration, and the redundant solutions that could be done with the redundant baseline set, made a large improvement, and these improvements made it also possible to do some other types of observations. If you correct by some other technique the errors caused by the ionosphere, you in essence measure some properties of the ionosphere. This lead to an increase in the existing cooperation with ionospheric scientists who were already us-

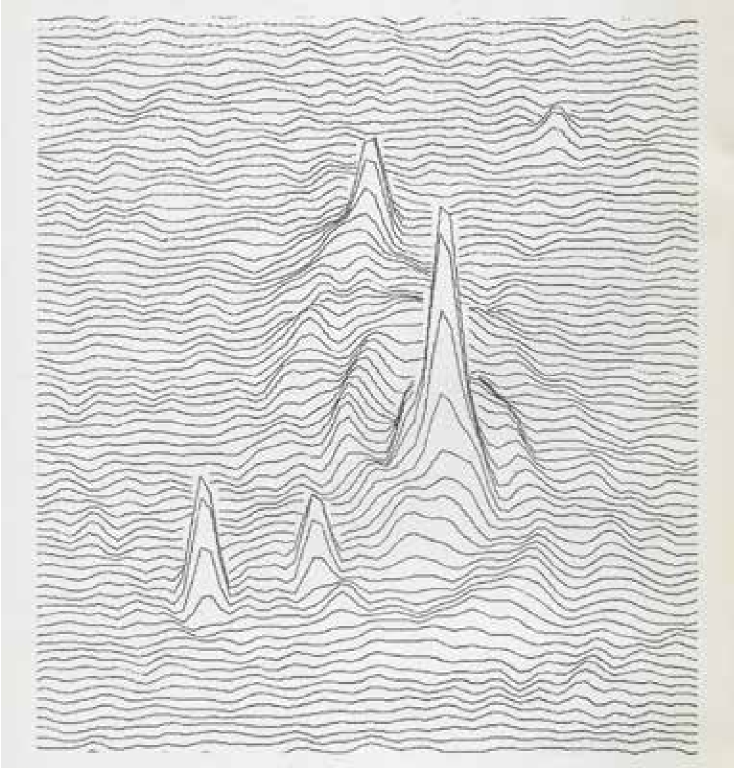


Figure 4: The WSRT was the first to image the spiral arms in radio continuum of an external galaxy: M51. The continuum radiation followed the optical spiral arms, giving rise to interpretative theories. In subsequent observations of outer galaxies, it turned out that M51 was an exception. (J.H. Oort, Jaarboek ZWO 1970)

ing polarisation observations with the Dwingeloo telescope. The WSRT could measure the properties of e.g. Travelling Ionospheric Disturbances. This co-operation led directly to 3 PhD theses. The cooperation with the geophysicists and geodesists, who have to do statistics with large numbers of measured data points, led also to use their knowledge in the Hipparcos satellite processing and VLBI data handling – and more PhDs!

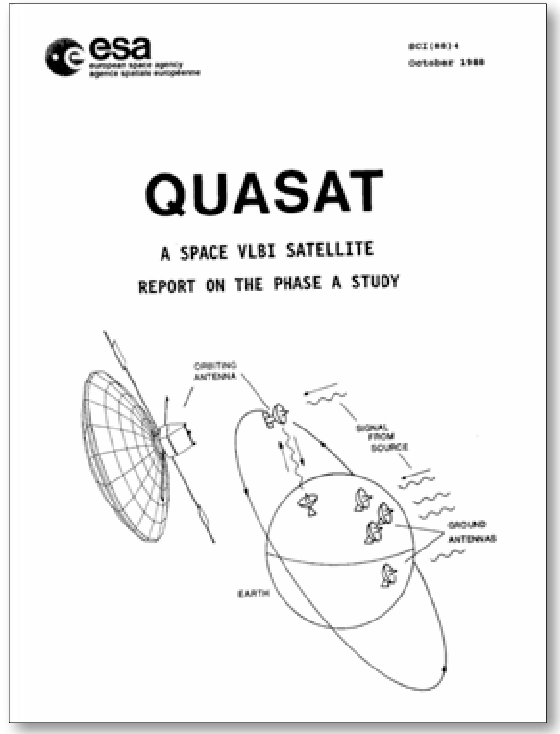
Other disciplines also need methods to convert measured data by Fourier Transforms. In the early days of the WSRT a more or less bi-annual set of symposia was organised. It started with an imaging conference by the Dutch Space Organisation (*Image Processing Techniques in Astronomy, Astrophysics and Space Science Library, Volume 54, 1975*) who wanted to research the possibility of infrared heterodyne receivers to measure correlations. Sensitivity was the big issue, since the channels had to be very narrow in order to get reasonable phase resolution. Optical interferometry was looked into, and again imaging was very difficult (only the last decade saw real imaging occur). Phase-less imaging was also proposed and tried, to limit the influence of fast fluctuating phase errors. The meetings were organised around the world. The Dutch tried to connect with other disciplines. Examples were medical imaging (*Groningen, Tomography*, ...); NATO submarine sonar (*Underwater Acoustics and Signal Processing, Copenhagen, 1980)* and X-ray crystallography. Most of these contacts did not lead anywhere directly, although in later years statistical methods crossed disciplinary boundaries.

One issue of aperture synthesis is the missing spacing problem. No short baselines are available. In principle the missing short baselines could be deduced from observations with a single large telescope. However, calibration of these baselines to match the calibration of the aperture synthesis baselines turns out to be difficult. Groningen staff proposed a method called "nodding", where 2 element telescopes of the array are moved differently on the sky. It turned out by detailed analysis that "nodding" was not really necessary. The short baseline information was available anyway.

The long baselines, beyond the 3 km of the WSRT, were also badly missed. The WORST (Westerbork Owens Valley Radio Synthesis Telescope) telescope was used to solve some of that. In essence 2 images were made. One with the WSRT, and one with Owens Valley telescope, which has a larger baseline, but was very insensitive to extended regions. Combining the two gave both extended regions and high resolution. Tests with radio links between Dwingeloo and WSRT (some 25 km) did not really work out, largely due to intervening trees in the line of sight.

The real long baselines came with the advent of Very Long Baseline Interferometry. VLBI started in 1967 in the US and Canada, but it wasn't until 1976 when the first 3-element European VLBI was done, largely organised by NFRA. this was the start of what became EVN, the European VLBI Network.

Figure 5: First page of the European proposal in 1988 for a VLBI satellite (Quasat) sent to ESA



Not satisfied, a European proposal for a VLBI satellite (Quasat) was sent to ESA, again, with a large input from NFRA (see Figure 5). Test on a communication satellite for time exchange was done by NFRA, to show the feasibility of space VLBI. Ultimately, the Quasat proposal was not funded by ESA. NFRA was involved with a Russian proposal, RadioAstron. However, that did not fly until this decade; 20 years after the Japanese VLBI satellite (HALCA) was launched.

Many other trials and tests were done in the first decade of the WSRT and a new window on the universe was opened up which included microsecond solar flares; search for lunar neutrino flashes, and topography of the Earth. The Annual reports of NFRA/ASTRON are a source of many firsts!

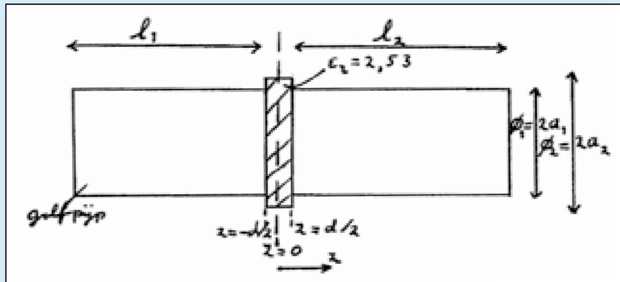
Early data reduction and computing in the Dwingeloo lab computers

Arnold van Ardenne

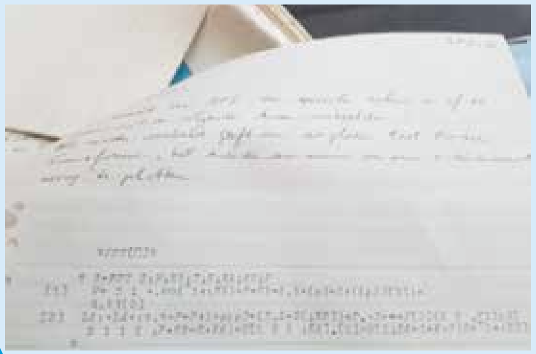
Before the advent of the PC, the Dwingeloo lab engineers programmed either in Fortran on the central IBM computer in Leiden, or on a small dedicated PDP11 computer in the lab.

Programs were written on punch cards or on paper tape and the process was extremely cumbersome. Often, "serial" computing was used in which the data output was used as input to tackle broader problems. Such was the case with computing the complex filters for use in Westerbork by Bou Schipper who as RF engineer in the lab also had the PDP11 near to his heart in the mid-seventies. Around 1976-1977, Wim Brouw and I had different problems to solve and were now using a programming language actually called by that name i.e. APL. It was versatile and relatively fast to run from Dwingeloo on the Leiden computer. The picture shows such a problem solved using APL.

APL was incredibly compact as it was programmed as a mathemathical operator language, operating from right to left, and lacking any clarifying words about the functions to be done. It all worked fine for me, but Wim's imaging software needed even more concise programming. He succeeded in writing a one-line Fast Fourier Transform! It was a truly amazing achievement.
After that, the lab problems were solved mostly in "Basic" in the dawn of the PC-era using the terrible DOS operating system Wim (and many others) despised.



APL was used for the microwave modeling of the modal effect of the plastic (actually Rexolite) vacuum window in the waveguide sections of the cooled frontends (1977 Westerbork Note 258)



An amazing one line FFT programmed by Wim Brouw in APL.

Chapter 3.2 Early WSRT receiver work in the Leiden Laboratory

Jean Casse*

I joined at the Leiden Observatory the design team of the BCAP (Benelux Cross Antenna Project) in June 1961. The BCAP design group in Leiden included a number of telescope and receiver experts from Australia, Sweden, India and the USA (Cyril Murray, John Murray, Don Williams, Kel Wellington, Bill Erickson, Sarma, Jan Högbom, Arthur Watkinson) and a small group of locals. The leader of the project, Professor Christiansen, had been chosen for his experience with building radiotelescopes in Australia, the most recent being the Fleurs interferometer. The permanent local staff had no experience with radioastronomy techniques, in particular interferometry. Thanks to the help of the foreigner experts, we learned quickly. Lout Sondaar (see also *"Time Adventures", Eds*) and I went to a one week radioastronomy seminar in Jodrell Bank to learn the trade. I am still amazed at how quickly we produced design results. There were periodic visits by a team of international experts to advise us on the techniques and evaluate our plans. Amongst the team of advisers were two technically oriented experts, Sandy Weinreb from NRAO and Emile Blum from the Meudon Observatory. Sandy was to be of great help to us.

The BCAP project began as an idea from Prof. C. Seeger, and was initiated by Prof J. Oort after the success of the Dwingeloo telescope (1956). It was meant to be a 5 km long 408 MHz cross antenna with parabolic cylinders as reflectors. The task of the project group in Leiden was to produce a working design of the receiver. When I joined the project, Sarma and Högbom were testing a prototype 408 MHz feed system. Cyril Murray and I worked first on low noise, wide band electronics for the IF chain. Loet Sondaar joined the project a little later as the second engineer. Then we had Theo Bennebroek who designed the demodulator and integrator modules. Lout was extensively involved in the measurement of interference levels at the proposed site (Weert later Westerbork) and in the design of the local oscillator electronics.

Around 1963-1964, Belgium withdrew from BCAP. I could have gone back to Belgium but in the mean time I had discovered ice skates and frozen canals and return was a not an option!Bill Erickson was the project manager and

* ASTRON, The Netherlands

the project was modified into a synthesis instrument with 12 (later 14) 25 m diameter paraboloids and a baseline of 1.5 km (later 3 km) working at 21 cm wavelength. Aperture synthesis is a technique started in Cambridge whereby a small number of antennas on a baseline, observing for 12 hours the same position on the sky, can simulated a full aperture. Aperture synthesis had recently been shown to work by professor Ryle at Cambridge University. Jan Högbom who joined the Leiden team, got his PhD there, and knew the problems well. Jan was a great help and was our interface to the astronomical world. In 1965 Bill Erickson returned to the USA and Lex Muller took over the leadership.

An interferometer system like ours required high accuracy in phase and amplitude. The reason for this is that the interferometer data collected during a run of 12 hours needed to be transformed (Fourier transformed) into a map. The accuracy of the computed map depends on the accuracy of the phase and amplitude of the data. Furthermore, the sensitivity of the receiver needed to be maximized in order to be able to detect the faintest radio sources. We had to take into account that the ambient temperature could vary between -25 and + 40 degree C, and many other factors. The most promising system was one with identical and stable channels.

The first receiver design for 21 cm wavelength was based on a balanced Schottky microwave mixer followed by a 30 MHz preamplifier. The noise properties of the preamplifier were very important as the mixer has no amplification, only loss. A microwave image filter in front of the mixer added more loss. The noise temperature of the front end mixer was 800 K. A prototype analog correlator working at 11 MHz was also designed and built. The Local Oscillator System

The WSRT on its own

Hans van Someren Greve

WSRT started producing observations on a regular basis from 1970 onwards, but the computer facilities on the site were minimal. It took another 10 years before observations could be inspected and calibrated on site at Westerbork.

Computer technology was very limited, and there was little market for mini computers. Personal Computer's did not even exist at that time! The WSRT relied on the IBM 360/50 mainframe located at Leiden University in the Central Reken Instituut (CRI). This computer was used for all the steps necessary to produce, verify and calibrate images, and finally to produce astronomically relevant maps and plots.

At Westerbork there was only a Philips P9202 mini processor. This processor took paper tape as input, and controlled the telescope steering, the delay system, and the fringe stopping for the centre of the observing source field. The coordinates of the centre of the field had to be apparent coordinates (i.e. the coordinates as seen from the telescope site). Converting epoch coordinates (like B1950) to apparent, was not possible for the P9202. Instead, this task was done by the program SOURCES on the IBM 360 in Leiden. Long printed lists of converted coordinates for all observations planned for the coming period were sent by surface mail to the WSRT where the observers could enter the apparent coordinates on the input punched paper tape.

During the observation, the output of the analog 160 channel receiver (10(fixed) x 2(movable) x 4(polarizations) x2 (cos/sin) was written to an 800 bitsperinch magnetic tape. After the observation was done, this tape was shipped to the observatory in Leiden, sometimes by train. On one occasion the tape was forgotten on the train!

All this meant that inspection of the observed data was not possible at the site. The staff had to wait until the data reduction took place in Leiden. Daily jobs were submitted with punched cards to the IBM 360, and then the next day the output could be inspected. First the programs MAKEOBS and SRTPLOT all written by Wim Brouw or under his guidance, were run on the calibration observations, so the people from the reduction group could inspect the average amplitude and phase values, and produce amplitude/phase plots on a calcom plotter. Somewhat later, Wim Brouw added MAKECAL which permitted high accuracy calibration of the position coordinates to around 1mm, and the overall data quality improved accordingly.

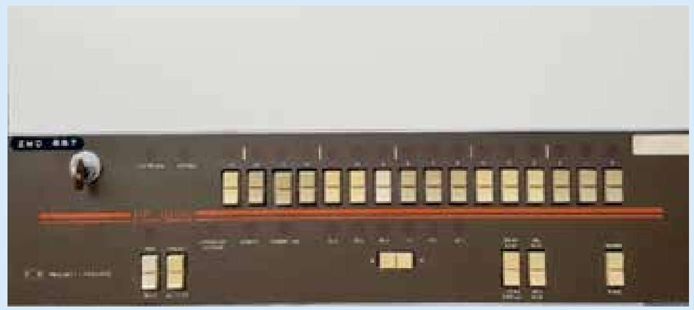
After the calibration observations, there was a telephone call with the astronomer at WSRT during which the results were discussed, and the staff at the WSRT was informed about possible receiver failures. Very often this process took at least half a week, and in case there was a receiver malfunction, then all observations done in the mean time were of course compromised.

Finally, after the astronomers received their MAKEOBS output they could reduce and analyse their data by making maps with MAKEMAP, and plots with PLOT (ruled surface plots) and CONTOUR, and find positions of point sources with FIND. They had to do this by submitting jobs on punched cards to the reduction group, and the reduction group took care of running the jobs on the IBM 360, and after all that, the astronomers received their output.

Things started to change after 1975, when it became possible to buy minicomputers, and the HP1000 with RTE system (Real Time Executive) was purchased to operate on site. At the same time, computer facilities in Groningen (a CDC) and in Dwingeloo were updated to become less dependent on the IBM 360 mainframe computer in Leiden. In Dwingeloo, a PDP11/70 from Digital was purchased, and later replaced by a VAX machine. Also, the P9202 telescope control processor was replaced by the LSI/11 mini processor from Digital.

The software group started developing software on the HP1000 machine (see picture). For that I moved from Leiden to Dwingeloo to work on the on-line control software, while Lepe Kroodsma, joined later by Teun Grit, developed the off-line processing software. This software was developed for a new backend receiver, the DLB, developed in the Dwingeloo labs using the Dwingeloo telescope as a testbench. The DLB was a 5120 channel digital line backend build by Albert Bos and his team (see chapter 10).

The on-line software was developed in order to specify, execute, control, and store observations. The off-line software was developed to inspect the amplitude and phases, and spectra of calibration observations. With that software the overall quality of the observations with the WSRT could be judged on site directly after the observation was finished, instead of waiting for results from Dwingeloo, Leiden, or Groningen. Finally, from 1980 onward the WSRT was on its own!



and the low frequency modules where the correlated signals are decoded and integrated had been developped by respectively L. Sondaar and T. Bennebroek. This prototype receiver, including cables, was assembled and moved to the field station in the Pesthuis polder (near Leiden) to test the phase and amplitude behaviour of the system.

Cyril Murray, a senior lecturer from Sydney University, and I designed and tested a preamplifier using a germanium transistor (AFZ12 from Philips) at 30 MHz. A report was produced and a presentation was given by Cyril at the OECD Paris meeting on Radio Telescopes. The tests showed that transistors were adequate in terms of sensitivity, stability and reproducibility for radio interferometry purposes. The noise temperature at 30 MHz was about 210 K. Using transistors in radio astronomy receivers was a novelty and not much was known at the time concerning their phase and amplitude stability and also their noise behaviour.

In first instance, a front end system using microwave mixer with Schottky barrier diode 1N21F from Microwave associates was considered and built. Since single side band operation was required i.e. a SSB filter was necessary, the SSB noise was as high as 1500 K. Later a parametric amplifier was developped in Dwingeloo by C. Muller with a noise temperature of 350 K and the IF became 132 MHz.

In order to limit man made interference the receiver needed a well reproducible flat bandpass but with steep skirts to avoid interference outside the protected band (4 or 10 MHz wide band). This was achieved with DSB circuits for which no adequate design rules at that time were available. With Ian Docherty we developed the theory for the design of double tuned network. As a lot of complicated computations were required for deriving the design curves, we were lucky to be able to use the computer which had just arrived at the university of Leiden. The necessary programing was written in Algol on a punched tape to be delivered to the computing center. This was our first experience with computers and software. It is at that time that I met Wim Brouw. Wim helped us connecting to the computer.

For the intermediate frequency chain, we designed an original printed circuit for double tuned networks. The technique was applied for the double tuned IF circuits at 132 MHz and also for matching the parametric amplifier to the preamplifier. This technique helped to produce practically identical channels easing the problem of meeting the phase and amplitude stability requirements.

The Leiden laboratory also designed the IF amplifier system at 132 MHz and the 160 channel analog correlator as well as the analog delay system. The delay lines (radio frequency cables) lie in one arm only of each interferometer. It is hence their absolute stability which is most important. A lot of attention went into this item. For instance we learned to our surprise that we had to calibrate carefully all the digital switches and then pass the information to the software team.

After protoypes had been built and thoroughly tested, the preparation for the mass production of receiver items began. A number of documents for building and testing were prepared for this purpose. For their preparation we had the assistance of Don Williams, an American engineer expert in mass production problems. We produced documents for each module showing the description, the construction and the testing. Detailed technical description of the designed items have also been made available though the Reports and Notes System. The mass production took place at the Dwingeloo Observatory under Professor Muller who had been made overall Project Manager.

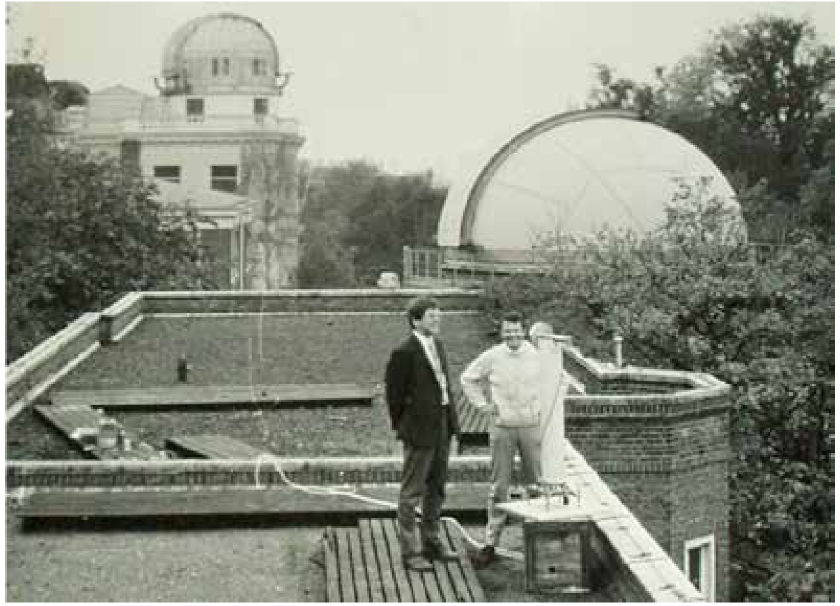
With the prototype receiver we were in a position to perform site tests at 1414 MHz on the electronics, including the cable system. Testing the WSRT receiver took place at the Pesthuis Polder, a site near the train station of Leiden. It consisted of 2 equatorial mounted dishes of 4 m diameter and separated by 84 m on an east-west baseline. Buried in the ground were 1.2 km of RF coaxial cables to simulate the situation with the real telescope. The field station was initiated by W. Erickson and realised by A. Watkinson, an Australian engineer from the Fleurs radiotelescope site. Erickson had replaced Christiansen as head of the project after he returned to Australia in 1963.

The work at the Pesthuis polder station was our first encounter with radiotelescope techniques. The tests showed that cables and electonics were stable enough for our purpose. The front end receiver was a balanced mixer followed by a 30 MHz preamplifier. Buried helical membranes cables were used for the transport of signals. The tests used the transit time of a number of strong point radio sources like Cas A , Virgo A and Taurus A to verify the phase stability. With Taurus we needed some manual integration to achieve sensitivity.

The blockdiagram of the first receiver, except for the front end, includes all the ingredients which appeared in the final receiver except that the receiver scheme had to be modified later as a result to the success in Dwingeloo in building reproducible and stable parametric amplifiers for 21 cm wavelength. The prototype receiver went to Westerbork and we succeeded in achieving first fringes at the WSRT with the Leiden prototype on 17 March, 1969.

In 1968 Jaap Visser joined the laboratory in Leiden as a microwave engineer. He started work on parametric amplifiers and cryogenic techniques. This step was essential for the future of radioastronomy in Westerbork. A year later Bert Woestenburg joined us and contributed a great deal to this development. These were the first steps with low noise receivers using cryogenics. After the design phase for the 21 cm system had ended, we had also started the design of the 6/50cm front end using uncooled receivers. Wellington was the project leader. The front end made use of an uncooled parametric amplifier purchased at AIL with a FET amplifier as second stage. It was on the telescope in 1972 exhibiting noise temperatures at 6/50 cm of respectively 115/350 K.

Figure 1: Kel Wellington and Jaap Visser testing a 6 cm antenna at the roof of the Leiden Observatory in 1970 (picture courtesy Casse)



The first closed cycle cryogenic receiver was using a BOC cooler which was later rejected because it was unreliable. In 1974, the 18 cm receiver used for the first VLBI observation in 1976 with Dwingeloo was our first cooled system using a CTI 1020 refrigerator. The preamplifier was a parametric amplifier designed by Visser. After Visser left ASTRON, all the cryostats with the exception of the one for the MFFE, were handled by Bert. He even designed and built the prototype closed cycle 4 K cryostat for a maser test receiver in collaboration with Twente University in 1977-78 for use in Dwingeloo.

In 1973 the laboratory in Leiden was moved to Dwingeloo as part of a reorganisation of ASTRON allowing a much tighter connection to the Observatories in Dwingeloo and Westerbork, which lead to my moving as well.

Figure 2: Jean Casse with the then head of the mechanical workshop Isaac Starre and Leo van der Ree with a prototype of the 21 cm receiver in Leiden in 1970 closely watched by a student. The receiver was tested in the Pesthuis Polder interferometer nearby shown on the right. This was perhaps the first Dutch Radio Interferometer! (pictures courtesy Casse)

First Discoveries

Chapter 3.3.1 Polarization and depolarization

Richard Strom*

It was my Ph.D. supervisor (and polarization guru), the late Robin Conway, who began a talk on polarization in radio astronomy by noting:

Antennas on the roofs of homes in England have their dipoles aligned vertically, while in the United States they are directed resolutely horizontal. This reflects the upright moral fiber of the Englishman, and the fact that Americans watch television reclined in bed.

Whatever the case, the point is that if you want to see television, in the UK or US, then you have to choose the right polarization (if you don't – if you do it wrong – then you'll get no signal). For natural sources of radio waves, one is usually interested in the two polarizations, horizontal and vertical, and we astronomers want to observe both. The WSRT was able to measure the complete polarization properties of radio sources right from the start.

The discovery that radio sources are polarized proved the importance of magnetic fields in the emission process. It also gave astronomy a tool for mapping the magnetic field direction in radio sources. In addition, and almost as important, was the discovery that the direction of polarization changes with the wavelength of the radio waves. To understand this, we have to go back by a century and a half, back to 1845 to be precise. In September of that year, the English physicist Michael Faraday observed that the polarization direction of light rotates when passing through a magnetic field, a phenomenon since called the Faraday effect (or Faraday rotation). It was the first hint that light has something to do with electromagnetism.

Faraday rotation in space is caused by charged particles (electrons) in a magnetic field. The rotation of polarization direction is proportional to the electron density times the field strength integrated along the line of sight. Faraday rotation affects not only the polarization orientation, but also the polarized intensity at long wavelengths. Emitting regions with aligned polarization at short wavelengths, but differing rotation measures, will exhibit diminished polarized emission at long wavelengths. Strom and Jägers (1988) observed this effect around the optical galaxies of double radio sources. They found that polarization at a short wavelength (21 cm) is greater than at a longer one

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(49 cm). Examples for two radio galaxies are shown in Figures 1 and 2. Note how polarized emission almost completely disappears from the red circle at 49 cm (Figures 1d and 2 right). The gas density decreases with increasing distance from the galaxy, but is sufficient that even at 100 kpc the effect is observable. The amount of gas involved is relatively small: At most 1% of a galaxy's gas (1% is however some 10 billion solar masses).

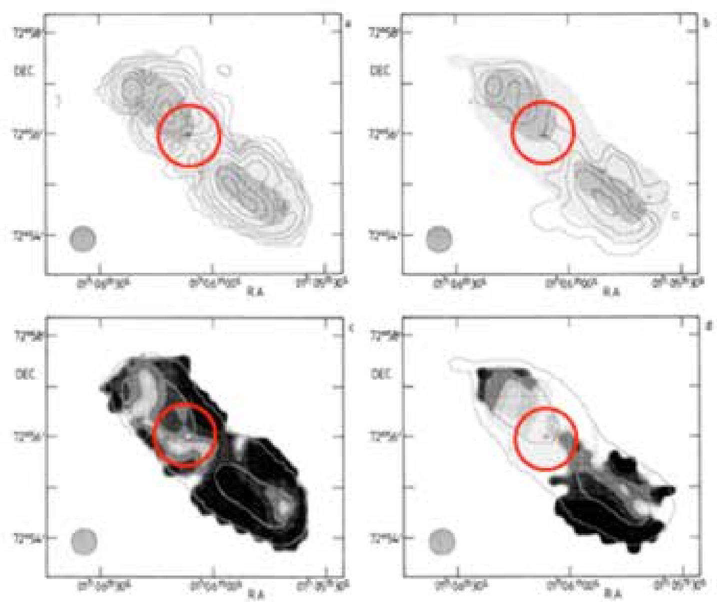

Figure 1. The radio galaxy 3C 33.1 observed by the WSRT at 21 cm (left-side images, a and c) and 49 cm (right, b and d). Contours show the strength of polarized emission (a and b). Strong polarized emission (c and d) is shaded dark. A region about 200 kpc diameter is shown by a red circle centered on the optical galaxy (cross).

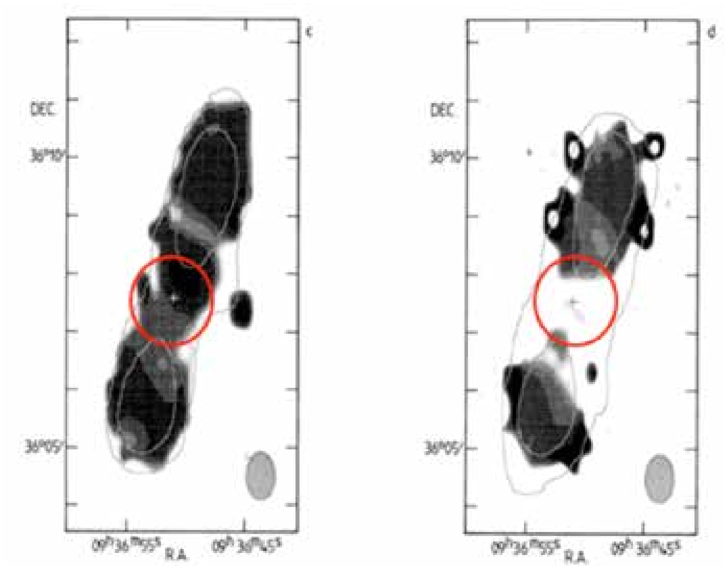

Figure 2. Polarization of the radio galaxy 3C 223 observed with the WSRT at 21 cm (left image) and 49 cm (right). Strong polarized emission is dark in both maps. A region about 200 kpc in diameter is indicated by a red circle, centered on the optical galaxy (cross). Note the absence of polarization around the galaxy at 49 cm.

To boldly go...

Michael Garrett, Jon Lomberg

Voyager 1 has travelled further that any other spacecraft, currently cruising out of the Solar System at 17 km/s. Many of you will know that hitching a ride on both Voyager 1 and 2 is the Golden Record – a metal, analogue recording, bolted to the side of each spacecraft that includes various images and sounds of the planet Earth, and other representations of human civilisation, including music. The idea was originally conceived in 1977 by Frank Drake and Carl Sagan, just in case the spacecraft were ever found by another space-faring civilization. Drake suggested the medium and devised a way to include video frames as well as sound. Lomberg directed the creation of the ensuing picture sequence–all done on a six-week deadline!

Figure 1: The photo of the WSRT included in the Voyager 1 and 2 Golden Record.

What you might not know, is that an image of the WSRT is one of only 116 images included on the record – why was this particular image chosen? Well the aim of the designers of the Golden Record was to tell a coherent story using images an extraterrestrial civilisation might easily comprehend—with sight being assumed to be a universally valuable sense. The photo by James P. Blair (see Figure 1) contains a lot of information. Radio antennas and bicycles (bikes are shown elsewhere on the record too) are designed on the basis of "form follows function", and the image also shows that we simultaneously use hi-tech and muscle power. One person points to the dish, perhaps explaining its function? There is also the suggestion that both learning and biking are important social activities. An array of dishes in a line presents a very particular observing technique, and together with another photo of Arecibo also included on the record, also hints at our interest in exploring space and indeed SETI, where Drake was a pioneer.

Reference

Sagan, C. et al. 1978,. *Murmurs of Earth*. New York: Random House, ISBN 0-394-41047-5

First Discoveries

Chapter 3.3.2 1974: the discovery of giant radio galaxies

Richard Strom*

In its first years of operation the WSRT was an instrument for mapping radio sources, but only at the single wavelength of 21 cm (a frequency of 1415 MHz). In 1973 this changed with the arrival of a new receiver system which could observe at two other wavelengths: 49 cm and 6 cm. The short wavelength of 6 cm gave the telescope a beam area 10 times smaller than at 21 cm. This meant sharper images of radio sources. At 49 cm the resolution was admittedly poorer, but the larger beam (5 times greater than that of 21 cm) has an advantage – it is more sensitive to extended radio emission. In addition, the primary beam of the 25 m antennas (which determines the sky area being imaged) is also wider than at the shorter wavelengths, so more extended radio sources could be mapped in a single observation.

With this in mind, Willis, Strom and Wilson (1974) chose a number of known radio sources as suitable candidates for observing with the new 49 cm system. Two sources – with the prosaic names DA 240 and 3C 236 – were possibly "confused" (jargon for overlapping, but unrelated, sources). The new maps were eagerly awaited by the team.

One morning during the coffee break at the old Sterrewacht in Leiden we all could admire the first maps. To our pleasant surprise, the sources weren't "confused" at all! The adjacent emission consisted of resolved lobes clearly associated with each source. The radio galaxy known until then as 3C 236 is the compact nucleus between two huge radio components (Figure 1). There could be no doubt that all three belong together. It was already known that the nuclear source coincides with a galaxy whose redshift is 0.0988 (or a distance of 380 Mpc): with an angular size of 2/3°, the radio emission of 3C 236 extends over 4.3 Mpc (in 1974, sources as large as 1 Mpc were completely unknown). To achieve this result, the instrumental dynamic range (the ability to see weak emission features – like the lobes – close to strong ones – the bright nucleus) had to be excellent. The WSRT passed this critical test with flying colors!

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The second source had been previously catalogued in radio surveys as 4C 56.16 (at a frequency of 178 MHz) and DA 240 (at 1420 MHz), but this only refers to the brightest emission peak in the source, and in contrast to 3C 236, this is not the galaxy's nucleus, but a lobe "hot spot". It was thought that this was the nucleus of a galaxy (called VV 91366) whose redshift was 0.0352. It was immediately clear from the new 49 cm map that DA 240 has a bright nucleus between two balloon-like components (Figure 2). The nucleus coincides with another galaxy, VV 91357, whose redshift was quickly found to be z = 0.0356. With almost the same z, VV 91366 turns out to be a companion of the much brighter VV 91357.

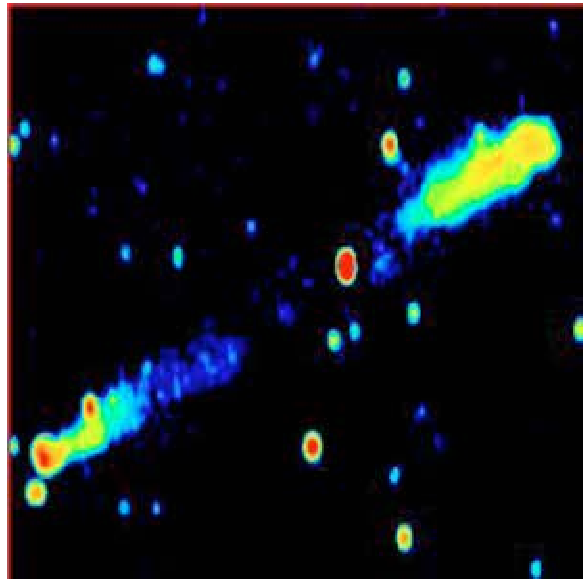

Figure 1: The radio source 3C 236 observed at a wavelength of 92 cm with the WSRT. The red ellipse near the middle of the map is the bright nucleus (the original 3C 236). It has a length of 2 kpc oriented (to within 10°) in the same direction as the outer components. (The other elliptical spots in this image are background radio sources unrelated to 3C 236.)

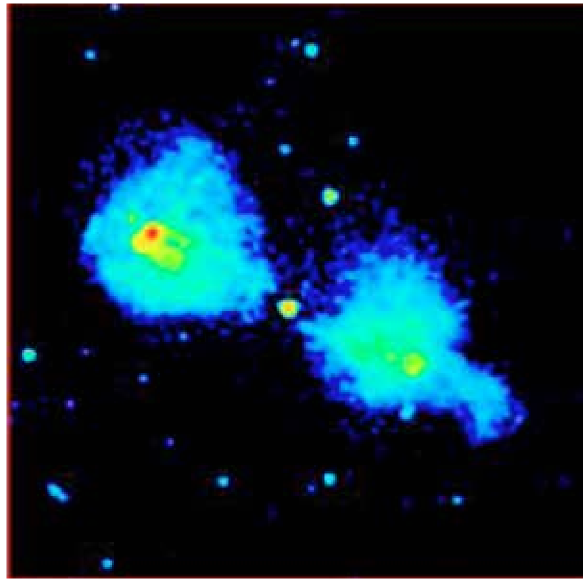

Figure 2: A WSRT map of DA 240 observed at 49 cm wavelength. The nuclear component which coincides with VV 91357 is in the center of this image. The other galaxy (VV 91366) lies just left of the brightest peak (red, upper left). In addition to these two galaxies, there are some 20 others which form a group around DA 240. VV 91366 and several others are also (weak) radio sources.

Chapter 3.3.3 1981: the expansion of a supernova remnant

Richard Strom*

Stars don't change. At least that's what people thought before 1600. But scant decades before, when turbulence of the Eighty Years' War invaded the low countries, and in the same year as France's St. Bartholomew's Day massacre, the impossible happened. A star appeared where no mortal had ever seen one. It was a miracle according to a young Danish astronomer, who later wrote (in Latin), *I was so astonished by this that... when I found that others could see it... I no longer doubted that truly a new star had been found there. It was really the greatest wonder to emerge from Nature since the creation of the world.* The observations of "his" *nova stellum* by Tycho Brahe provided us with the light curve and position of the new star.

However, the star was not new. A (super)nova is a nuclear explosion on (or in) an existing star, but one which as a white dwarf has an active life behind it, with only its death throes awaiting. We now know on the basis of (among other facts) the light curve from Tycho's measurements that what he observed must have been a supernova, an explosion in which the entire white dwarf was destroyed. After such a symmetrical outburst, shock waves rush out in all directions from ground zero. Eventually, the outermost shocks have all travelled about the same distance, resulting in a spherical remnant: In projection against the sky, a circle. This 400 year old supernova remnant is indeed almost perfectly circular (see 1971 image, Figure 1a).

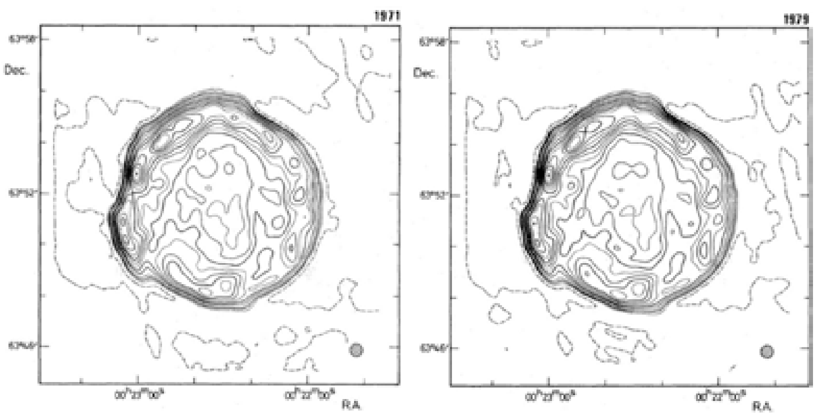

Figure 1a (left, Tycho SNR in 1971), and Figure 1b (right, Tycho SNR in 1979)

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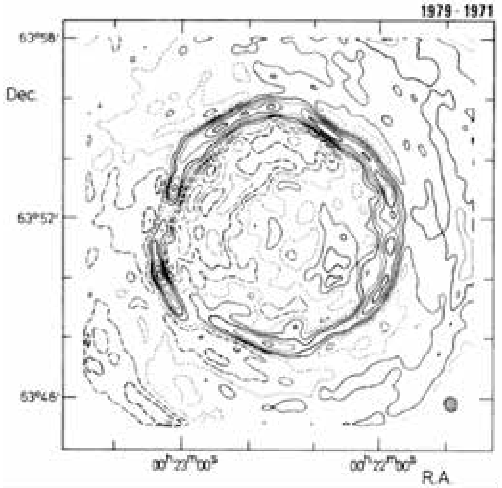


Figure 2, the thin shell which remains after subtracting the image of 1971 from that observed in 1979

In 1979, Strom, Goss and Shaver re-observed the remnant of the 1572 supernova with the WSRT. The resulting map hardly differs from the one made in 1971. It is clearly the same object (Figures. 1a and 1b). A careful examination (for example, switching quickly between the two) clearly shows, however, that the 1979 shell is a bit larger than the earlier one. This can be demonstrated by subtracting the 1971 image from the later one. The result is a thin shell (Figure 2): the precursor of the radiation from 1979 is just beyond the reach of the emission mapped eight years earlier. By carefully comparing the images, one can map the expansion of the remnant in detail.

The result (Figure 3) is expansion overall, which can be compared with the motion of the optical filaments (thick bars). The brightest optical emission is found on the east (left) side of the remnant. The expansion there agrees well with the prediction of the Sedov solution for adiabatic expansion (shown in Figure 3), but the motion of the optical emission can only be measured over a limited section of the shell, while the radio expansion can be determined around the entire rim. It reveals an average expansion (horizontal dashed line) higher than the Sedov estimate. This is the most important result of the radio measurements.

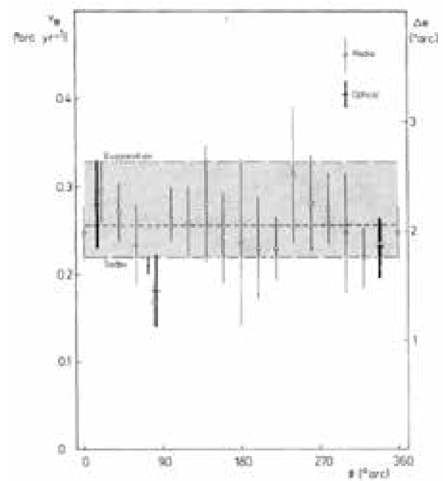


Figure 3, the expansion of Tycho measured from north (0, 360) to south (180) and west (270)

First Discoveries

Chapter 3.4.1 WSRT Contributions to the Black Hole Paradigm A Personal Perspective

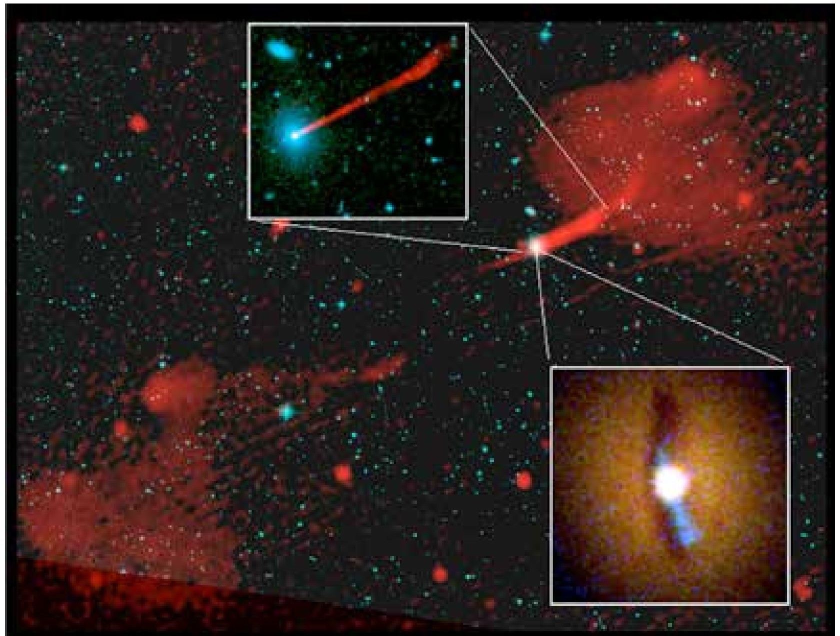
Tony Willis*

Strange as it may seem today, at one time black holes were just considered mathematical curiosities that came out of solutions to General Relativity equations but would never be detected in the actual universe. Einstein himself dismissed the idea as did my 1965 undergraduate text on General Relativity. Things began to change with the 1963 discovery by Maarten Schmidt, a Leiden University graduate, that quasars were distant objects in the universe, but must be of small intrinsic size. The 1967 discovery of pulsars by Jocelyn Bell provided further confirmation that compact objects exist in nature.

As its name suggests a black hole, by itself, cannot be seen. Today astronomers believe that it makes its presence known by its effects on the surrounding environment. Typically a black hole 'feeds' by sucking nearby gas and objects into an accretion disk, heating the in falling gas to a high temperature and generating X-ray emission. At the same time 'jets' may form perpendicular to the accretion disk. These jets may contain magnetic fields and high energy electrons accelerated near the black hole. This combination of electrons and magnetic fields produces electromagnetic radiation in the radio part of the electromagnetic spectrum.

As is described elsewhere in this book, the WSRT played a critical part in the first discovery of an actual black hole by providing an accurate position for the X ray source Cygnus X-1 (1970 era X-ray telescopes themselves provided very poor source positions). This allowed optical astronomers (including a Canadian, Tom Bolton at the University of Toronto) to make spectroscopic observations revealing that a massive 'dark' companion of the star HDE 226868 must be responsible for the X-ray emission. Today it is generally accepted that this dark companion is a black hole with a mass of about 15 solar masses at a distance of about 6000 light years from the Earth. It makes its presence known by, as described above, sucking gas off HDE 226868. Amongst others, Ed van den Heuvel of the University of Amsterdam has made significant contributions to the theory of how binary star systems can evolve to such a configuration.

* National Research Council of Canada



Radio Galaxy NGC 6251 Radio/Optical Superposition
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The discovery of the Cygnus X-1 black hole made the concept of black holes of a few solar masses acceptable. However making the mental leap to the size of 'engine' needed to power extragalactic radio sources required additional observational evidence. By the early 1970s it had been found that many extragalactic radio sources had a double structure with a radio lobe on either side of a companion galaxy seen at optical wavelengths. This led to models of radio sources in which the radio lobes were generated by some sort of massive explosion inside the optical galaxy. However a major problem with this sort of model was that a lot of energy should have been lost in the expansion and the radio lobes should not have been visible. This was the situation when I, Richard Strom and the late Andrew Wilson discovered the giant radio galaxy 3C236 with the WSRT in 1974. The important thing about 3C236 was not its large size but that the central nuclear source was aligned precisely within about 1 degree to the orientation of the outer lobes. This gave a clear indication that there was a direct relationship between nuclear activity and the outer radio lobes. Further confirmation of such a relationship was provided by the detection of radio 'jets' connecting the central nucleus to the outer lobes of numerous radio sources, first from observations made with the Cambridge 5 km telescope and the

WSRT, and culminating in the iconic image of Cygnus A made with the VLA in the 1980s.

While these radio observations were being made, advances were also being made on the theoretical front. In 1969 Donald Lynden-Bell published what came to be seen later as a seminal paper in which he made detailed calculations showing how giant black holes could provide the energy required to power distant quasars and radio galaxies. However, as far as I can recall this paper did not receive much attention at the time. This may be partly due to the fact that the author apparently had some doubts about this result. A few years ago I came across a presentation from Ron Ekers where he quotes from a 1971 Lynden-Bell letter in which the author says that he 'sees no evidence that calls for any such explanation'. However, by 1977 he was clearly back in the black holes camp. At the 1977 Copenhagen 'Active Nuclei' symposium both he and Martin Rees presented papers in which they argued that black holes were the power sources for radio galaxies and quasars. Both papers used the 3C236 axis alignment as evidence to support their arguments. In addition, Lynden-Bell showed images of the long jet emanating from the nucleus of the giant radio galaxy NGC6251, then newly discovered with a distant precursor of LOFAR, John Baldwin's 151 MHz array at Cambridge. Martin Rees was certainly the most vocal advocate of the black hole paradigm. In 1978 he published a number of papers in both professional and popular science journals in which he often used the observations of 3C236 and NGC6251 as supporting evidence (see especially his article in the October 19, 1978 edition of 'New Scientist' which you can read on-line in Google Books). I think that thereafter the black hole paradigm was pretty well accepted. Later observations have gone on to show that probably all galaxies, including our own, have black holes at their centers.

Both 3C236 and NGC6251 continue to be studied over the entire electromagnetic spectrum from X-rays to low frequency radio waves.

The attached figure shows a montage of NGC6251 observations - a large scale WSRT 610 MHz observation from the mid 1980s showing the entire 1 degree extent of the galaxy, with inserts showing (top) a VLA 1400 MHz observation of the radio jet emanating from the galaxy nucleus and (bottom) a HST observation of ultraviolet light coming from the central region surrounding the black hole.

First Discoveries

Chapter 3.4.2 Identifying WSRT Radio Sources in the 1970s

Tony Willis*

As Hans de Ruiter recounts elsewhere in this volume, he and I worked together for something like four years in the 1970s on a 'scavenger' radio source survey, the WSRT Background Source Survey, or BGS. We took WSRT 21cm fields originally observed for other purposes, such as the famous M51 field, and determined the properties of the presumably unrelated background sources. There were about ten sources per field on average with an apparent flux density greater than about 5 mJy). We laboured mightily for three years and obtained a catalogue of about 1000 sources from some 99 fields. One can contrast this source detection rate with the sensitivity of current telescopes such as ASKAP or Apertif where one can detect that number of sources in a single night of observing!

At the time the standard method of searching for optical counterparts to radio sources was to look at the Palomar Sky Survey prints. These prints went down to about magnitude 20 and the typical identification rate was about 20 percent. Since many of the fields in the BGS had well-known optical galaxies at the field centre, we thought that there might exist optical plates that went to fainter magnitudes than did the Sky Survey prints. At the time Halton 'Chip' Arp was trying to prove that quasars were objects shot out of normal galaxies and not at cosmological distances. Also, in that era of pre-computer-controlled telescopes Arp was an excellent observer and made many very high quality plates. In his book 'Seeing Red' Arp says that Professor Oort was the person who arranged for Hans and myself to visit Arp at the Hale Observatories in Pasadena California. So off we went for a three month visit in early 1975. Our visit was very successful. When we got to Hale Observatories Arp just pointed to a big filing cabinet and said 'Go to it, chaps.' It turned out that Arp had deep plates of some 53 galaxies made with the same wide-field Palomar Schmidt telescope used for the sky survey and these plates covered the entire one degree field of view of the WSRT at 21cm. We increased the radio source identification rate to about 27 percent. Arp was a really nice person and did not try to force his radical views on to junior researchers such as Hans and myself. Years later I was saddened

* National Research Council of Canada

to hear that his observing privileges at Palomar had been revoked because he would not change his view. Interestingly the paper we wrote together with Arp on the identifications is still one of my top three cited papers. Not because of any particular identification but because Hans produced a nice mathematical equation to calculate the probability that a given radio source and its apparent optical counterpart (both of which had errors in their positions) were actually associated. This equation, which Hans called the Likelihood Ratio, is still in regular use some forty years later (most recently by the Fermi Gamma ray telescope team) by observers who wish to determine the probability that detections seen at different wavelengths represent a physical association. Of course Hans and I worked very hard during our visit, but on the weekends we rented a car and took in such Los Angeles tourist attractions as Disneyland and a LA Dodgers baseball game. And of course Arp took us to Mt Palomar where we got to sit in the prime focus cage of the 200 inch telescope, not something the average tourist gets to do!

Finally I would like to mention 'the one that got away'. By 1976 we had been working on this survey for four years and we had to wrap things up and start producing some papers. At the time Ger de Bruyn, with whom I shared an office at the Leiden Observatory for four years, was working on his thesis. One of the galaxies he observed was centered on the galaxy NGC3079. He showed me the plot of the field and asked me if I would be interested in using the background sources in the field for our survey. I declined because we had already collected data for some thousand sources and another 10 or so objects would not make any differences to our source count statistics. I still remember that there was a quite strong extended source about 10 arcmin or so to the south west of NGC 3079. Of course three years later Dennis Walsh and his co-workers had a sensational paper in Nature announcing that this radio source represented the first detection of a gravitational lens! Cosmology might be quite different today if we had worked with Arp on this object and we had found two quasars near each other with identical redshifts and spectra!

Chapter 4

WSRT Observations of Radio Source Structure in the 1970s

George Miley*

I joined the Leiden-Westerbork group in December 1970, just as the WSRT was being commissioned. And the "Stichting" (forerunner to ASTRON) was still located in Leiden. My main scientific passion was and still is with the spectacular luminous radio sources that are associated with some galaxies and quasars. Having been "formed" scientifically" by a baptism in radio-link interferometry at Jodrell Bank and NRAO (hundred kilometre baselines and sub-arc second resolutions), I was sceptical as to whether the WSRT, with its low ~ 20" resolution could contribute significantly to unravelling the nature of extragalactic radio sources. I was very wrong. The WSRT was indeed revolutionary. Its design was highly conservative one and in several ways copied the Cambridge One-Mile Telescope. However, with the large number of simultaneous baselines and collecting area, a redundant design and rock-stable electronics the WSRT probed a hitherto neglected parameter space: *dynamic range* – the ability to observe faint emission in the region of extremely bright radio sources. Its huge dynamic range enabled the WSRT to make many fundamental discoveries on the seventies and keep at the forefront of astronomy for the past 50 years.

Exploiting the unprecedented dynamic range of the WSRT was not straightforward. Until the early seventies radio source structure was displayed using contour maps, but these could not delineate the large contrast between high and low brightness structures revealed by the WSRT. Walter Jaffe, then a Leiden PhD student, tackled this problem by developing the then novel technique of displaying radio maps in the form of photographs. Walter's radiophotographs could show structures with an order of magnitude larger contrast than the old contour displays.

I will here mention three important discoveries that were made by simply inspecting images of radio source structure during the first decade of the WSRT (e.g. Miley, 1980, Ann. Rev. Astr. Astrophys. 18, 165-218):

1. One of the most intriguing characteristics of extragalactic radio sources is the narrow collimated double structure that emanate from the nuclei of their parent galaxies. The existence of giant radio sources with sizes spanning several megaparsec, such as 3C 236 and DA 240 were first revealed

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by the WSRT (Willis, Strom & Wilson, 1974, Nature, 250, 625). These large extended lobes had previously been missed by the Cambridge Telescopes due to their limited dynamic range and sensitivity.
A surprising related discovery was the demonstration the kiloparsec-scale radio nucleus of 3C236 is aligned to within a few degrees with its mega-parsec-scale structure. This meant that the collimation axis of 3C236 must have stayed fixed for many tens of millions of years (Fomalont & Miley, 1975, Nature, 257, 99). The long-term memory is presumed to be associated with the fixed rotation axis of the super massive black hole located deep in the nucleus of the radio galaxy.

2. “Radio jets”, that are now known to channel the transport of energy from the galaxy nucleus out to the radio source lobes were first recognised and their name coined through WSRT observations of the radio source B0844+31 (van Breugel and Miley, 1977, Nature, 265, 315). Subsequently M87-type optical emission was detected from WSRT radio jets in 3C31 and 3C 66 using the video camera on the Kitt Peak 4m telescope (Butcher et al. 1980, ApJ, 235, 749).

3. One of the most spectacular early discoveries made by the WSRT concerned the nature of radio sources in clusters of galaxies. In the late sixties, the Cambridge group showed that two galaxies in the Perseus Cluster, NGC 1265 and IC310, had long radio tails that pointed away from the bright radio galaxy, NGC1275 at the centre of the cluster. They explained the strange narrow structures by a far-reaching hypothesis in which streams of electrons ejected from NGC 1275 travel for hundreds of kiloparsec and “light up” fainter radio sources in the other two galaxies (Ryle and Windram, 1968, MNRAS, 138, 1). Subsequently Hill and Longair found a comparable configuration around 3C129 (Hill and Longair, 1971, MNRAS, 154, 125). They developed the galaxy interaction theory with a detailed model that explained how radio sources could be ignited over large distances, producing narrow radio tails that point away from the “igniter”. Prompted by these results, we made deep WSRT observations of the same fields.

We were surprised to find faint a radio galaxy on the WSRT map of the Perseus Cluster that had a tail that pointed *towards* the presumed igniter, i.e. in the opposite direction to what was expected (Figure 1a). This was the nail in the coffin of the Cambridge interaction theory. But what could cause of the peculiar long narrow radio tails that were very different structures from “normal” double radio sources? The answer was clear from the high dynamic range from WSRT radiophotographs. These were developed by Herman Kleibrink, the head of the Leiden Observatory photographic department. “Mijnheer” Kleibrink was a brilliant photographer who had published several highly praised photo books of his beautiful Leiden. He was also a modest Dutch “gentleman” who wore a formal suit. When he showed me the radiophotograph of 3C129 he was excited. “Mr. Miley”, he said. “this

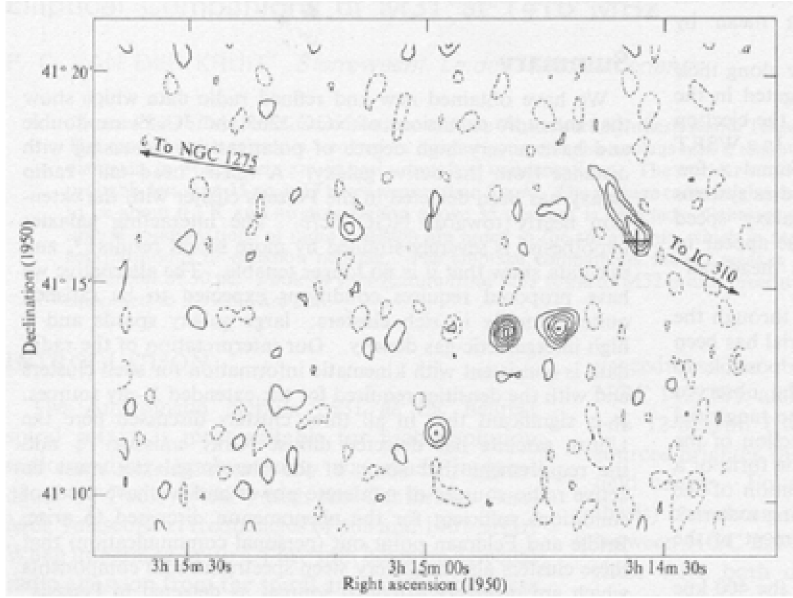
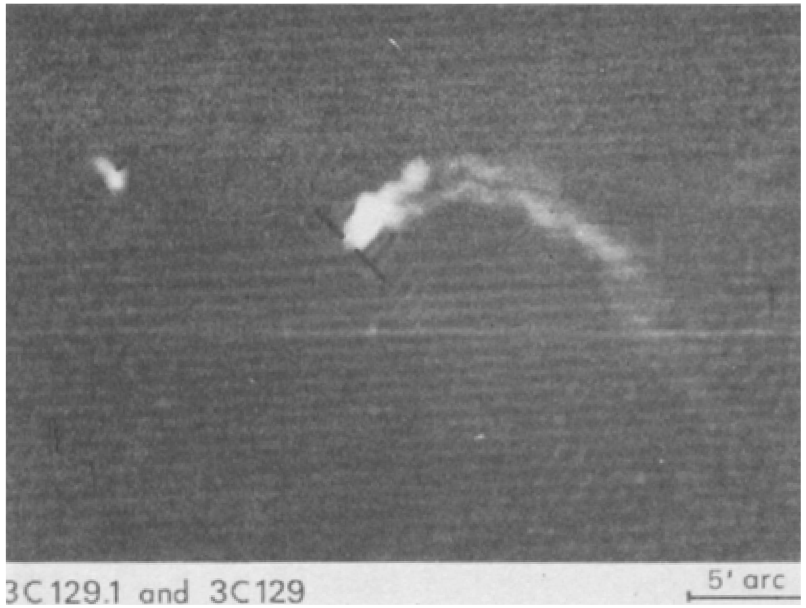


Figure 1. Radio Trails in Clusters .

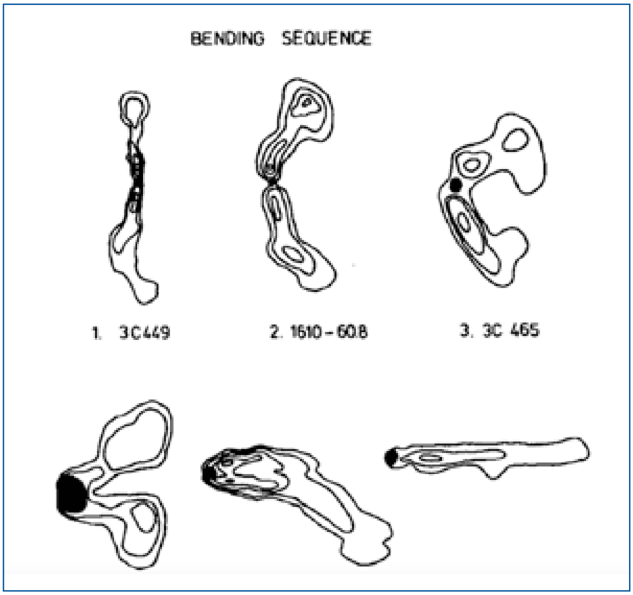
1a. The presence of a hitherto unobserved weak tailed radio galaxy in a deep WSRT observation of the Perseus Cluster. The new tail pointed in the “wrong” direction and was difficult to explain by the Cambridge interaction theory of head tail radio galaxies



1b. Herman Kleibrink’s “World War II fighter being shot down”. Reproduction an original Jaffe WSRT radiophotograph of 3C129 at 1415 MHz. It led to the idea that the narrow radio structures are trails left behind as the radio galaxies move through the cluster gas (Miley, Perola, van der Kruit and van der Laan, 1972, Nature 237, 269).

looks just like a World War II fighters being shot down”. Our subsequent paper indeed proposed that the radio tails are trails deposited by the host radio galaxies as they move through the cluster gas. (Figure 1, Miley, Perola, van der Kruit and van der Laan, 1972, Nature 237, 269). The WSRT discovery of radio trails began an important WSRT “industry” of cluster studies that involved e.g. Walter Jaffe, Cesare Perola, Alan Bridle, Galen Gisler and most prominently Ger De Bruyn.

Figure 2. Sequence of radio-source bending, illustrated by schematic drawings of WSRT maps. This shows how the shape of radio sources in rich clusters can be influenced by relative motions of the host galaxies through the cluster gas. (Miley, 1980, Ann. Rev. Astron Astrophys. 18, 165-218).



It was a great privilege to have had the opportunity of coming to Leiden and working with WSRT during the seventies. The youthful and exciting atmosphere provided by the gifted group of postdocs, PhD students and engineers under the leadership of Harry van der Laan and inspired by the enthusiasm and vision of Jan Oort was very special and made this era one of the most memorable in my life. I am delighted to congratulate the WSRT on being 50 years young. It's great to see that the "prima donna" is still very much alive and kicking and I'm sure that the renewed WSRT/Apertif will produce many exciting results in the future.

Exploring the time-varying Universe

Chapter 5.1 The earliest start

Richard Strom*

Introduction

The WSRT interferometrically measures Fourier components of the sky brightness distribution from a region set by the primary beam of the telescope elements, at a radio frequency determined by the receiver. This information is used to construct a two-dimensional image of radio emission from the piece of sky observed. Because it is an east-west interferometer array, the information obtained at any instant of time can only be used to construct a one-dimensional map (the telescope so synthesized has the response of a fan beam – narrow in one direction, but orthogonally very elongated). The information needed for a full map is obtained by observing for one or more 12-hour periods.

On short timescales the sky signal received carries no information useful for constructing (synthesizing) a map, so the data can be smoothed with a long time constant (typically 10 seconds). This limits the amount of data which has to be read out and stored, and the interval at which it must be done. But it also means that sources which vary rapidly will have their fluctuating signal smoothed out. For most natural radio emitters this is no problem: before 1967 few sources were known which flickered at a frequency of 1 Hz or more (solar active regions were one exception). But in August of that year, the first pulsing radio star was discovered with a large radio telescope at Cambridge, UK.

Pulsars, as they came to be known, are neutron stars formed during the huge explosion of a young, massive star which has almost exhausted its energy supply. The resulting supernova, SN, (explosion) also initiates a rapidly expanding hot bubble, a remnant (or SNR) which produces luminous radio and X-ray emission (see highlight from 1981 on the SN of 1572). As the lifetime of the extended remnant ($<10^5$ yr) is much shorter than the typical age of a pulsar (10^6-10^7 yr), only a few pulsars can be associated with SNRs: of these, the best known (and most extensively studied) is the Crab Nebula. It resulted from a SN seen in 1054.

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Figure 1

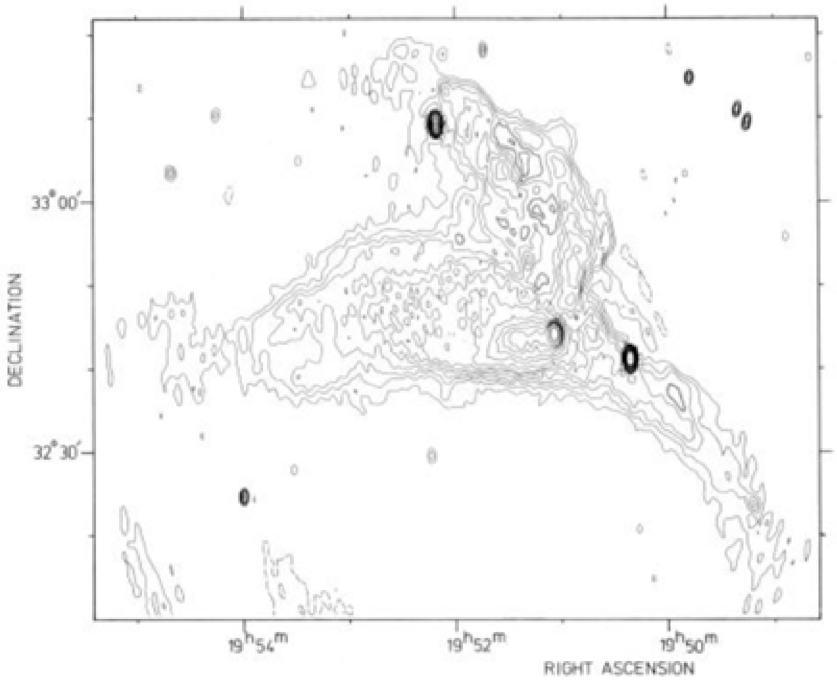
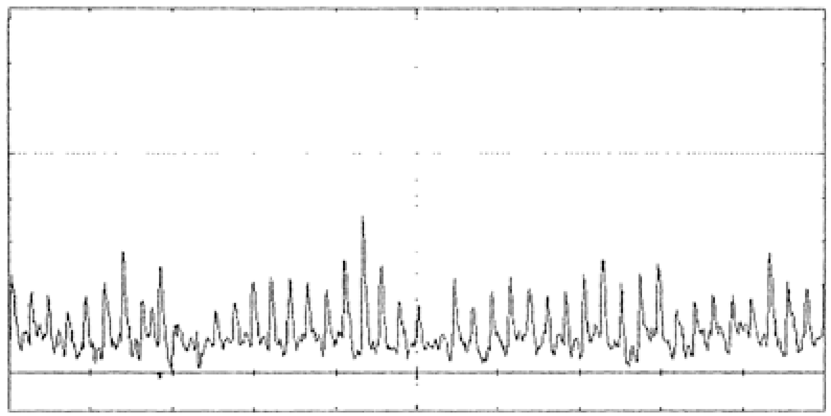


Figure 2



Around 1987, R. Strom became interested in the possibility of using the WSRT to search for pulsars. Specifically, the unusual SNR CTB80 (Figure 1) has a component with some of the characteristics of the Crab Nebula: it might harbor a pulsar. With the help of A. van Ardenne, the tied-array system (for VLBI) was adapted so it could be readout rapidly to observe pulsars. An example is an observation of PSR 1929+10 (Figure 2). Although the system clearly could observe pulsars, it was unable to detect pulsed emission from the presumed pulsar in CTB80 (which was detected shortly thereafter by the group in Berkeley). Its period (39 ms) was too short, and the emission probably too weak for detection with the improvised setup used by Strom and Van Ardenne.

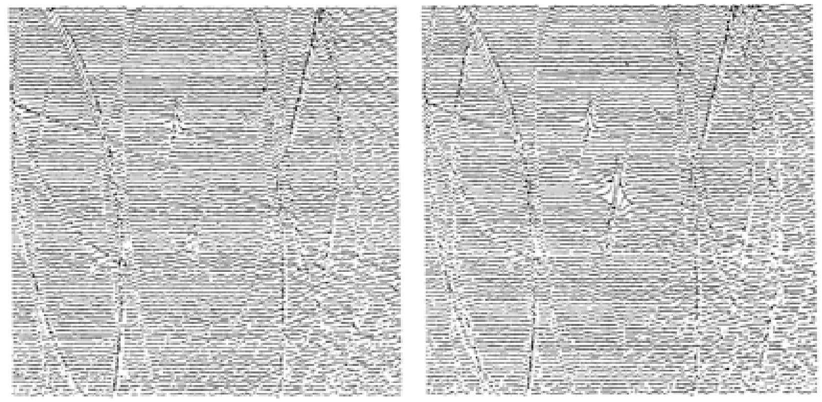


Figure 3

Despite its shortcomings, the system, with some minor modifications, was used to observe several known pulsars. In collaboration with H. van Someren Gréve, Strom worked on a method for observing pulsed emission using the WSRT in synthesis mode. By restructuring the system for reading out the interferometer signal, it was possible to create eight temporal windows which run synchronously with the (known) pulsar frequency. Each window samples a different phase of the pulse period, and so one is able to create maps of pulsars both on and off the pulsed emission. Figure 3 shows an example of such a pair of maps. Of some 40 pulsars observed in this way with the WSRT, the positions of ten were improved by the method.

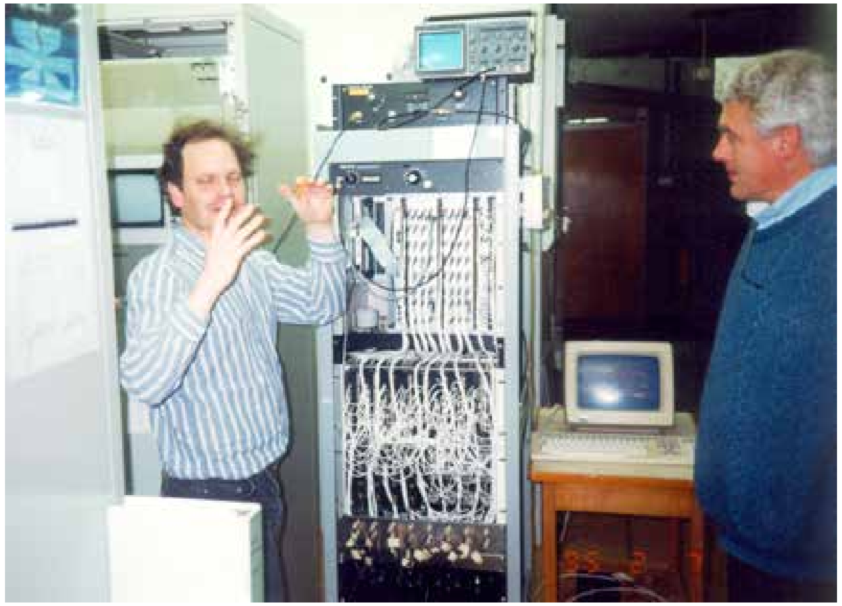
Full-fledged observing of pulsars only came with the inauguration of PuMa. See the following contributions for the evolution of the WSRT and Pulsars.

Exploring the time-varying Universe

Chapter 5.2 WSRT goes Transient

Lodie Voûte*

Up until the early nineties of last century WSRT was in essence a baseline interferometer and very suitable for long pointing and 12-hour integration observations. In view of the increasing interest in pulsar research it was decided that WSRT should join the radio pulsar community. This meant that the signals of the fourteen telescopes should be fed directly into a suitable backend, fast enough to record signals of relatively short duration. To achieve this ASTRON co-financed the design and construction by Caltech (prof. Shrinivas Kulkarni and his PhD student Gautam Vasisht) of two prototypes of a pulsar backend. This “Flexible Filter Bank” (FFB) comprised 32 analogue radio channels for each polarisation. However, the various analogue low pass filters (for bandwidth limiting[1] and data reduction) as well as the data recording were already under digital control.



Will Deitch (Caltech/ASTRON, FFB software) and the author with Beauty. The ‘spaghetti’ is where the telescope signals and local oscillators meet at the mixers, and their outputs go to the eight X and Y polarisation detector boards above.

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1 To reduce the ‘smearing’ of the signal due to dispersion in the interstellar medium.

At that time (1994) a new PhD student (albeit somewhat grey haired and the author of this section) was asked by his supervisor prof. Dr Jan van Paradijs (UvA, astronomical institute Anton Pannekoek) to familiarise himself with the intricacies of WSRT and to assist with the installation of the FFB at its site. With this new equipment it was hoped that the research for his thesis on the subject of so called giant pulses from some radio pulsars could be done. After a visit with Hans Weggemans (ASTRON, digital electronics) to Caltech, it was agreed to continue and complete the development of the second prototype in-house at the Westerbork observatory.

A year later[1] after modifications and additions[2], a change in its nickname from The Beast to Beauty and the gaining of a lot of insight by its crew[3] into the art of “how to observe pulsars” – the filterbank was up and running. However, in order to be at the forefront of pulsar research we realised that for observing these fast, shortlived transients, for measuring the four Stokes Parameters of (giant) pulses, to partake in pulsar timing and for detecting highDM pulsars at lower sky frequencies, a more comprehensive backend was required.

Up until then, pulsar backends at the various observatories were either fully analogue or hybrid filterbanks, and correlators. The advent of fast Digital Signal Processors (DSPs) gave Dr Ir Paul van Haren (then UU, Instrumentele Groep Fysica (IGF)) the idea to consider the possibility to go “all digital”. In itself quite a challenging exercise as this hadn’t been done before. After a feasibility study in 1996 by him and the author, a proposal for a new pulsar machine, nicknamed PuMa, was presented to ASTRON.

For maximum flexibility the operation of this new machine should be entirely under software control. For instance, when acting as a filterbank, the proposed backend should have a variable number of channels. Each of these channels should have (unlike the FFB) such a bandwidth that the full bandwidth range of the telescopes could be covered for an optimal signal to noise ratio. In this mode the power of the signals of each polarisation is recorded in each channel whereby the phase information is lost; this is called incoherent dedispersion. At the time, WSRT could observe a sky frequency range of eight bands of 10 MHz each. PuMa would split each band, with a choice of 16 to 1024 channels, into bands of 625 to 10 kHz. The user then had a choice to observe the two polarisations or to record all four Stokes-parameters.

In another mode PuMa could be used as a baseband sampler, allowing for off line coherent dedispersion later on. It would then sample the X and Y polarisation of two 10 MHz bands at 50 ns each or more bands at a lower rate.

2 Accounted for in his thesis “The many shapes of Giant Pulses - radio pulsar research at WSRT”, https://www.ASTRON.nl/sites/ASTRON.nl/files/cms/PDF/Voute2001.pdf
3 Will Deitch (Caltech/ASTRON, FFB software), Hans Weggemans (ASTRON, digital electronics), Harm Jan Siepel (ASTRON, analogue electronics), Marco Kouwenhoven (UU, Astronomical institute) and the author.

The completed PuMa pulsar backend ready for its shipment from IGF to WSRT.

In each of these modes the user could specify the number of bits for each sample, ranging from 1 to 8.

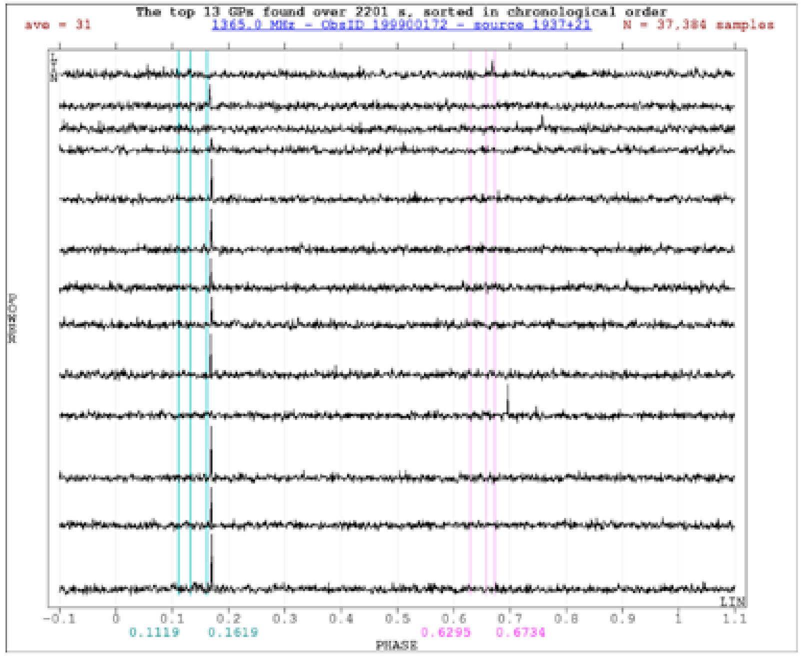
For its realisation a steering committee was set up in 1996. This team had representatives from ASTRON, IGF and the astronomical institutes of the universities of Amsterdam and Utrecht. The actual design and construction were done at IGF with Paul van Haren as the project leader and the author as its project scientist.

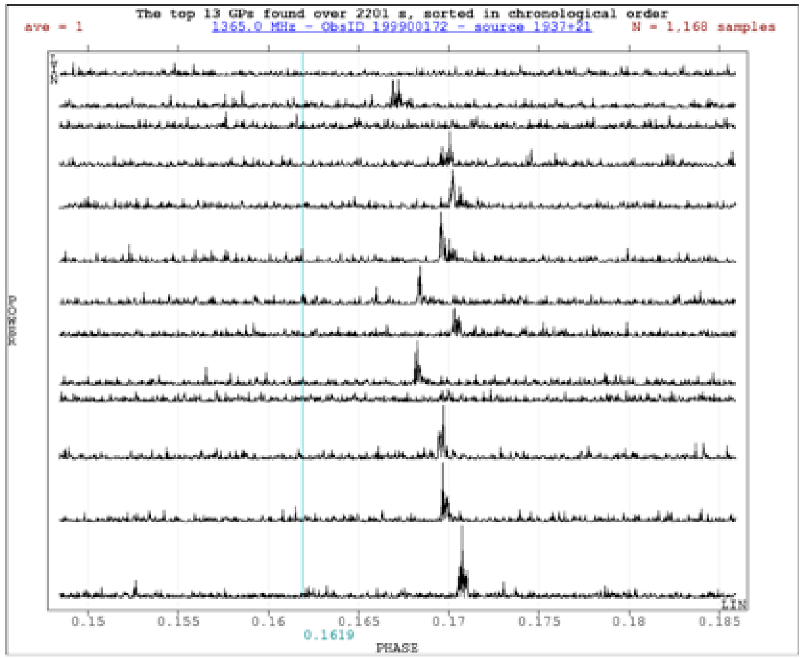
On its input side PuMa had sixteen A/D converters for the X and Y polarisation of the eight analogue WSRT bands. Together with the general timing unit, allowing for a (then exceptional) few nanoseconds timing accuracy, these were designed by Theo Beijaard. They were followed by eight clusters of four, homemade, digital processing boards using in total 192 SHARC DSPs as designed by Jaap Langerak. Quite an achievement, as its first design turned out to be spot on. The software for the DSPs, covering all the modes of operation of PuMa, was written by Dennis Driesens. The processed data from these boards were assembled by two in-build workstations (programmed by the author) and written to eight, then very fast, Cheetah hard disks, prior to final storage on DAT tapes. The whole setup allowed observation runs of up to several hours. With a PuMa, SHARCs and Cheetahs our team sometimes felt like Zoo keepers, under the most appreciated and inspired leadership of 'tamer' Paul.

An essential aspect of the reliability of the hardware and software was to validate all modes of its operation. To this end Marco Kouwenhoven (UU, then also a PhD student) wrote independent software that simulated pulsar signals from the telescopes and the corresponding output that should be produced by PuMa. To our great relief all results were well within established parameters.[4]
Two years later, in 1998, the completed PuMa backend was shipped from IGF to WSRT and installed successfully[5]. Its completion almost within the estimated time and well within budget, which is, also in the scientific community, rather exceptional. At last the author could start with the observations for his PhD thesis[6].

4 For more information on this subject see https://www.imdb.com/title/tt0708727/quotes
5 Shortly after PuMa's installation at WSRT, Jan van Paradijs passed away. Prof. Dr Richard Strom took over as the author's supervisor.
6 The author wishes to express his profound gratitude to Ir Jan (ASTRON) and Johanna Noordam for looking after his social needs during all of his 'WSRT' years.

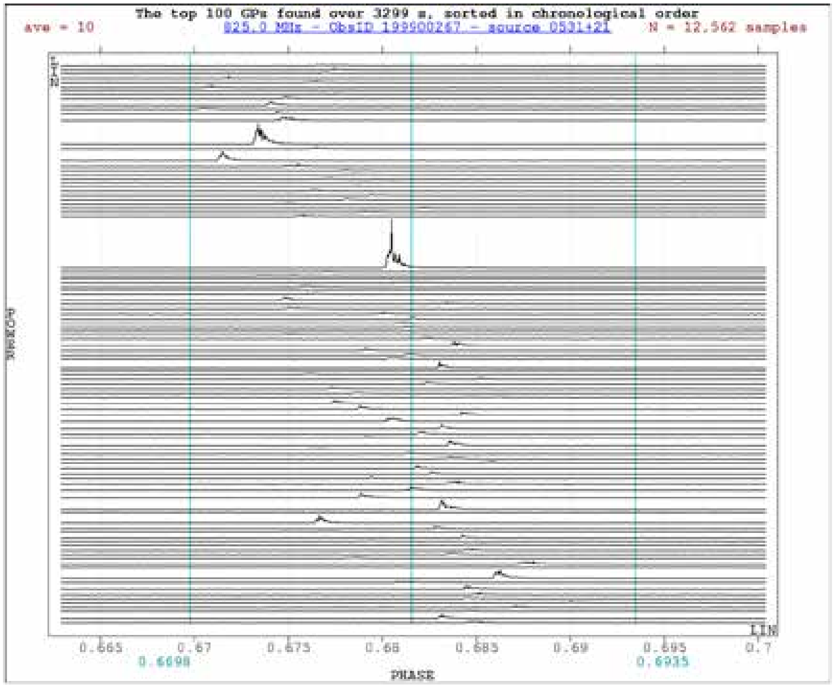
PuMa's high sampling rate of 50 ns made it possible to study accurately the variations in the arrival times of giant pulses, as shown below for the "millisecond pulsar" 1937+21.





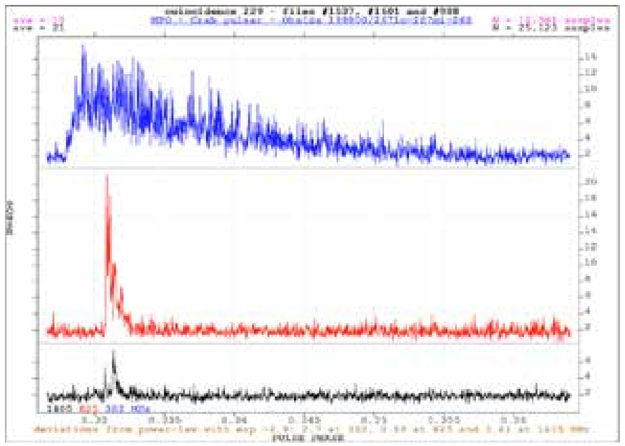
These two panels above show detections of giant pulses of the millisecond pulsar observed at 1365 MHz. The two sets of three vertical lines in the top panel mark the peak and edges of the main pulse (left/cyan) and interpulse (right/magenta). The lower panel is a zoom-in, just right of the main pulse, its sample time resolution is 50 ns.

As these graphs show, there are some minor variation in the arrival times and all observed giant pulses arrived shortly after the main pulse. This is in contrast to the giant pulses of the "Crab pulsar" 0531+21, which were observed to arrive almost anywhere during the main pulse as shown below.



Variations in longitude of the various giant pulses of the Crab pulsar, all coinciding with the main pulse. The three vertical lines show the start, peak and tail of that main pulse.

Another aspect of study was whether there was a relation between the power of giant pulses and the time between the previous or following giant pulse. Such a relation would, like the "earth quake" model, suggest that an underlying, power generating, mechanism for giant pulses would be existing. However, an observation run with some 1400 giant pulses of the Crab pulsar showed no such relation. This seems to indicate that the mechanism that generates giant pulses has no memory of its history, their generations seem truly random.

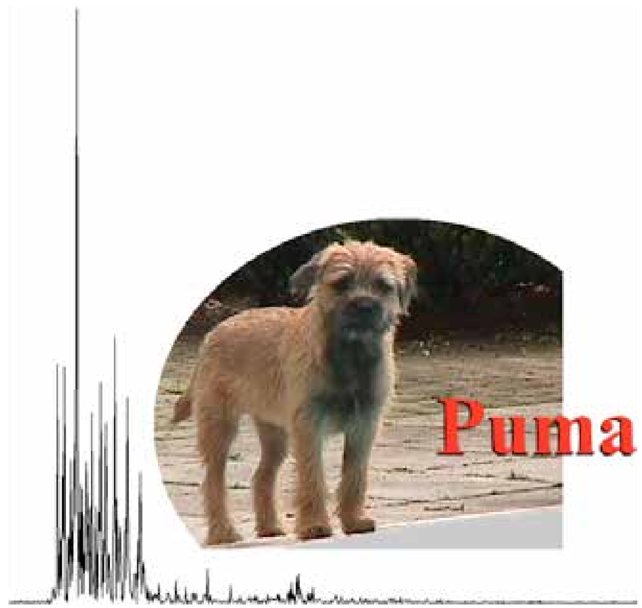


The arrival times of a giant pulse of the Crab pulsar (0531+21) at three sky frequencies, relative to the phase of the normal pulses at these frequencies.

Due to its flexible setup PuMa was also suitable for concurrent multi-frequency observations, whereby subsets of the fourteen WSRT telescopes were tuned to different sky frequencies[7], for instance 382, 825 and 1405 MHz. This feature allowed us to study various aspects of the giant pulses in detail.

For instance we did indeed find that the average flux of giant pulses, as a function of the sky frequency, satisfies a power law (spectral index), which suggest that its emission mechanism is indeed broad band. However we found that there are considerable deviations from this law for individual giant pulses. In one Crab pulsar observation, with over a thousand giant pulses, only less than three hundred could be observed significantly at all three sky frequencies.

It was quite exceptional that in one of the early multi-frequency observations we found a giant pulse from the Crab pulsar which had a signal to noise ratio (SNR) of approximately a 500,000 times stronger than the SNR of an average normal pulse. Up until then these giant pulses were only detected at several hundreds of times stronger.



The very strong giant pulse from the Crab pulsar as shown on the cover of the author's thesis, together with his dog Puma.

7 This was then a WSRT novelty, made possible by Hans van Someren Gréve MSc (ASTRON).

Exploring the time-varying Universe

Chapter 5.3 Taking the pulse of Neutron Stars with WSRT

Benjamin Stappers*

With the imminent arrival of a top of the range pulsar machine (see previous section) at the WSRT the author was hired by the University of Amsterdam to work with Ramachandran (ASTRON and UvA) and the team working on building the machine to help develop the data analysis software and to start undertaking the science.

The excitement of being part of something new, pulsar research using the WSRT with cutting edge instrumentation, combined with the strong pull of the "home" country of the Netherlands for the children (or their partners) of Dutch immigrants not only attracted the author (New Zealand) but also the very talented post-doctoral fellows: Edwards (Australia), van Straten (Canada) and Hessels (Canada) who have all helped shape pulsar research in the Netherlands.

It was immediately clear that the top quality instrumentation combined with the excellent sensitivity of the WSRT when compared to the other telescopes undertaking pulsar research that it would be excellent for high precision pulsar timing (see Section 5.4). This was particularly true due to the range of frequencies, and the speed with which the receivers could be changed, with the MFFEs. However building up a significant time baseline to be competitive with other instruments takes time. The distributed nature of the dishes in an interferometer also mean that, without significant compute resources, they aren't particularly good for wide-area pulsar searches. So it was recognised very early on that we could make significant contributions to the understanding of the radio emission from pulsars using the combination of high-quality WSRT data and sophisticated new analysis techniques.

The majority of these initial projects evolved around understanding the single pulse emission, which again benefitted from the high sensitivity of the array. These formed an important component of the PhD theses of Voute, Kouwenhoven, van Leeuwen and Smits, and the Masters thesis of Janssen.

* Benjamin Stappers, Jodrell Bank Centre for Astrophysics University of Manchester, UK

The pulses of some pulsars are made up of subpulses which appear to drift through the pulse window, defined by the average of thousands of pulses, in an organised fashion and this proved to be a rich vein of research with the WSRT. A particular favourite object was one of the first pulsars found, PSR B0809+74, which was known to have drifting subpulses but also was known to null, i.e. there are entire rotations, or series thereof, when no radio emission is detected at all. In a pair of papers led by van Leeuwen (2002,2003) it was shown that the nulls affect the rate of drifting and tells us about where the emission is coming from in the pulsar magnetosphere. In 2003 Edwards and the author came up with a new method to study the drifting subpulses called the two-dimensional fluctuation spectrum, which we applied to PSR B0809+74 initially and then to a series of other pulsars (Edwards et all 2003a,b). The latter work took advantage of the frequency agility of the WSRT to study the frequency dependence of these effects.

The development of the new technique allowed one to search for drifting subpulses and other pulse modulation mechanisms in weaker pulsars and it was recognised that understanding the phenomenon required a much larger sample than the handful of well-studied bright sources. The main topic of the thesis of Weltevrede was therefore to undertake a survey of as many sources as possible with the WSRT at two relatively widely separated frequencies of 1400 and 350 MHz. The results were published in two influential publications in 2006 and 2007. This work showed that many more pulsars than had previously thought exhibited subpulse drifting and suggested that the phenomenon may be ubiquitous amongst pulsars and that it may be geometry which governs whether they are visible. There was also some evidence that the phenomenon is more often seen at the lower radio frequencies. See Figure 1.

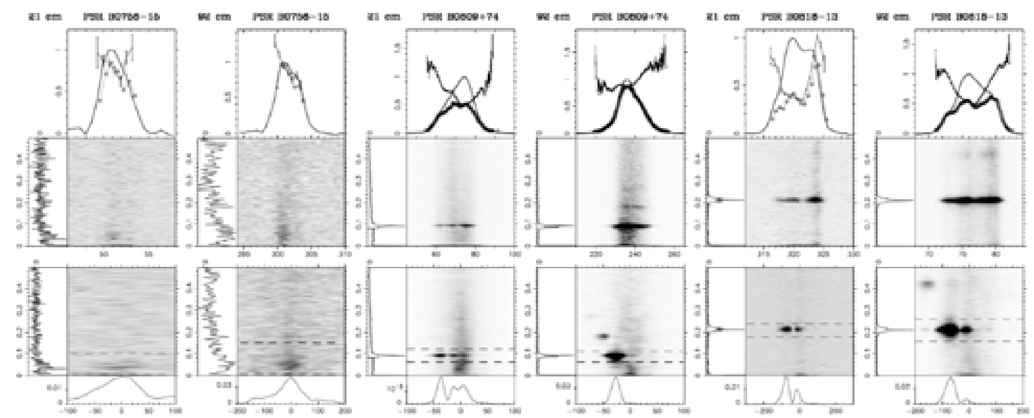


Figure 1 Some examples of pulsars which exhibit pulse-to-pulse modulation taken from the thesis of Patrick Weltevrede. PSR B0809+74 and PSR B0818-13 have seen a number of publications using WSRT (and LOFAR) data over the years. The integrated pulse profile (solid line) and the modulation index (solid points) of each pulsar are shown in the top plot. The middle plot shows the longitude-resolved-fluctuation spectrum where the dark areas correspond to the frequency of the drifting subpulses and is shown as a function of pulse phase. The lowest plot shows the result of the two-dimensional fluctuation spectrum developed by Edwards and the author and it also shows the frequency of the drifting subpulses but also from the separation seen in the x-axis one can determine the separation between the driftbands.

The new technique also allowed us to look for pulse-to-pulse modulation properties in millisecond pulsars. These are the pulsars that are spun-up to spin periods of just a few milliseconds and which are famed for their high precision clock-like stability. They are being used for experiments to test theories of gravity and also to try and detect gravitational waves (see Section 5.4). Understanding their use as clocks requires us to understand how they pulse and in a paper led by Edwards we showed that a number of millisecond pulsars showed strong modulation and there was also evidence that they exhibit drifting subpulses, so despite their very different spin period and magnetic field strengths they show properties analogous to their young bretheren.

The flexibility of the WSRT and the PuMa backend also allowed us to undertake some unique experiments that are only now being implemented at other arrays where the greater number of dishes makes them more suitable for science. In preparation for the ballet that would use live pulsars sounds, which unfortunately never happened, we implemented a mode which enabled sub-arraying (the modern term) the WSRT dishes and point them simultaneously at 3 different pulsars and process the data in real time. Also using the sub-arraying concept we split the array to observe some pulsars simultaneously at multiple frequencies. The most successful of these were the observations of the Crab pulsar which are part of Lodie Voute's thesis.

The single pulse work with the WSRT and PuMa will be a lasting legacy of the contribution they have made to pulsar astrophysics.

Exploring the time-varying Universe

Chapter 5.4 Pulsar timing with the WSRT

Gemma Janssen*

Pulsars are highly magnetised, rapidly rotating neutron stars. They emit radio beams along their magnetic axes, acting like cosmic lighthouses. One of the most important features of pulsars is their highly stable rotation. Using pulsars as distant clocks through high-precision timing measurements gives a unique tool to probe various astrophysical processes. Besides monitoring the intrinsic spindown behaviour of pulsars, pulsar timing can be used to measure orbital parameters of pulsars in binary systems, and in specific cases test Einstein's theory of gravity by measuring relativistic effects in the orbits (see Section 5.5). When having a large observing bandwidth, or multiple observing frequencies available, effects of the ionised interstellar medium on the pulse arrival times can be studied and monitored.

A pulsar timing programme has been running at WSRT using the pulsar machines PumaI from 1999 to 2010, and using PuMaII from 2006 until the shutdown of the MFFE system in 2015. The timing programme using PumaI started observing about 10 millisecond pulsars (MSPs) and 10 slow pulsars. More pulsars were added every year, with the observing time also gradually increasing from 18 hours per month at the start to more than 48 hours per month in the later years allowing the coverage of more than 50 (mostly millisecond) pulsars at two or three observing frequencies. A revised timing programme will be started with the ARTS backend this year (see Chapter 15).

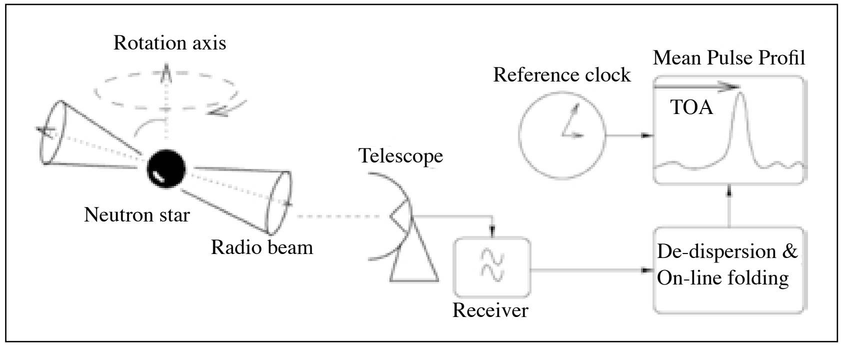


Figure 1: A basic description of pulsar timing. Figure from the Pulsar Handbook (Lorimer & Kramer 2004, Cambridge University Press)

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The next-generation Pulsar Backend: PuMaII

With the PumaI backend already delivering good results for single pulse work and pulsar timing, a new step was taken in the early 2000s towards the development of a new pulsar instrument. PuMaII, as this was called, was designed to be capable to handle the full observing bandwidth that was covered by the MFFE frontends (160 MHz > 1 GHz, 80 MHz < 1 GHz).
PuMaII was designed to be simultaneously capable of storing recorded data from each band, on 8 storage nodes, and had 32 independent processing nodes available for handling the data after observing. Most importantly, this new PuMaII cluster was capable of coherently dedispersing the data, which significantly improved the timing precision for millisecond pulsars due to the fact that inter-channel smearing due to dispersion was mitigated (Karuppusamy, Stappers and Van Straten 2008, PASP 120, 191). Also, with largely extended storage space, baseband data could be recorded up to 12 hours and temporarily stored for later processing (which was in particular used by the LEAP project).

Using the MFFE capabilities of observing at different frequencies, PuMaII was routinely used to probe and monitor the effects of the interstellar medium on pulsar arrival times. Overall, the multi-frequency observing availability, in combination with the excellent timing resolution of the data and the large storage and processing capability, the PuMaII-WSRT pulsar timing data has generated a long-term data set on over 50 millisecond pulsars that has been extremely valuable for various pulsar timing experiments.

Figure 2: The Dutch Pulsar Group in 2005 on site for the PuMaII opening. Left to right: Patrick Weltevrede, Ramesh Karuppusamy, Eduardo Rubio-Herrera, Roy Smits, Gemma Janssen, Ben Stappers.

Using millisecond pulsars in a pulsar timing array

In 2005, a team of European pulsar astronomers including ASTRON's Ben Stappers were awarded the EU Descartes Prize for their collaborative research in pulsar astronomy. Building from this collaboration, in 2006 the European Pulsar Timing Array (EPTA) collaboration was founded. The EPTA is a collaboration using the five large radio telescopes in Europe: besides the WSRT, the EPTA combines data from the Lovell telescope at Jodrell bank, and the Effelsberg, Nançay, and Sardinia radio telescopes. In all pulsar timing experiments, both the total baseline (in time) of observations, as well as the quality and the cadence of the observations are relevant to the quality of the timing solutions for each pulsar. Since the total observing time at any telescope is limited, it directly pays off to collaborate with other teams, and create larger data sets by combining the pulse Time of Arrival (TOA) from each telescope in a combined timing solution. Besides improving timing for many individual millisecond pulsars, and studying the many aspects of the various pulsar systems themselves, the overarching goal of the EPTA is to detect gravitational waves in the nanoHertz (nHz) regime. Gravitational waves (GWs) are small disturbances in space-time that are caused by the acceleration of masses. They originate from a variety of sources, and are expected to exist over a wide range of frequencies. A pulsar timing array (PTA) uses an array of MSPs as the endpoints of a Galactic-scale GW detector. It is sensitive to GWs with frequencies in the nHz regime, being complementary to the frequency bands addressed by other experiments like LIGO/VIRGO and LISA. The most important sources of GWs in the nHz regime are supermassive binary black hole systems (SMBHBs) formed in merging galaxies in the early universe. Understanding the formation and evolution of SMBHBs on cosmic timescales provides unique information on galaxy evolution and star formation processes in general, and studying them through GWs will open up a completely new era of astronomy. In this way, the PTA experiment will complement the recent detections of stellar-mass black hole mergers in the higher-frequency LIGO/VIRGO GW band.

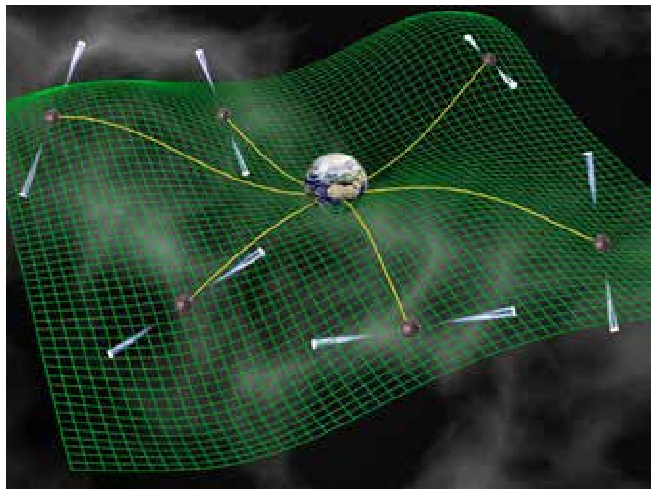


Figure 3: A pulsar timing array. The arrival times of each pulsar are delayed due to the effect of gravitational waves, and detected by observing correlations in arrival times as a function of angular separation between the pulsar pairs. Figure: D. Champion

A PTA will detect GWs by measuring correlations in the timing residuals of pulsars that are distributed across the sky. To reach this goal, the prime requirement is to observe a large number of millisecond pulsars and measure the arrival times of their pulses to the best precision possible. Since observing GWs in the nHz regime means that the signals are stretched out for years, a total observing campaign over at least a decade is required to make a detection. Recently, the EPTA has used a combination of WSRT observations with data of the other European radio telescopes of the 6 best timed millisecond pulsars to set an upper limit on a nHz gravitational wave background generated by SMBHBs (Lentati et al. 2015, MNRAS 453, 2576), which is already excluding some of the most conservative scenarios for SMBHB evolution.

The Large European Array for Pulsars

Figure 4: The location of the EPTA telescopes, and showing the LEAP network.

Even with large-bandwidth instruments and processing techniques like coherent dedispersion, the achievable timing precision that is required for GW detection is at the limit of what is possible with single telescopes today. To increase overall sensitivity, the Large European Array for Pulsars was developed since 2009, where in a VLBI-like way (but in the time domain) the EPTA telescopes were coherently combined to produce a 200-m equivalent dish (Bassa et al 2016, MNRAS 460, 2207). After simultaneously observing a set of millisecond pulsars, raw voltage data of each telescopes were transferred to Jodrell Bank where those were coherently added with specifically designed software for beamforming and correlating pulsar observations (Smits et al. 2017, A&C 19, 66). Regular observations for the LEAP project have been running since 2010, and the resulting data is now routinely used to improve the EPTA GW detection efforts.

Combining PuMa and PuMaII to discover new pulsars: the *8gr8* survey

Although in present times it has become common standard to use radio interferometers as search instruments, at the time that the pulsar machines for WSRT were developed, interferometers were not deemed useful for large area pulsar (or transient) surveys due to the small tied-array beams. A first attempt at creating multiple beams to solve this problem was started in the early 2000s (by Stappers, van Straten, Edwards and Braun). The new method called *8gr8* used the fact that the first 12 WSRT telescopes (an East-West linear array), could be placed at fixed and equal separation. When creating a tied-array beam, their equal separation results in a grating response on the sky consisting of highly elliptical fan beams. WSRT had eight independent signal chains, which were usually covering adjacent frequency bands to maximise the observing bandwidth for pulsar observations. However, when tuning all eight bands to the same centre frequency, but slightly shifting their phasing respective to each other, the combined mapping of the grating patterns of each band provides full coverage of the total primary beam of a single dish.

During a 2 hour observation, PumaI was used to record the signals of the eight bands separately. The rotation of the Earth leads to rotating of the fan beam patterns, and a complicated offline-processing weighting scheme was devised using the new PuMaII computing cluster to form small subbeams, formed by combining different elements of each grating pattern over the observation. For each observation, this effectively results in many small subbeams on the sky that could be searched for pulsar signals.

The survey was mostly sensitive to relatively long-period pulsars due to data-rate limitations. A promising part of the sky was selected (Cygnus area) where stars can be expected to be formed, and therefore young, slow-rotating pulsars should be present. The initial observations were completed in 2004 and 2005, and over 200000 subbeams were searched on the PuMaII cluster. Candidates that were present in both initial and confirmation observations were later followed-up in a timing programme. Eventually, three pulsars were found (Janssen et al. 2009, A&A 498, 223) of which one turns out to be a mode-switching pulsar.

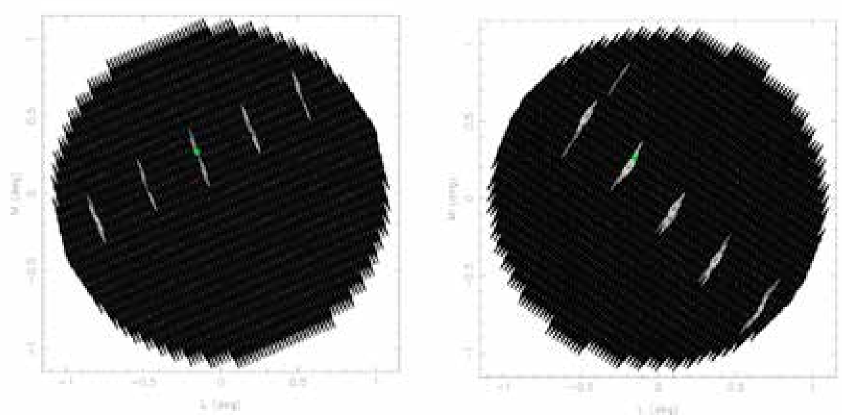


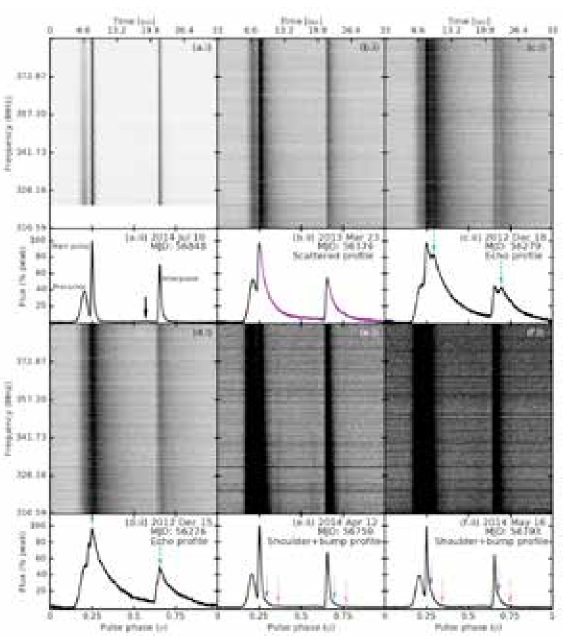
Figure 5: A pulsar detection in 8gr8 mode. Cross-matching two observations allowed for selecting the correct position of the pulsar and confirming the candidate. Follow-up timing observations were used to characterise the pulsar.

Scattering features and variability in the Crab pulsar

For pulsar timing, observations above 1 GHz generally give the most precise results. However, low-frequency data play a key role in the efforts to optimally measure and correct the data for interstellar weather influences, since those effects are strongly dependent on frequency and more easily measured in that range. The WSRT MFFEs have played a key role in many EPTA projects, providing both the high precision 1.4 GHz measurements, and also providing the 350MHz Interstellar Medium (ISM) measurements to optimally correct for dispersion and scattering. For example, we have seen (Bassa, Janssen et al. 2016, MNRAS 460, 2207) that by including low-frequency observations the first-order Dispersion Measure (DM) effect is better constrained and can be disentangled from the spin noise contributions to the timing residuals.

Another great example of the power of the low-frequency observing with the MFFEs at WSRT is the study of scattering in the Crab pulsar. The Crab pulsar is known for its rich possibilities of studies based on its pulse profile features: both giant pulses and individual pulses can be detected, and the changing shape of the integrated profile allow for studies of the interstellar medium and the properties of the Crab nebula itself. Shortly after the discovery of the Crab pulsar, variability in scatter-broadening was already presented, and several periods of anomalous increases in scattering, as well as traceable additional features in the pulse profile have been published before.
When another anomalous scattering event was detected in 2012 by the Jodrell Bank 42-ft Crab Monitoring campaign at 600 MHz, we decided to start to observe the Crab pulsar regularly with WSRT at 350 MHz to study if the features were more clearly visible ISM effects scale inversely with frequency, so the effects are expected to be more pronounced at lower frequencies. We observed the Crab pulsar from 2012 till the closing of WSRT in MFFE mode in 2015, with a relatively high cadence that varied between a few times per week to monthly.

Figure 6: Profile features seen in the Crab pulsar observed with WSRT at 350 MHz. Besides changing scatter-broadening, copies of the complete pulse profile in two or three different forms can be recognised, which present themselves on varying time-scales.



In 2014, ASTRON summer student Laura Driessen analysed the available data and discovered that indeed the 350 MHz band was the sweet spot for observing the ISM effects on the Crab pulsar. She found that besides variable scatter-broadening of the profile, additional features due to multi-path propagation effects in the interstellar medium or Crab nebula can be detected in almost all observations. Contrary to what was thought before, these events did not happen every few years, but are present almost continuously. The figure shows the broad range of features, that can all be attributed to effects of changes in the path of propagation. We discovered that the commonly-used thin-screen model cannot be applied to all effects shown, and that the variations can happen on a fast timescales of less than a day. (Driessen et al. 2018, MNRAS)

Exploring the time-varying Universe

Chapter 5.5 Putting gravity to the test using a unique pulsar in a triple star system

Jason Hessels*

The discovery of radio pulsars just over 50 years ago gave the first direct evidence for the existence of neutron stars, as well as a handy tool to study their properties. The radio pulsations provide a clock-like tick that we can use to measure a pulsar's spin rate with fantastic precision. Using a large radio telescope like the WSRT, along with a high-time-resolution recording backend like PuMaII, astronomers register up to billions of pulses from a pulsar and then model these to distill important physical insights. These "rotational ephemerides" enable us to model all the recorded pulse times of arrival at the telescope and then infer exactly how many rotations the pulsar has made in between observing sessions.

For instance, measuring the spin rate and how it changes with time gives properties like the dipole magnetic field strength of the pulsar, its age, and how much rotational energy it is losing. Some pulsars are in binary systems with another star. In this case, we observe the pulsar's apparent spin rate being Doppler-shifted as it swings around in its orbit. This allows us to measure the pulsar's orbit with great precision. As an example, the projected size of the orbit of PSR J1909-3744 – a particularly good "pulsar clock" – is known to be over a million kilometres, but the uncertainty on this determination is only about 20 metres.

Why would we care to measure pulsar orbits with such ridiculously high precision? Simply put, because pulsars are extreme objects that bend space-time strongly and challenge our understanding of the physics of dense matter. For some binary pulsars, we can measure how the pulses are delayed as they travel through the curved space-time around their companion star. This allows us to measure their mass precisely, and hence better understand the physics that describes dense matter. We can also compare the observed orbital effects to the predictions of Einstein's theory of general relativity and use these systems as

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natural laboratories for testing gravity. Famously, the first indirect detection of gravitational waves was made by measuring the orbital decay of PSR B1913+16, which is a binary pulsar whose stellar companion is also a neutron star. In this system, general relativity predicts how the orbit will shrink as gravitational waves are released; this prediction matches with the measurements perfectly, thereby providing an important test of Einstein's theory. Russell Hulse and Joe Taylor were awarded the 1993 Nobel Prize in physics for the discovery of this Hulse-Taylor pulsar binary system.

More recently, our team has used the Green Bank Telescope (GBT), in West Virginia, to discover the first known pulsar in a stellar triple system (Ransom et al. 2014, *Nature*, 505, 520). This pulsar system goes by the name of PSR J0337+1715 (or just "J0337" for short). Discovered by PhD student Jason Boyles (West Virginia University), regular monitoring of this pulsar soon showed that it was behaving strangely. The pulsar was clearly in a 1.6-day orbit with another star (a white dwarf), but after correcting for the Doppler effect induced by this orbital motion the pulsar's spin rate still appeared to be speeding up.

All radio pulsars slow down with time because their huge magnetic fields act as a brake. So how could this pulsar be spinning faster with time? Continued monitoring using the GBT, Arecibo and WSRT revealed the answer: the pulsar and its binary companion were actually orbiting yet another white dwarf star once every 327 days (Figures 1 and 2). This was causing the pulsar to move towards us, and thus further Doppler-shifting its period to make it appear like it was rotating faster and faster. Such an orbital configuration is known as a hierarchical triple system because it is effectively a binary system nested within another binary system. The orbits of the three stars can be stable as long as the inner binary separation is much smaller than the outer binary.

We had an exciting new system to study, but also a big challenge at hand: given the complicated way in which the pulsar and the two white dwarfs pull on each other, was it going to be possible to accurately model their motions?

High-cadence monitoring observations were key to understanding this system. Though GBT and Arecibo provided very sensitive measurements, WSRT was able to play a critical role because it could make near-daily observations during the early preparations for Apertif in 2012 and 2013. Even if only a subset of the dishes was available, and even if only for 30 minutes at a time, this still provided valuable pulsar timing data. Having observations each day meant that we could start with a rough model of the system, and then slowly refine this description each time a new measurement was added. However, this modeling was inaccurate because it assumed that the nested inner binary and outer binary do not interact with each other. In reality, however, the two orbits are constantly tugging on each other and changing the pulsar's motion in subtle, but measurable ways.

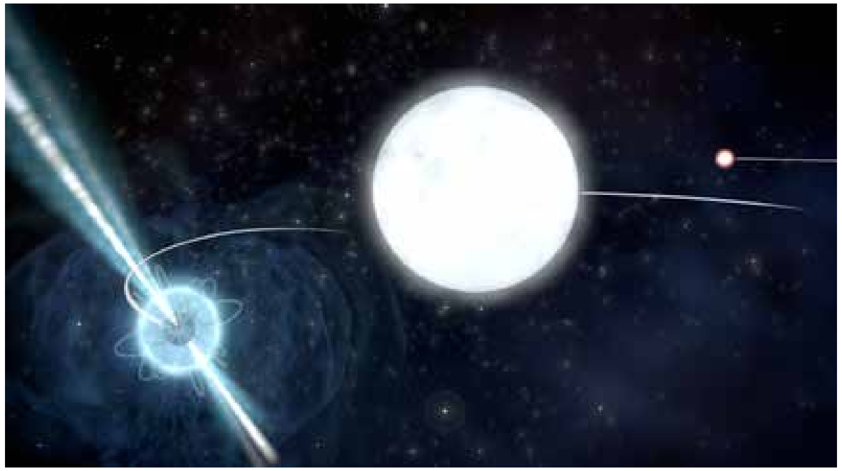
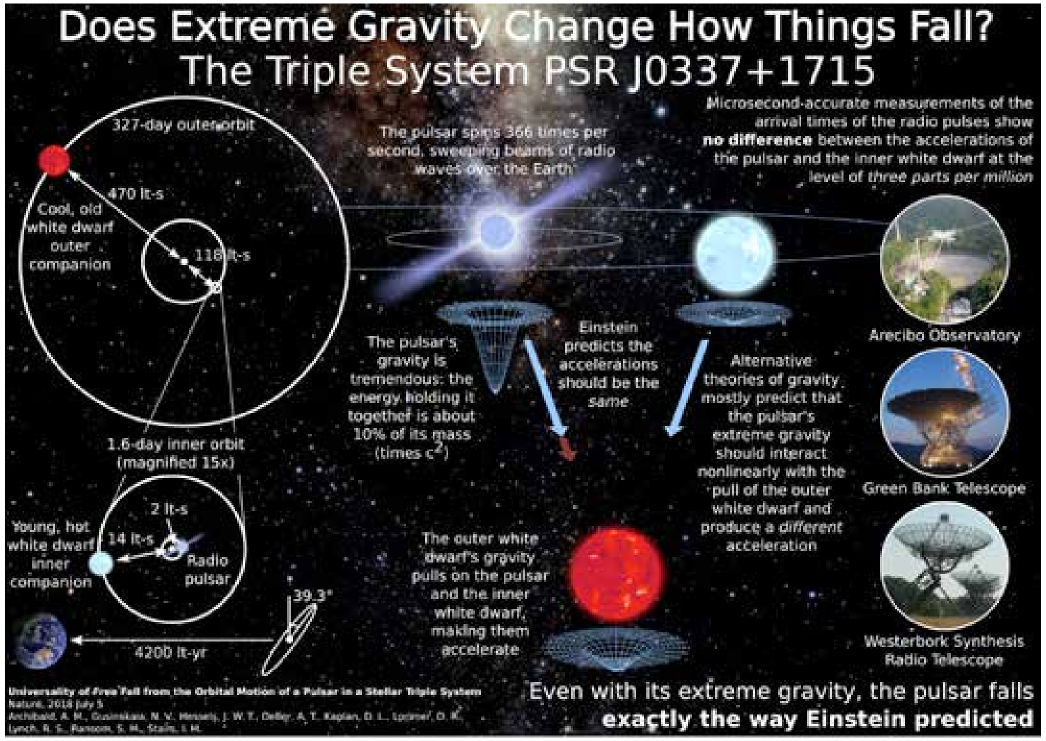


Figure 1: An artist's conception of the PSR J0337+1715 system. The pulsar and the inner white dwarf are in a 1.6-day orbit. This pair is in a 327-day orbit with the outer white dwarf, much further away. Credit: SKA organization.



Enter Anne Archibald, who fearlessly took on the ambitious task of accurately modeling all effects in the system. In her approach, Anne created a computer simulation of the orbital motions, tracking how the three stars dance around each other under the influence of gravity. She then tweaked the starting point of this simulation, the orbital properties, and the masses of the three stars, until the simulated motion matched with the observed arrival times of pulses from the pulsar.

Figure 2: An overview of the key ideas behind this test of Einstein's gravity. Credit: Anne Archibald & Neil Blevins.

From this modeling, nearly the full geometry of the orbits can be determined, as well as the individual masses of pulsar and two white dwarfs. We found that the pulsar has a mass 1.4 times that of the Sun, whereas the inner and outer white dwarfs have masses of 0.2 and 0.4 that of the Sun, respectively. Each of these masses could be determined with a precision of one part in 10 thousand.

Understanding how such a triple system can exist at all is already an interesting puzzle in stellar evolution. Importantly, the pulsar spins with a period of only 2.7 milliseconds – i.e. it rotates hundreds of times a second. The paradigm for the origin of such rapidly rotating neutron stars is the recycling scenario, in which a low-mass companion star can steadily transfer matter and angular momentum onto a neutron star and thereby spin it up. Recycling is certainly part of PSR J0337+1715's creation story, but the formation and evolution likely involved several stages of mass transfer, possibly also a stage where the outermost star was transferring mass onto the inner binary and creating a circum-binary disk. Though there must certainly be other pulsars in our Galaxy with two white dwarf companions, such systems are not easy to form and thus must be quite rare.

Fortunately, we can use PSR J0337+1715 as a unique natural laboratory, even if we don't understand the details of how it was formed. As previously mentioned, pulsars have been used to perform important tests of gravitational theories. In the case of the Hulse-Taylor binary, that was by detecting orbital decay from gravitational waves. Other pulsar systems can test gravity in complementary ways.

Millisecond pulsars in very wide orbits with a white dwarf star have been used to test a fundamental aspect of general relativity: the universality of free fall. Universal free fall dictates that all objects, regardless of their mass or composition, will experience equal accelerations in an external gravitational field. Apollo astronaut David Scott demonstrated this principle in the near vacuum on the Moon by dropping a hammer and a feather. Sure enough, they hit the lunar surface at the same time. It is sometimes said that Galileo performed a similar demonstration from the leaning tower of Pisa, but it's unclear whether he actually performed that experiment. Much more serious and precise tests have been done using lunar laser ranging, in which the exact distance to the Moon is determined by bouncing signals off a reflector left by the Apollo astronauts. In this way, we can see whether the Earth and Moon experience equal accelerations towards the Sun.

In the case of a pulsar and a white dwarf binary, the external gravitational field is provided by the Milky Way galaxy itself. Here we can see whether the pulsar and white dwarf also experience equal accelerations. If not, one would expect their orbit to become elliptical (oval shaped) in a way that points towards the centre of the Galaxy.

Such tests are important because, while general relativity perfectly describes the falling feather and hammer, maybe the extreme gravity of a pulsar will allow us to see where the theory starts to break down. Newton's theory of gravity is an excellent practical description unless objects are moving very rapidly or bend space-time strongly, like a neutron star or black hole. So far, Einstein's theory of gravity has shown that it provides an accurate description of gravity in the extreme conditions under which Newton's theory breaks down. That said, maybe under even more extreme conditions, or with sufficient experimental precision, we'll see that Einstein's general relativity also has flaws. Testing the universality of free fall is key because it is a fundamental principle on which general relativity is based: gravity is purely a reflection of the geometry of space-time, and inertial and gravitational mass are equivalent.

The PSR J0337+1715 triple system allows us to test the universality of free fall like never before. Here the pulsar and inner white dwarf are falling freely in the gravitational field of the outer white dwarf. The accelerations that they are experiencing are many orders-of-magnitude stronger than those experienced by pulsar binaries in the gravitional field of the Galaxy alone. Hence, we can perform a much more powerful experiment compared to previous studies.

To do this, we collected over 1,200 hours of observations using WSRT, GBT and Arecibo. This provided over 27,000 measurements of the pulse arrival time, where each such value is derived by averaging close to a half million individual pulses. This is necessary to distinguish the pulsar signal from the noise of the telescope. What we found is that the pulsar and inner white dwarf experience identical accelerations towards the outer white dwarf, to within a few parts in a million (Archibald et al. 2018, *Nature*, 559, 73). This test is about 1,000 times more constraining than previous studies, and again Einstein's general relativity has passed with flying colours.

Many alternative theories of gravity have been proposed, and our result enables us to place limits on how much these theories can deviate from the predictions of Einstein's general relativity. At the same time, the quest to better understand the fundamental nature of gravity, dark matter, and dark energy continues. While the PSR J0337+1715 test will likely stand as the most stringent constraint on universal free fall for some time to come, observations of gravitational waves with LIGO/Virgo will also be testing gravity in other ways. With the upcoming Square Kilometre Array, we expect to discover a large fraction of all the pulsars in the Milky Way, and among this harvest will surely be other pulsar triple systems that may provide the next, even tougher exam for Einstein to pass.

Chapter 6 An Ever more penetrating View

Jan Noordam*

Between the astronomer and his result, stands software...

An instrument like the WSRT makes measurements of astronomical objects. These include images, frequency spectra, polarization and time variability. Apart from nominal parameters like sensitivity and resolution, the quality of such "Views on the Universe" depends critically on our ability to calibrate the various instrumental effects. In our case, this is done primarily by means of software.

Over the last five decades, the quality of radio astronomical observations has been improved by several orders of magnitude, allowing astronomers to penetrate ever deeper into (the secrets of) the Universe. Throughout, the WSRT group has played a leading role in this.

Introduction and Overview

In order to separate astronomical "truth" from instrumental effects, an accurate model of the instrument is required, and of the intervening propagation medium. Such a Measurement Equation (ME) contains many parameters, whose values have to be estimated with great accuracy. Especially if very faint objects are to be studied in the presence of very bright ones. Fortunately, the contaminating bright sources can be used to solve for ME parameters, and thus to calibrate the instrument.

> One rather useful definition of calibration is "the capability to subtract the effects of bright sources from the data with (very) high accuracy", so that faint objects may be studied. This capability implies a (very) accurate knowledge of the values of all instrumental parameters.

The development of calibration algorithms in radio aperture synthesis over the last 50 years has been remarkably successful. Apart from making many astronomical discoveries, it has put us in a position to contemplate the creation of much larger and more sensitive radio telescopes. On the other hand, we have not been particularly good at offering these algorithms effectively to the users of our telescopes, thus causing them to be under-utilised. This is a matter of some urgency.

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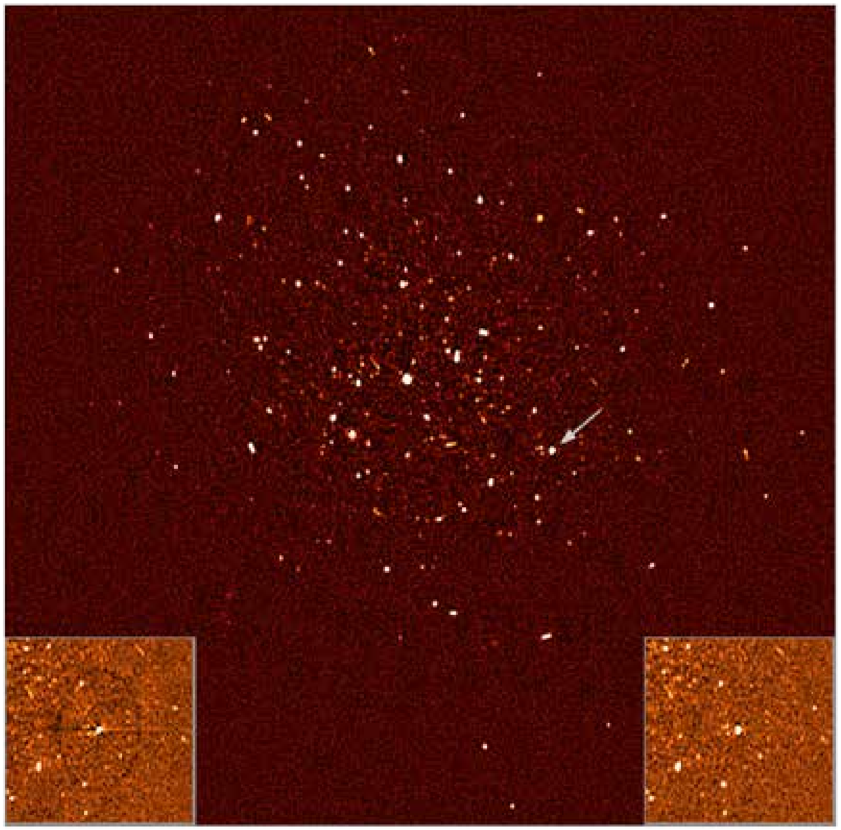
The WSRT group has played a leading role in the development of calibration algorithms. For instance, for most of the 50 years under discussion, the WSRT has held the world record of "Dynamic Range". This widely used quality measure is the ratio between the flux of the brightest source in the field, and the faintest source that can be discerned. This ratio has improved by almost five(!) orders of magnitude, from about 100 in 1970 to 8.000.000 (8 million!) in 2017.



3C147 (Smirnov/ Perley) The Dynamic Range of radio images has improved by almost five(!) orders of magnitude, from about 100 in 1970 to 8.000.000 (8million!) in 2017. The WSRT group has played a major role througout

An important reason for the accuracy of WSRT calibration is that the instrument has been very carefully engineered, which leads to better starting conditions for the calibration process. In addition, the WSRT has a number of features that lead to a simpler Measurement Equation, with fewer parameters to be calibrated. These features include equatorial mounts, on-axis receivers, redundant spacings and correlators with essentially zero closure errors.

The superior calibration of the WSRT has produced much admiration, but only a few astronomers were prepared to invest the considerable extra effort required to get the most out of the instrument. But the exercise has put ASTRON in a position to take the lead in thinking about the next generation of giant radio telescopes, like LOFAR and SKA, for which such precision is no longer a luxury, but a necessity.

In addition to the development of calibration algorithms, the WSRT group has also played a leading role in efforts to make it easier for astronomers to process data taken with the WSRT and other radio aperture synthesis telescopes. This ranged from offering a WSRT Data Reduction Service during the 1970's, to trying to unify the proliferation of software packages that sprang up after the Selfcal revolution around 1980. These worldwide efforts have only had limited success, despite the obvious advantages.

The glorious first ten years (1970-1980)

Radio astronomy is a relatively young subject, but tremendously important. 80% of the Nobel prizes awarded to astronomical subjects are in the radio regime. And the WSRT was precisely on time. For 10 years, it was the most sensitive telescope in this new and exciting wavelength window, where many important discoveries were made. In addition, there was not yet much competition from rival wavelength regimes, which required telescopes on mountain tops or in space.

The success of the WSRT was made possible by the fact that Prof Oort in Leiden had been one of the first to realize the potential of radio astronomy. As a result, considerable technical experience had been built up with the 25 m Dwingeloo telescope, led by a very thorough Lex Muller. But the cherry on the cake was a remarkable student called Wim Brouw, who not only extended the theory of aperture synthesis to help design the WSRT, but who also happened to understand the new but essential phenomenon of computers. Thanks to him, WSRT calibration and imaging fully operated from day one.

Wim Brouw was one of the first to understand computers. As a student, he made sure that WSRT imaging and calibration fully operated at the opening in 1970. He later re-implemented the RSC software as NEWSTAR

As a result, many talented people from all over the world flocked to the Netherlands to use this marvellous instrument, and to pick the abundant low-hanging fruit. One might say that the first decade was the most glorious period of the WSRT, even though the image quality was still relatively poor because calibration techniques like Selfcal had not yet been discovered. Fortunately, the CLEAN deconvolution technique had been invented by Jan Högbom in 1972. Arguably the high point of the WSRT was the 1977 Symposium in Groningen on "Image Formation from Coherence Functions in Astronomy", which was attended by everyone who was anyone in radio astronomy processing.

After 1980, the WSRT remained at the scientific forefront for decades, despite being somewhat overshadowed by newer telescopes elsewhere, with more active PR departments than the modest Dutch were comfortable with. The WSRT also remained a technological leader, with cutting-edge correlators, frontend receivers, IF systems, observation modes (including VLBI, the Sun, and pulsars), time/frequency dissemination, shielding against interference, and calibration software. All these aspects are treated in detail elsewhere in this book. As a last hurray, the WSRT is now pioneering the art of using receiver arrays in the focal plane of the dishes, which significantly widen the field of view.

Imaging by means of Aperture Synthesis

WSRT is an aperture synthesis telescope. It consists of an array of 14 dish antennas, with a diameter of 25 m each, placed on an East-West line of 3 km length near the village of Westerbork, in the Netherlands.
An aperture sythesis telescope is an imaging instrument, just like an optical telescope. Both receive electro-magnetic radiation from objects in the sky through a given aperture (literally: opening). The resulting distribution of electric fields in the aperture gives rise to something called a "visibility function", which can be turned into an image of the sky by means of a Fourier Transform (FT). In an optical telescope, the FT is performed by a lens or mirror that is placed in the aperture. Physically, it concentrates the light from different "stars" on different locations in the focal plane, thus forming an image of the sky.

The same principle can be used to make images of the radio sky, since optical and radio waves are both electro-magnetic waves, albeit with different wavelengths. The visibility function of the incoming radio waves may be sampled by means of an array of radio antennas, and then turned into an image by a performing the Fourier Transform with a computer. This was first demonstrated in a practical instrument by Ryle, who was awarded the Nobel Prize in 1974.

So radio aperture synthesis measures the Fourier Transform of the image, rather than the image itself. For this reason, it has been called "indirect imaging", as opposed to "direct imaging" with optical telescopes. As mentioned elsewhere, indirect imaging has considerable advantages for calibration, and for building large telescopes.

The first radio telescopes consisted of single dishes, which were used for a time-consuming form of direct imaging, observing only one pixel at a time. Such dishes soon reached their mechanical limits, with a diameter of about 100m. Fortunately, indirect imaging with arrays of many modestly-sized dishes greatly increase the sensitivity and the spatial resolution.
The field of view of an aperture synthesis telescope is determined by the primary beam, i.e. the response pattern of a single element of the array. At an observing frequency of 1400 MHz (21 cm), the 25 m dish of the WSRT is sensitive to an area of half a degree on the sky, the size of the full Moon. The spatial resolution is determined by the overall size of the array, which can be as large as the 12000 km diameter of the Earth, or even larger.

Sampling the Visibility Function

The visibility function (i.e. the Fourier Transform) of the sky may be sampled by correlating the signals from "interferometers", i.e. pairs of antennas. Each interferometer represents a point in the "aperture plane", or uv-plane. Its coordinates (u,v) are determined by the length of the baseline between the two antennas, and its orientation w.r.t. the observed sky (i.e. as it is "seen" from the observed source).

Because of Earth rotation, the projected length and orientation of the baseline changes slowly in time, so each interferometer samples the visibility function along a curved line (an ellipse) in the aperture plane. In this way, the equivalent of an aperture might be said to be "synthesized". As soon as enough "visibilities" have been collected, they may be transformed into an image of the sky by means of the inverse Fourier Transform. Obviously, the image quality will be better if the aperture is more fully sampled, simply because more complete information is available. In that case, calibration is also easier.

The process of sampling the aperture plane can be greatly speeded up by using arrays of many antennas. The N=14 dishes of the WSRT contain N*(N-1)/2=91 independent interferometers, i.e. combinations of two dishes. Obviously the antenna locations should be chosen in such a way that each interferometer samples a different ellipse in the aperture plane.

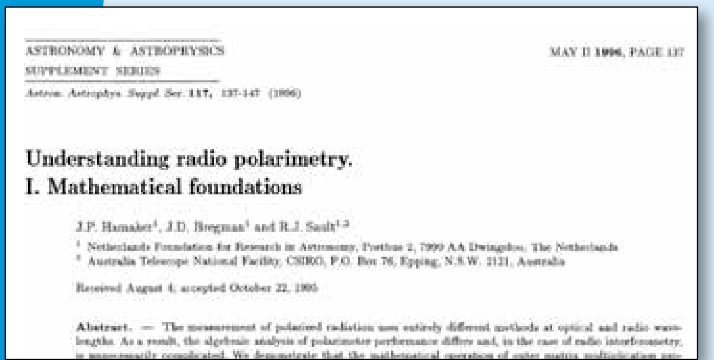
Most (10 out of 14) WSRT dishes are located at regular intervals of 144 m on a straight line. This was done because the WSRT was designed in the 1960's when computers were not yet very powerful, and certain imaging algorithms had not yet been discovered. Nowadays, such a configuration is not considered efficient because it does not maximize the number of independent interferometers. For instance, there are 10 baselines with the same length (144 m) and orientation, so they sample the same uv-point. On the other hand, these "redundant" spacings can be used for calibration (see below).

Re-formulating Theory: The Measurement Equation and Polarimetry

Johan Hamaker

The first experiments in radio-astronomical interferometry used pairs of identical antennas each with a receptor for a single component of the incoming radiation. Such interferometers can be represented by a simple algebraic equation relating the single output to the intensity of the incident radiation. An obvious way to double the sensitivity of the instrument is to add second receptors for the complementary component that the first receptor pair misses. The two signal pairs travel through separate channels through the interferometer and can be independently calibrated.

The front page from the famous paper by Hamaker, Bregman and Sault which introduced the Measurement Equation to aperture synthesis imaging.



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Understanding radio polarimetry.
I. Mathematical foundations

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Abstract. — The measurement of polarized radiation uses entirely different methods at optical and radio wavelengths. As a result, the algebraic analysis of polarimeter performance differs and, in the case of radio interferometry, is unnecessarily complicated. We demonstrate that the mathematical operation of outer matrix multiplication pro-

Many radio sources exhibit the astronomically important property of *polarisation* which produces a correlation between the two signal components. Similar correlations are spuriously produced by errors in the interferometer itself. To handle these effects, the pair of interferometer equations must be dissected and patched up with auxiliary equations that in turn must be made tractable through approximations. For most sources the polarisation effects are small enough to justify the approximations and the same is true for the instrumental errors. The very large effect of ionospheric *Faraday rotation* must be treated separately. In all this, it is also tacitly assumed that all antennas and receptors are identical, invariable and mechanically tracking the motion of the source during an observation.
This method has been coded in software packages and prescriptions for their use. They have been discussed at length in papers with page-wide formulas which only a very few specialists fully understand. For most others, polarimetry remained a black art whose fruits they happily consumed. Whether the rules were always correctly applied we cannot know, but in general the outcomes reported have been credible enough

Kurt Weiler added a twist that could be applied only in the WSRT designed with rotatable receptors. By rotating those of the movable telescopes at 45 degrees relative to the fixed ones (the '*crossed dipole*' configuration) he made calibration simpler and more robust. In this mode the WSRT observed successfully for a decade, with the world suspiciously watching. In the 1980s when, for the sake of higher sensitivity, the fixed-fixed and movable-movable interferometers were activated, the crossed-dipole mode had to be abandoned.

Many may have felt uneasy with the complexity of polarimetry and its inelegant treatment, yet the astronomical community accepted it because it produced plausible results – and anyway there was no alternative in sight. Meanwhile, maintenance of this software was becoming an intolerable burden and the hard decision to make a fresh start from scratch was made at several places.

In 1991 the international *AIPS++* consortium was set up to develop a new universal software infrastructure that would serve the needs of all of astronomy once and for all. At ASTRON, inconclusive discussions were bypassed by Wim Brouw who single-handedly managed to develop (in old-fashioned Fortran) a complete system (later to be named NEWSTAR).

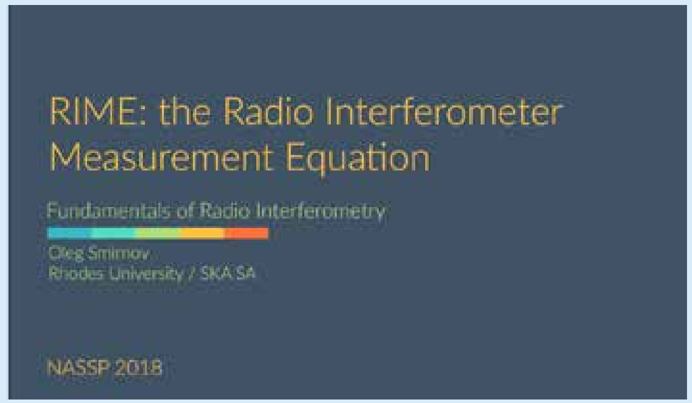
Both efforts stumbled on fundamental problems associated with polarimetry. Tim Cornwell found that *AIPS++* lacked a fundamental cornerstone which he called the *Measurement Equation.* Wim was bothered by ambiguities about the order in which multiple errors in interferometric polarimetry should be corrected. Johan Hamaker was horrified by the ugliness of customary polarimetric processing and decided that there must be a more proper way.

For half a century, radio astronomy had been built upon the scalar interferometer equation that ignores the two-component *vector* character of electromagnetic radiation. Instead of ordinary algebra, mathematics offers a tool to handle such vectors known as Linear Algebra, the algebra of *vectors* and *matrices.* In a breakthrough paper *Hamaker, Bregman and Sault (1996)* reformulated interferometer theory from scratch, showing how matrix algebra can represent all familiar features and quandaries of the traditional theory in a simple and natural way.

When Cornwell received a preprint, he immediately recognised the proposed matrix equation as the one that he had been groping for in vain and promptly orchestrated a changeover in AIPS++. Observing astronomers on the other hand rejected the 'matrix nonsense', claiming that AIPS++ had better things to do.

Indeed the conversion job, though inevitable, came on top of a project that had been overloaded with ambitions and expectations from the beginning. A few years later it collapsed under the burden, but it has not lived in vain. Its legacy is a large body of well-designed software infrastructure (now known as CASA) which is properly maintained and upon which others can build further for their own purposes. Major beneficiaries are ALMA and our own LOFAR.

LOFAR with its mechanically static hardware cannot in any way be made to satisfy the demand that the antenna hardware tracks an observation. It is therefore fair to say that LOFAR as we know it could not have existed without the Measurement Equation. Conversely, the needs of LOFAR have enforced a software development that might otherwise have happened much more slowly.
Replacing the very root of interferometer theory, the Measurement Equation represents a true revolution in radio astronomy. Since its introduction, an entire new generation of astronomers has been brought up who consider it as self-evident. Yet in practice they, too, must in many cases resort to legacy programs from the previous century. It is very fortunate that two major events came at the right moment to speed up modernisation: The establishment of AIPS++ and the construction of LOFAR as prototype of a new generation of *phased-aperture* telescopes.



In real use: Oleg Smirnov teaching about the Measurement Equation in South Africa (courtesy: Oleg Smirnov, formerly ASTRON, now at SKA S.A.) See also his MOOC lecture: https://www.youtube.com/watch?v=Ipsyz9Ngv_g&index=9&list=PLVc4L-hESHSokNTcWD4NWuQkkyzkFDSQL&t=0s

Deconvolution

In all imaging instruments, a point source will not be imaged as a point. It will be imaged as a "blob", which will be larger (i.e. the image will be fuzzier) if the aperture is smaller. In addition, an incomplete sampling of the aperture will cause such a blob to be surrounded (i.e. convolved) by a "point spread function" (PSF) which can be quite extended. The PSF around bright sources can contaminate the entire field-of-view.

An optical image taken with the Hubble Space Telescope illustrates how point sources are convolved with a PSF that is caused by the imaging instrument. In this case, it is cross-shaped, caused by the struts of the secondary mirror

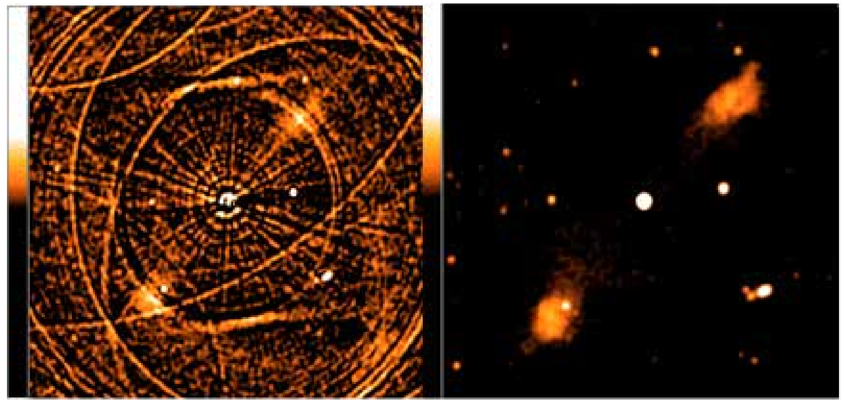
If the PSF of an imaging instrument is accurately known, it can be subtracted from the image, centered on the position of bright sources. This process is called "deconvolution". The CLEAN algorithm developed by Jan Högbom in 1972 greatly contributed to the early success of the WSRT. Eventually it became clear that it is much more accurate to subtract bright sources from the visibility data, rather than from the pixelated image.

> At the 1977 colloquium in Groningen, there was a fierce debate between Steve Gull and others about the most fundamental merit function to be used in a deconvolution technique called Maximum Entropy. This was settled by Jan Högbom, who showed that any convex function would work equally well.

During the design of SKA in the 1990's, there was a debate whether the collecting area should be distributed over a relatively small number of large array elements, or a large number of smaller ones. This was settled by the realization that fewer elements cause higher PSF sidelobes, giving rise to considerable PSF sidelobe noise caused by the many faint radio sources that cannot be detected for individual subtraction. Their number will greatly increase with the highly sensitive new telescopes. This problem can only be remedied by using arrays of many elements, and thus low PSF sidelobes.

Calibration of aperture synthesis radio telescopes

The nominal PSF (determined by the aperture sampling pattern) will be distorted by instrumental errors, caused by the receiver electronics or the atmosphere. Therefore, the calibration of an aperture synthesis instrument may be defined as "the capability to subtract the PSF of (very) bright sources with (very) high accuracy", clearing the view for faint objects in the field. For this, it is essential to estimate the instrumental errors very accurately.



A WSRT image of 3C236 before and after subtracting the Point Spread Function (PSF) of the synthesised beam from the "dirty" image (left) to produce the sharp image (right) in this case of the Seyfert galaxy 3C236. Note the rings and radial spikes caused by the WSRT PSF.

In terms of calibration, indirect imaging has a number of huge advantages. First of all, in direct imaging, all instrumental effects are mixed up in every pixel. But since a visibility sample only depends on the signal from two antennas, the main instrumental effects are conveniently separated in the data, which makes it much easier to determine their values (see also Selfcal below). Secondly, bright sources may be subtracted much more accurately from visibility samples than from a pixelated image. Thirdly, the electronic measurement noise on visibility samples affects the PSF in a different way than the photon noise in direct images.

Three categories of instrumental effects

As explained above, aperture synthesis measurements are made by interferometers, i.e. pairs of antennas (e.g. dishes). So, each visibility sample depends on only two antennas, and contains information about all the sources in the field-of-view. In this context, we can distinguish three categories of instrumental errors/effects:

1. IBE: Interferometer-based effects are associated with individual interferometers. They can be either additive (thermal noise) or multiplicative (correlator errors).
2. ABE: Antenna-based effects are associated with individual antennas. Examples are cable-lengths, electronic gain, atmospheric phase, etc.
3. DDE: Direction-Dependent effects depend on viewing direction, i.e. they vary over the field-of-view. Examples are (differences in) antenna beamshapes (including pointing), ionospheric phase, etc.

These categories are not mutually exclusive, i.e. an instrumental effect can belong in more than one category. Most effects also dependent on time and frequency.
The key to calibration is the reduction of the number of independent parameters that have to be solved for. In any case, the number should be considerably smaller than the number of visibility samples. The huge success of Selfcal (see 2GC below) is based on the assumption that all instrumental effects are ABE, so in an array of N antennas there are only N independent errors for every set of N*(N-1)/2 interferometers. Since the advent of digital correlators, which do not generate their own IBE, we may assume that this "Selfcal condition" is largely satisfied. Except of course for thermal noise, so Selfcal does not work for low S/N.

The number of independent parameters can also be reduced considerably if it can be assumed that they are roughly constant, or vary only smoothly, in time, frequency or direction. In that case, one may solve for the coefficients of smooth functions.

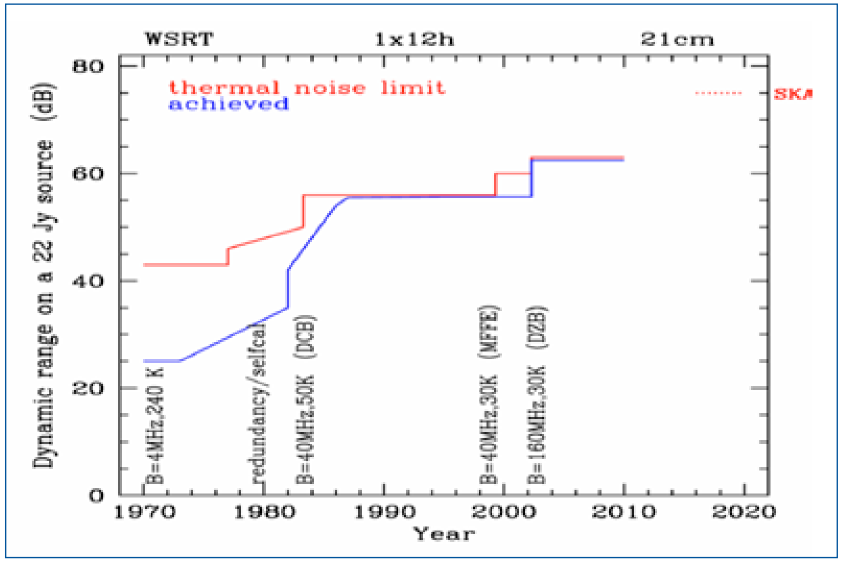
Note that visibilities can only be corrected for one direction in the sky, so "corrected visibilities" do not exist in the presence of DDE. Therefore, DDE corrections can only be applied during gridding, which greatly increases the processing requirements.

Four Generations of Calibration

In the development of radio astronomical data reduction, we may (roughly) distinguish four Generations of Calibration (GC):

- 1GC: Reliance on instrument stability (1960)
- 2GC: The Selfcal Revolution (1980)
- 3GC: Direction-Dependent Effects (DDE, 1995)
- 4GC: Statistical analysis of the residuals (2010)

After the Selfcal revolution around 1980, the calibration kept up with the increasing sensitivity of the WSRT (see also Chapter 10).



After the Selfcal revolution around 1980, the calibration kept up with the increasing sensitivity of the WSRT. Thanks to the "unnecessary"attention to detail of the WSRT group, we might be in a position to calibrate the much more sensitive new telescopes.

In the following sections, the four generations of calibration will be discussed in some more detail.

1GC: Reliance on instrument stability

The measured Visibility samples are complex numbers, each with an amplitude and a phase. To first order, the instrumental errors caused by the receiver electronics or the atmosphere can also be expressed as a complex number, with which the "true" Visibility is multiplied. During the first decade, the WSRT was calibrated by observing a bright point source with a known flux and position. For each interferometer, any deviations from the expected phase (zero) and amplitude (the calibrator flux) were interpreted as the instrumental error for that pair on antennas.
These instrumental errors were assumed to be constant over the 12 hours of the subsequent observation of the desired source. For the most common observing frequency of 1400 MHz (a wavelength of 21 cm), this assumption was accurate to a few degrees of phase, and a few percent of amplitude. The result was a dynamic range of about 100, i.e. the residuals between the nominal and actual (distorted) PSF for the brightest source in the field were about 1% of the peak flux of that source.

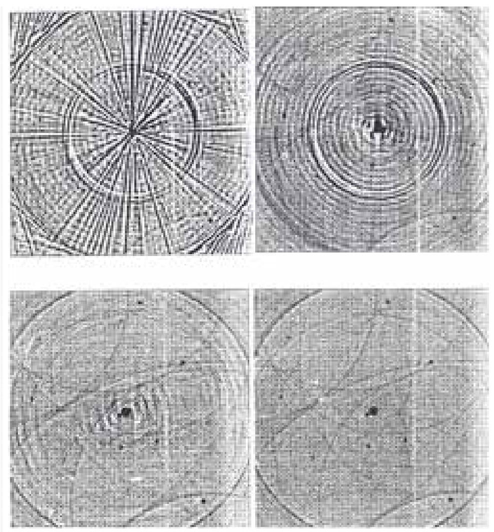
As mentioned above, 1GC was good enough to pick the low-hanging fruit in the glorious first decade of the WSRT. Meanwhile, there were serious concerns about the phase stability of the new Very Large Array (VLA) in the USA, which had longer baselines and operated at higher frequencies. Plans were made for calibrating much more frequently than every 12 hours. Fortunately, that proved not to be necessary.

2GC: The Selfcal Revolution (1980)

The analog electronics that were used to correlate the signals from the two antennas of an interferometer caused a significant "closure error" of its own. This changed with the introduction of digital correlators in the late 1970s. From then on it could be assumed that the instrumental error of an interferometer was simply the product of the (complex) errors of its two antennas (the Selfcal Condition). This meant that the N*(N-1)/2=91 samples measured simultaneously by an array of N=14 antennas shared only 14 independent errors. This reduction of the number of free parameters made it possible to "self-calibrate" the instrument continuously during the observation.

> In a well-designed aperture synthesis telescope, the only closure error, and thus violation of the Selfcal Condition, is the thermal noise, which is different for each interferometer. This will only affect the calibration solution if there are no bright sources in the field, i.e. the S/N ratio is low. And even then the problem is minimised because random noise will not cause any systematic effects.

Selfcal starts with an initial model of the observed field, e.g. a single point source. For each timeslot (e.g. 1 minute) the values predicted by the model are compared to the actually measured visibilities of all 91 interferometers. The differences are then used to solve for the instrumental errors of the 14 antennas. After correcting the measured data for the estimated antenna errors, an improved model of the observed field is derived, perhaps including some of the fainter sources. This iterative process is repeated until the residuals between predicted and measured data are small enough.



Four stages of the calibration of a SRT field that contains the bright source 3C48, made with the wonderful imaging software of 1980. Since the nominal PSF of the WSRT is corrupted by instrumental errors, it can only be properly subtracted if these errors are known accurately. If not, faint sources in the field cannot be studied because the entire image will be contaminated with the remains of the PSF of 3C48

Of course this process may appear a bit like Baron Munchhausen pulling himself out of the swamp by his own hair. It converges because the sky is "empty" in the sense that the observed field contains only a limited number of bright sources, which are well separated from each other. It also helps that we may assume that the sources have positive flux, and that they must be within the primary beam. Obviously, Selfcal will converge more quickly (and reliably) if the number of antennas is larger. The minimum seems to be about N=6.

Selfcal was invented by the VLBI community because the phases on the very long baselines involved were too unstable for 1GC. It was initially missed by the WSRT group because the measured data were (for excellent reasons) organised by interferometer rather than by timeslot. The WSRT version of Selfcal was developed when Noordam started using the redundant baselines of the WSRT array for calibration (see below), which required organization by timeslot.

Selfcal caused a worldwide revolution. It made VLBI possible, it saved the VLA, and everywhere the image quality improved by leaps and bounds. The best results were obtained by the WSRT, partly because the telescope was more carefully (over-)engineered than its competitors, and partly because the WSRT group was a bit more obsessive about it. During the 1980s, more than 20 software packages were written to exploit this wonderful new technique. About 4 have survived to this day: AIPS, MIRIAD, DIFMAP, NEWSTAR (see also below).

NB: Since interferometers essentially measure phase differences between widely separated points in the incoming wave front, the absolute position of a source is lost. Therefore, observations are always relative to bright calibrator sources with a known position (and flux).

Redundant Spacing Calibration (RSC)

RSC was the WSRT road to the discovery of Selfcal. If two interferometers are redundant, i.e. if they have the same baseline length and orientation, they should yield the same visibility value, irrespective of the observed brightness distribution. Any differences must be caused by instrumental effects. This can be exploited for calibration if it may be assumed that all instrumental effects are associated with the N antennas in the array, rather than the N*(N-1)/2 different interferometers, i.e. that the Selfcal Condition is satisfied. As mentioned above, this became the case with the Digital Line Backend (correlator) built by Albert Bos in the late 1970's.

RSC by itself produced perfect "scans" of N*(N-1)/2 complex visibility samples that had been observed simultaneously. Since comparison of redundant visibilities is insensitive to absolute phase and amplitude, different scans still had to be "aligned" to each other to produce a perfect image. This was done with a model of the observed brightness distribution, just like Selfcal.

It was soon realized that RSC should be seen as a (model-independent) extra constraint on the Selfcal solution. The joint solution is easily implemented, but it is not much used in practice.

It should be noted that RSC only works well if all antennas "see" the same sky. This is not the case when the antennas have different beamshapes. Therefore, RSC will only be of limited use for calibration of LOFAR or SKA

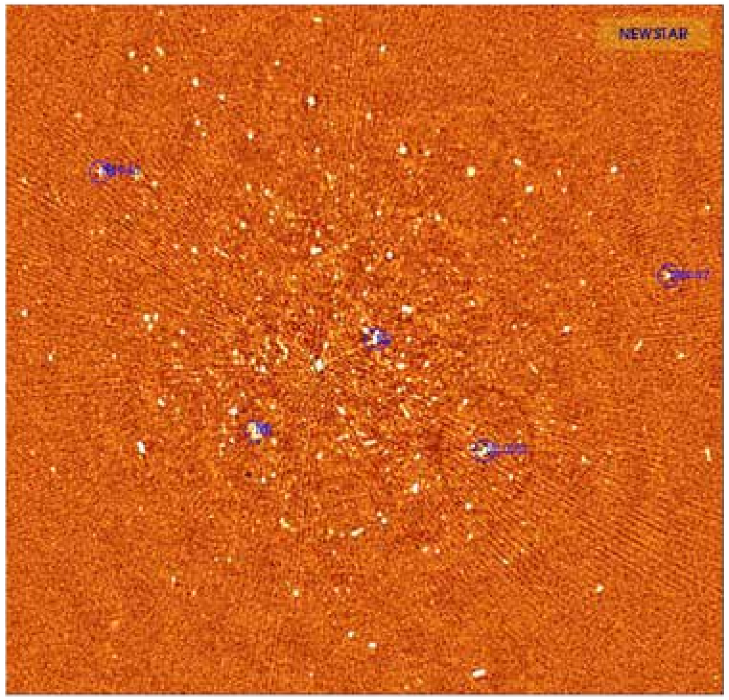
3GC: Direction-dependent effects (DDE)

During the first decade or so, Selfcal was used to solve for a single complex error per antenna, which was assumed to be valid for the entire field of view. This worked well enough for fields that were dominated by a single bright source. Since the estimated errors were most valid for the position of that source, it could be subtracted very effectively, making all the fainter sources much more visible.

But as telescopes became more sensitive, it became a problem that the response beams of the N antennas were slightly different, so that antenna errors varied differently as a function of position (direction) in the field. The ionosphere also causes significant “direction-dependent effects” (DDE), especially at observation frequencies below 400 MHz.

During the 1990s, selfcal was generalized to take account of DDE. For instance by solving for different antenna errors separately for other moderately bright sources in the field. Or by assuming that errors vary smoothly over the field, and solving for the coefficients of loworder smooth functions.

Since uv-data can only be corrected for a single direction, the existence of DDEs meant that corrected uv-data do not exist. This meant that it became much more difficult and expensive to generate calibrated images of the sky. The only way to apply DDE is as part of gridding the uv-data onto a regular grid, prior to Fourier Transforming them to make an image.



3rd Generation Calibration (3GC) deals with Direction Dependent Effects (DDE), i.e. instrumental errors that not only differ per antenna, but also vary smoothly over the field-of-view. In this WSRT image, the bright source 3c147 has been completely removed from the centre by 2GC, but there are still remnants of the PSF of other sources that are affected by DDEs. This problem gets worse with increasing telescope sensitivity and field-of-view.

The generalization of Selfcal was extended also to the (smooth!) variations of antenna errors as function of time and frequency. Smoothness can usually be assumed for time variations, but not always for variations over the frequency band. Estimating smooth functions requires solving for fewer parameters, so it is less expensive in processing. And of course, it is only possible to solve for (much) fewer parameters than the number of available data.

NB: If the field is dominated by a single bright source, good results may be obtained by assuming that the response beams of all dishes are identical (2GC). But for the best results it is necessary to take into account the small differences between the beams (3GC).

4GC: Statistical analysis of the residuals

After 3GC has succesfully removed the PSF of all sources brighter than 3-10 times the instrumental noise, the image residuals still contain many treasures, and problems. They must be approached by statistical means, which is the realm of a new kind of astronomer, who is much more mathematical. They must try to extract the signature (if not the image) of the EoR from the deviation of the noise from a Gaussian distribution.

The Final Frontier is the PSF sidelobe noise of the sea of ever fainter sources that are left in the image after 3GC. The number of those sources increase with faintness, and at some point they start to flow together because of confusion. It would be nice if there were some way to remove the sea of faint sources from the data without knowing their individual positions and fluxes, but with just their overall statistics. Unfortunately, that probably violates the Second Law of thermodynamics.

Observing in more Dimensions

Much of the discussion above is about imaging the radio sky, which is after all the main observing mode of an aperture synthesis radio telescope. Over the years, the WSRT developed into a most superior imaging instrument, through careful engineering, and excellent software. After the Selfcal revolution in 1980, the image quality kept up with the increasing sensitivity brought by better receivers and (much) wider observing bandwidth.

Spectral studies

Images are all very nice, but most (80%) of the astronomical information is in the frequency spectrum. It contains information about the velocity of astronomical objects, and of their temperature and chemical composition. Therefore, the default mode of operation is to making a 3D image cube in which the observed field is imaged for a range of different frequencies. Calibrating the frequency response of the telescope is a serious complication, especially since this response may vary over the field of view.

In the case of the WSRT, standing waves between the dish and the focus box caused the baseline of the frequency response to be sinusoidal, with a typical period of 17 MHz. The latter was determined by the length of the support legs of the focus box, and the observing wavelength. This effect became more serious as the total observing bandwidth increased over time, from 2 MHz to 100 MHz or more. Fortunately, the standing waves have disappeared with the introduction of focal plane arrays which do not reflect radio waves like the old single-pixel feeds.

Time variability

On the whole, the Universe is pretty constant on human time-scales, and most of the time variations are caused by instrumental effects. When astronomical objects do vary in time, they are invariably point-like. This makes it easy to distinguish their variations from instrumental effects. This is greatly helped by the fact that the variations are only in amplitude, and that the WSRT has excellent amplitude stability.

The most rapid, and intensively studied, time-variations are those of pulsars. Since the 1990's, the WSRT has dedicated hardware (PuMa) to search for regular subsecond variations in the raw signals from the various antennas, and in which signals are processed differently e.g. because of de-dispersion required to add the pulse structure and for increased sensitivity.

Polarization

The WSRT has excellent polarization properties. Most of the instrumental polarization is eliminated by having circular dishes and onaxis receivers. There are also advantages to having equatorial mounts because the dishes do not rotate w.r.t. the sky during observations.

Polarisation calibration is difficult because there are not many bright calibrator sources with linear polarization in the sky, and even fewer with circular polarization.

Serving the users of our radio telescopes

The WSRT Data Reduction Service

Radio aperture synthesis telescopes like the WSRT were the first to use computers for observation and data processing and it was deemed too difficult for astronomical users in the early 1970s. Moreover, few astronomers had experience with indirect imaging, i.e. observing the Fourier Transform of the radio sky, rather than the image itself. And finally, the WRST was made available to anyone who put in a worthy observing proposal, rather than just to the expert owners. For all these reasons, it was decided that WSRT data reduction would be done by experts, using programs written largely by Wim Brouw. The users would receive science-ready data products, like images.

Although this was hailed as an enlightened policy, it was soon met by cries of ingratitude. First of all, since the WSRT was a unique and revolutionary telescope with great discovery potential, the impatient users fretted about the delay of several weeks before they received their images. Even then, the Service personnel was not perceived to be particularly responsive to polite inquiries, muted complaints or constructive suggestions. To be fair, these officials were not really in a position to take effective action, for instance by reducing the data in a different way, or by modifying the software themselves. The situation did not improve when the Service was moved from Leiden (where most of the early users were) to Dwingeloo.

In the early 1980s, another model was pioneered by a new competitor of the WSRT, the recently finished Very Large Array (VLA) in the USA. The Americans gave the users their raw visibility data and a software package (AIPS) and told them to do the rest themselves. This worked much better, since the AIPS developers were moderately responsive to feedback, and the users could also write their own software in AIPS.

Eventually, the WSRT developed and distributed its own data reduction package (NEWSTAR, see below), and many WSRT users also used other packages like AIPS or MIRIAD to process WSRT data. At the same time the WSRT User Service continued operation until well into the 1990s.

Of course the whole issue of Service Data Reduction will surface again in the present day. The reason is that the data volumes that are produced by the new generation of radio telescopes are thought to be too large to be taken home by the user, who in any case will not have a suitable computer (or software) to process it. The problem may be solved by developments in computer networks and software. In any case: "Those that do not learn the lessons of History, are doomed to repeat it".

The NEWSTAR data reduction package

During the 1970s, WSRT observations were transported to Leiden by means of 40 MB tapes, to be processed on the mighty IBM360 computer. Amazingly, the staff in Westerbork or Dwingeloo were not supposed to make images or even inspect the data. Fortunately, Johan Hamaker developed calibration and imaging software to test some ideas of his own. This was used gratefully by Jan Noordam to investigate the use of the redundant spacings of the WSRT for calibration. The rapidly improving image quality then attracted the attention (and hard work!) of Ger de Bruyn, a highly respected and knowledgeable WSRT user, to whom this book is dedicated. The result of this collaboration was the WSRT version of Selfcal, which was described in a Nature paper (Noordam, de Bruyn, 1981) after the Dynamic Range exceeded 1:10.000, on 3C84 @6cm.

A picture is worth a million image points: Per 5 aspera ad astra

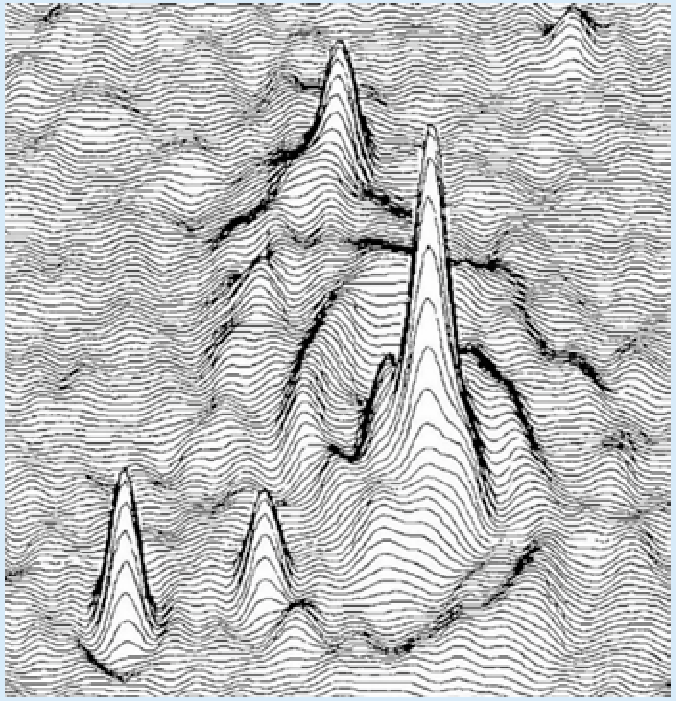
Johan Hamaker

From its very beginning astronomy has been based on visual information. Even today our visual abilities are unsurpassed for recognising scientific patterns in the flood of new observations. Ever since this flood took the form of *rasters* of numbers in computers the quest for suitable visual representations has been on. How can we translate such an array into an image that we can *look* at? With modern technology this may seem a trivial question to ask, but in the 'dark ages' before the utopia of fast high-quality monitors and printers became a reality for every household, we had to resort to much more primitive techniques.

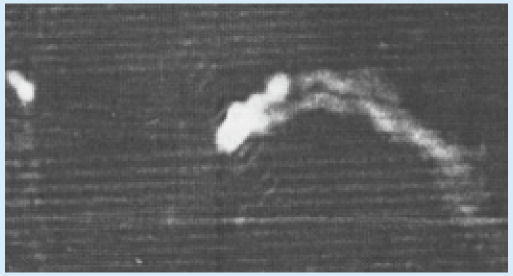
1. In the 1960s the only device that we could harness was a 'plotter', capable of drawing lines of arbitrary shape on a flat piece of paper. With it we projected mountainscapes out of parallel cross-sections of digital rasters. Our eye is reasonably sensitive to subtle elevation differences in this representation, but no more than that. And, of course, we may need additional view angles to see what is behind the mountains.

To use the plotter, one had to submit a 'job' to the University's mainframe computer.

An early WSRT picture of M51. Its spiral arms are clearly visible and details of their position allowed speculation about their relation to the optical spirals.



2. It would be much better if we could translate digital intensities photographically into grey scale. In principle one can replace the plotter paper by a photographic material and the pen by a light point, digitally controlling its brightness. The technique works, but is beset with many complications in practice.



The 'photograph' that revealed the true nature of 3C129: A 'head-tail' source. The sensitive film is mounted on a rotating drum, the light point travels from left to right. The quasi-horizontal streaks is an artefact that is typical for mechanical arrangements with moving parts.

3. Could we have the plotter draw dots, varying their surface density to represent grey shades? It turned out that plotter pens do not survive such abuse for more than a few thousand dots, but we did find a viable alternative: Replace the pen by a metal stylus striking against carbon paper in the way a classic typewriter does.

With a 5x5 dot raster per data point we can represent 26 shades of grey. In doing so we must correct for the strongly nonlinear relation between dot density and visual impression. Moreover, our eyes are experts in picking up unintended accidental patterns over large distances. The only way to suppress these was by adding random noise.

This plot technique was intensively used at ASTRON. Plotting a WSRT image took a whole night, but the result was worth waiting for.

A plot made with the 5x5 dot-raster technique. (In successive Xerox, reproductions the crispness of the original image got lost).

4. Around 1980 a plotter based on the Xerox technique appeared that could translate digital data directly into halftones. This precursor of modern printers would deliver an image in a few minutes. It was a great step forward, although it required frequent repair and maintenance and the printed images were often defaced by bands and stripes of deviant intensity.

At the same time colour monitors became available on which digital brightness and colour distributions could be faithfully and flexibly rendered. Only the Kapteyn Lab in Groningen managed to set aside the 70k guilders to buy one. For years on end it was used day and night and one had to reserve time in advance.

With the 1990 workstations the utopia from the 1960s became a reality. They marked the end of three decades of fascinating experiments on – or just beyond - the brink of the possible.

Ger de Bruyn discussing matters with Rick Perley from the NRAO. Ger has played a major role in the development of better data reduction software, as a motivator and as a high-profile "customer". New techniques are accepted faster if they are espoused by a respected astronomer. Ger was prepared to work through the night to test new features, and never moaned but provided useful feedback. And he was always prepared to show and discuss some new puzzle on his screen.

The RSC software package contained some new features, like the use of parametrized source components as a sky model (rather than a pixellated image). This allowed a much more accurate subtraction of bright sources, leading to better images. After 1983, the RSC package was reimplemented by Wim Brouw, again in close collaboration with Ger de Bruyn. The resulting NEWSTAR package could be distributed to WSRT users to process the data themselves, but few took the trouble to learn yet another user interface (see also AIPS++ below).

The features of NEWSTAR reflect the pride of the WSRT group in the excellence of the WSRT, and the somewhat unusual determination to get the most out of the instrument. Its Selfcal solution could be made more robust by using the redundant spacing information as a powerful extra constraint that did not depend on a sky model. In addition, it could solve for many different (groups of) parameters, even for complex ones. It offered a new way to specify a subset of data to be processed, and was the first package to pioneer automatic flagging of "bad" data. All this prepared the way for generalized Selfcal (see MeqTrees below). Its polarization calibration created the conditions for discovering the Measurement Equation (see below). And it had a calculator (NCALC) that allowed users to play with the data.

The WSRT images produced by NEWSTAR have held the "Blue Ribbon" of Dynamic Range for three decades, until this distinction was taken over by MeqTrees. After Wim Brouw moved to Australia in 1991, he continued to help maintain NEWSTAR remotely, in exchange for a weekly box of Dutch cigars (this is still the best value for money in the history of ASTRON). The package can still be used, and is even available online (in Github), but it effectively died with its only, but very worthy user, Ger de Bruyn, in 2017.

The AIPS++ project

After 1980, there was a proliferation of software packages that exploited the Selfcal revolution. Since they all offered roughly the same functionality, many WSRT users reduced their data with their favourite package, notably AIPS or MIRIAD, rather than learning yet another user interface. In order to reach more users, it was tried for a while to implement some of the special features of NEWSTAR in the widely used AIPS package, but these mysteriously disappeared in the next release.

Still, it was widely recognised that the radio astronomy community would be served better by a single software package that was designed to deal with data from all the different telescopes, and maintained in such a way that new algorithms would quickly reach all users. The idea was adopted by Govert Croes, the new Director of Computing of NRAO, with the enthusiastic support of ASTRON. The result was the formation in 1991 of the AIPS++ consortium, by seven major radio astronomy institutes worldwide. (ATNF, ASTRON, BIMA, DRAO, MRAO, NRAO, TIFR).

The AIPS++ Steering Committee in 1994, and 25 years later. It consisted of self-propelled developers from the various institutes, who had all written their own software packages. Convinced of their own creations, "culture" tensions led the inevitable dynamics.

The outcome was a "qualified success", i.e. it did not achieve its main goal. Eventually, the consortium did produce yet another package, now named CASA, which is primarily aimed at the processing data of the ALMA telescope and the upgraded VLA.

Apart from increasing the interaction between software developers worldwide, AIPS++ did produce some valuable by-products. Most notably the Measurement Set (MS), a well-supported and generally accepted vehicle for the storage and access of visibility data. It was written by ASTRON's Ger van Diepen, who still maintains it as part of the "CasaCore" collection of software utilities. Other valuable modules include Measures and Fitting, both written by Wim Brouw. There was also talk about making it easy for users to contribute new software, in a so called Freedom Layer. And finally, the creative tension around AIPS++ served as a catalyst for the formulation of the Measurement Equation (see below) during the six months that ASTRON hosted the AIPS++ Calibration Design Team in 1992.

In retrospect, AIPS++ was doomed to fail because it would soon have turned into a White Elephant (see below). Nevertheless, it could have been much more successful for a while if we had started off by offering the users a vastly better package for handling uv-data than they were used to. This would have lured them to use AIPS++ for inspection and flagging, before turning to AIPS, MIRIAD or NEWSTAR for calibration and imaging. Only after they were hooked in this way should we have offered our own well-maintained set of well-tested applications, under a nifty user interface. Unfortunately, rather than letting the project grow by the pressure of customer enthusiasm, we started at the wrong end, turning potential users away.

So, even though the AIPS++ project did not achieve its ambitious goal, it was a necessary learning experience, with lots of useful lessons that might be heeded in a second attempt to address what is after all a real problem.

Formulation of the Measurement Equation (1995)

Radio waves are transverse electromagnetic waves, and may be polarized. For a particular source, the polarized state is fully described by four Stokes parameters (I,Q,U,V). A full measurement of the incoming radiation requires two perpendicular dipoles in the focus of a dish, called X and Y in the case of the WSRT. A visibility sample then consists of four complex numbers, which are the result of correlating the two dipoles of the first dish with those of the second one, in all four combinations (XX,XY,YX,YY).

It took a remarkably long time to find a mathematical expression that describes a radio interferometer in full polarization. For more than 50 years, people used separate expressions for the four correlations, which contained approximations to simplify things. Until, in 1994, Johan Hamaker realised that the Kronecker matrix product would lead to an elegant expression without approximations. The instrumental behaviour of each antenna can be expressed as a multiplication of a sequence of 2x2 Jones matrices, each describing a separate effect on the incoming signal. Kronecker multiplication of the two antenna matrices then gives a 4x4 matrix that fully describes the conversion of the four Stokes parameters of the incoming radiation into the four correlations of a visibility sample.

This is now called the Measurement Equation (ME) of a generic radio interferometer. It is believed to describe interferometers with all kinds of antennas, which may not have to be of the same kind. A single dish can be described as a zero-baseline interferometer of the dish with itself.

The ME has been published in four elegant papers by Hamaker, Bregman and Sault in various combinations. It is also sometimes called the HBS formalism. The ME has later been extended for Direction-Dependent Effects (DDE) by Oleg Smirnov. MeqTrees is the only software package that fully implements the matrix formalism.

Oleg Smirnov is standing on the shoulders of Johan Hamaker, Jaap Bregman and Bob Sault, the authors of the HBS-formalism, a.k.a. the Measurement Equation.

The MeqTrees data reduction package

The MeqTrees software package (Noordam, Smirnov) was started in 1995, partly out of exasperation with the AIPS++ project (see above), in which ASTRON was heavily involved. One of the bones of contention was the existence of Direction-Dependent Effects (DDE), like differences in antenna beamshapes. Such effects had been ignored in earlier packages, but were felt (by ASTRON) to be important in the much more sensitive new telescopes.

MeqTrees was designed to implement an arbitrary Measurement Equation (ME), with an arbitrary number of parameters. Moreover, it supports "generalized" Selfcal, in the sense that ME parameters may be smooth functions of time or frequency, or even sky position. The coefficients of such smooth functions (like low-order polynomials) then become the parameters of the ME. MeqTrees also pioneers new ways of visualizing the quality of the result, and of what is going on during the calibration process.

Obviously, there is a price to pay for solving for (substantially) more parameters. It takes more processing, and touches on deep questions of how many independent data points are needed to solve reliably for a given subset of parameters.

In the meantime, very fast algorithms have been developed to solve for the much smaller number of parameters of the simple traditional ME. For instance "StefCal" which was developed in the SKADS context by the Oxford group, in collaborations with ASTRON's Stefan Wijnholds. Because of the flexibility of MeqTrees, it has been the first to offer such techniques to the user. (Needless to say, users have not really taken up the offer, but have clung to their old packages).
Nevertheless, MeqTrees has taken over the world record of Dynamic Range from NEWSTAR, first with WSRT observations, and now with data taken with the new VLA correlator (Smirnov, Perley). The software has moved to South Africa with Oleg Smirnov.

Interaction with the world-wide software community

Prior to 1980, software developers were not really encouraged to visit sister institutes and interact with others who were trying to solve essentially the same problems. At ASTRON, it was considered sufficient for Wim Brouw to bring back enthusiastic reports of what he had learned abroad. This gradually changed with the UK/NL collaboration, which involved more travel for everyone, and with the advent of email and internet. The communication was greatly facilitated by the fact that the Dutch take easily to English, and had been exposed to the many foreigners that were attracted to the wonderful WSRT.
After attempts to distribute NEWSTAR software as part of the much more widely used AIPS package had failed, the first real international software collaboration was the AIPS++ project (see above), which brought together the leading developers of seven major radio astronomy institutes. In the discussions, ASTRON insisted (unsuccesfully) on consistency in nomenclature and units, and tried to set right some sloppy practices that had crept in over the years.

ASTRON developers also started to attend ADASS, a yearly gathering of software developers in all branches of astronomy. Some even rose to membership of the Program Organizing Committee, and conducted a special discussion session on the "Future of Astronomical Data analysis Systems" (FADS). The latter were very popular (developers love grand-standing), and even came up with some ideas that might now be implemented with technology that did not exist in the 1990's.

After the radio astronomy community became serious about building SKA and its precursors (e.g. LOFAR), ASTRON actively participated in yearly meetings about calibration and imaging issues (CALIM). As usual, ASTRON attempted (and failed) to impose a little structure on these discussions, in the hope of identifying priorities and perhaps steering some of the worldwide developments.

Finally, from 2000 onwards, it was felt that the tools now existed to collaborate effectively with a widely distributed group of developers. The primary motivation was to involve talented developers without luring them away from their home institutes. Apart from all kinds of internet tools, we expected great things from PURR, a tool developed by Oleg Smirnov that made it really easy to report in great detail on a data reduction process. The MeqTrees group experimented with a "3GC Community", in which developers worldwide could collaborate remotely in furthering 3rd Generation Calibration. Part of the plan was to offer simulated data-sets, which would reveal hidden delights to those that managed to reduce them well enough. Contenders might use any reduction package they liked, but it was assumed that MeqTrees would win.

Every year, experts from the worldide SKA community gather at one of the participating institutes do discuss calibration and imaging issues (CALIM) pertaining to the new generation of giant radio telescopes. This one was in Dwingeloo in 2010.

From the above it might be concluded that all this interaction did not achieve anything tangible. That would be the wrong conclusion.

A Tale of White Elephants

After half a century of processing the data taken with radio aperture synthesis telescopes, this might be a good moment to take stock of the situation. First of all, we can be proud of a phenomenal worldwide success story, in which ASTRON played a leading role throughout. In 5 decades, the quality of the result has improved by orders of magnitude in all important aspects. For instance, a widely used quality criterion like the Dynamic Range of our images has increased from 1:100 to 1:8.000.000 (eight million!)

We may also note with satisfaction that more sophisticated techniques and faster algorithms are still being developed apace, all over the world, and certainly also at ASTRON. Together with the rapid increase in speed of the hardware for computing, I/O and data transport, we will probably be able to process the huge data volumes from the new telescopes with sufficient accuracy. At the same time we must conclude that we have had, and still have, a substantial (worldwide) user interface problem.

The WSRT was the first aperture synthesis telescope with an open user policy, but felt compelled to reduce the unfamiliar visibility data for the users as a service. This was unsatisfactory for more ambitious users, who wanted more control. After the Selfcal revolution of 1980, various self-propelled developers at different institutes created software packages like AIPS, NEWSTAR, MIRIAD, DIFMAP, etc, with which astronomers could reduce the data of particular telescopes themselves. They often did this in close collaboration with an ambitious user (Golden Teams), and were reasonably responsive to evolving needs. However, the packages all had their own user interfaces and data formats, and suffered from personality quirks and installation issues. Also, the ageing heroes found it increasingly difficult to adopt the newest developments. Still, single-hero packages evolve better than software under the care of teams, because the latter represent the priorities of institutes, and tend to have little emphatic contact with active users.

The result is that our valuable radio telescopes could be utilized much better by many more astronomers if the data reduction software would be easier to use. This includes looking for the hidden treasures in the very substantial data archives that have been accumulated over the years. After all, the large fields-of-view of radio telescopes contain much more than just the target object.

> WIKIPEDIA defines a White Elephant as “a possession which its owner cannot dispose of and whose cost, particularly that of maintenance, is out of proportion to its usefulness. In modern usage, it is an object, building project, scheme, business venture, facility, etc., considered expensive but without use or value”

As it is, only users with special skills and/or resources (like teams) are able to cherry-pick the best features from the available software, to get results of the advertised quality. At the same time, existing software packages are turning into White Elephants, either because their creator dies, or they are under the care of institutional teams.

The AIPS++ project was an attempt during the 1990’s to address the problem. A consortium of 7 leading institutes would jointly create a single package that would offer the best features of existing packages under a single user interface. It would be implemented with the latest technology (C++, OOP), would be well-maintained by an international team, and would smoothly evolve with the newest algorithms and technology. The story of its “qualified success” is a rich treasure trove of lessons that might be heeded in a next attempt. For the dream behind AIPS++ is still as valid as ever.

The key to a solution of this increasingly urgent problem is to recognise the proper role of, and relationship between, the various stake-holders, i.e. the telescope institutes, the self-propelled developers, and the scientific users. We should also look carefully at some highly successful models outside our small world, but this is outside the scope of a WSRT 50-year history.

Chapter 7

Very Long Baseline Interferometry: the EVN, WSRT, and JIVE

Huib Jan van Langevelde[1], Richard Schilizzi[2], Arnold van Ardenne[3]

1. Introduction

Very-long-baseline interferometry (VLBI) is the technique used to study small radio sources using an array of telescopes with separations typically ranging from a few 100km to many thousands of km, including telescopes in Earth orbit. Such an array can be either a dedicated array of telescopes like the US VLB Array or an array of existing national telescopes like the EVN. The network elements must all observe the same target at the same time and with the same frequency sampling, in order to allow their data to be correlated in a central data processor for all telescope pairs. The resulting 'fringe visibilities' can be processed by astronomers to yield high angular resolution images of the astronomical targets. Until the advent of fibre links between telescopes, each telescope operated independently under the control of an atomic oscillator providing frequency and time stability, recording the incoming signals on tape for later shipment to a central location for data processing.

This chapter will take a brief look at the development of VLBI in the Netherlands including use of the WSRT and the gradually emerging leadership role in European and global VLBI undertaken by the NFRA, later ASTRON, and the Joint Institute for VLBI in Europe (JIVE), later JIVE ERIC. It will also briefly review a number of technical developments including the WSRT-specific instrumentation developed for the WSRT as a VLBI element, the EVN MkIV correlator at JIVE, VLBI using optical fibre networks, and the use of the WSRT as a test platform for advancing the VLBI technique for world VLBI. Finally we review some of the major scientific results resulting from VLBI observations using the WSRT as one of the elements, and conclude with some observations on the future of this subject.

1.1 *A brief history of VLBI in the Netherlands*

To put the VLBI developments in the Netherlands in context, Table 1 lists the major events in international VLBI as seen from a Dwingeloo perspective (see also [1] [2]).

[1] Joint Institute for VLBI in Europe ERIC, Sterrewacht Leiden, Leiden University , The Netherlands
[2] University of Manchester , UK
[3] ASTRON , The Netherlands

Table 1: Major events in the development of VLBI, from a Dwingeloo perspective

1967	first VLBI observations, in Canada and the USA	1982	MPIfR MkIII tape recorder-based data processor starts operation
1968	first US-Europe (Sweden) observations	1993	JIVE established as a Dutch Scientific Foundation in Dwingeloo
1975	first discussions of European VLBI		US VLB Array opened
1976	US VLBI Network formed	1997	Japanese space VLBI telescope, VSOP-HALCA, launched
	first 3-station intra-European VLBI observations	1998	JIVE Data Processor opened
1978	first VLBI observations with WSRT in tied-array mode	2004	First e-VLBI observations using optical fibre connections between telescopes and data processor at JIVE
	MPIfR MkII tape recorder-based data processor starts operation	2011	Russian space VLBI telescope, RadioAstron, launched
1980	European VLBI Network formed	2015	JIVE becomes a European Legal Entity (ERIC)

The first discussions in 1975 on the use of national telescopes in a European VLBI network involved George Miley (ULeiden), Roy Booth (UManchester, later Onsala Space Observatory), and Ivan Pauliny-Toth (Max-Planck Institute for Radio astronomy, MPIfR) and took place in the MPIfR cafeteria in Bonn, West Germany. Dutch participation in a second meeting a few months later in Bonn expanded to include Boudewijn Baud, Harm Habing and George Miley from Leiden, and Wim Brouw and Jean Casse from SRZM in addition to a larger delegation from Germany. Early in 1976, a VLBI recording system was ordered for the Dwingeloo 25m telescope and plans were laid by Miley, Habing, Baud and Schilizzi for the first 3-station intra-European observations involving Dwingeloo, Onsala and Effelsberg (Figure 1). These were successful and led to a paper on the compact radio structure in the centre of the largest known extragalactic radio source, 3C236 [3]. This signalled the beginning of a new and

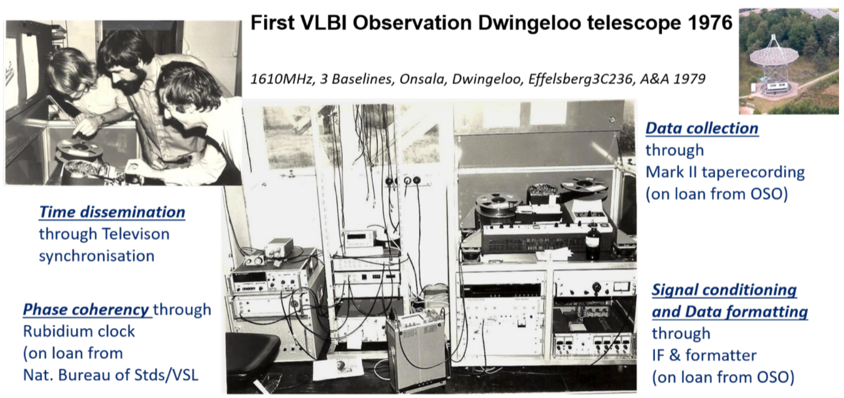


Figure 1. 1976 Dwingeloo 18 cm observation inside the telescope pedestal (!) with Richard Schilizzi and George Miley actively adjusting the recording terminal on loan from the Onsala Space Observatory

exciting strand of astronomical research in the Netherlands whose prospects were outlined in [4].

One of those prospects, much increased VLBI sensitivity, quickly led to plans to phase up the WSRT to create the equivalent of a single telescope with a 93m diameter. Arnold van Ardenne succeeded in designing a first generation tied-array backend in 1978; a photograph of first fringes as they appeared on the screen of the MPIfR MkII data processor is shown in Figure 2. The tied array design and its evolution are described in Section 2.1.

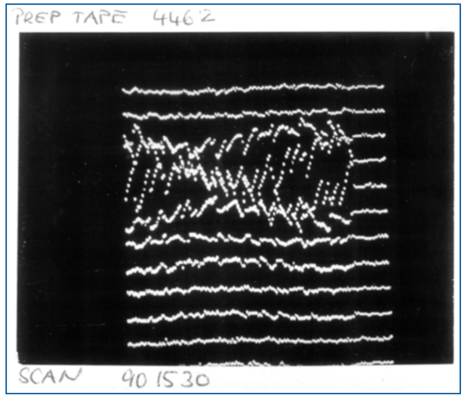


Figure 2. First interference fringes on the WSRT-Effelsberg baseline in 1978. The plot shows fringe amplitude versus delay (vertical axis) and time (horizontal axis) for a compact hot-spot in a 3C source [5]. The WSRT was operating for the first time in tied-array mode.

In the 1970s and 80s VLBI observations were still called "Experiments" because any errors in set-up (e.g. feed polarisation orientation or clock failures) would go undetected until correlation took place, usually well after the data was recorded. But by the late 1980s, VLBI had grown into a mature observing mode in Westerbork making use of increasingly sophisticated adding systems and VLBI recording systems, and the 92 cm, 18/21cm, 6/50cm and later the MFFEE receiver systems.

During 1977 to 1980, plans were laid for the establishment of the European VLBI Network (EVN) including a Program Committee to allocate observing time in six sessions each year. The EVN Board was composed of the Directors of the five founding member observatories – WSRT/Dwingeloo, Effelsberg, Jodrell Bank, Onsala, and Bologna. Harry van de Laan represented the NFRA. Ivan Pauliny-Toth (MPIfR) and Richard Schilizzi were the first Chair and Secretary respectively of the EVN PC.

One of the main issues discussed by the Directors in 1980 was the need for a larger data processor than the 3-station MkIII correlator purchased by the MPIfR from Haystack due to come online in 1982. Driving this idea was the requirement for a "real-time" correlator for 8-station geostationary satellite-linked VLBI, the study of which by ESA had been initiated by NFRA in 1977 [6] following successful tests by a Canadian-US collaboration using a Canadian satellite [7]. In parallel with the ESA studies, Arnold van Ardenne, John O'Sullivan and Jan Buiter carried out tests of local oscillator transfer via the Orbital Test Satellite (OTS) in geostationary orbit [8, 9].

Following an exchange of letters between the EVN (spearheaded by Harry van der Laan) and ESA in 1982 on the L-SAT opportunity, the EVN Board decided that L-SAT use would be too expensive and that was the end of satellite-linked VLBI. However, by then, additional existing telescopes had joined the EVN and new telescopes were planned in Italy and Poland, so the requirement for a large data processor remained.

In the ensuing two years, two proposals were developed, the first to upgrade the MkIII processor at MPIfR to 8 stations (estimated cost 10 Mfl, 4.5 M€), and the second to develop a new generation (12 station) user-friendly data processor in Dwingeloo (estimated cost 15 Mfl, 6.8 M€) [10, 11]. In 1985, the EVN Board decided to create a stronger governance structure and established the European Consortium for VLBI with eight members and a mandate to continue to carry out VLBI observations with the EVN and to seek funding for a large correlator. The nexus surrounding the data processor alternatives was broken in 1984 by a meeting of the NFRA and MPIfR to discuss collaboration on the future large correlator. MPIfR decided that a better match to its mission was to expand its MkIII processor with its own funding, primarily for the scientific use of its staff; this led to the Consortium agreeing in 1985 to seek funding for a new generation processor in Dwingeloo.

In 1986, contact was made with the European Commission in the person of Prof. Paolo Fasella, Director-General of the Science, Research and Development Directorate) by a Dutch delegation consisting Ruurd van Lieshout (ZWO Director), van der Laan, and Schilizzi. Parallel to this, contacts were also made with senior officials in the Dutch Ministry of Education and Science by van der Laan and Wim Brouw. Two years later, a proposal was made to the EC for a 20-station data processor capable of handling observations from all the then possible VLBI stations in the northern hemisphere. The estimated cost was 17.8 M€ (8.1 M€). The EC called in the European Science Foundation for an independent review of the proposal which the ESF Space Science Committee subsequently endorsed in 1989. This allowed the EC to provide an initial grant from the second Framework Program (FP2) for the European VLBI project in the form of a Penny & Giles MkIII tape recorder to be installed at the MPIfR data processor in Bonn.

A few months later in 1990, the Dutch government (Education and Science Minister, Wim Deetman) called again on the ESF to establish a review panel on ground-based astronomy to help put the VLBI proposal in context on a European scale. The result was resounding support for the VLBI data processor. Then followed a year-long hiatus in which some exploratory inter-government discussions took place, particularly with the French Science Minister, Herbert Curien. In 1992 the then new Dutch Minister of Education and Science, Jo Ritzen, convinced the EC Vice-President, Prof Filippo Pandolfi, of the desirability of further EC support for the data processor in order to trigger national contributions. This was forthcoming in the form of a 1 M€ grant for Human capital and Mobility in FP3.

Figure 3. (left) Commissaris Relus ter Beek, with the help of JIVE director Richard Schilizzi, loading a tape on one of the 16 tape drives just before successfully pushing a button to demonstrate fringes from the new data processor. (right) a view of the 16 tape drives and auxiliary electronics and data processor operators.

Following this announcement later in 1992, 5.5 M€ was made available by the Dutch Ministry of Education and Science, 0.3 M€ from the French National Centre for Scientific Research (CNRS), and 0.55 M€ from the Swedish Wallenberg Foundation. In addition, the Jodrell Bank Observatory in the UK agreed to provide manpower for the data processor design. And in early 1993, design, prototyping, and construction of 16 station MkIV processor by an international consortium including the Haystack Observatory in the USA began. It ended almost six years later at a cost of 8.7 M€ including manpower. Further details of the data processor are given in Section 2.2.

On 22 October 1998, the official opening of EVN Data Processor at JIVE was carried out by "Comissaris van de Koningin in Drenthe", Relus ter Beek (Figure 3).

In 1991, internal discussions in the NFRA led to a decision to propose that the VLBI data processor in Dwingeloo be the focal point of a new European centre for VLBI, which came to be called the Joint Institute for VLBI in Europe (JIVE). At the end of 1993, JIVE was formally established as a Foundation in the Netherlands with Schilizzi as the first director.

1.2 Establishing JIVE as a European Research Infrastructure Consortium (ERIC)

Already in the early days of JIVE, it was a recognized to be desirable to transform JIVE into a truly international entity, away from the Dutch 'stichting' legal entity. JIVE being an outstanding example of a distributed, bottom-up organized European research facility, one can suspect that the EC was well aware of this fundamental problem for JIVE and similar entities. In the 4th Framework Programme, the EC started to support a number of distributed or collaborative facilities like RadioNet in which JIVE and ASTRON featured prominently, and this carried on in the 5th, 6th and 7th Framework. During which time the need to have light-weight, truly European entities became much clearer. The ERIC construct was established in 2009 and it allows one to register a legal entity in Brussels as a collaboration of member countries.

For JIVE there were many attractions to becoming an ERIC including formal recognition as an excellent European research infrastructure provider, VAT exemption, and a governance structure based on collaboration of countries rather than the joint responsibility of a mixed bag of universities and national research organizations with different objectives. The latter was also the greatest hurdle to the transformation of JIVE to an ERIC; not in all JIVE member countries it was easy —or even possible— to transfer the interest in JIVE to a ministerial level. In a process that took several years, the Dutch representatives at ASTRON, NWO and the ministry made it clear that the transformation into an ERIC was a requirement to continue JIVE operations at the same level in the Netherlands, especially in an era in which the definition and design of the SKA were also consuming resources.

Figure 4. Dutch key players at the JIV-ERIC inauguration on 21 April 2015. From left to right: JIVE director Huib Jan van Langevelde, EC Science director-general Robert-Jan Smits, NWO astronomy domain leader Ronald Stark, ASTRON director-general Michael Garrett and Westerbork director Rene Vermeulen.

JIVE ERIC was established in December 2014 with four nation members. Since then the membership has increased to six countries and further support comes from research organizations in three more countries, some of which intend to become full members in the future.

1.3 Space VLBI

The early history of space VLBI is described in references [12] and [13]. After the successful participation in the Japanese VSOP-HALCA mission, JIVE and ASTRON staff led by Leonid Gurvits were also eager to contribute to the Russian RadioAstron mission when it was finally launched in 2011. As the EVN decided to accept observing proposals with the Russian telescopes, Westerbork and JIVE staff became involved in supporting various aspects of the mission. The JIVE SFXC correlator was made available on a best efforts basis for correlating RadioAstron observations observed via the normal EVN proposal process. One non-standard project involved procedures developed at JIVE to measure the RadioAstron orbit with simultaneous observations of the spacecraft by a number of telescopes on the ground [14].

2. VLBI Instrumentation

2.1 The Tied-Array at Westerbork

Following the first VLBI observations with the Dwingeloo 25m telescope in 1976 mentioned in Section 1.1, attention turned to using the large collecting area of the 14x25m dishes of the Westerbork array (equivalent to a 93m diameter dish) for VLBI. This required additional and VLBI-dedicated instrumentation to be added to the WSRT in order to gain this large increase in sensitivity and involved adding the signals from all 14 telescopes while maintaining phase coherence to create a so-called tied array, which could act as a single element of a VLBI network or array. The term "tied-array" was coined by Wim Brouw in a corridor discussion in 1977 with Arnold van Ardenne and Richard Schilizzi.

The concept is summarised in Figure 5.

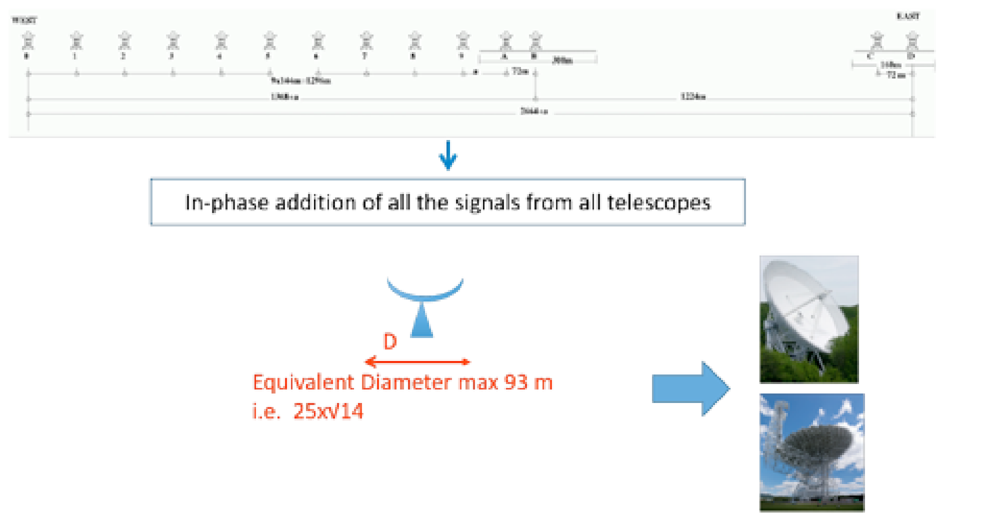


Figure 5. Adding all the individual WSRT telescope signals would ideally result in a telescope with equivalent diameter of 93m. This is comparable with the 100m MPIfR Effelsberg telescope in Germany and the 100m NRAO Greenbank telescope of the NRAO in the USA.

Since this was the first time this had been attempted anywhere in the world, many questions needed to be answered including i) what loss factors affect the VLBI coherence for the tied array signal, and what was the resulting effective area of the tied array, ii) what were the polarization characteristics of the resulting tied-array and what calibration procedures needed to be developed, and iii) what point would be adopted as the phase centre of the array. Efforts to solve these problems were carried out in parallel with early tests of prototype units.

This challenging project to implement and test a number of versions of the new tied- array mode lasted from 1978 to 1986. It was led by Arnold van Ardenne and involved a number of SRZM staff including Hans van Someren Greve, Arie Hin, Jaap Bregman, Harm Jan Stiepel, Jan Buiter, Roelof Kiers, Sip Sijtsma, Piet van den Akker, and others.

Initially, the tied-array system for the 2 MHz bandwidth MkII tape recorder system was implemented on the WSRT DLB. Later versions were implemented first for the DXB, then on the DCB to handle the 56 MHz bandwidth MkIII recorder system, and on the DZB to handle the 112MHz MkIIIa, MkIV system and e-VLBI (described later in this section). The DZB version was given an official name: the Tied Array Adding Unit ("TADU"). These will now be described briefly.

The tied-array adding units

Four versions of the adding unit were built:

1) 1978: an analogue system [15] built for the Digital Line Backend (DLB) comprising a number of custom units inserted at the point where the telescope signals from the 14 telescopes in 2 polarizations were about to enter the analogue-digital converters of the DLB. These units were made in the Dwingeloo lab mostly by Jan Buiter who remained at the centre of the development of dedicated VLBI equipment for more than three decades. The output of the DLB was digitised before recording on the 2 MHz MkIIc system.
2) 1981: a digital combiner system [16] built to provide output to the MkIIc terminal and which used the DLB for calibration and phase/delay alignment. Understanding how to analyse and calibrate the tied array benefitted from fruitful discussion with Jaap Bregman, then system engineer at the WSRT. This digital combiner anticipated use with the MkIII recorder which had been ordered from Haystack and the digital delay lines then being implemented for the WSRT. However, use of the combiner with the DLB would have limited the input signal bandwidth to the MkIII recorder input to 8MHz whereas a 56 MHz bandwidth could be recorded. This led to the next step in tied-array development.
3) 1983: the bandwidth bottleneck for MkIII VLBI was removed to a large extent by a digital combiner [17] designed to use the Digital Continuum Backend (DCB) infrastructure and in which the "bulk" fringe rotator was located before input to the correlator. The much more complicated VLBI-specific system used a residual fringe modulator based on the so-called Cordic iteration principle and a subsequent Weaver scheme to recover the folded sideband technique used in the signal conditioning of the DCB. The unfolding inside the DCB was done by digital cross correlation techniques in combination with 90 degrees phase shifting. Photographs of the equipment are shown in Figure 6.
4) 2006: The Tied Array Distribution Unit (TADU) was developed in combination with the DZB as the interface to Mark5 terminals for VLBI recording and to PUMA II, the Pulsar Backend of the WSRT. It is a flexible all-digital, FPGA-based system that functionally follows the Tied Array Adder Module ("TAAM") in the DZB ADC subsystems [18]. TADU is extremely flexible by design using time variant digital (interpolation) filtering, and allows a variety of output "customers".

Figure 6. Left: VLBI interface equipment - MKIII tape recorder and electronics system on the left and the WSRT-specific VLBI system on the right. Right: A 1987 picture of the digital adding boxes including fringe rotation which were connected to the DCB (not shown). The digital adder was located inside the RFO shielded cabin. That year, a Hydrogen Maser frequency standard was also installed in Westerbork replacing the Rubidium frequency standard. This allowed the longer integration times essential for 6cm and shorter wavelength observations.

Sensitivity loss in a tied-array

Analogue combiner

The main concern initially [19] was calibrating the level of phase coherence of the added signals at the point of analogue addition knowing that full calibration was only possible using the correlator located "after" the point of addition. In practice, any differential effects proved effectively negligible and others were more important.

One of these factors was the presence of the 6/21 cm cooled receivers in the movable telescopes which were much more sensitive than the receivers in the fixed telescopes (Note: At 50 and 92 cm, all receivers were the same). The cooled receivers dominate the added signal and thereby reduce the effective diameter of the equivalent dish. In practice, the cooled receivers had about 3x lower system temperature, assuming no other losses, so the equivalent diameter ranged between 50 m (only the cooled receivers on the movable telescopes contribute) and 93 m (all telescopes contribute with equal system temperature).

Digital combiner

A more complex issue was the sensitivity loss with the later digital combiners [20]. Extra losses were caused when the digital signals output from the delay system are added and then again resampled for the VLBI recording terminal. For a 1- or 2-bit re-digitized signal from the WSRT as one input to the VLBI correlator, extra losses are introduced that are quantified in reference [20] using probabilistic ("multi-variate") analysis.

The conclusion is that the most significant degradation losses occur for a small number of telescopes in the WSRT which, say, are 1-bit digitized before addition and re-sampling. In particular, with an even number of telescopes correlated signal power is "lost" in the equivalent "zero" state. It is interesting that only in 2001, over 20 years later, the more general case was solved by Kokkeler et al [21].

Today, with multi-bit sampling techniques and large numbers of telescopes, this early realization is hardly of practical use!

Location of the tied-array phase centre

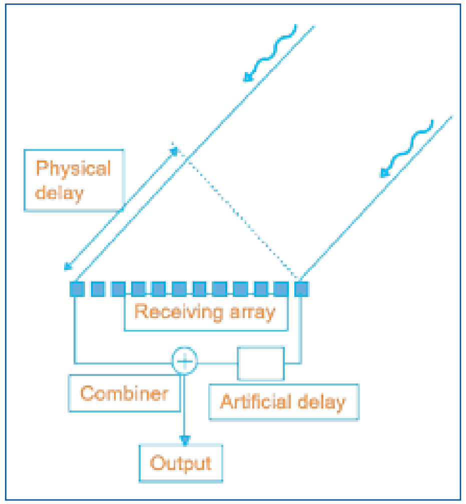


Figure 7. Off-zenith pointing of an array of radio telescopes (filled blocks) achieved by applying an artificial delay to compensate for the incurred physical delay. The dotted line depicts the wave front originating from the remote radio source.

For a single dish telescope, the phase centre is at the focus of the telescope at the point where the reflected power from the telescope is maximum. In an array like Westerbork as in all arrays, the wave front from the remote radio source passes through each telescope's phase centre simultaneously if they all point toward the zenith. Pointing in any other direction is controlled by a delay system that ensures all signals from the same wavefront arrive at the correlator at the same time (see Figure 7 by Felix Smits).

The location of the "common" phase centre of the added array is the physical location of the centre of the array assuming that all receivers have equal system temperature. For much the same reasons mentioned in the discussion of tied-array sensitivity, the apparent phase centre will shift toward the telescopes with cooled receivers along the line connecting all individual phase centres, simply because their "weight" in the added signal is larger. This argument is illustrated in NFRA Note 315 [19] and originates from John O'Sullivan then working at ASTRON. This is not desirable because an antenna reference position is required for the VLBI correlator model and receiver gain or other changes would result in changes in the apparent location of the tied-array phase centre. This in turn would cause changes in length and orientation of baselines to other telescopes in the VLBI array and result in imaging and astrometric errors.

The situation is even more complicated as the WSRT telescope array orientation is East-West and the observed source moves with hour angle in that way i.e. from east to west. In pre-digital days, Hans van Someren Greve, responsible for the online system, implemented the control software such that the proper delay per telescope was achieved by controlled insertion of different cable lengths in the signal paths while observing. By the nature of adding delays, it must be ensured that the delay is always "positive". This was done by defining a "delay-centre" outside the array and in practice at a fixed location to the east of the easternmost telescope. After some analysis, it was possible to show that for VLBI, this centre is also the "location" of the tied array telescope!

When the Philips Computer controlling the analogue cable delays was decommissioned in 1978, an all-digital delay system for the DLB (later the DXB) was introduced. With those digital delays, the telescope signal amplitudes were "normalized" by the converters in the digital system before adding, and gain changes, and phase centre changes became largely irrelevant
A final note: the massive computing power of LOFAR allows formation of multiple tied-array beams for pulsar work. This was foreshadowed by the inclusion of an "auxiliary" output for the first digital combiner [16] which was used for the first pulsar observations with the WSRT (see Chapter 5 on the "Time varying Universe").

2.2 The EVN MkIV correlator at JIVE

The development of the EVN MkIV correlator required the bundling of a range of expertise [22]. The correlator design was in the hands of Albert Bos (ASTRON), Sergei Pogrebenko (JIVE), Alan Whitney (MIT-Haystack) and Bryan Anderson (Jodrell Bank), and was eventually used in four data processors, at JIVE (EVN MkIV correlator), ASTRON (DZB correlator), Haystack (Haystack MkIV correlator) and Bonn (MPIfR MkIV correlator). A new chip was designed and manufactured, and local ASTRON expertise was employed for the configuration and data routing on the correlator boards. A UK company, Penny & Giles Pty Ltd supplied the tape drives and the Station Units under the leadership of Steve Parsley who later joined JIVE. Moreover, it was decided that the EVN correlator was going to run on totally new software, its design being led by Roger Noble from Jodrell Bank. With the emphasis for the EVN correlator on astronomical applications, the output data format was chosen to be the AIPS++ MeasurementSet definition.

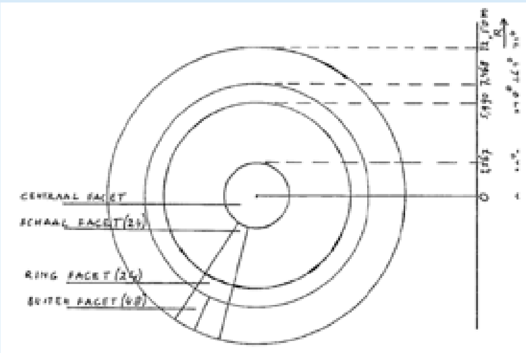
The introduction of the MkIV correlator not only provided for more sensitive observations with increased bandwidth, but the use of detailed CALC/SOLVE geodetic models provided accurate interferometer models in the direction of both target and nearby calibrator. This enabled phase referencing between the two and allowed the detection of weak targets, as well as providing very accurate positions for astrometric applications.

After its opening in 1998, the EVN MkIV correlator at JIVE rapidly became the operational heart of the European VLBI Network. By 2000, essentially all EVN observations and ~50% of global observations were correlated at JIVE. A professional user support structure had been put in place in Dwingeloo as well, funded for a substantial fraction by the RadioNet TNA (transnational access) funds, a mechanism though which the EC basically bought a fraction of the observing time for users from all over Europe. It allowed JIVE to implement a rigorous data scrutiny practice and support users in all stages from proposal preparation to data processing. Users were also encouraged to come to Dwingeloo, stay in the guest house, and work with the support scientists on their data.

Closing the holes

Arnold van Ardenne

Not always is an apparent good idea translated into hopeful dreams and subsequent realities. In this case, it started with the demand for higher frequency VLBI, but VLBI wasn't the only motivation for improving the reflector mesh. Improvements to performance of the feeds and receivers was hindered by the inherent loss of the reflector mesh. The loss of reflectivity with increasing frequency has a negative impact on



Schematic of a WSRT telescope showing the division of the surface into panels.

the antenna coupling efficiency, and also, for the same reason, the loss of reflectivity is accompanied by an increase in unwanted thermal noise of the "hot" environment. As the ratio of these two are important for the overall sensitivity, it was important to look into possibilities for improvement.

This was done by exploring two routes with the first to look into painting the mesh with conductive paint. This would partially fill the holes and therefore reduce the transmission. After lots of experimenting with different paints and performing microwave measurements as a function of angle of reflection in the labs (lots of younger people still wonder about the purpose of the waveguide segments with varying widths), it was concluded that about 40% reduction would result at 5 GHz, and less at higher frequencies.

The second approach was to close the mesh by gluing thin stainless steel slabs on the panels! Questions were of course: Which panels? Some or all of them? This was studied by looking at the mechanical layout of the panels (see Figure 1 taken from the 1978 "Internal Note"). It turned out that by closing the panels from the centre ("apex") out to a 6 m radius comprising 25% of the physical area, a 60% reduced transmission was achievable, and this improved even more by painting the 75% of the remaining area.

The obvious other question was regarding which glue should be used and could it withstand the Dutch climate? This was especially on our minds in view or our experience with the loosening of the mesh on their frames (see insert by Wout Beerekamp). So outside the lab, spare panels with stainless steel slabs glued with the selected glue, were placed and tested in all conditions including intense solar radiation etc. Until very recently these panels were still outside near to the Dwingeloo telescope and people were wondering again what they were doing out there! Of course, they could not know that the idea was not pursued because with all the slabs plus paint on the WSRT antennas the additional windload turned out to be unacceptable.

In this way, JIVE built up a reputation as the 'friendly, local correlator', where the staff would help to get the most out of the EVN data. In this way its support staff also had an opportunity to become part of the scientific teams around the EVN and many of the JIVE postdocs were able to progress their career in science after their JIVE post. In order to support astronomical use, much attention was paid to improving the calibration of the EVN and the support staff also monitored network performance through a reliability index. With external funding the PC board-based Integrator ("PCInt") was developed to overcome the limits on bandwidth and time sampling, research was done on ionospheric calibration, and JIVE staff developed ParselTongue to allow users to script large or innovative data reduction problems [23].

2.3 e-VLBI and parallel developments

After the important introduction of phase referencing in the nineties [24], another revolution took place in the EVN around the turn of the century. Probably this was a silent revolution to most astronomers, as the sensitivity, and thus the advertised scientific potential of VLBI did not change dramatically at first. However, very noticeable to the users (and operators) were the improvements in robustness, calibration and flexibility when VLBI operations moved away from spinning tape as the recording medium. The transition to disk units rather than tapes was the first and maybe the most noticeable innovation that used off-the-shelf components, but not the last. The introduction of fibre-linked e-VLBI, software correlators and high-speed digitizers would all open up capabilities for new research areas. The WSRT often played a special role in these developments because of its close location to the correlator at JIVE, and its unique nature as the only linked element interferometer in the EVN, capable of providing simultaneous images.

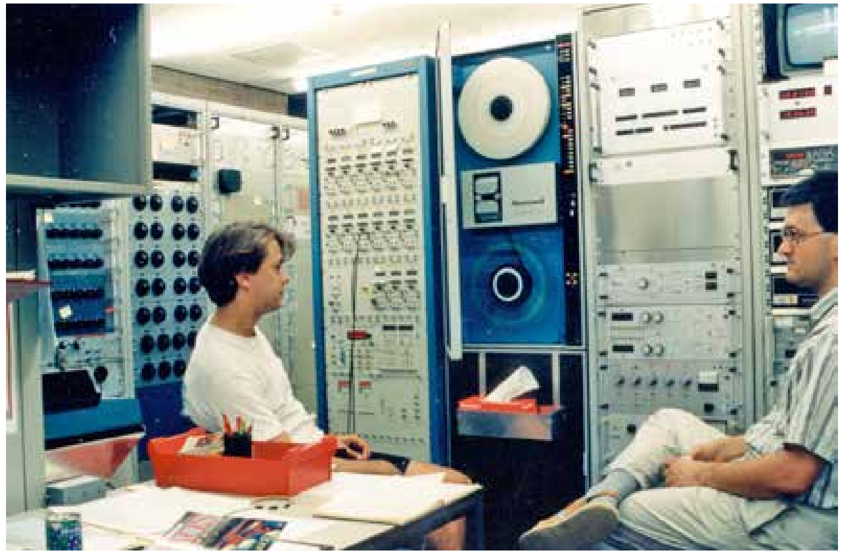


Figure 8. For the global campaign on SS433 in 1987 students spent the night at Westerbork to help changing tapes. Huib van Langevelde and Anton Jongeneelen doing their duty in the late eighties.

In 2001 MIT-Haystack introduced the MkV data acquisition and playback units, which were no longer using spinning tapes for recording. Instead a PC board was used with a special card that distributed the data in parallel over eight hard disks mounted in a special chassis. These units were connected to the telescope outputs, as well as to the input of the correlator. The motivations for MkV5 were cost savings on the recording medium (disk-packs vs tape) and transport costs, no requirement for the almost annual replacement of expensive write-read heads on the tapre machines at the stations and correlators, and reliability. JIVE and WSRT staff worked together to update the telescope and correlator interfaces to accommodate MkV.

The introduction of disk recording did magic to the operations of the VLBI network. Immediately the data error rates were much better and no longer required fine-tuning of tape alignments and (reading/writing) head calibrations. Moreover, the recording efficiency improved, even if the disks systems did not readily offer the same bandwidth, because the disk units were immediately ready for recording and required no tape conditioning. At the correlator, data read-back became direct access, where before complex tape priming was required to align all station recordings at the same micro-second of the original observation.

In addition, with the data stored on 'normal' hard disks, the data had become directly accessible for the station or correlator staff. It made it possible to implement a number of diagnostics to study the statistics of the digitizers and the telescope passbands. It also made it much easier to send short data samples to a correlator and do the ultimate check of VLBI by making sure that fringes were achieved. Looking ahead to the internet era, JIVE staff already made a first attempt to implement a software correlator for fringe verification around the turn of the century. The so-called ftp-fringe tests introduced in 2004, often using the WSRT as the "home station" but the bottleneck for such tests was the very restricted internet bandwidths for some stations, based on telephone lines.

On the initiative of Richard Schilizzi, discussions started in European forums in 2000 on the possibility of implementing e-VLBI using the broad-band, fibre-based infrastructure then under development for European science in order to connect the telescopes to the correlator. With the help of SURFNet a pilot project was carried out with a limited number of stations. Then, JIVE Director Mike Garrett led an EC proposal named EXPReS (Express Production Real-Time e-VLBI Service, funded in 2006) to turn the full EVN into a real-time VLBI instrument that could track transient phenomena in the Universe. It promised to deliver e-VLBI functionality for European astronomers who would be able to inspect the state of their (transient) targets within hours of the observations. That new functionality did require major adjustments to the correlator workings; this was a machine that was designed to run on a rigid reconstructed observing time and the correlator processes were designed to ask for the data from specific times. But for e-VLBI it also needed to correlate data with time stamps streaming into Dwingeloo in real time. Obviously, the project also addressed the connectivity and bandwidth issues. For this aspect, the Dutch SURFNet was an important partner; they were instrumental in helping to establish the connections to Dwingeloo and Westerbork, but moreover they had an ambition to make the Netherlands an important hub in international networking. When the e-EVN switched on in 2005, the Internet traffic at the Amsterdam Internet exchange doubled.

The EC project could not pay for the operational investments needed for the fibre connections from the EVN telescopes to the broad-band network, which was often more than a "last one mile" away. However, gradually the majority of the telescopes came on-line with bandwidths increasing from 128 Mbps to 1 Gbps. Being close to JIVE, the Westerbork telescope had a special place; it was linked on a dedicated fibre connection, providing a perfect testbed for pioneering protocols for the data relays. Many tests were done with different routing hardware, internet protocols and clever data packaging [25].

The EVN also adopted new operational modes to engage in e-VLBI. Dedicated e-VLBI observing days accommodated tests and user experiments. At first, the users had to come forward with compelling arguments why they needed quick access to their data, later —when the bandwidth was competitive to recorded VLBI— any experiment could be transferred to the e-VLBI days. Some examples of the resulting science are listed in Section 3.

Another activity funded in the EXPReS project was the development of a distributed correlator platform, based on high-performance computing nodes, in which Westerbork staff collaborated. Arguably, the data transport requirements could be distributed differently from the traditional all-telescopes-to-one-correlator star configuration. Research was done on how data copies could stream from each telescope to each other in a network configuration. The load-balancing, distribution software that was developed never became operational, but the linux-based, software correlator, derived from the Huygens processing algorithm (see Section 3) later became the SFXC platform [26].

After EXPReS, the EC also granted funding to NEXPReS (Novel EXplorations Pushing Robust e-VLBI Services) in 2010, a project led by JIVE Director Huib Jan van Langevelde, for which the major deliverable was to ensure the European collaborations that had started under GEANT would be sustained. It allowed JIVE and the EVN to continue support for e-VLBI at competitive bandwidths. The R&D shifted towards defining a recording standard independent of MIT-Haystack, who were already announcing MkVI data acquisition units. The focus was on using standard Linux data file systems on these units, such that more flexibility was possible between recording and streaming data. At this time JIVE also developed new data acquisition platform software to allow robust integration of recorded and streamed VLBI modes. Again, the WSRT proved to be an important testbed.

In early 2013 the MkIV correlator at JIVE was switched off and dismantled after almost 15 years of operation, its functionality replaced in the previous years by a Linux cluster running the SFXC software. JIVE and ASTRON staff, led by Arpad Szomoru and financed by EC project RadioNet, also developed an FPGA correlator named the UniBoard platform [27]. The UniBoard was later used for LOFAR station processing, the Apertif system at Westerbork and considered for processing SKA data. The SFXC correlator, completely based on locally developed software, proved to be a huge success for JIVE and the EVN. It allowed new science modes for wide-field imaging, time domain processing and spacecraft applications (see Section 3). Moreover, it proved vitally important that JIVE staff could easily control the channelization of input data streams, as cheap and powerful digitization technology led to a proliferation of telescope data acquisition systems.

Figure 9. The Westerbork telescope is also a great place to teach students interferometry; Michiel Brentjens explaining the details at the 2013 European Radio Interferometry School.

Time Adventures

Lout Sondaar, Albert Jan Boonstra, Arnold van Ardenne

In radio interferometry the combined receivers act as a phase-coherent system. In practice this is done by locking all analogue and digital receiver electronics to the same frequency reference source. For local observations using only the WSRT telescopes, the requirements for such a reference source are differential and modest. However, for VLBI and pulsar timing observations, a very accurate atomic clock is needed to ensure coherency with radio telescopes throughout the world.

In the early eighties, the Westerbork VLBI system was in dire need of its own precision clock. Until then precision time was delivered through a rather complicated method involving synchronization through television with help of the Netherlands Measurement Institute (“VSL”). The budget to acquire a clock, a state-of-the-art Hydrogen maser, was beyond our means. A more elaborate scheme came to mind which involved close collaboration with the Swiss Clock Research Laboratories in conjunction with their company Oscilloquarz in Neuchatel. They had an early prototype of a working maser which was available to be modified for use in Westerbork for a fifth of the price. This was win-win for all as in principle it had already served its research purpose!

Therefore Lout Sondaar, working at our Technical Laboratories, moved to Neuchatel in 1983 to adapt the maser for use in Westerbork. The picture shows Lout standing beside the complete maser in the Neuchatel Labs.

The principle of the maser was to generate the 21 cm line frequency in the so-called physics package (the large structure in the picture). As this is an atomic transition, its frequency is ultra-stable and has tremendous precision making it ideally suited as a precision clock. This 21 cm line corresponds to the

Lout Sondaar preparing the first Westerbork Hydrogen Maser in the Oscilloquarz Labs in Neuchatel early 1984.

one we are “commonly” measuring using the WSRT and our own receivers and hence improvements were made to 21 cm receiver of the clock by our engineers.

In March 1984 the LSHG-H3 passive H-maser was shipped to Westerbork assisted by Harm Jan Stiepel, the electronics expert in the Observatory. Weighing close to 1000 kg, the maser package allowed for only a few cm tolerance of the suspension springs of the available truck making it a truly delicate ride to the Netherlands!

Continuing the feat of fine engineering, the maser was successfully installed in the temperature stabilized basement area of the Observatory by April 1984. It afterwards performed well during 15 years of continuous operation!

With the nineties-upgrade of the WSRT system, including the extension of the frequency range to the 3.6 cm geodetic VLBI band, an upgrade of the central frequency and time reference was needed. This became even more urgent as the reconditioned Swiss atomic clock, at that point serving for 15-years as WSRT hydrogen maser, was beginning to show its age! A comparison of hydrogen masers on the market led to an attractive ‘turnkey’ solution. In 1999 the DATUM (currently Microsemi) MHM2010 maser was installed at the same location in the temperature stable basement. After switching the machine on, only a two-week stabilization period was needed before the maser could be used as the new maser clock showing a solid frequency stability of 2×10^{-15} in a 1000 second interval.

This long period of delivering stable and precise time, and the collaboration with the geodesy group of the Technical University in Delft, resulted in the Observatory “time” and precise location becoming part of the International GNSS Service Network in 1998.

The Datum H-maser in the temperature stabilized room in the basement of the Westerbork Observatory building, now in use for almost 20years! Note that further maser evolutions led to much smaller ones used in the Galileo navigation satellites.

Reference:
The Hydrogen Maser LSHR H3 in Operational use at the Westerbork Synthesis Radio Telescope, L.H. Sondaar, First European Time and Frequency Forum, Besancon, Fr., 1987

3. Science

By its nature, very high angular resolution VLBI requires high brightness targets (high intensity radio emission from a small solid angle on the sky). Therefore, astrophysical sources that emit through non-thermal emission processes are the prime targets for mas-scale studies. Before phase referencing techniques were established, the additional requirement was that sources needed to be detected within the coherence time, typically 2 to 10 minutes. So traditionally, bright Active Galactic Nuclei (AGN) and their jets have been a prime target for VLBI.

Zooming in on AGNs, VLBI observations were key in establishing that relativistic jets were launched from close to the central massive Black Hole. Studies focused on studying jet physics, beaming ratios and superluminal motions. Important progress in the EVN was obtained in the field of Gigahertz Peaked Spectrum sources and Compact Symmetric Objects (e.g. Figure 10). There was a joint interest from JIVE, ASTRON and staff at the Dutch universities to disentangle the orientation and evolution of active radio sources.

Another area of joint expertise was the study of (HI) absorption associated with the gas surrounding the AGN. In fact, the first science result with the new JIVE MkIV correlator revealed the HI in NG4261, on scales that had just become accessible in the optical through observations by the Hubble telescope [28]. In synergy with the Westerbork telescope, that could access a wide range of redshifts, many galaxies were targeted for HI absorption VLBI.

Also sparked by the observations with the Hubble telescope, were radio observations of its deep fields. Long integrations in the optical and radio showed a cosmic zoo of galaxies, some of them radiating from the early days of the universe. After Westerbork, VLA or MERLIN surveys, VLBI observations were called for, in order to understand the nature of their radio emission. But time and bandwidth averaging would limit the field of view to a single galaxy target, while in principle the primary beams of the individual telescopes encompass many sources [29]. With target lists from the low-resolution surveys in hand, clever correlator modes at the JIVE correlator were introduced to facilitate such wide-field studies.

The early motivation to study the radio emission in galactic compact objects was that this was an opportunity to study jet physics on much shorter timescales. A famous campaign was the monitoring of SS433 in 1987 with VLBI [30,31]. Over the years the interest shifted from studying the jet physics and launching mechanisms to making out the stellar evolution that led to the various exotic objects. As is the case for pulsar origins, VLBI makes important contributions to this research by measuring parallaxes and proper motions.

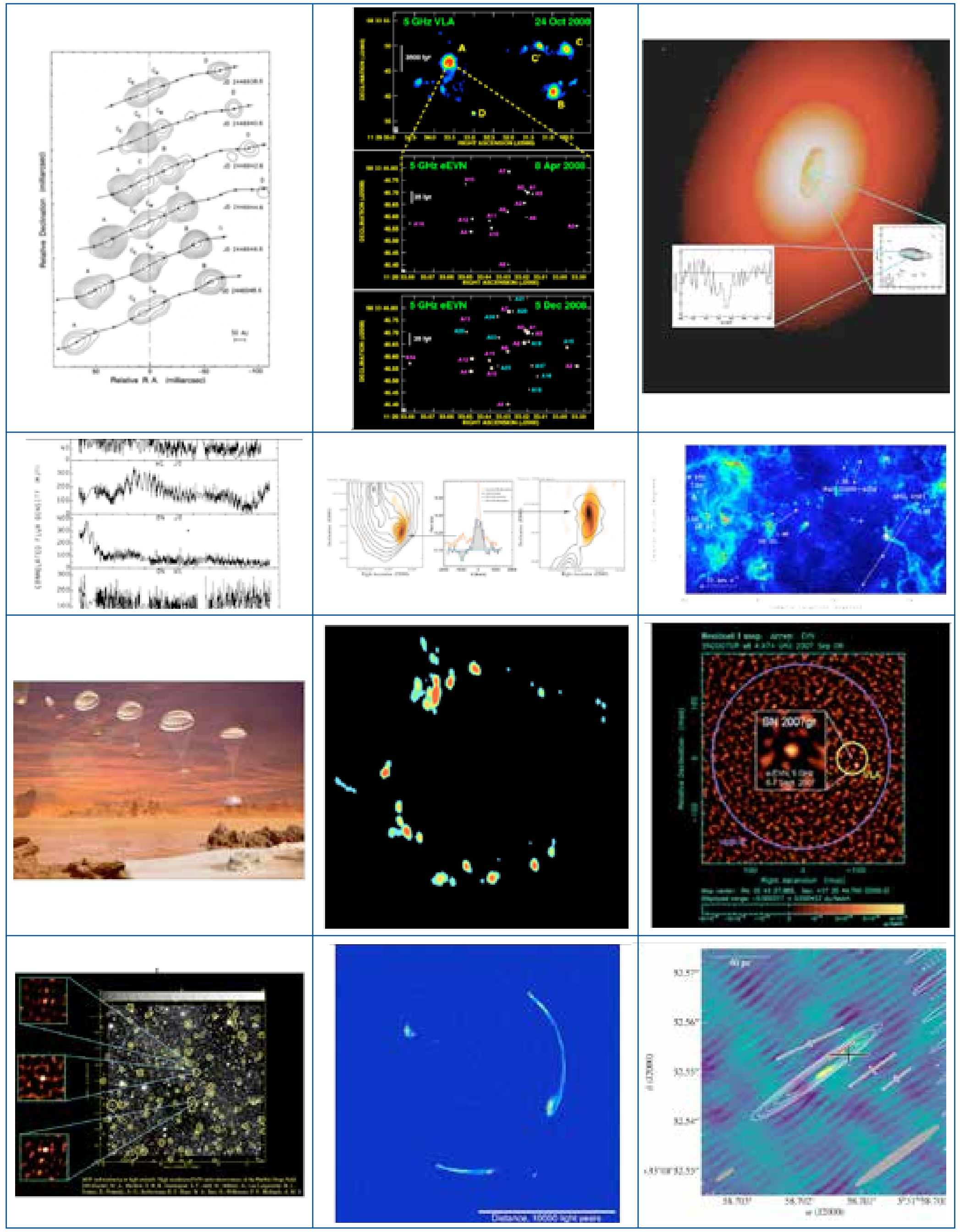


Figure 10. left to right: Some of the iconic images of the EVN: SS433 from [30], supernovae in IC694 [35], HI absorption in NGC4261 [28], the CSO 3C343.1 [36], HI absorption in 4C12.50 [37], distances and proper motions of methanol masers in the Cygnus region [33], an artist impression of the Huygens lander [38], a ring-shaped methanol maser [39], the VLBI detection of SN2007gr [34], VLBI sources in the HDF-N [29], global VLBI image of a gravitational lens [41], the localization of the repeating FRB [42]. See the text for explanations of the acronyms.

High brightness emission from molecular masers that can spontaneously exist in the low-density interstellar medium, make for another category of interesting VLBI targets. These masers are signposts for regions where infrared emission excites molecules faster than collisions with other molecules relaxes them, such as circumstellar regions around evolved stars or star forming regions, or even the dense parts of active/starburst galaxies. The EVN is particularly sensitive to OH emission from starburst galaxies and IR stars, even though the 18cm part of the spectrum has been compromised in many places by man-made interference.

Additionally, the EVN excelled for many years in observations of the 6.7 GHz methanol maser. This ubiquitous maser was only discovered in 1991 and not many telescopes had receivers that covered this transition. In fact, coverage of the line was also not realized in the MFFE receivers of the WSRT, but one dish could be outfitted. And so, together with the EVN, a major contribution was made to studying this transition which was uniquely associated with the earliest stage of high mass star formation. The EVN demonstrated that the masers were linked to the accretion and outflow mechanism on scales of something like a thousand astronomical units, sometimes showing ring-like configurations [32]. With the phase referencing technique, it proved even possible to measure parallax distances to some of these sources [33]. And EVN users showed how high spectral resolution could be used to prove that magnetic fields are important in controlling the formation of high mass stars [34].

The introduction of e-VLBI raised interest in studying transient phenomena, which has turned out to be a very exciting subject. Initially the targets were galactic black holes or other compact objects, particularly those with binary companions. But extragalactic targets were also showing transient phenomena accessible to VLBI. It turned out that the extended radio emission in some nearby starburst galaxies could be resolved into the radio shells of individual supernova by VLBI [35] Invisible in the optical, VLBI could be used to obtain a census of the high mass stars in colliding galaxies.

Following the alerts from robotic telescopes monitoring Gamma Ray Bursts, the EVN started to target these objects. Pinpointing their host galaxies was one objective, but VLBI can in principle also distinguish various explosion models by resolving the source, either directly or through the scintillation properties, as a function of days since the explosion [40]. In these studies the inclusion of the Westerbork array was often crucial; not only did it provide fantastic sensitivity, but also crucial simultaneous lower resolution data, important for calibration and interpretation of the VLBI results.

A triumph of the expertise that was built up in Dwingeloo on correlators, was the VLBI pinpointing of the repeating Fast Radio Burst in 2017 [42]. The FRB phenomena was discovered about a decade ago when the Parkes telescope discovered single millisecond bursts from unknown objects. When Arecibo confirmed that one such source repeated, a world-wide campaign started to pinpoint the source of these radio flashes. The VLA associated the repeater with a dwarf galaxy at cosmological distances, but the EVN could even associate it with a specific nebulosity in this galaxy as observed with Hubble. It required very complex data processing at the SFXC platform, which was outfitted with the capability to gate very short visibilities after correcting the signal to compensate for the record-high dispersion between the source and the telescopes.

The option to implement such special functionality had been inherent to the SFXC platform from the start, when developed for space applications. Indeed, man-made transmitters on board of spacecraft are also bright enough to do VLBI, even if their detection requires the largest telescopes in the world. The most outstanding achievement in this field remains the VLBI tracking of the Huygens lander as it descended in the atmosphere of the Saturn moon Titan on 14 January 2005. The ultimate objective was to measure the trajectory of the probe as its motion was impacted by the winds in the atmosphere of this moon that may resemble planet Earth in original composition. Indeed, led by Leonid Gurvits, JIVE scientists published a detailed trajectory later after detailed analysis of the data [43]. However, the biggest visibility for the team came about a few hours after the descent, as only real-time detection by the VLBI telescopes could confirm the proper working and time of touch down of the Huygens lander.

4. The future

With the advances in digital devices continuing to offer upgrade options, it is clear the VLBI field will deliver more discoveries in the future. And as SKA (and its precursors and pathfinders, like LOFAR) are engaging more astronomers in radio science, there are initiatives in many countries to establish a radio astronomy station. One can expect future VLBI telescopes to deliver enormous instantaneous bandwidth as both direct digitization and wide band receivers are being developed (BRAND EVN, a research activity in RadioNet). More processing and storage capacity will allow the VLBI correlators to offer increasing flexibility for the user products, for example time domain products and multiple, large fields of view or high spectral resolution.

One major cost item for establishing new telescopes is the need to have not only data acquisition instruments at the telescope, but also a highly precise maser clock for time and frequency stability. A hydrogen maser atomic standard is a fundamental requirement to ensure that only atmospheric fluctuations set the calibration intervals, a telescope with poorer stability is useless for phase referencing observations. A pilot project funded by the EC in the ASTERIC (Astronomy ESFRI and Research Infrastructure Cluster) project, is underway to test the transfer of precise clock information between two telescopes over the fibre network. The aim is to do a test transferring the clock signal from the maser at the Westerbork telescope to the Dwingeloo telescope, bringing it back as a VLBI element after some 40 years! This same research is informing the design of the signal and data transport sub-system of the SKA.

But of course, the main cost item, certainly in modern times, for constructing a new VLBI telescope is the steel construction. Fortunately, space exploitation also requires large dishes and some of the expansion of the EVN (particularly in China, but also partly for the Sardinia telescope) has been motivated this way. Moreover, in other places, dishes previously used for other (communication) purposes are being retrofitted for VLBI, in Latvia, Ghana and possibly the Portuguese Azores. The case for retrofitting retired communication antennas in African countries is particularly compelling. Such an African VLBI Network complements the SKA_1 with long baselines, providing the capability to pinpoint transient phenomena, measure accurate pulsar and maser positions and distinguish AGN from starburst galaxies. But it is also a chance to involve African scientists and engineers in the inspiring and innovative trade of radio astronomy.

With the Apertif upgrade [See Chapter 15 of this book], the parameters of the WSRT element in the EVN have changed. The phased array is now only available at L-band, albeit with a larger bandwidth than before. For all other bands, MFFE and 5cm, only a single telescope can participate in the EVN. But the Apertif system, certainly the transient trigger functionality, has important synergies with VLBI and it even has been considered to connect each individual WSRT dish to JIVE for transient and wide field imaging. Maybe one day even VLBI will profit from the multi-beam capabilities on the WSRT. It is hard to predict what the fate will be of the Westerbork array by the time the EVN turns 50 in 2030, but with the continued interest in global VLBI, it seems reasonable to argue that the historic investments in the sturdy steel Westerbork dishes will still be serving science.

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Chapter 8 Preparing for LOFAR

Jaap Bregman[1], Stefan Wijnholds[2], Michiel Brentjens[3]

In a way, preparing for LOFAR was a step back in time, back to the origins of radio astronomy and back to the origins of our Universe. Radio astronomy started in 1932 when Karl Jansky discovered radio emission from the Milky Way at a wavelength of 14.6 m (20.5 MHz). He used an array that combined the signals of eight antenna elements. This compound antenna of 30 m width and 4 m height had sufficient resolution to identify the direction of thunderstorm static, a strong interference encountered at short wave communication. Further investigations showed that the interference decreased at higher frequencies, driving radio communication to higher frequencies. Grote Reber, a radio engineer interested in astronomy, built in 1937 a reflector antenna of 9.5 m diameter in his backyard. Detection of celestial radiation at wavelengths of 9.1 cm (3300 MHz) and 33 cm (910 MHz) failed, but spring 1939 brought the first detections at 1.87 m (160 MHz). Finally, in 1944, he published the first quantitative sky map showing the Milky Way and peaks of emission in the constellations of Sagittarius, Cygnus, Cassiopeia, Canis Major, and Puppis. The radar development during wartime pushed to even higher frequencies providing more sensitive electronics and advanced dish technology that dominated radio astronomy for the second half of the 20th century.

By 1965 the various stellar and interstellar radio emission mechanisms had been identified by their spectral and polarization properties. It was therefore decided to operate the WSRT initially at three wavelength bands at 50 cm, 21 cm and 6 cm with accurate polarization characteristics. Operation at 92 cm wavelength started in 1983 and at 1.8 m only in 2005!

Attempts at other institutes to image the sky at wavelengths of 4 m (74 MHz) and 8 m (38 MHz) with long arrays failed to reach the potential resolution due to ionospheric disturbances. Only the strongest sources that provided sufficient sensitivity per interferometer within an ionospheric coherence time could be properly imaged using the self-calibration technique. Even then, only a small field around the strongest source could be properly imaged and all other sources were smeared, producing a raised noise floor all over the image.

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Again, improved technology would open up the spectral window below 200 MHz after 2005. Optical fibre technology made data transport between antenna stations affordable over distances from a few hundred meter to 50 km using bandwidths of 1 Gb/s by 2000. Bands of 100 MHz could be digitized to 12-bit including all interference that would be removed later by digital processing. Only after 2005, large computer clusters would be affordable to perform the multi-source self-calibration processing required to image all objects within a station beam and reach the theoretical noise floor. This can only be realized when the station beam is sufficiently narrow and sensitive. So, plans started in 1998 to design a Low frequency array covering 10 - 90 MHz. Even in the bands between 10 and 30 MHz, allocated to shortwave transmission, sufficient channels of only 1 kHz wide could be selected for astronomical imaging, thanks to digital spectral Fourier filtering.

By 2003 all required technology had been demonstrated successfully with an all sky image produced with the Initial Test Station. In the meantime, it was also decided to include a second field with smaller antennas to cover the 110 - 250 MHz high band, where the Epoch of Reionization (EoR) would be visible. This EoR marks the time when the first galaxies in the Universe were formed and the first stars illuminated and ionized their surrounding neutral gas.

With LOFAR we are back at the frequencies where radio astronomy started, but now with much larger antenna fields filled with short dipole antennas having a much larger effective collecting area than their largest physical dimension and where low noise transistors contribute far less system noise than the sky itself.

The WSRT again played an important role in preparation of LOFAR's hunt to detect the EoR signal by the introduction of the Low Frequency Frontends (LFFEs) operating from 120-180 MHz in two polarizations. See: LFFE:

Figure 1: A Low Frequency Frontend mounted on a WSRT dish. The LFFE consists of the white "handrail" style contraptions to the left of the focus box. In this image, they are in their active position. When observing at other frequencies, these are swept out of the way using compressed air.

de Bruyn, Woestenburg & van der Marel (2004).[1] The project was lead on time on budget by Bert Woestenburg in less than two years (ASTRON LFFE Design Review Report, LFFE-00968, 2004) . As the MFFE did at higher UHF frequencies, a double dipole arrangement was used. Their performance was simulated by Marianna Ivashina and Michel Arts. The receiver design was robust in view of Interference from local transmitters. The LFFEs consisted of additional antennas placed on the focus box that could be swept in front of the MFFEs. The signals of a pair of antennas were combined and formed the first Phased Array Feed on the WSRT telescopes that provided a high sensitivity illumination pattern. Figure 1 shows an image of one of the LFFEs.

With the LFFEs, an observing campaign was conducted to select appropriate fields for the EoR experiment. After this campaign, two fields were selected (the 3C 196 field and the North Celestial Pole field) with other fields being rejected due to, for example, very complicated (but highly intriguing) Galactic foreground polarization. A side effect of this campaign was the first publication of detailed, wide-field polarimetry of the Galactic "FAN" region in the 150 MHz band (de Bruyn, A.G.; Bernardi, G; LOFAR EOR-team; "The First Deep WSRT 150~MHz Full Polarization Observations", Proc. ASP Series, Vol. 407, 2009).

Another goal of this observing campaign was to investigate the ionospheric disturbances at the scale of the LOFAR core area with a diameter of about 2-3 km and to understand the RFI situation. The latter posed an interesting engineering challenge. Since a nearby TV transmitter, which would go out of operation only in 2006, produced a strong signal that could not be handled by the 2-bit digitization of the DZB, additional filters had to be placed in the receiver module in the focus box. These observations were thus instrumental to gain experience in the data processing techniques that would be needed to analyze LOFAR data, in particular for techniques dealing with the radio interference at these low frequencies, and the direction dependent calibration that would be required to deal with the distortions of the received wavefront caused by the ionosphere. As such, the LFFE system played a pivotal role in understanding the challenges that LOFAR would face and allowed us to start developing solutions and software to deal with those problems well before the roll-out of LOFAR started.

With low-frequency phased array systems like LOFAR, direction dependent gain variations are not only caused by the ionosphere, but also by the varying beam shape of the receiving system while a source field is tracked on the sky. This behavior is distinctly different from the behavior of a dish beam, so there was a clear desire to properly understand this. A second experiment was therefore to combine the 14 dishes of the WSRT with a flat phased array station that used 64 prototype antennas for the LOFAR high band antenna system (HBA) system.

1 https://www.astron.nl/r-d-laboratory/projects/wsrt-observes-lofar-highband/wsrt-observes-lofar-highband .

Initially, the HBA beams were validated by drift scans on satellite transmissions as integration in the WSRT system turned out to be more challenging than expected. For example, a clever interface to the WSRT control software needed to be developed. This allowed us to exploit the full capabilities provided by electronic beam steering the HBA prototype in a joint observation with the WSRT dishes, while the analog receive paths had to be tuned carefully in view of the higher susceptibility of the HBA prototype to RFI. Once these technical issues were sorted, this setup was successfully used to make joint observations.

Figure 2: Pre-production prototype of a single LOFAR HBA tile at the WSRT site (excerpt from Panorama picture made by Harm-Jan Stiepel and Adriaan Renting).

Figure 2 shows the 16-element pre-production prototype of a single LOFAR HBA tile that succeeded the 64-element engineering prototype after some further improvements to the designs of the HBA beamformer electronics were made. Its performance was, amongst others, assessed by a drift scan on Cassiopeia A while the tile beamformer output signals was correlated against the signals from the WSRT dishes that were tracking Cas A. Figure 3 shows the measurement results.

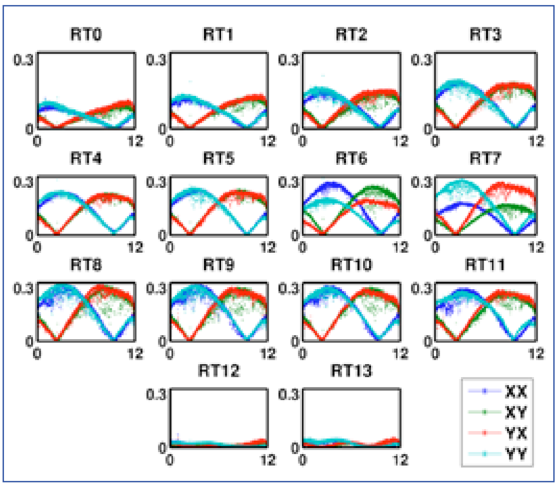

Figure 3: Correlations measured on Cas A between the WSRT dishes indicated and the pre-production HBA prototype tile (image credit: Sarod Yatawatta, AJDI 29 November 2006).

As a bonus of all these efforts, the first Ultra-High Energy Cosmic Ray event was detected, again demonstrating the serendipitous discoveries that can be made when a new receiving system is installed.

Chapter 9 The Magnetic Universe

Marijke Haverkorn[1], Michiel Brentjens[2]

Introduction

Radio emission has opened a new window on the Universe. Radio *polarization* opens yet another. It is the interaction with magnetic fields that polarizes radio waves, and properties of this magnetic field are imprinted in the polarization signature. Hence, radio polarization is one of the few methods to study elusive, largely invisible, cosmic magnetic fields.

Magnetic fields are hugely important in space, in many objects and on many scales. Most of the (baryonic) matter in space is ionized, which means that the gas is closely coupled to magnetic fields, often almost frozen into them. Magnetic fields influence star formation: by delaying it in the first stages, and stabilizing (through magnetic braking) in the last phase. Magnetic fields cause acceleration of cosmic rays, and guide their transport across the Universe. Magnetism is the origin of the Solar cycle and Solar activity. The Earth's magnetic field protects us from harmful radiation from space, and magnetic fields around exoplanets are thought to increase the habitability on those planets.

One of the main physical processes emitting radio waves in space is synchrotron radiation, which is emitted by electrons moving at velocities close to the speed of light, while spiraling around magnetic field lines. The intensity of this radiation depends on the magnetic field strength and direction, integrated over the line of sight. Synchrotron intensity is intrinsically highly linearly polarized perpendicular to the direction of the local magnetic field component in the plane of the sky. However, if magnetic fields vary along the line of sight, the orientation of polarization angle varies as well, which results in partial depolarization. Therefore, the degree of polarization indicates the degree of tangling of the magnetic field.

A second, equally versatile, method that uses radio polarization to measure magnetic fields is Faraday rotation. Faraday rotation is the effective rotation of the linear polarization angle as a function of frequency, caused by the birefringence in their circular polarization while radio waves propagate through an ionized, magnetized medium. The amount of rotation is called the Rotation Measure (RM), which depends on the free electron density in the medium, and the local magnetic field component parallel to the line of sight, integrated over that line of sight. Therefore, measuring linear polarization as a function

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of frequency allows the calculation of the RM. Using known models for the free electron density, we can calculate the weighted, average, magnetic field strength along the line of sight. A method to calculate RMs correctly in complex situations, called RM Synthesis, was proven to be applicable in practice by Michiel Brentjens and Ger de Bruyn, using WSRT observations as the proof of concept (Brentjens & de Bruyn, 2005, A&A, 441, 1217).

The WSRT is an excellent instrument to measure synchrotron radiation, including its angle and degree of polarization. Its short spacings allow a high sensitivity to extended, diffuse structures such as galaxy cluster gas, Galactic objects such as supernova remnants, and diffuse Galactic synchrotron emission. The excellent 6x12hr uv-coverage and parallactic mounts made achieving high dynamic range and high image fidelity relatively easy. In particular, the wideband multi-channel MFFE receivers at 92cm were a unique tool to derive weaker magnetic fields and exploit RM Synthesis to the fullest.
In this chapter, we will briefly highlight some of the scientific contributions that the WSRT has made to discover the diffuse polarized Universe, with emphasis on the large role that Ger de Bruyn has played in this. We will close with a brief outlook to the immediate future for polarization with the WSRT.

Galaxy clusters

Clusters of galaxies are the largest gravitationally bound structures in the universe. These clusters can contain hundreds to thousands of galaxies, embedded in a huge cloud of hot thermal gas. Radio emission is commonly observed in clusters: emission from the cluster galaxies themselves, non-thermal emission from the cosmic rays centered at the cluster center - called radio halos - and non-thermal emission from the outskirts of the cluster - called radio relics. These radio relics are elongated, sometimes remarkably long and straight, and highly polarized. They are thought to indicate the location of huge shock waves, created in a past merger of two smaller clusters.

Roberto Pizzo, then PhD student with Ger de Bruyn, used the WSRT to study galaxy cluster Abell 2255 at a wide range of wavelengths from 18 cm to 2 m - the latter being the wavelength range where LOFAR is now producing many exciting results on this topic. He was the first to detect a galaxy cluster with the WSRT using the newly available technique of RM Synthesis (see Figure 1). He studied Faraday rotation from the hot gas inside the cluster (the intracluster medium), and showed that known radio filaments are highly-polarized radio relics at the outskirts of the cluster.

Subsequent WSRT polarization work mostly focused on radio relics, producing magnificent results due to the exquisite sensitivity and polarization characteristics of these measurements. From detailed mapping of the variation of the synchrotron emission across the relics, it as been possible to gain knowledge about the location and process of particle acceleration at those shocks. The po-

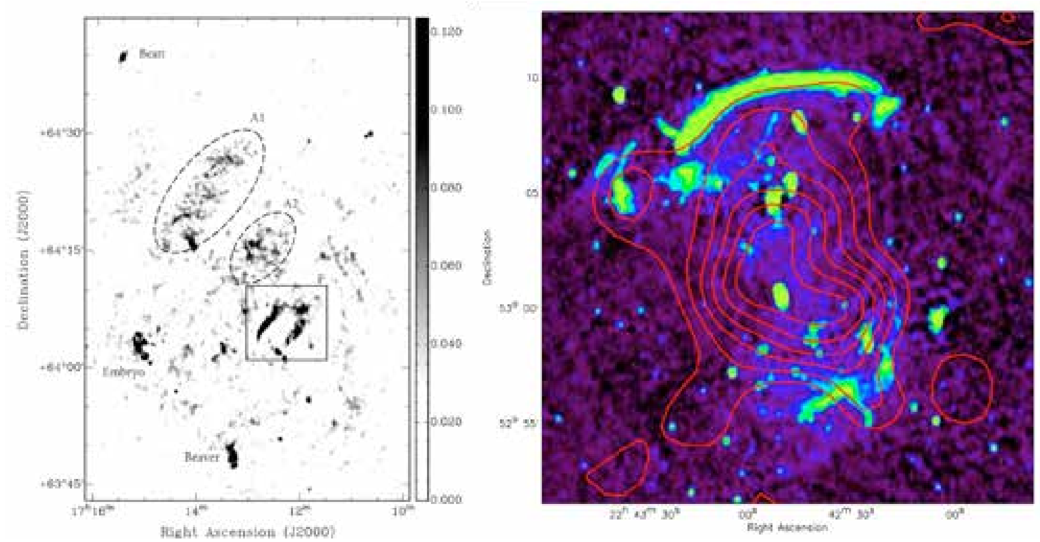


Figure 1: Left: One frame from a WSRT 3D RM Synthesis data cube of the cluster Abell 2255. The image shows cluster galaxies and large-scale filaments, that share a common Faraday depth, which is an approximate proxy for magnetic field. (Pizzo et al. 2011, A&A, 525, 104) Right: the "Sausage relic" as observed by the WSRT at 21-cm continuum in color scale. Overlaid in contours is X-ray emission from the hot cluster gas, as observed by the ROSAT satellite (Van Weeren et al. 2010, Science, 330, 347).

larization in these filaments complements these observations by revealing the strength and direction of the magnetic field. Magnetic fields are aligned parallel to the relic, as expected for a shock wave, and depolarization or polarization angle directions can be used to infer information on the relative location of the relic inside the cluster system.

Radio galaxies and quasars

Radio galaxies are a special, prevalent type of galaxy in the Universe. The centers of these galaxies, which can be spiral or elliptical galaxies, host an active, supermassive black hole. This black hole sucks in matter from its surroundings through a rotating disk around it. This process causes huge magnetized jets of matter and radiation to be expelled in either direction of the galaxy. At the distance where they significantly interact with diffuse, intergalactic gas surrounding the galaxy, these jets fan out to become large-scale structures called lobes (see Figure 2).

Both jets and lobes are strong non-thermal (synchrotron) emitters in the radio band. Much work on interpreting their polarization characteristics has been done with the WSRT, primarily in the 80s and 90s. Ger de Bruyn pioneered this starting with his PhD thesis work on Seyfert galaxies. At that time, he obtained only non-detections of linear polarization, giving upper limits of a few percent to up to ~15% linear polarization.

The degree of polarization is often interpreted as a measure of small-scale fluctuations in density and/or magnetic field. Polarimetric surveys of a large number of (mostly unresolved) radio sources show fairly low polarization degrees, indicating that radio galaxies live in a magnetized (depolarizing) environment.

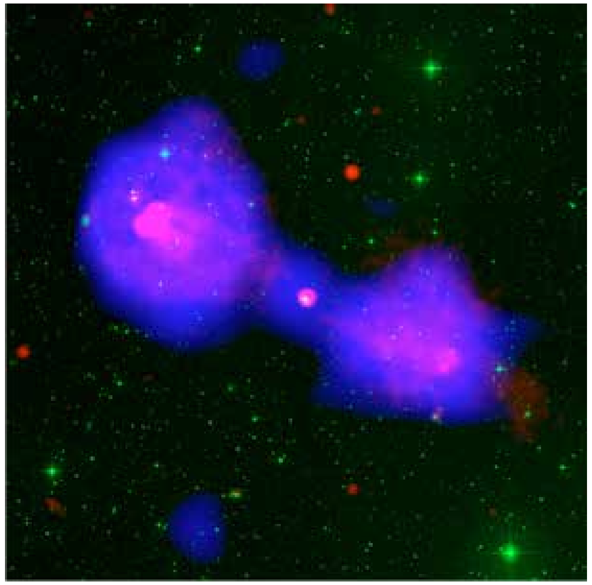
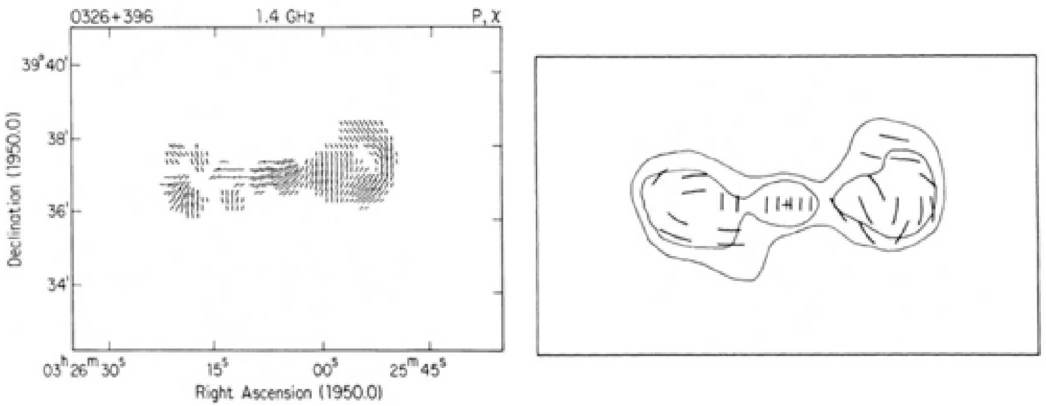


Figure 2: Image of the typical radio galaxy DA 240. WSRT radio observations at 50 cm (magenta and red) show the central source, jets and lobes. VLITE radio observations at 90cm (blue) show the large extension of the lobes. Optical data (green, DSS2) shows the central galaxy and background sources. Credit: Produced at the U.S. Naval Research Laboratory by Dr. S. Giacintucci and collaborators from data obtained with the VLA Low-band Ionosphere and Transient Experiment (VLITE).

This can be compared to independent density estimates from the assumption that the lobes would be in ram-pressure equilibrium with their surroundings. The polarization vectors (corrected for Faraday rotation at low frequncies) indicate the orientation of the magnetic field component in the plane of the sky. An example of this is given in Figure 3, which shows electric-field vectors and the magnetic field configuration derived from WSRT 1.4 GHz data across the lobes of radio galaxy B2 0326+39. Work by Arno Schoenmakers, then PhD student supervised by Ger de Bruyn and Harry van der Laan, also indicates that typically, magnetic fields in (FRII) radio lobes are observed to be tangential to the lobe boundaries. This agrees with the theory that magnetic fields are compressed in outward moving shocks due to interaction with the surrounding intergalactic medium. Weak radio sources tend to have jets with transverse magnetic fields, as pictured here, whereas in more powerful radio sources, magnetic fields tend to be parallel to the sources (Feretti et al 1983, A&A, 126, 311).

Figure 3: Left: E-field vector orientations in 1.4 GHz WSRT observations of radio galaxy B2 0326+39. Right: implied orientations of magnetic field after correction for Faraday rotation (Bridle et al 1991, A&A, 245, 371).



Many studies have measured the Faraday rotation in the central galaxy, jets and/or lobes of radio galaxies. Using traditional RM determination makes it often hard to distinguish whether the observed Faraday rotation is due to a medium in or near the radio galaxy, or due to foreground magnetized gas in the Milky Way. RM values have been interpreted as Faraday curtains in front of the radio sources, containing irregular magnetic fields and/or a clumpy medium (Rossetti et al 2008, A&A, 487, 865). However, RM Synthesis in 585 unresolved radio sources revealed the existence of multiple RM components in many sources, rendering earlier RM determinations potentially unreliable (Farnsworth et al 2011, AJ, 141, 191).

Normal galaxies

Our Milky Way is just one in many spiral galaxies, consisting of a thin disk with stars and gas mostly contained in spiral arms, and a halo of more diffuse gas and fewer stars around it. Studying nearby spiral galaxies in detail gives a picture of the variety in spiral galaxies, but also their common properties. These studies help to understand our own Galaxy: since we are immersed in the Milky Way, it is hard to see the global structure. External spirals provide us with the overview picture we are missing for the Milky Way.

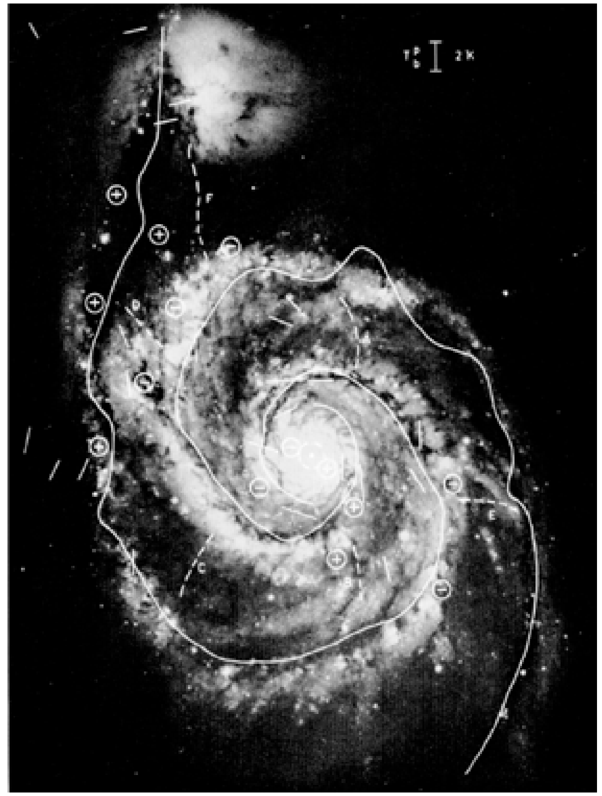


Figure 4: The first tentative detection of linear polarization in nearby galaxy M51, made by the WSRT. The long solid lines denote ridges of 1415 MHz radio emission, and the short solid lines indicate the E-vectors of the polarized radio emission. The length of the line represents the polarized brightness temperature.

The WSRT has pioneered polarization measurements in nearby galaxies by a first tentative detection of polarization in nearby grand-design spiral galaxy M51 (Mathewson et al, 1972, A&A, 17, 468, see Figure 4). Since then, it has been used extensively to map out magnetic fields and polarization properties of nearby galaxies in detail. Ger de Bruyn's PhD thesis also contains the first attempts to detect polarization in spiral galaxies with the WSRT, again resulting in only upper limits. He continued work in this area with his PhD student Alexander Segalovitz, who solidly confirmed linear polarization detections in M51 and concluded that magnetic fields in its disk are oriented preferably tangentially (Segalovitz et al, 1976, Nature, 264, 222). Since that time, the WSRT has mapped magnetic fields in spiral galaxies such as the Milky Way, in interacting galaxies, dwarf galaxies, starburst galaxies and irregular galaxies.

In particular, the magnetic field configuration in halos of galaxies, away from the star-forming disk, is important as it provides clues about the dynamo mechanism that maintains these fields, and may be dynamically important for the gas kinematics (see Chapter 11). The low-frequency MFFE receivers on the WSRT have played a major role in determining weak magnetic fields in galaxy halos; however, follow-up investigations at a broad range of frequencies are essential to obtain the complete picture.

The largest survey of polarization properties of nearby galaxies with the WSRT is its follow-up of the Spitzer Infrared Nearby Galaxies Survey (SINGS) galaxies, named "Westerbork SINGS" (Braun et al 2007, A&A, 461, 455). In 21 of the 28 SINGS galaxies, polarized emission was detected and RM Synthesis was applied. Coherent depolarization and RM patterns led to a model of corkscrew-magnetic field configurations in the halos of these galaxies (Braun et al 2010, A&A, 514, 42, Heald et al 2009, A&A, 503, 409). In M31, diffuse polarized emission from a nearby galaxy below 1 GHz was observed for the first time (Giessuebel et al 2013, A&A, 559, 27). After this proof of concept, LOFAR continues to map out nearby galaxies with exquisite sensitivity at low frequencies.

Diffuse Galactic radiation

In the late 1980's, PhD student Mark Wieringa, supervised by Peter Katgert and Ger de Bruyn, saw something unexpected in his WSRT radio data of far-away radio galaxies when he looked at the polarization maps. He discovered large diffuse structures of many degrees in size in polarized emission, which were not visible in total (unpolarized) emission. Their analysis of this emission in terms of synchrotron emission in the Milky Way, Faraday rotated by the Galactic magnetized interstellar medium, started a new avenue for investigating Galactic magnetism. Peter and Ger continued this with a follow-up PhD project, by Marijke Haverkorn, which focused completely on observations and interpretation of these enigmatic polarized structures. Since then, large polarized structures have been found in every field on the sky that was investigated. At lower latitudes, some of these structures are aligned with the Galactic plane,

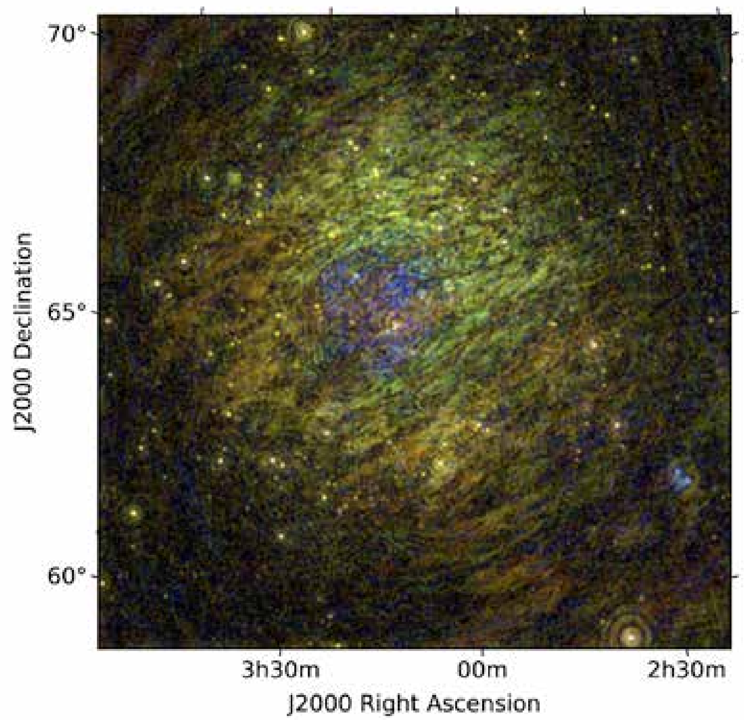


Figure 5: Polarized intensity at various Faraday depths (a proxy for density-weighted magnetic field) in a magnetized bubble in the Fan Region. (Bernardi et al 2009, A&A, 500, 965; color scale optimized to mimic response of human eye by Michiel Brentjens.)

suggesting a directionality along the regular magnetic field in the plane. Ger de Bruyn initiated polarimetric analysis of parts of the Westerbork Northern Sky Survey (WENSS, see Chapter 10), demonstrating the ubiquity and coherence of these polarized structures (Schnitzeler et al, 2007, A&A, 461, 963). Enigmatic bubbles (e.g. Figure 5), filaments, depolarization canals and other odd-shaped structures have been detected, showing us magnetic field features otherwise undetectable. The WSRT has played a pioneering role in early interpretation of these structures, most notably in early RM Synthesis results and in the broad long-wavelength coverage when combined with LOFAR. Much of this effort was led by PhD students Gianni Bernardi and Vibor Jelic in Ger de Bruyn's group. A recent exciting discovery -- amongst others in WSRT data --is the correlation of such synchrotron polarization structures with magnetic fields as probed by Planck polarized dust emission (Zaroubi et al 2015, MNRAS, 454, 46) or by filaments of neutral hydrogen (Kalberla & Kerp, 2016, A&A, 595, 37).

The Future

The upgrade of the WSRT to the Apertif Focal Plane Array system will enable exploring broadband spectropolarimetry at frequencies of 1-2 GHz, which unfortunately meant largely decommissioning the 92 cm system. At the Apertif frequency band, the sensitivity for low-RM signal will decrease, but high RMs will become detectable, and the polarized source density on the sky will be higher than at lower frequencies. The largest planned polarization survey with Apertif is the Westerbork Observations of the Deep Apertif Northern-Sky (WODAN) survey. The many 100,000's of expected detections of polarized radio sources across the sky will provide a detailed RM Grid with which to test Galactic magnetic field models. In addition, the polarized diffuse Galactic emission will allow determination of the properties of the small-scale structure in this field. In this way, the WSRT will stay at the forefront of cosmic magnetism science for many years to come.

Acknowledgements

The authors thank Rainer Beck, George Heald, Arno Schoenmakers, and Reinout van Weeren for their valuable input.

Chapter 10.1 Ever growing sensitivities

Jaap Bregman*

Installation of the multi-beam Apertif system on the Synthesis Radio Telescope in Westerbork (WSRT) completes the full range of efficient image forming capabilities realized by inventive implementation of available technology. It is therefore appropriate to look back on 50 years of development of the receiving systems that followed the construction of ten fixed radio telescopes and a few more on a rail track, completed in 1968 three years after the tender.

We will follow the development of the sensitivity of the complete interferometric receiver system as stepwise upgrading of its constituent parts using the then most advanced and affordable technology. As with LOFAR, it is interesting to note that ASTRON developed the base technology of the latest WSRT receiving system by its technology development program funded in 1996 to prepare for next generation radio telescopes. For WSRT, the concept of a Phased Array in the focal plane of each reflector creates many adjacent beams on the sky. It transformed our synthesis telescope into one where 37 synthesized instruments based on advanced signal processing techniques are now at work simultaneously.

Introduction

A synthesis radio telescope like the WSRT makes, just as other telescopes, pictures of the sky. This is realized by combining the signals from a number of reflector antennas, and processing these combinations with a computer system that finally produces the sky pictures. The underlying combination principle for electromagnetic radiation comprising the received wave front was first analysed in 1934 by Pieter van Cittert, a physicist from Utrecht University in The Netherlands. The Groningen University Professor and Nobel Laureate Frits Zernike simplified the derivation in 1938 now known as the Van Cittert-Zernike theorem.

It took until 1962 when Professor Martin Ryle at Cambridge University demonstrated this principle for the first time with just two radio telescopes, which

* ASTRON, The Netherlands

brought him a shared Nobel Prize. The WSRT, operational in 1970, had 12 telescopes on a perfectly straight East-West line of 1,6 km length. With its correlation receiver system for the 21 cm band, it was the first 'picture machine' available to the scientific community internationally. As a result, some of the most gifted young radio scientists settled down at the Universities in Leiden and Groningen contributing to the world fame of Dutch radio astronomy.

It was especially the sensitivity of the WSRT, an order of magnitude greater than of existing university instruments, which formed the basis of international success. The collecting area of its reflector together with the equivalent system noise of its receiver in the focus is the first component which determines the sensitivity of a synthesis instrument. Secondly, the number of telescope combinations, the bandwidth and the duration of an observation determine the noise in a synthesis image. More instantaneous beams just speed up the observing of large fractions of the sky. Data processing provides the third component in the sensitivity by removing the many artefacts in a synthesis image that increase the effective noise level above the theoretical one. This latter aspect is discussed in Chapter 6.

Global development path of the WSRT

The invention of the transistor in 1947 started a new era for designing electronic circuits. At first for professional and military equipment, but in 1956 the first transistor radios appeared on the consumer market. The demand for semiconductor components in consumer products was an important stimulus for mass production providing by 1963 high frequency transistors for TV applications. These devices were not only cheaper than the electronic amplifier tubes, but also much smaller and produced far less heat allowing the design of compact units needed for our interferometric receiver system. Only the low-noise amplification of the extremely weak antenna signals from the sky at frequencies above 1 GHz required a different concept i.e. the parametric amplifier with a special semiconductor diode.

This new and affordable technology allowed us to start in 1965 with design and building the first large synthesis radio telescope in the world. It is not surprising that The Netherlands could make this daring step, since the natural gas reserve in Groningen just started to deliver, and was also the largest reserve in the world at that time.

Five instrumental development periods can be identified as determined by technological possibilities on the one hand and by Astronomical research requirements and their budgets on the other hand.

Instrumental development and enabling technologies:

1965 - '70	Discrete transistors for amplification and correlation
	Homemade quasi-degenerate parametric low-noise amplifiers
1970 - '76	First chips in digital lag-correlator operating at 1- and 2-bit digitization
	Commercial non-degenerate parametric low-noise amplifiers
1976 - '82	Custom chips in digital complex-correlator
	Cryogenic cooled parametric amplifiers and low-noise FETs below 1,8 GHz
1986 - '98	Full custom chips for digital lag-correlator
	Cryogenic cooled low-noise FETs
2005 - '15	8-bit Fast Fourier Transform correlator in Field Programmable Gate Arrays
	Ultra-low-noise HEMTs at L-band in Focal Plane Array

WSRT Heydays

We may consider a first phase from 1965 until '82 during which the upcoming semi-conductor technology is quickly implemented to take the lead in the radio aperture synthesis branch in astronomical research and kept it for a long time. An important driver was the American plan to build a synthesis array with 27 telescopes with 3 arms, each 21 km long. This Very Large Array, the VLA, would achieve more than twice the sensitivity and 25 times sharper view due to its longer baselines. The first realization activities for the VLA started in 1973 and the first phase of operation began in '80.

However, the WSRT was in 1976 still far ahead with just two additional telescopes on the rail track and a digital lag-correlator providing 2560 spectral channels for twice the number of unique baselines. In 1979, two movable telescopes were relocated to an additional rail track 1.3 km to the East extending the length of the synthesis array to about 2.8 km. This would provide sufficient resolution at 21 cm to see details in nearby galaxies that would only just pop-up in line emission even with the most sensitive cryogenic cooled receivers of the future. Therefore, the WSRT would stay competitive in all areas as the VLA would be hit by the same brightness sensitivity limitation.

Much more important was the increase in sensitivity of the receivers in the focus of the telescopes. That sensitivity has two components of which the noise of the first amplification stage is the most important one. The effective noise temperature was a factor of two reduced by replacing the quasi degenerate parametric amplifiers by nondegenerate ones. Further improvement resulted from cryogenic cooling of the low-noise amplifier stages in the four movable telescopes.

Multiplying in Cotton

Bou Schipper

Around 1977 a retrofit of the workhorse 6 cm Westerbork receivers was planned in order to introduce the latest technologies and improve the performance. In these receivers, an auxiliary signal is generated such that the resulting lower frequency carries the astronomical signals through long cables to the central building for further processing. The modules that generate this auxiliary signal were called multipliers because the output frequency was n times the input frequency fed to the receiver. These modules were not commercially available largely because of their specific and critical character, including a requirement for very high stability. As a consequence, they were designed and built in the lab.

However, and a bit to our surprise, it turned out that by now there was an opportunity to buy them based on our custom specifications. The UK company Bradley was selected and tasked to provide the 14x frequency multipliers with precise specifications with respect to frequency tuning, temperature, and phase stability. Phase stability is especially important for an interferometer like the WSRT! It turned out pretty soon that with regard to this stability requirement, the company had hardly any experience. In order to minimize the delays of the ongoing project with a clear demand for quick availability to the (staff) astronomers, I was asked to visit the company every 2 weeks to monitor progress and advise them on the design. This, of course, fit our experience very well. In the end, and in spite of my input, it turned out that the company was unable to achieve the required temperature-and phase stability. After some intense negotiations with the company, Jean Casse, then head of the labs succeeded to purchase them for half the price, leaving me with the issues to resolve.

With some creativity using industrial cotton to fully stuff the modules so as to stabilize the temperature and hence the phase, it ended up working properly! After also solving the unwanted radiation from the modules with help of Harm-Jan Stiepel and the use of neatly soldered copperfoil around the modules, this adventure page could be turned. The picture tells the story!

The second important factor is the effective frequency bandwidth, which is in practice limited by the digital correlator. There, the total bandwidth is divided into a large number of sufficiently small channels to properly image the velocity distribution in line emission over objects. This signature of source motion arises due to the Doppler effect, requiring a large number of frequency channels at the expense of processing power.

Although the 10 MHz bandwidth of the digital lag-correlator was sufficient for line studies and an improvement over the 4.2 MHz of the 1970 correlator, it would by no means be competitive with the planned 80 MHz of the American VLA. Therefore, it was decided to build a separate digital correlator providing that same bandwidth, which became operational in 1983.

Consolidation

After a break in the receiver development for the WSRT and the first successes of the VLA, it became clear that all telescopes needed cryogenic cooled receivers and that many more spectral channels were required for significant scientific results. In addition, the periodic change of the three sets of receivers could not support the wish for rapid change in frequency for objects that changed their wide-band spectral behaviour. Therefore, plans started in 1986 to construct a so-called Multi Frequency Front End (MFFE) where 5 feed systems could be quickly rotated to the focus of the reflector supporting 9 different frequency bands. With the MFFE, the sensitivity would only be a factor 1.6 worse after 12-hour observing compared with an 8-hour synthesis at the VLA at the most crucial 21 cm band. However, combining additional 12-hour observations with different positions of the movable telescopes provides a regular set of baselines. This greatly reduces the artefacts in a wide field synthesis image, which has always been the hallmark of the WSRT.

This flexible MFFE together with a first segment of the new lag correlator became operational in 1999. Only after completion of the new signal conversion system in 2001 the full number of 262,144 spectral channels became available for 8 bands of 20 MHz reaching over 1 million channels when 8 times 5 MHz was selected. These two workhorses, together with refurbished telescope reflectors, new drives and a new on-line control system, operated smoothly until the shutdown in 2015 to prepare for the next step.

From multi-frequency to multi-beam

After a second break in receiver and correlator development for the WSRT, it became time for a last upgrade where the WSRT could remain in serious competition with the upgraded VLA after 2010 and until the planned Square Kilometre Array takes over after 2020. In 2005 the focused design and development started of a revolutionary multi-beam telescope system using ASTRON's base technology for phased array antennas and Fourier transform correlators. After earlier engineering demonstration tests, the system implementation on the telescopes started in 2015 combined with a major telescope maintenance and improvement cycle. This Apertif system will commence full operations in 2018. Instead of one, Apertif creates 37 synthesis arrays, where each field has 350 MHz bandwidth and 10 million spectral channels for its 91 baselines. Its purpose is to image the neutral hydrogen in all galaxies to an unprecedented depth in the sky, as well as the time varying universe of which full scientific accounts are presented in Chapter 15.

Sensitivity Progress over Time

We summarize the increase in performance in a sensitivity for continuum surveying "Pcs" given by the square root of the product of number of interferometers N, total bandwidth B and number of beams per telescope "Nb", and then divided by the system noise temperature Ts at 21 cm. The last column gives the impressive relative increase "RI" with a factor of over 500x since 1970 (first line) of the WSRT system. The increase in processing power is even more impressive (see below).

Year	Ts	N	B	Nb	Pcs	RI	remarks
1970	260	20	4.2	1	.0353	1.0	quasi-degenerate paramps
1974	85	20	4.2	1	.0515	1.5	non-degenerate paramps
1977	85	40	10	1	.235	6.7	4 movables and DLB
1980	50	40	10	1	.4	11.3	cryogenic movables
1983	50	40	80	1	1.13	32	DCB
1998	27	91	160	1	4.47	127	MFFE and DZB using all baselines
2015	50	66	350	37	18.5	524	Apertif uncooled HEMT

The first 21 cm receiver and correlator system for the WSRT took 4 years to develop prototypes and to build a complete system for 12 telescopes. It had one beam on the sky, a system noise temperature of 260 K using only 20 baselines with 4 polarization channels and 4.2 MHz bandwidth.

Fifty years later the Apertif receiver and correlation system used again 12 telescopes but it took some 13 years from early design to operation. It provides about 3.3 times as many interferometers for each of its 37 beams on the sky. The receivers are 5 times more sensitive and the correlator provides for each interferometer about 115,000 spectral channels in an 83 times wider band. This is more than 370 million correlations compared to only 80 in 1970 and reflects a doubling every 2.2 years, close to the prediction by Moore's law for digital processing performance.

Although the inflation corrected costs for equipment and labour are roughly equal, the time from conception to completion differs by a factor three. The reason for this delay is that critical specialists had to share time with other projects as well, while the impact of all the new observing and calibration aspects on the control system was underestimated.

The first steps in Synthesis imaging

The call for tender in April 1965 to construct 12 telescopes with 25 m diameter reflectors and erect them at a site near Westerbork, followed shortly after completion in 1964 of the one-mile synthesis radio telescope at Cambridge University, UK. The one-mile array had three telescopes with 18 m diameter reflectors, of which the middle one movable on a rail track of 800 m starting near one telescope along an almost East-West line. Seen from the polar star at a large distance every telescope describes in 12 hours Earth rotation, half a circle around the other telescopes. In this way, the linear distances between the telescopes fill the 2-dimensional plane of the correlation function with half circles. The two correlations between the movable and the two fixed telescopes produce two baseline tracks for each setting of the moveable telescope. After 60 steps along the rail-track a complete 2-dimensional correlation function with 120 halfcircular tracks on a regular concentric grid is obtained. According to the Van Cittert-Zernike theorem, a Fourier transformation would give a projected image of the full sky but with enhanced intensity in a field defined by the beam profile of the telescopes that tracked a specific sky location. Also, every object in the field is broadened by the much narrower beam profile of a telescope with a diameter of one mile.

We do not only get a nice image with all the objects in the field, but each object is surrounded by a set of so called concentric grating rings. When the step along the rail track equals the diameter of the telescope, the rings of an object in the centre fall just at the edge of the field defined by the telescope beam. For smaller increments, the rings widen up, for larger increments, the rings narrow in and could disturb the object of interest.

The synthesis array in Westerbork would get 10 telescopes at a distance of 144 m from each other and 2 movable ones on a rail-track of 300 m all within a few mm from a perfect East-West line. With 20 unique correlations between the fixed and movable telescopes, 6 steps of 12 m on the rail would also provide a regular concentric grid with 120 half-circles. Twice the collecting area per telescope and the same receiver technology then provides double sensitivity and makes the telescope a factor 10 faster for a full synthesis. In practice, increments of 18 or 36 m were chosen with lower sensitivity and additional disturbing grating responses in the produced images, but many more fields could be observed in a given period.

This speed was important, since the English had already completed their 5C catalogue at 408 MHz before 1970 and had just begun with 21 cm observing. A new window on the sky opened up and which ones of the 100,000 visible fields on the sky would contain groundbreaking scientific discoveries waiting there for eons to show their secrets?

Continuum system 1970

An interferometric receiver system has different parts. The signals from the radio source enters the Front-End (FE) in the prime focus box of each telescope and while keeping its information moves to the Back-End (BE) in the central building. There the telescope signals are brought together with coaxial cables for further processing. In the FE the sensitive low-noise pre-amplifier stage and further amplification stages overcome the transport and other losses.

The most critical element in a FE is the low noise preamplifier. Reduction of the noise by factor two has the same effect on the sensitivity as increasing the collecting area by a factor two. This would be very costly, and would also reduce the size of an observed field by a factor two.

In 1966 a team at Dwingeloo Radio observatory led by Prof. Muller developed a parametric amplifier. This state-of-the-art device had a bandwidth of about 50 MHz around 1.410 MHz and an equivalent noise temperature of 55 K. This amplifier was of the quasi-degenerate type, which meant the output also contained an amplified version of a folding input band. The consequence for interferometric and spectral line work is that all noise contributions of sky, antenna, filters and connectors ahead of the paramp input and of the paramp itself have to be added and then doubled resulting in an effective system noise temperature of 260 K. However, this was sufficient for the moment since a nondegenerate type could replace these amplifiers in a later phase.

The Back-End had different parts to amplify the signals and shape them to 4.2 MHz bandwidth, crossmultiply and integrate them to interferometer correlations, all in analogue transistor technology. A scanner system read the correlated signals with a digital voltmeter under control of a Philips P9202 computer that wrote the data to magnetic tape.

Fixing the Mesh: “Het Boutjesproject”

Wout Beerekamp

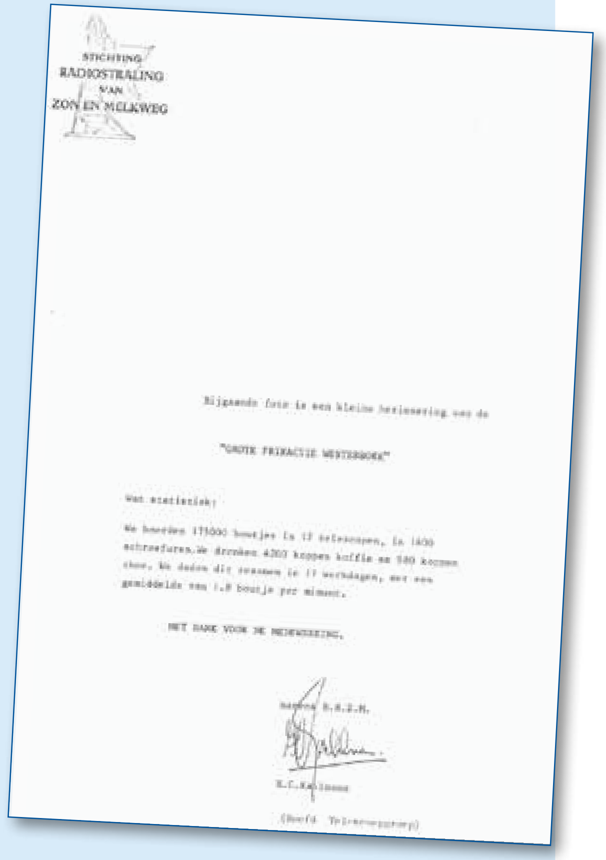
After 8 years operation of the WSRT, it turned out that the reflecting mesh glued to the individual panels was coming loose in rapid progression. Thus was born “The Fixing Project” (“Het Boutjesproject” in Dutch) placed under the capable technical leadership of Ton Wolfers† (then WSRT lead mechanical engineer) and Wout Beerekamp (then leading WSRT operations).

The solution was to fix the stainless steel mesh frames to the 2 mm thick panels using small selftapping screws. These were to be mounted by compressed air driven handheld drilling tools. In an incredible display of communal solidarity, many astronomers, students and engineers from all around the national astronomical community answered our distress call for help to restore “their” monumental WSRT. Volunteers were housed in caravans and tents on the nearby camping sites.

The pictures tell the story! We see (left) Ron Harten and family, (middle) Susan Simkin as hard working volunteer drilling screws at ground level, and (right) high up, Cees Slottje and Hans van Someren Greve. In one incident, a basket was accidentally driven into the reflector, but the antenna performance loss turned out to be minimal (and there were no injuries to our volunteers).

Besides using our own cherrypicker, three others were hired to get the job done in minimum time. One of those was capable to stretch to 25 m height to reach the outermost panels ensuring a great view, but there was some difficulty to convince our volunteers to get into the pickers basket! However, after a short and intense course by Ton and Wout, most volunteers accepted the challenge to do the job way up there, moving the cherrypickers to all heights while others remained on solid ground.

In the end Hans Kahlmann, head of the Telescope Group, expressed his appreciation by a written declaration to all who brought the WSRT back on track (see facsimile). Our volunteers drilled 175,000 screws, in 1600 hours over 17 days. And by the way, they also drank over 5000 cups of coffee and tea!



STICHTING RADIOSTRALING VAN ZON EN MELKWEG

Bijgaande foto is een kleine herinnering aan de

"GROTE FRIKACTIE WESTERBORK"

Wat statistiek:

We boorden 175000 boutjes in 12 telescopen, in 1600 schroefuren. We dronken 4200 koppen koffie en 580 koppen thee. We deden dit tezamen in 17 werkdagen, met een gemiddelde van 1.8 boutje per minuut.

MET DANK VOOR DE MEDEWERKING,

Namens S.R.Z.M.

H.C.Kahlmann

(Hoofd Telescoopgroep)

With 12 telescopes 66 cross-correlations can be formed. Since the 10 fixed and 2 movable telescopes have regular distances, 46 combinations appear in every observation. Therefore, only 20 combinations are unique and different for shifted movable settings that densify the regular grid of correlation tracks. This notion considerably simplified and reduced the correlation system.

Every FE had two orthogonal dipole antennas and required four correlation channels per interferometer. Since a correlation signal has two components, 160 channels had to be read every 10 seconds.

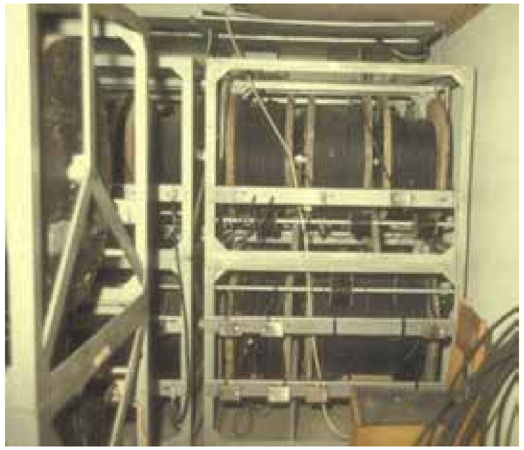


Figure 1 (left): Prof. C.A. Muller left and receiver engineer A.C. Hin right

Figure 2 (right): Delay cable rack with spools for 640, 320, 320, 160, 80, 40, 20 and 10 m, max 1590 m

The delay racks are an important and bulky subsystem of the BE. During an observation, the telescopes follow a track on the sky, which means that during the rising part the eastern telescopes receive a wave front earlier than the western ones. This needs compensation for proper correlation of all spectral components in the 4.2 MHz wide signal, which happens in steps of 10 m. The gradual path change between steps causes phase changes that are corrected in the correlation system by signals from the control computer, which depend on the instantaneous position of the observed field on the sky.

Line system 1971

The first surprise in 1970 was the discovery of a galaxy where the spiral arms in continuum radio emission did not coincide with the bright arms illuminated by starlight. It was therefore essential to observe line emission that would reveal location and velocity of the gas in the arms.

The rest frequency of emission by neutral Hydrogen is at 1420.406 MHz, but appears at higher frequencies for approaching velocities due to the Doppler shift. The typical range of frequencies in spiral arms of a galaxy is of order 250 km/s and at least 16 frequency channels are required to record a spectrum including some empty channels for a proper reference.

The correlator system provided for 2 x 10 interferometers with four polarization channels each and could be reconfigured into 2 x 5 interferometers with 8 spectral channels of 129 kHz wide and 190 kHz separation for a single polarization. This corresponds to a channel width of 27 km/s and velocity steps of 40 km/s spanning a range of 280 km/s. For a complete spectrum, two observations are required shifted by 95 kHz to fill the gaps between the filters. Compared to the continuum bandwidth of 4.2 MHz with full polarization on all telescopes, a factor 11 in sensitivity is lost for a single line channel. This loss needs compensation by additional observations providing more baselines and by decrease of the system noise temperature.

Purchasing two non-degenerate parametric amplifiers with 42 K noise temperature permitted the modification of one polarization in each Front-End of the two moveable telescopes, bringing their system noise temperature down to 75 K. When combined with 5 fixed telescopes at 260 K it translated in a geometrical mean system temperature of 140 K. Line observations started by the end of 1971.

These amplifiers were extremely expensive. After inflation correction this amounts to a quarter million Euro, to be compared with only a few Euros for the very low noise transistors for Apertif in 2015. Still, it was only 0.3 % of the total cost of the WSRT while almost doubling its performance. The funds therefore had to be found as the Astronomical community needed a sound explanation for the spiral structure of gas and stars in galaxies, a challenging situation that had to be addressed!

6/50 cm system

The first switchable receiver system became operational in 1972 and allowed comparing the intensity of sky sources at three different frequencies which is important for the identification of the radiation mechanisms. The field at 50 cm wavelength was a factor 2.3 larger than at 21 cm allowing larger objects to be imaged. At 6 cm the resolution was a factor 3.5 higher showing more imaging detail, with the 21 cm receiver in between. Figure 3 shows the 6/50cm receiver suite in the Westerbork Observatory building.

6 cm subsystem

The commercial quasi-degenerate double stage parametric amplifiers had a limited bandwidth around 4,995 MHz and realized an effective system noise temperature of 220 K. In preparation for the new digital line Back-End the bandwidth of the complete receiver chain was 10 MHz.

An upgrade program in 1977 installed new non-degenerate parametric amplifiers realizing a system noise temperature of 120 K and 100 MHz output bandwidth. An additional modification in 1980 to the multiplier ensured stable

Figure 3 (left): Looking into the 6/50 cm FrontEnd (right): Rack with 15 6/50 cm FE's in Westerbork

working over the full tuning range from 4,770 to 5,020 MHz, making two recombination lines accessible.

50 cm subsystem

The 50 cm receiver used a bipolar low noise transistor, which in combination with the narrow band input filter realized a system noise temperature of 350 K. This high loss filter centred at 610 MHz had to pass the 5.5 MHz wide TV channel 38, left free for radio astronomy, and reject other TV channels. Unfortunately a TV transmitter at about 150 km distance suffered from internal interference causing spurious signals in our channel 38, which was cured by an additional high power filter at the transmitter. The new digital line BE provided in 1977 a 2.5 MHz filter allowing much steeper filtering in addition to the FE filter eliminating weak interference from two German TV transmitters. A further upgrade in 1981 used a Ga-As FET as low-noise input transistor with a far larger signal dynamic range, allowing placement of the narrow band TV filter after the low noise transistor. The consequence was a much improved system noise temperature from 350 K to 110 K.

21 cm upgrades

A first step in 1971 replaced in two FEs the quasi-degenerate parametric amplifier of one polarization by a non-degenerate one from Micromega having 42 K noise temperature and a frequency range from 1.365 MHz to 1.425 MHz. Another important step was that the single dipole was no longer rotatable and had a straight low-loss connection to the paramp, which resulted into a system temperature of ~75 K.

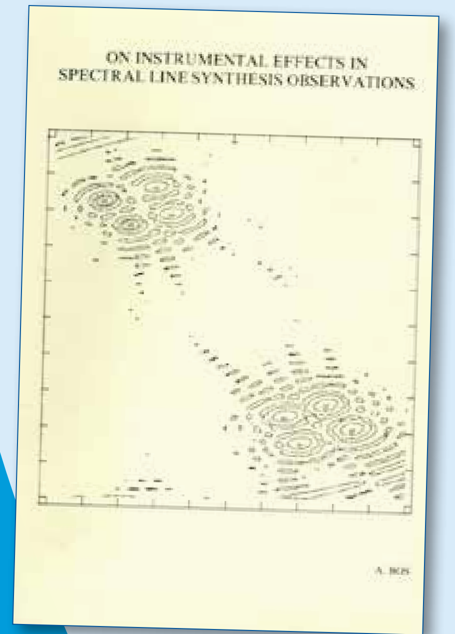
A second step was made in 1974 when all 21 cm FEs got non-degenerate paramps. However, the limited rotation over 45 degrees caused higher losses and resulted in 85 K system noise temperature.

At the last step was in 1984 when the complete electronics, except for the paramps, was replaced to increase the output bandwidth to 100 MHz in preparation for the new wide band continuum backend.

Mr. Correlator

Arnold van Ardenne

It is my great pleasure to contribute this page in honour of Albert Bos, ASTRON's own Mr. Correlator. Of course Albert is retired now and following many other aspirations and activities, but when he allows himself to look back, he may smile at his technical legacy of many state of the art digital lag correlators which he and his team built in the ASTRON lab. One can even say that the digital age started at ASTRON with Albert's first correlator in 1976. It was equipped with the so called "Bos" chip which was the very first in-house designed TTL chip, and it remained available on the commercial market for some years. This first Digital Line Backend (DLB) operated for a decade into the mid-eighties, with the help of some improvements along the way. Albert acquired his PhD from Leiden University in 1982 based largely on his success with the DLB. The thesis was focused on the instrumental effects on line synthesis observations as a result of the many imperfections in the observing system, including correlation and processing. Albert's work on the DLB was recognized with the prestigious national Veder award in 1996. The DLB was followed by the DXB with a sidetrack to make the correlator (the "DAS") for the JCMT, the submm Hawaiian telescope for which, rather unknown by many, ASTRON built the complete 350 GHz receiver-IF-correlator system in the mideighties. As the making of correlators took quite some time partly because of the flexibility resulting from the large number of functional configurations, his last correlator was called the DZB. This top of the line system was equipped with a custom specific chip based on the Bos architecture in collaboration with JIVE and others including Haystack/MIT in the US. It was a formidable achievement, which together with frontend upgrades, concluded the WSRT system upgrade around 2000. Albert was extremely dedicated and often stayed late in the Observatory building working on system improvements. Such was his enthusiasm and dedication that sometimes I felt that upon opening one of the correlators 19" racks Albert would jump out! Time passes on and we can truly say that the ultra-stable WSRT performance from which many astronomers have benefited owe a great thanks to Albert's correlators!


ON INSTRUMENTAL EFFECTS IN SPECTRAL LINE SYNTHESIS OBSERVATIONS

A. BOS

Digital Line Back-end and Recirculation

The Digital Line Back-End or DLB was a major step forward to handle 10 fixed and 4 movable telescopes at a maximum bandwidth of 10 MHz. It improved the continuum sensitivity only by a factor 1.4 due to additional digitizing losses at the highest bandwidth. The system has 320 blocks of 8 complex spectral channels that allow various distributions of the 2,560 channels over baselines and channels. One extreme has even 5120 channels in autocorrelation mode on a single telescope, and another configuration could cross correlate all telescopes together. The latter configuration was instrumental in developing the so-called redundancy calibration technique. Since the fixed telescopes are placed on a regular grid some baselines appear multiple times. Since the sky response is only baseline dependent, comparing the various results allows interpreting actual differences as disturbances from telescope and atmosphere (see Chapter 6).

The design and development of a prototype started in 1970 and the complete system became operational in 1977. There are 4 racks each with 4 crates containing 20 correlation cards each as can be seen in Figure 5. About 10,000 wires connect the boards in the crates and have a crossed layout as seen in Figure 6 to prevent crosstalk. To prevent the radiation of unwanted interference cause by the digital equipment they are placed in a closed metal cabin. See Figure 4 also showing the in-between boards wiring technique called wire-wrapping. This kept digital engineers Arie Doorduin, Hans Weggemans, Roelof Kiers and perhaps others, quite busy at the time!

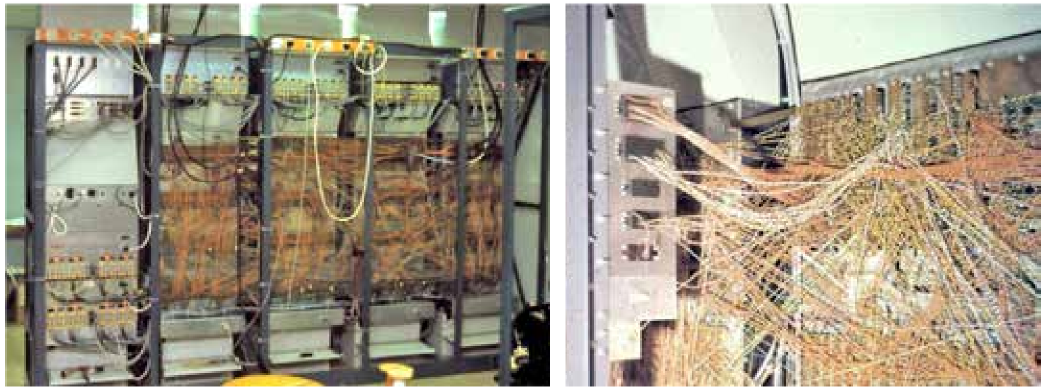


Figure 4 (left): DLB racks in the Faraday cage for RF-shielding. (right): DLB wire wrap closeup.

The Digital Line Back-End has four subsystems. Following the signal chain, the first is where the Intermediate Frequency (IF) signal from each telescope is converted to a video signal of sufficient strength. Also, the bandwidth is limited from a selectable range from 10 MHz down to 78 kHz in steps of a factor two. The second subsystem contains the digitizers where each video signal is digitized to 2 bit, a sign bit and a high/low bit. High means higher than the root mean square value of the noise signal. The third subsystem is the digital delay and the fourth system is the correlator, where the signals from different signals paths are cross-multiplied and integrated.

Multiplying 1 and 2bit signals is realized with a few logic gates while integration requires a counter. In 1970, these functions were already available in Schottky TTL chips. The digital lag correlator has a shift register where 16 steps of a signal stream are stored and clocked through. The 16 delayed samples are all cross-multiplied with the same sample of the second data stream and at each lag integrated in a separate counter. The samples are delayed in steps of 50 ns as defined by the 20 MHz clock, which is according to the Shannon theorem sufficient for sampling of a noise signal of 10 MHz bandwidth. The Wiener-Khinchin theorem, also from 1934 when Van Cittert gave his first formulation for wave fronts, states that Fourier transformation of 16 samples of an auto-correlation function gives 16 spectral channels of the input signal. Cross-correlation results in 2 numbers for only 8 spectral channels reflecting the complex nature of a signal with intensity and a phase.

Recirculation option

Correlating two polarizations for the fixed movable combinations provided in full 2-bit mode only 16 spectral channels, which is marginal in many applications. Since most line work is done with 2.5 MHz total bandwidth, sampling at 10 MHz is, according to the Shannon theorem, overdone. In fact, processing power of the correlator is wasted by repeating unnecessary operations. With an additional memory in the input data stream, only every fourth sample of the 2.5 MHz stream is stored. Then, processing a block with a four times longer time sequence at full speed provides a four times longer spectrum in a larger output buffer. In this way, the number of processed lags doubles for every halving of the input bandwidth. Finally, a maximum recirculation factor 16 was chosen providing 40,960 spectral channels in 1-bit mode. Team Albert Bos dubbed the additional unit DXB. It became operational in 1985, marking maturity of the lag principle.

It is interesting to note that the world's first multipurpose single board PC based on the Motorola 6800 microprocessor using an on-board OS9 real time operating system, might have been developed by Rob Millenaar in 1979. It was used in the delay controller system of both DLB and DCB (see below).

Cryogenic 6/21 cm with 18 cm option on the movable telescopes

In the late sixties, it was already clear that the system noise temperature was dominated by receiver losses that could only be reduced by reducing the actual temperature. This started the development of cryogenic cooling in 1970 (see Chapter 3). Lead by Bert Woestenburg, this resulted in an operational system in 1979 with 6/21 cm cooled receivers on the four movable telescopes.

Figure 5: Inside the 6/21 cm cryostat of the cooled frontends (see the text).

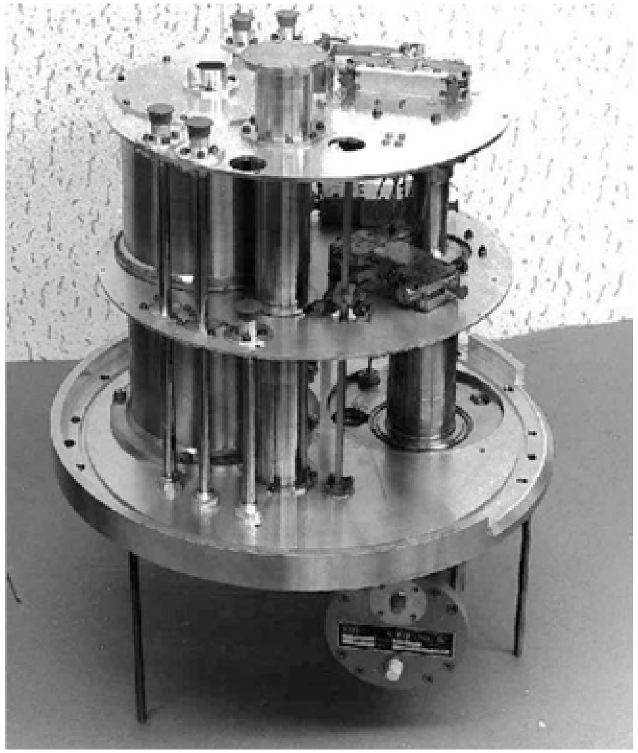


Figure 5 shows the CTI cooling system with two plateaus at the right. The top plateau at a temperature of 20 K has two non-degenerated AIL parametric amplifiers for 6 cm operation. The second amplification stage using Ga-As FETs is located on the second plateau at 70 K. The complete chain provides on the telescope a system temperature of about 55 K. Together with the 120 K system on the fixed telescopes the geometric mean of 81 K, is a factor 2.7 better than in 1972.

After lots of tough lab work, including the removal of unwanted resonances only noticeable with closed cryostat cover, the 21 cm up-convertor provided a receiver noise temperature of 13 K and 29 K system temperature on the telescope, a new milestone in 1980 Westerbork. Together with the fixed telescopes, the equivalent was now 50 K system, a factor 4.6 improvement over 1970.

18 cm option

For VLBI observation with the WSRT in tied array mode an 18 cm observation capability was important. The 18 cm band was added by replacing the 21 cm up-convertor for a self-developed wide-band Ga-As FET amplifier. This 18 cm system needed a different dipole system mounted outside the cryostat. The uncooled connection cables raised the system temperature to 55 K.

Digital Continuüm Backend

By 1973 our American colleagues embarked on a project for a serious synthesis radio telescope. This Very Large Array or VLA, would have 27 telescopes with 25 m diameter reflectors and a suite of receivers in the Cassegrain focus, becoming operational after 1980. With cooled receivers on all telescopes and making all possible correlation between them, the system would provide after an 8 hour synthesis a factor 1.7 improvement in sensitivity over the WSRT with a 4 x 12 hour synthesis at the 21 cm line. For continuum observing a bandwidth of 80 MHz was planned, giving an additional improvement factor of 2.8. To stay competitive for continuum observing it was therefore essential to increase the 10 MHz bandwidth of the DLB. This was done by a new, additional Back-End, the DCB. In 1983, after 7 years of design, prototyping, and mass production, the Digital Continuum Back-End, the DCB, started regular operation at the WSRT. Figure 6 shows the happy DCB team.

Figure 6 The DCB team: John O'Sullivan (centre) surrounded by Yde Koopman most left, Rob Millenaar, Anne Koster , Sjouke Zwier, Bert Poot and Dick Hoogeraad†. In front a student (Wim Westerhof) (courtesy Sjouke Zwier)

The Low Power Schottky TTL chips still had the same maximum clock speed of 20 MHz as used in the DLB. This required division of the 80 MHz band in sections of 10 MHz, each with their own set of digitizers, delay modules and cross correlators. Since the 80 MHz range in the 21 cm contained parts with strong radar signals, each band had filters to select 10 MHz or 5 MHz bandwidth operation at a dedicated centre frequency.

The 1970 system correlated a set of fixed telescopes against a set of movable telescopes. To obtain the two components of the correlation function, the signal of a movable telescope was duplicated, but with an additional phase shift of 90 degrees. A comparable trick was required when every telescope needed correlation against all other telescopes. The trick was found by using the principle of a modified Weaver mixing scheme, where the first step was done in the analogue domain at conversion of the IF signal to video, and the second step in the digital domain after correlation. The Weaver down conversion process uses two mixers that each fold the 10 MHz wide signal band around a selectable IF frequency providing two 5 MHz video bands of which one with a 90degree phase shift. This approach requires digitization of twice as many signals, but still using the 20 MHz clock results in oversampling. Fortunately, twofold oversampled 3-level correlation has 8% digitization loss comparable to 4-level (2-bit) cross-correlation. This 3-level correlation gave considerable simplification of the digital correlator circuitry, but doubled the number of video convertor, digitizers, and delay blocks. Correlation was now not between two 10 MHz signals but between two pairs of 5 MHz signals requiring four cross-correlators instead of one.

Despite the integrated chips, the cables remained a nightmare as indicated by Figure 8.

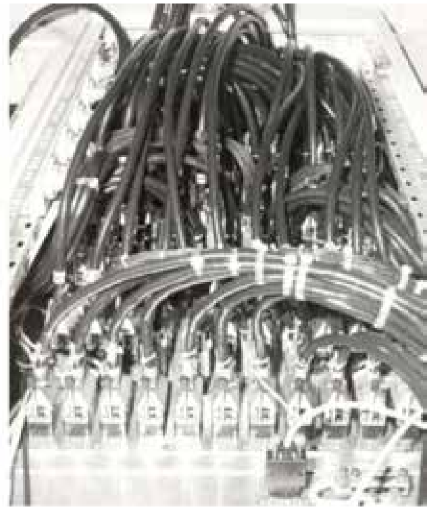
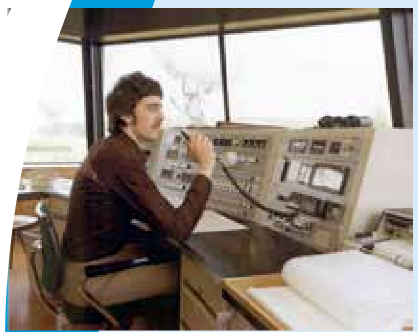


Figure 7: (left): "Organized" DCB correlator circuit board

Figure 8: (right): DCB cabling on a digital rack

Controlling the WSRT

Teun Grit



When I started working at ASTRON in March 1976, working with computers was so different from today that many of you cannot even imagine how it was in those days. That same year I became an observer and one of the tasks was making large piles of punch cards holding the observations for the weekend. The punch cards were converted and combined into one long punch paper tape. On Friday, the 16 bit computer with 32 kByte memory read this paper tape, started the observations and the results were stored on magnetic tape. These tapes were sent to Leiden on Monday for further analysis.

Programming was also time consuming. All software was written in assembler (machine instructions one by one) and was typed on punch cards. Then the stack of punch cards with source code was fed into the computer for compilation. The result was a punch tape with one or more routines. With every error, the process had to be repeated. This was very time-consuming, but the instrument was in production and we were pressed for time. When you finished all the compilation work, the small paper tapes had to be assembled into one "sector" punch tape of about 10 cm diameter. In the end, 32 of those big punch tapes had to be read in before you could start testing your modifications. This happened with a fast optical reader and afterwards the tape ended up in a large basket. "So you want to learn how to program? Then help me by winding those punched tapes in that basket." As a junior, you did not dare to refuse!

Meanwhile, "new" HP1000 computers were installed and they were equipped with a Fortran compiler. I left the assembler language for what it was and focused on Fortran 4X. Programming was fun and therefore I started an "AMBI" study with the languages Algol and Fortran. I officially started as a programmer in 1981. For about 25 years, Hans van Someren Greve and I shared the same room and while Hans worked on the on-line (control) software, I focused on the off-line (processing) software. Hans was my supervisor in that period and I owe him a lot.

When the mathematics became problematic, Hans would supply me with a well-tested routine. On the other hand, Hans was not happy with system administration and so we formed a good team. In those years, I also managed the RTE and HP-UX systems. In the mid-1990s, the first Suse Linux systems arrived.

One of those HP1000 systems has lasted for 25 years as an embedded system in the Digital Continuum Backend. We did not dare to turn it off anymore because we were afraid that the power supply would fail! Such a HP1000 computer had a fixed and a removable hard drive of 2 MByte. I remember the crash of my first hard drive around 1980. While I was working, I suddenly heard a screeching sound coming out of the disc. Fortunately, there was a backup on tape. I still have the crashed disk at home!

The internet started in 1983. Some years later, the WSRT was connected to the Internet with a modem. We could send 75 bytes / sec and receive 1200 bytes / sec. This made ASTRON one of the first internet users in the Netherlands. As a result, my passport photo was for years the most popular passport photo of the Netherlands. Every time one searched for "pasfoto", my face showed up! ☺ I did not find out until years later.

When the HP9000 arrived around 1990, languages such as C, Perl and Pascal were also used. With the arrival of the Telescope Management System (TMS) in 1995 the C++ language became popular. The Fortran programs from the 1980s are still in use as the IWOS (the WSRT Control Software) package. I am proud of that. That is legacy code of almost 40 years!

In 2007 I started working full-time as a system administrator for LOFAR and WSRT. Today the WSRT systems such as ARTS have 128 GB of memory, which is more than 4 million times more per machine than the Honeywell/Philips 9200 computer from 1970. Soon we will have archive systems of 4 PetaByte (or 4,000,000,000,000,000 bytes), that is 2,000,000,000 times more than my first work drive!

When retiring in May 2020 I will leave ASTRON with pain in the heart. ASTRON was and still is, a fantastic institute and I feel very lucky to be part of it!

The 1976 paper tapes contain plot routines that are still in use in IWOS.

The resulting four numbers needed proper recombination to produce the two numbers representing the complex correlation of a single 10 MHz band. This operation was in essence a complex multiplication and required another one to perform the fringe de-rotation before final integration in computer memory. A Hewlett Packard 21MX computer, integrated in the correlator system, got a dedicated high-speed operating system to perform these operations every 0.2 s, before finally transferring the integrated data every 10 s to the on-line control processor.

Another novelty was the custom-specified ULA chip from Ferranti. This Uncommitted Logic Array contained sufficient gates to perform high-speed integration for a set of eight three-level correlations. This allowed much cheaper further integration by a low-speed counter section that provided sufficient precision for the 0.2 s read-out cycle.

Each of the eight band sections had 1024 cross-correlators for 256 interferometers of which 160 for the fixed-moveable combinations in full polarization. The remaining channels covered most of the dual polarization combinations between the redundant baselines in the fixed and the moveable telescope subsets.

90 cm receiver system

Initial plans for a 90 cm system took a few years of cooperation with the Technical University of Eindhoven to develop a compact feed system with dipoles in the launcher part on the FE frame and a ring on the focus box. The challenge of obtaining proper electromagnetic operation without impairing observing with the other FE series successfully concluded in 1983 with a full series of 92 cm Front-Ends.

Although the FET pre-amplifiers had a noise temperature of about 100 K, the narrow-band antenna filter of 3 MHz at the low frequency deuterium line at 327 MHz raised the system temperature on the telescope to about 200 K. The measurement of the deuterium (a heavier version of hydrogen) and hydrogen ratio is of importance to cosmology.

The WENSS program, a large Survey of the Northern sky at 50 cm and 90 cm, required a lower noise temperature at 92 cm comparable to 110 K at 50 cm. An uncooled FET amplifier in 1988 already showed a low noise temperature of 25 K. Together with a new lower loss 5 MHz input filter the system noise temperature was 135 K measured on the telescope.

The last upgrade in 1993 provided a FE bandwidth up to 80 MHz relevant to support dispersion correction for a pulsar detection program. It turned out that the 86 cm band between 310 MHz and 390 MHz could be used very well by careful setting of the eight 5 MHz DCB bands, although it is an assigned aircraft communication band. In addition, the fluctuations in total power of the whole band posed no problems to the IF system, which allowed removal of the high-loss narrow-band filters in the FE. Together with the most recent FET's, the system noise temperature on the telescopes was 100 K.

Multi Frequency Front End

Changing frequency band required replacing the FE in the focus for all 14 telescopes, an operation taking a few days once every few months. However, for many scientific programs it is essential to compare images at different frequencies made at about the same time. This requires a single frontend to be capable of changing frequency. The plans for such a front end that would handle 9 frequency bands ranging from 0.3 to 8.3 GHz, and the highest ones with cryogenic cooled preamplifiers, started in 1988. As a full account of the MFFE is given below, only a few milestones are given here.

The prototype cryogenic MFFE demonstrated a system temperature of 27 K at 21 cm in 1994. Around 2000 all 14 telescopes had a complete MFFE covering 9 frequency bands. Five bands have cryogenic launchers and amplifiers at 21 cm/18 cm/13 cm/6 cm/3.6 cm, and four noncooled amplifiers at 92 cm, 49 cm, UHFlow and UHFhigh.

In June 2015 the MFFE era came to an end to start preparing for the multibeam receivers. Two MFFE's (plus some spares) remain in operation for VLBI and e.g. Galileo Satellite observations, on telescopes "0"and "1".

DZB, the last lag correlator

The first ideas for the DZB correlator date back to 1992 when cooperation with MIT/Haystack started to develop a full custom integrated circuit containing 512 cross-correlation cells. This CMOS chip would run at a maximum clock speed of 40 MHz to support a signal bandwidth up to 20 MHz. The chip was based on the famous Bos architecture developed at ASTRON in 1986 for a16channel chip running at a maximum clock speed of 55 MHz. This chip got worldwide usage and was used on the vertical board (Figure 12 left), which shows the typical configuration of boards on a backplane for use in a crate.

The new chip included additional features developed by MIT/Haystack for VLBI applications. Just as for the previous chip, there was worldwide interest and five different Astronomical institutes used the correlator boards each containing 32 chips. The WSRT and the Smithonian Submillimeter Array at Mauna Kea used direct telescope input, while JIVE, Haystack Observatory, US Naval Observatory, and MPfRA at Bonn used the signals from MKIV tape recorders for VLBI processing. See Figure 9 (right picture).

Developments in programming; *Encapsulating legacy sotftware*

Marco de Vos

It must have been early 1995 that I sat in the office of Arnold van Ardenne discussing the WSRT upgrade when at some point concluded that something seemed to be missing. Almost all hardware systems were being either replaced and at the very least seriously revamped. Of course those changes had software repercussions. These had been identified, and each of them could be implemented individually. That was the way things had always been done. Software follows hardware: new modes are added to the existing programs, new fields are allocated in the real-time memory. This had worked in the past, most people were convinced it would work now as well. We had our doubts....

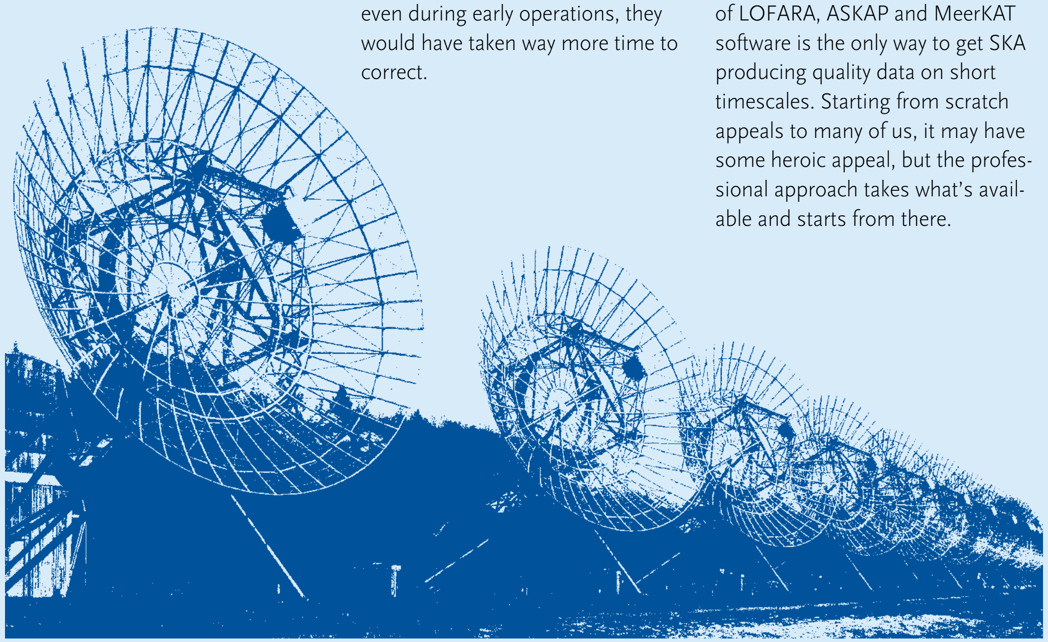
What seemed to be missing was a systems approach. The software running the WSRT had grown organically over more than a decade. There was no guarantee, either formal or heuristic, that it would continue to do so. Thus yet another subproject was added to the grand WSRT upgrade program: the Telescope Manager System, TMS. The big idea was to do things different, to professionalize the way we did software development. In retrospect, there were indeed several various new elements. Whether they shook the way we did software development to their foundations, I'll leave to the reader. But they certainly where new in 1995, and they are useful to reflect on even now.

First was the choice for an object oriented design approach. This is not the same as "using C++." The TMS team made a serious effort to follow the formal methods that had been laid out by Rumbaugh in 1991. I still think this was a major improvement, mainly because it forced us to think in terms of architectures and interactions before we started coding. In 1997, when TMS development was well underway, we did some analysis on rework on infrastructural modules. It turned out that the amount of rework in modules with fully worked out designs was about 10% (one of every ten lines of non-comment code modified after initial release). The amount of rework in modules with marginal designs was up to 100% (almost every line of code modified!).

Another element of change was the use of external consultants. They were of course received with great suspicion. To start with, they did not understand a thing about radio astronomy, so what good could they do (we of course knew a great deal of software engineering....). Soon several colleagues realised this weakness provided an opportunity as well, in that these consultants, being good listeners, were quite willing to be educated. This in turn led other colleagues into some deep reflections on the economic models of the firms employing the consultants. Apparently unaware of all this turmoil they were creating, the external experts came up with several object oriented architectures that formed the basis of the Telescope Manager System. In my recollection, the most important thing they introduced was the use of multiple perspectives on a complex system. We've brought that to the next level when applying IEEE standard 1471-100 for the Architectural Design of Software Intensive Systems to LOFAR.

In addition to bringing in experts from outside, we also brought in software packages (other than operating systems and compilers). The core of the "old" WSRT software was a large shared memory block that contained all the vital parameters. This was first mapped on an object oriented model of the WSRT and then implemented in a commercial real-time database. This was a major change with a very high impact. The database came with a lot of nice features, like graphical dashboards, browsers and triggers. But for those who were used to a single big table, the added flexibility was hardly gain. However, this major change prepared us for the distributed control model that was essential to handle the much more complex LOFAR system.

A final element of change was the introduction of peer reviews and change control. This may sound trivial now, but I can still hear people complain about colleagues looking at "their" code. With inspections in TMS we found on average two errors per non-trivial function before actual test. If these errors had to be found while testing or even during early operations, they would have taken way more time to correct.



The TMS development enabled many new operating modes that would at best have been very difficult to implement in the old architecture. They showed us the strengths and weaknesses of formal methods and of external experts and tools. But they also showed us how important it is to maximise continuity when possible. One of the key design decision we made in the TMS project was to wrap wherever possible the existing software. Maximizing reuse by encapsulating legacy software is to be seriously considered for any major software intensive project. It helps enormously if the existing software has a high cohesion (e.g. is in the form of libraries like CASA Core), but it should be considered anyway. I'm convinced that proper reuse of LOFARA, ASKAP and MeerKAT software is the only way to get SKA producing quality data on short timescales. Starting from scratch appeals to many of us, it may have some heroic appeal, but the professional approach takes what's available and starts from there.

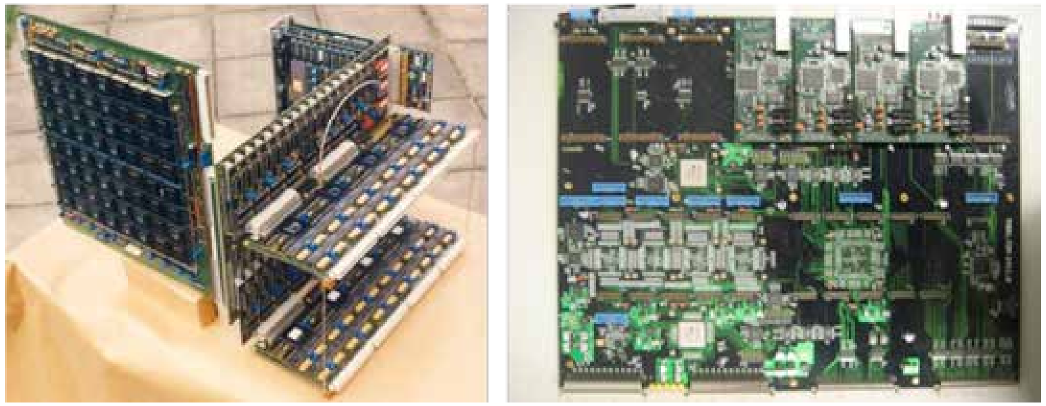


Figure9: (left) Correlator board (the "DAS") build for the James C. Maxwell Telescope on Hawaii in the eighties and (right) a DZB board again with custom chips.

The WSRT would get a system with 1024 correlator chips and additional memory to support a maximum recirculation factor 16. The new system had to replace DCB and DXB, make all correlations between 16 dual polarization inputs, including the auto-correlations, and provide for 160 MHz bandwidth of the MFFE signals as well as for higher spectral resolution. The first segment of the DZB became operational in 1998 using one section of the DCB broadened to a bandwidth of 20 MHz. The system was completed in 2001 with a video converter system for 16 dual polarized telescopes signals. Each signal could be separated into 8 bands of 20 MHz bandwidth down selectable to 156 kHz in steps of a factor two.

The insert on page 175 shows ASTRON's Mr. Correlator, Albert Bos, who was responsible for all lag correlators.

From multi-frequency FE to multi-beam system the next stage

In 2006 plans started to succeed the MFFE's and the DZB with a system that would give the WSRT a competitive edge over the upgraded VLA (now the JVLA) expected to be operational by 2010. This is Apertif using results from the ASTRON technology development for the SKA wide band aperture arrays with Vivaldi antennas (see Chapter 15).

Ever growing sensitivities

Chapter 10.2 The Multi Frequency FrontEnds; The ultimate single pixel Receivers for the WSRT

Gie Han Tan*

Starting at the end of the eighties and continuing during the nineties of the previous century the Westerbork Synthesis Radio Telescope (WSRT) underwent a major upgrade. The purpose was to overhaul it thoroughly and, more importantly, to put it again at the forefront of radio astronomy.

The ASTRON Strategic Plan issued in 1986 and updated in 1988, identified the need for this major upgrade and the ASTRON Board approved the plan for the design and construction of the ultimate single pixel receivers for the WSRT: The Multi Frequency Frontends (MFFE).

The major effort of this general system upgrade was the development and construction of new frontends for all 14 telescopes. The MFFEs would provide hugely increased frequency coverage. The frequency agility of the new frontends was one of the main advantages enabling new areas of astronomical research while at the same time eliminating the need for multiple sets of receivers. Apart from the huge cost saving and operational advantage, the MFFE construction with a single cryostat while extremely complicated, proved to be reliable and sturdy.

Science drivers

The astronomical community played the key role in defining the requirements for the MFFE. The obvious one was to improve the sensitivity in the existing WSRT receiver bands by applying the latest technological developments, e.g. High Electron Mobility Transistors (HEMT), using cryogenic cooling in all frontends. Thus far only the receivers of the four movable telescopes were cooled.

A major challenge was to increase the frequency coverage of the frontends to satisfy evolving and new interests from the astronomers. At the high frequency end, beyond the existing 6 cm band, the need for a 3.6 cm receiver band covered interests in observing spectral lines and VLBI observations. The decision to include the 3.6 cm band was pushing the limits of the WSRT system given the relatively high mesh transmission increasing the system noise level due

* European Southern Observatory, Germany

to the ground radiation. While the very low system temperatures on the Very Large Array (VLA) with full metal panel reflectors could simply not be reached, the substantial WSRT collecting area (14 x 490 m^2), nevertheless allowed a very reasonable sensitivity.

Primarily driven by the interest to observe red-shifted neutral hydrogen, there was a strong desire to expand the frequency coverage at the low end. The WSRT had a long and successful history in observing the HI line with the various 21 cm frontends. With the MFFE, the receivers were planned to cover 1421 MHz with ~250 MHz tuning bandwidth. This frequency range is well outside the bands exclusively allocated to the radio astronomy service by the International Telecommunication Union (ITU) and in practice is heavily in use by television broadcast transmitters and the then upcoming mobile phone (GSM) networks. Another technical issue was to develop compact feed systems to cover these bands. The size of feed systems more or less scales with wavelength and the available space in the WSRT antennas was rather limited. Astronomers were also unwilling to accept a performance degradation, and, in fact, desired improved performance in all the existing WSRT bands. As frontends around 610 MHz (combined with the 6 cm receiver) and later also at 327 MHz were added to the receiver suit, this led in the end to the decision to have all these frequencies available in the new MFFE and then eliminate entirely the old receiver sets. Two new receiver bands covering the ranges 250 MHz to 460 MHz (UHF_{low}) and 700 to 1200 MHz (UHF_{high}) were added to explore the lower frequency universe in the Northern skies as in the south the Indian GMRT came into operation. In response to the VLBI community, the decision was made to add a 13 cm receiver band to the MFFE to bridge the gap between the existing 18 cm and 6 cm bands. This of course added to the complexity of the MFFE design even further!

A good summary of the WSRT upgrade from a science point of view with more details about the background of the MFFE technical requirements is provided in NFRA note 571 *"Thoughts on upgrading the WSRT"* by Ger de Bruyn. The most essential specifications are shown in Table 1.

Table 1: MFFE performance summary

Wavelength	Frequency coverage	System temperature	IF Bandwidth
92 cm	310 MHz – 390 MHz	75 K	10 MHz / 80 MHz*
49 cm	540 MHz – 610 MHz	110 K	10 MHz / 80 MHz*
21 cm	1200 MHz – 1450 MHz	27 K	160 MHz
18 cm	1590 MHz – 1750 MHz	26 K	160 MHz
13 cm	2215 MHz – 2375 MHz	58 K	160 MHz
6 cm	4770 MHz – 5020 MHz	55 K	160 MHz
3.6 cm	8150 MHz – 8650 MHz	90 K	160 MHz
UHF_{low}	250 MHz – 460 MHz	175 K	10 MHz / 80 MHz*
UHF_{high}	700 MHz – 1200 MHz	100 K	10 MHz / 80 MHz*

* - bandwidth remotely selectable

Fitting the operational constraints

Coming up with a design concept meeting the key specifications listed in Table 1 was only one part of the development challenge. The engineering constraints imposed by the requirement that the MFFE should be compatible with the existing system infrastructure at the WSRT were also a challenge. Arie Hin† then system engineer at the WSRT and amongst the pioneers of Dutch radio astronomy (see his obituary from the archive of the AJDI200117) considered the design challenges in a very comprehensive overview in his ASTRON *Note 516 "Aspecten WSRT 'Multifrequency Frontends'"* and in note 539 "'Westerbork'-feasibility aspecten MFFEs", both written in Dutch. Some of the more major technical design constraints are worth noting!

The WSRT Antenna configuration

Designed for 21 cm observations, the relatively coarse mesh size of the telescopes in the 3.6 cm band contributes about 50 % increase of the noise level. Also, the surface roughness at these short wavelengths reduced the aperture efficiency with negative impact on the system sensitivity. Some research had been done in the past (see Insert on *Closing the Holes*) and a further review led to the final decision that upgrading the reflector surface was not feasible due to mechanical constraints, wind load and weight, and associated costs for improvements.

The short ratio of focal plane length to antenna diameter of f/d = 0.35 required wide feed patterns. With more space available, it is generally easier to design high performance, broadband feeds for a somewhat higher f/d ratio. On the positive side it allowed the re-use some of the existing WSRT feed designs.

Frontend size and mass restrictions

Mostly for financial reasons, a major modification of the existing primary focus box on the WSRT antennas was not an option. This meant that the new MFFE should fit into the roughly one cubic meter space available. Some ingenious solutions discussed in following sections made this possible.

First of all, the maximum frontend mass needed serious attention. Thus far, the heaviest frontends were the cryogenically cooled 21 cm / 6 cm frontends weighting about 275 kg. To accommodate these older frontends the WSRT antenna counter weights already had been strengthened because of the increased stress on the tubing of the support structure. Also, the higher mechanical stress raised some concerns about metal fatigue. It was therefore essential for the MFFE to remain within the 275 kg maximum weight limit. Combined with the volume restrictions, the weight limit inspired an innovative design for all of the nine receiver bands to fit into each MFFE.

Westerbork for Cosmology; removing the Bottleneck with the IVC and more

While the work on the wideband digital backend (DZB) and the versatile MFFE receivers was progressing both of equal frequency bandwidth, the connection between the two turned out to be an unplanned bottleneck. Ger de Bruyn† wrote a proposal to NWO on "Cosmology with the WSRT" making the case for using the full bandwidth capabilities of the new MFFE and digital backend. Now funding was available to remove the bottleneck!

The IF-to-Video Converter (IVC) would be the new link between the MFFE and the DZB. A main feature of the IVC was its capability to process 32 channels with 20 MHz bandwidth of the 160 MHz IF bandwidth from the 14 telescopes plus two spare inputs. This led to a system with 256 converter units with associated modules like the Local Oscillator (LO) and controls. All the IVC hardware was fit into 5 large 19-inch system racks.

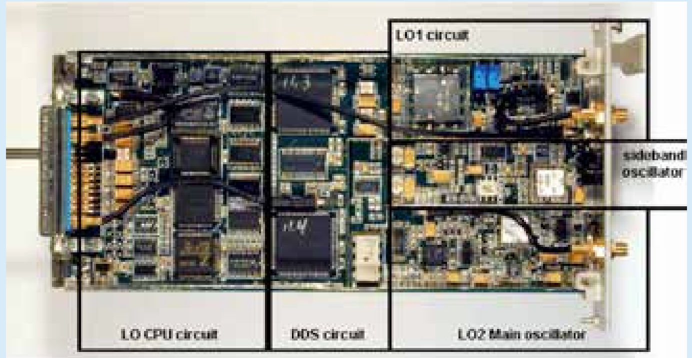
The frequency conversion board including the first analog custom Integrated Circuit in BiCMOS technology designed in collaboration with Catena and produced by Philips in 1997.

Bert Woestenburg was given the challenge to lead the IVC project which began in 1995. This would be a "high volume" production project and for the very first time, ASTRON decided to outsource design and production to industrial companies beginning a new era of industrial partnerships and radio astronomy development. Catena Microelectronics carried out a feasibility study to integrate parts of the IVC functionality in a single chip including digital filtering techniques. However, digital filtering still had some years to go before becoming a competitive alternative to the analog solution.

As always, cost reduction would lead to a performance reduction. Ger de Bruyn then suggested to limit the number of filter channels to 4 without sacrificing too much on the science capability. Tough requirements in a harsh environment of radio interference was not the only challenge. Amplitude and phase accuracy and stability were equally important.

The feasibility study in 1997 recommended the development of a custom image rejection mixer integrated circuit. This would become the first custom analog integrated circuit used in radio astronomy! The design included a double conversion concept to avoid unwanted LO signals in the pass-band, and ASTRON made an order to Catena for the development and production of the "IVC-mixer" chip.

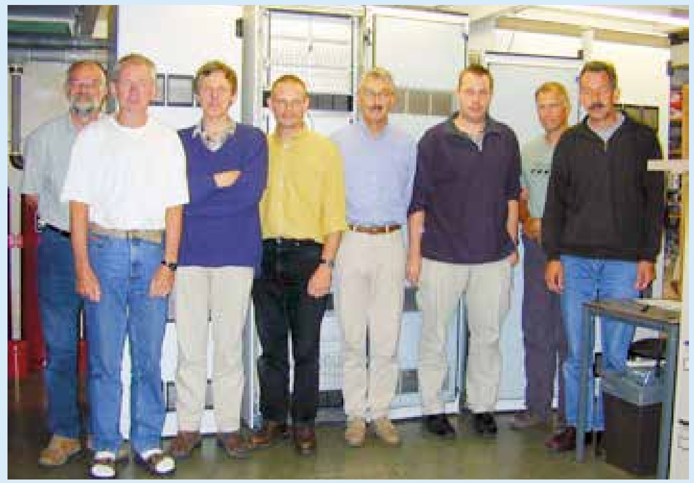
Nico Ebbendorf



One of the 256 Local Oscillator boards with two conversion stages including μHz fringe rotation.

Unfortunately, the original idea of a fully integrated on-chip design did not achieve the expected cost reduction, and a plan to outsource the development and production of the various subsystem modules was the next best option. A French company, Tekelec-temex, with experience in custom electronic design was approached to further develop the IVC modules, except for the converter module which was tasked to Lambert Nieuwenhuis†, and the converter control and filter module which were handed over to Hans Rosenberg. Tekelec-temex designed and produced excellent cable equalizer units necessary to compensate for the 3km cable loss to the telescopes. A narrow band (200 – 220 MHz) and very steep filter with ultra linear and equal phase relation was another custom designed component. Over 500 filters, each manually fabricated and tuned to the correct high filter requirements, were ordered from the UK company L.E.N.The local oscillator system remained an unsolved problem by Tekelec-temex, and so the IVC LO-system came back to the ASTRON design table. The major issue in the design was achieving the phase accuracy, stability, and noise within a compact module, and generating two frequencies for the converter unit. Fringe correction was one of the LO-module features and required a 14 micro Hertz step of the master oscillator. Phase stability over temperature was another difficult requirement, and it had to be addressed in all aspects of the IVC project, including development, production, installation, and ultimately, system maintenance. Nico Ebbendorf and Arduin Eybergen developed the LO concept while Arie Doorduin took care of the LO control board and software. Each LO-module was manually adjusted for temperature compensation before installation to achieve the required 0.1 degree phase accuracy per 1 degree Celsius temperature variation.

The IVC installation in the Westerbork basement in 2001 required additional cooling to limit the maximum temperature gradient to 2.5 degrees Celsius between the modules in the sub-racks. Endless experiments by Jan-Pieter de Reijer placing large cardboard panels around the IVC racks improved the temperature stability and also the quality of the overall IVC system. The IVC back-end was operational from 2000 until 2015.



The proud team formally handing over the "cosmology" system to the Observatory. It allowed to use the full capabilities of the new Multi Frequency Front Ends as well as the new DZB backend correlator system. From left to right: Hans Weggemans, Lambert Nieuwenhuis†, Albert Bos, Nico Ebbendorf, Bert Woestenburg, Mark Bentum, Rob Millenaar and Kees Brouwer

Signal distribution between MFFE and central building

Two types of critical signal transport between the antenna mounted frontends and the central system are:

- Distribution of a common reference frequency from a central master clock to each of the frontends, and
- Transport of the received astronomical signals to the common correlator.

At the time of development of the MFFE, optical fibre transmission systems were not mature enough to fit the stringent phase/delay stability requirements for the WSRT. Therefore, it was decided to use the existing, proven, coaxial cable network. These 3 km long coaxial cables, buried under ground and constantly flushed with dry nitrogen gas, had a proven excellent stability. The only remaining challenge was the rather high, frequency dependent loss over the larger bandwidths to transport the astronomical signal from the frontends to the central correlator. This compensation was done in the equalizers of another system (see Insert on *Westerbork for Cosmology*).

Streamlining WSRT operations

From an operational point of view, the capability of rapidly changing to another frequency band in the new frontend was the major design driver. As the previous frontends mostly covered only one wavelength band, it was necessary to change the frontend on all telescopes to switch to another wavelength. The burden of this process could take as long as two weeks depending on the type of frontend involved. Apart from the huge operational load, the advent of the Very Long Baseline Interferometry (VLBI) to the WSRT turned this into a serious problem. VLBI observations are normally organized as campaigns that last one or two weeks several times a year. During such a campaign, a number of different wavelengths were required and in practice this would limit the use of the WSRT. The new MFFE design had to overcome this problem which was reducing WSRT participation in VLBI.

Radio astronomy was facing an increasing level of interference, for which the MFFE frequency agility proved extremely beneficial. It allowed rapid changing from one frequency to another which was free of interference.

The increasing (level of) interference had two major causes. First, the nineties showed a dramatic increase of spectrum usage, especially in the range up to 2 GHz which was important for astronomy. This development directly affected radio observations, even in the frequency bands protected by international treaties under ITU supervision. For example, there is interference from GLONASS, the Russian counterpart of the Global Positioning System, and later, the global communication system Iridium. Titus Spoelstra†(see also the contribution in the Chapter covering Ionosphere) who then operated as frequency manager for radio astronomy, provided an overview of the spectrum allocations versus the MFFE receiver bands in *NFRA note 606 "Multi-frequency frontends: frequency coverage and frequency allocations"*

There was a growing demand to observe outside the protected radio astronomical frequency bands. The observation of neutral hydrogen at large red shift in the range from approximately 250 MHz to 1400 MHz is just one important example. Extensive spectrum monitoring at the WSRT site showed that some parts of this range are sometimes usable for radio astronomy when interfering signals are below a certain level. This depends not only on the actual occupation of it by the legitimate user but also on propagation conditions, making the availability of this spectrum very dynamic.

Finally, the simplified operation of a single MFFE for all telescopes instead of five different receivers had other advantages. The number of spare parts in stock was reduced, and there was a reduction of labour involved in service and maintenance. It also overcame the cumbersome situation of replacing a cooled frontend operating at 21 cm, 18 cm or 6 cm for an uncooled, less sensitive frontend, in one telescope in case of failure. This event happened regularly and would seriously affect the quality of observations.

MFFE Design Concept

Taking the requirements and constraints as described previously the MFFE project team started to investigate the various design concepts. This activity led to a design concept for the new frontend which was described in NFRA Note 555 *"Report Feasibility Study Multi Frequency Frontend"* by Gie Han.

The picture in Figure 1, shows an extremely early MFFE version brought from Spain and happily unpacked by Jaap Bregman and Bert Woestenburg on the traditional Dutch Sinterklaas day around 1990 in the cantine of the old building. While Gie Han lead the overall project, Jaap was responsible for the thermal design and Bert Woestenburg for the team leading the development of the Low Noise Amplifiers.

Figure 1: Unpacking the earliest prototype during Sinterklaas 1990 by Jaap Bregman and Bert Woestenburg. The picture of this event, and many others, was made by Harm-Jan Stiepel

Published in March 1990, Note 555 was thoroughly reviewed by an astronomy expert panel and external receiver engineers. Around that time it was also decided that Richard Strom as staff astronomer would be the Project Scientist on behalf of the user community and

Mechanically Rejuvenating the WSRT

Jan-Pieter de Reijer

Repainting
By 1992, the paint of all steelwork for the 14 WSRT telescopes was in poor condition. A detailed report listed all the maintenance necessary, and it would cost over 3 million Dutch guilders (nearly 1.5 million Euro). Only half of these costs could be funded so WSRT director Hans Kahlmann made the decision to do half the job with premium quality rather than doing the whole job cheaply. We would start with the most critical telescope elements.

The primary reflectors were the priority. While in the 1975-1976 period the originally glued stainless steel mesh to the 98 panels of each reflector was fixed with self-drilling screws and now seemed fine, the new problem was with the corrosion of the frames which have a wall thickness of only 2mm. On top of that, it also appeared that the mesh was attached to the frame on the rim but nowhere else, and permitted the centre area to divert from the parabolic shape. This was confirmed by holography measurements by Hans van Someren Greve. The interferometric surface area measurements accurately identify locations that deviate from the ideal parabolic shape.

In a most daring enterprise starting in 1994, the first reflector (RadioTelescope5 or RT5) was lifted from the supporting structure and transported to the old assembly hall. To preserve the correct reflector shape, only the even numbered panels were removed for sandblasting, painting and refitting. Blind rivets were dipped in paint and inserted in the holes, replacing the old self-drilling screws. Next the second, odd numbered half of the panels were taken out for refitting. New holography measurements confirmed that the reflector area performed equally well to the original parabolic shape whose accuracy was about 1.4 mm over the 25m diameter when measured in 1977 by Arnold van Ardenne.

For the retrofitting of the other reflectors, a plan was made for a smaller operating array of 13 telescopes for the next 3 years. The second reflector was removed in 1996 for revision, and RT0 would remain without reflector for a 3 year period. Every 12 weeks a refitted reflector was transported to the next telescope and interchanged within 3 weeks. The whole operation ended on December 1998 when the last reflector was lifted onto telescope 0.



Left to right: 1994 removal of outer-panel of RT5. 1994 reflector ready for transport to RT5. 1998 November, lifting of last revised reflector on RT0

Reinforcing the Counter Weights
A new observing mode called "mosaicking" required rapid alternating on-off source measurements over a prolonged period. This put a lot of mechanical stress on the telescopes during the continuous 8-12 hour observations and the situation became even more serious after 2000 when the new Multi Frequency Front Ends started their observing life on the telescopes. They each weigh 250kg!

The electrical drive can accelerate from 1.4 Hz to 100 Hz in 3 seconds but the 30 tons of counter weight, dangling a good 7 m from the polar axle, lags behind about 15 mm. The mosaicking observing mode caused metal fatigue and finally a fractured side tube on RT8 in January 1995.

RT8's seriously fractured west side tube of the hour-angle counterweight in 1995


Left: A repaired tube with an additional strengthening member added. Right: Hour-angle counterweight construction, with all members doubled in steel on all 14 telescopes.

Upon further inspection all the other telescopes showed cracks on this same location, sometimes as long as 8 cm. Additional steel reinforcement was subsequently welded on all tubes of the counterweight construction, while a hydraulic jack under the counter weight relaxed the steel members during the reinforcement.

The WSRT telescopes operated without further problems for almost ten years, including 4 years with the heavy MFFE's, but then a loud noise was heard in 2004! It turned out that the transition from circulair tube to the flat connector plate needed repair (see picture). We were able to add another reinforcement plate but the mosaic measuring mode continued to attack the stiffened construction, and in mid 2005 we found cracks in the steel at the end of our reinforcements that had been made in 1995. Additional steel was welded on this weak spot (see picture on the right) found on 12 telescopes, and so far no more cracks have been noticed. For the new Apertif era, the time to reach full speed has been increased to 5 seconds which will reduce the acceleration.



Left: RTC in 2004 connection to declination axle is completely broken. Middle: Connection to the declination axle, re-welded and reinforced on all 14 telescopes. Right: additional strengthening of the tube counterweight construction now on 12 telescopes the WSRT. The MFFE design concept was positively reviewed by the panel and supported the decision to proceed to the detailed design and construction phases.

Developing for the MFFE

Starting the developed phase formally then allowed a larger team to work on the MFFE, and in the electronic labs, the emphasis was on MFFE up to 1997. The following is a condensed description of the MFFE design.

Receiver electronic description

All MFFE receivers are electronically based on the double super heterodyne principle. For a single polarization channel at each observing band, a brief description is as follows.

The incoming astronomical signal focused by the parabolic reflector enters the feed and is split into its two orthogonal components by an Ortho-Mode Transducer (OMT). Between feed and OMT a noise signal can be injected through a directional coupler for level and polarization calibration.

Most of the OMT's, transfer relays, and LNA's that operate above 1.2 GHz are in the cryostat of which the inner part is cooled down to a physical temperature of approximately 20 K (equivalent to ~- 253 °C) to reduce their noise contribution.

After the LNA follows a RF band-pass filter. This filter suppresses the unwanted image frequency and multiple responses from the first mixer. Before the first frequency-down conversion the signal passes a 180° phase modulator. Together with a demodulator in the backend, this enables a further suppression for any possible interference.

A tunable, synthesized oscillator provides a Local Oscillator (LO) signal for the first mixer. The frequency synthesizer is tunable in 1 MHz steps.

The first Intermediate Frequency (IF) is centred on 1 GHz and the IF band-pass filters have a bandwidth of either 160 MHz, 80 MHz or 10 MHz. These band-pass filters provide the main selectivity of the receivers and set the maximum instantaneous bandwidth for further processing.

A fixed, 900 MHz, phase locked synthesizer provides the second local oscillator signal. It is used to convert the signal to the second IF frequency around 100 MHz using only low-pass filters which are adequate to suppress the unwanted sideband. After further amplification, the received signal is sent to the central back end by coaxial cable for signal processing.

By injecting a known power level between feed and LNA the absolute power level calibration of a receiver channel is measured. This power is generated by a broadband noise source with known level and can be switched on and off to make a comparison measurement. Consequently, the power level of the incoming astronomical signal is measured.

Polarization calibration for precise Stokes parameter measurements requires the comparison of orthogonal polarization channels in a receiver with each other to resolve the differential offsets in gain and phase. In the MFFE, two methods are used to determine possible offsets.

In the first method, the same signal is injected into each orthogonal polarization channel. Measured output differences characterize the offsets. In this method, the signal from the noise source for the power level calibration, is used. Depending on the selected receiver, the two identical signals to be injected in each of the two orthogonal polarization channels are obtained through a power splitter. For the waveguide systems above 1.2 GHz, the noise is injected into a circular waveguide at an angle of 45 degrees relative to the orthogonal, propagating the TE_{11} waveguide mode.

The second method of polarization calibration uses the transfer relay between the outputs of the OMT and the LNA of the orthogonal polarization channels. By making through and cross measurements and comparing the two results, the offsets in gain and phase can be determined. As the signal paths before the noise injection point and the transfer relay cannot be calibrated, the receiver design should take care such that these are identical for both orthogonal polarizations.

Signal levels and gain distribution in the receivers are chosen in such a way that there is minimal internal intermodulation.

All LO_1 and LO_2 synthesizers are locked to the two reference frequencies, 1 MHz and 180 MHz, fed into each receiver by a single coaxial cable, and derived from the central frequency standard in the main building. A diplexer inside the MFFE splits the two reference frequencies and distributes them among the synthesizers.

This first local oscillator is an indirect phase locked loop synthesizer. A custom made YIG tuned oscillator is used to achieve a wide tuning range combined with high spectral purity. A sample of the output signal is down-converted by a sampling mixer, sent to a programmable digital divider and compared with the 1 MHz reference frequency. The sampling mixer is driven by a second synthesizer operating in the frequency range 180 MHz – 183 MHz and phase-locked to the 1 MHz and 180 MHz references. The design is such that phase coherency is ensured between all MFFE.

Merely a Filter?

Jürgen Morawietz

"It doesn't work!", the WSRT telescope engineer Harm-Jan Stiepel said, when dropping a set of neat blinky filters on my workbench. This is not a comment you want to hear from a colleague, especially if you have just started your career as an RF engineer.

But let's start at the beginning of this story (and to give this away for the impatient reader: They actually worked!) In 1998 we rolled out 16 of the wonderful new Multi Frequency Front Ends (MFFE) at Westerbork. During the qualification tests some strong unexpected signals appeared in the 92 cm, 49 cm and UHF-High bands. It appeared that in August 1997 the regional television service, RTV-Drenthe, started analog broadcasts from the Smilde tower which is located only 13 kilometres away from the WSRT. The carrier frequency was 503.25 MHz. Immediately, Mark Bentum - the telescope scientist at the WSRT - found that the 503.25 MHz mixes with the 182.25 MHz carrier of the Nederland I service and provokes an intermodulation product at 321 MHz which exactly falls in the MFEE 92 cm receiver band and was the probable cause of the strong unexpected signals.

The above mentioned new engineer was charged to build a set of filters that suppressed the interference and had to be placed in front of the balanced low noise amplifier that was generating the intermodulation product at 321 MHz due to its nonlinearity. Leo van de Ree and Lambert Nieuwenhuis were in charge of the 49 cm and UHF-High solutions respectively.

I digged into filter synthesis, simulated, designed, prototyped, tuned, optimized, re-designed and reprototyped a bandpass filter. At the mechanical department they milled a

Figure 1: Characteristics of the low loss filter. The red line shows the transmission. Note the suppression of the unwanted 503.25 MHz and 182.25 MHz signals (Marker 1 and 2) while the loss inside the desired 92 cm band is only a tenth of a Decibel (2%). ã Jürgen Morawietz

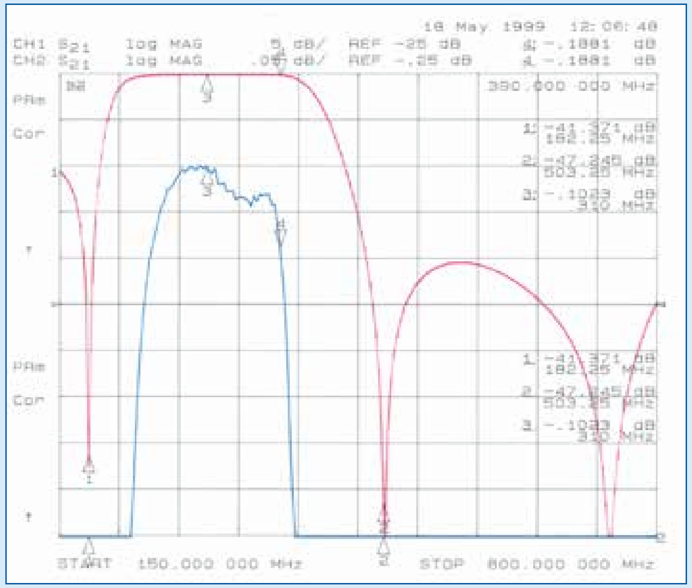


Figure 2: The filter for the Multi Frequency Front Ends. ã Jürgen Morawietz

neat aluminum enclosure and I had my filters ready for testing. I would impress my boss and project leader Bert Woestenburg!

The implementation and tests of this prototype in the MFFE ended up with the disastrous message that began this story, but SParameter measurements on the filters showed that they had the specified characteristics and should have worked!

Together with Harm-Jan and Mark we started an extensive investigation to determine what actually causes the intermodulation products in the MFFE. Even nonlinearities on passive components due to transition between different metals or bad connections - which is known to appear in high power RF systems - were considered. Nothing was found.

The conclusion was that we have a perfectly working MFFE (including filters) and the only solution was that the intermodulation was not caused by the frontend but was originated in the Smilde transmitter itself. Looking into the requirements of commercial TV stations showed that the specification for spurious signals is 60 dB below the carrier which in our case was exactly what we saw in our measurements. These were small signals nobody would bother about!

Okay, what to do now? Tell the NOZEMA that their transmitters work perfectly, but we need better? Well, that was indeed the only option[1], and surprisingly NOZEMA was very open and some weeks later Mark, Harm-Jan and I found ourselves on the tower of Smilde accompanied by very friendly and interested technicians to do some measurements on the high power UHF transmitters. We confirmed that the intermodulation was generated in the transmitter. We were even more surprised when they offered to install a filter at their expense! We hereby apologize that a large part of northern Netherlands couldn't watch television for some hours during the installation of these filters.

New qualification tests were carried out with an MFFE in the Westerbork telescopes. It performed well and the interference disappeared. Problem solved! So finally, series production of 64 filters could start, all crafted and handtuned by Anne Koster. The rookie engineer vindicated himself and 20 years later he's still a proud - and now a bit greyed - member of the ASTRON staff. He's designed many filters - some of them even located behind the moon. But that's another story.

Figure 3: The unfortunate and collapsed transmission tower in Hoogersmilde on the afternoon of July, 15th 2011. Obviously, no radio interference was noticeable afterwards! © Jürgen Morawietz

1 *Actually there was one other option that was demonstrated some years later when the Smilde tower caught fire and collapsed. I swear we have nothing to do with this incident!*

A single embedded microcomputer in the MFFE control system controls and monitors all functions in the sub-systems. The control system also handles the interface between MFFE and the central WSRT computer. However, the real time functions like 180° phase switching and switching the noise sources are directly controlled through separate hardware lines from the central control logic.

Finally, auxiliary systems include the temperature control circuits of the MFFE and the feed rotator drive system.

Using the MFFE system allows for *simultaneous* observations at the following wavelength combinations:

1. 92 cm / 3.6 cm
2. 13 cm / 3.6 cm
3. 49 cm / 6 cm
4. UHF_{low} / 3.6 cm
5. UHF_{low} / 6 cm
6. UHF_{low} / 18 cm
7. UHF_{low} / 21 cm

The possibility of dual band observations became fully operational with the advent of the DZB back end. However due to limitations in the coaxial transmission system between frontends and back end, dual band observations allows for only one polarization channel per band.

Mechanical design

As for the previous WSRT frontends, a support frame was designed and constructed of hollow metal tubes with square cross section. Figure 2 shows a 3-dimensional drawing of this frame.

The front of the frame (left hand side in the figure), is closest to the phase center of the feed. It is mounted on a support structure in the frontend box of the telescope with precision pins. In this way, the mounting results in the position of feed phase centre located precisely with the focal point of the parabolic reflector.

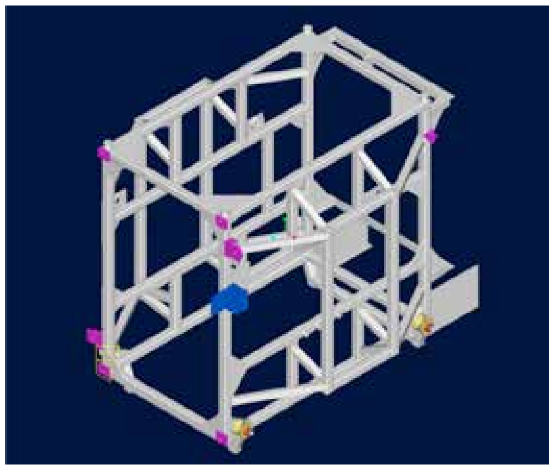


Figure 2: A 3-dimensional drawing of the MFFE frame (see text).

Other main requirements of the mechanical construction were (i) to accommodate all necessary sub-systems in the frame. This was in particular challenging for a proper functional placement of the feed systems, (ii) Overall weight lower than 275 kilograms, (iii) Maintain a maximum deviation of approximately 1 mm in both lateral and axial directions between the feed phase center and the focal point of the parabolic reflector for any telescope position. This is to avoid too much antenna gain reduction due to phase errors for an axial displacement and excessive beam squint for a lateral displacement. To fulfil the first requirement a construction was chosen where a rectangular box was used for the cryostat. Figure 3 shows a view of the single and completely mounted cryostat for all cooled observing bands in an MFFE including the cooled LNA for each band in two polarizations. The many windows to the cryostat required a thorough thermal design analysis which was done by Jaap Bregman.

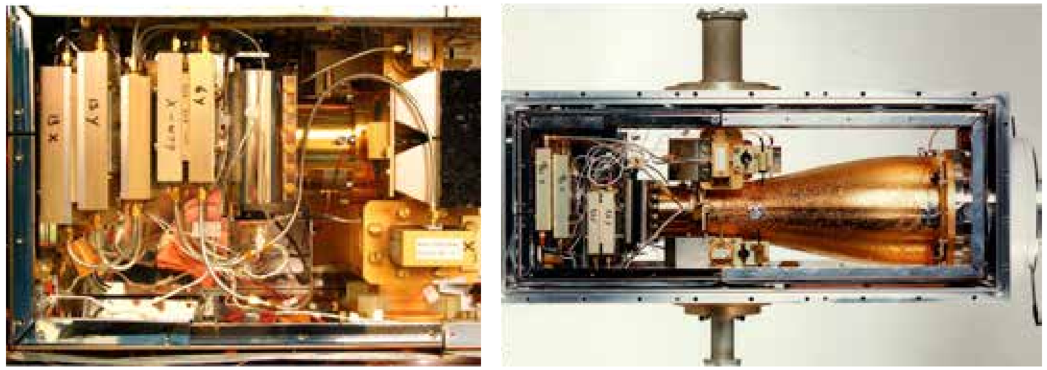


Figure 3: A view through a completely mounted (single) cryostat of the MFFE cooled section. All four cooled receivers are mounted in this cryostat for two polarizations. The 18/21 cm signals enters from the right, the 6 cm (of the 6/50 cm combined feed) from below and the 13/3.6 cm (of the 92/13/3.6 cm triple feed) from the top. On the left the cooled amplifier arrangement shown in more detail

By rotating the whole structure inside the frontend frame, each feed system can be placed in the feed focus. The picture in figure 4a/b gives an impression of this construction, which as a whole fits inside the focus box.

Figure 4: Left: Overall MFFE construction with rotatable feedsystems around a single cryostat. Right: Looking into the feed systems rotated for each position; top-left 92/13/3.56 cm, top-right 50/6 cm, bottom-left UHF high, bottom-right 21/18cm. Both UHF high and low antennas are 2x2 folded dipoles of which the UHF low is fitted on the telescope frontend box.

The requirements concerning frontend weight and stiffness were extremely hard to combine. An extensive use of aluminum instead of steel as was used in older frontends, resulted in a major weight reduction. This was made possible by the first time use of advanced mechanical 3D CAD tools in combination with finite element programs to simulate the static behavior of mechanical structures. It made it possible to optimize the geometry and minimize the material weight for given mechanical specifications. This resulted in the rigid frame construction shown in Figure 4. A special high strength aluminum alloy, Al 7075 T6, is used for the square tubes to guarantee the set requirements.

Using these exotic materials without deterioration of their properties needs special skills and knowledge. While the prototype was built by the NFRA mechanical workshop by Jan Idserda, the series production was contracted out. A small Dutch company who was specialized in building aluminum chassis for racing cars built all the production frames for the MFFE. Their expertise in this area resulted in familiarity in working according to standards of high accuracy and a capability in special aluminum welding techniques and this contributed to the making of the MFFE frames. Other companies were involved in adapting the antenna boxes for the MFFE on which the air-pressured antenna removal system for UHF_{low} was mounted.

A further major weight reduction was obtained due to the use of advanced honeycomb material for some of the cryostat walls instead of solid aluminum ones. Instead of a weight of 13 kg for one single cryostat lid consisting of solid aluminum, a honeycomb lid weighs merely 2 kg.

Lightning and electromagnetic compatibility

Albert Jan Boonstra, Jan Pieter de Reijer

During the nineties, the WSRT upgrade included increasing the astronomical receiving bandwidths and reducing the receiver noise by developing cryogenic receivers: The Multi Frequency Front Ends (MFFE). This basically meant replacing all receivers. Since support equipment and systems were nearing end of life, they had to be replaced or refurbished as well.

With all these upcoming changes it was clear that the grounding, lightning protection, and in general the electromagnetic compatibility situation (EMC) had to be thoroughly reconsidered, and that the do's and don'ts were taken into account in the new designs. It was not only for safety and lightning susceptibility considerations. EMC is also important to ensure that the very weak astronomical signals are not distorted by externally generated and by self-generated interference, and also to ensure that the time and frequency reference systems can provide stable signals, and meet the geodetic and pulsar timing stability requirement of 0.3 ps per day and 0.3 ns over years.

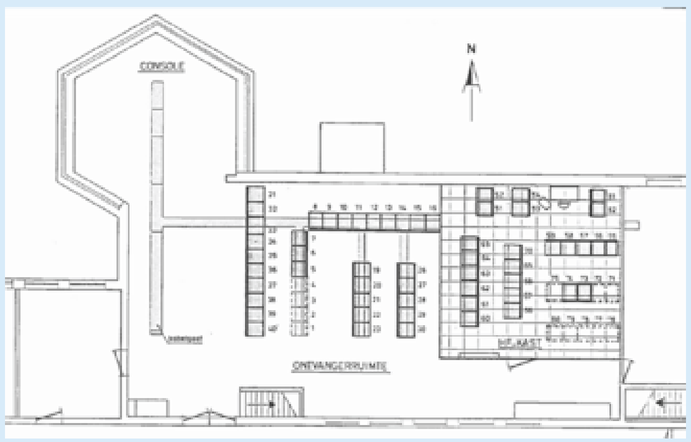


Figure 1: Floor plan of the WSRT control room, showing cabling ducts of the electronic equipment (numbered squares); the advice was not to use a star-grounding pattern, but to create a dense mesh pattern in order to prevent loops susceptible to interference

In 1992 at the R&D laboratories, Gie Han Tan started an analysis concerning the lightning protection of the MFFE, and concluded that the best way to protect the receivers was to place them into a fully closed Faraday cage, integrated within the telescope focus box, except obviously for the antenna part. In the design, the control and power lines were to be protected by special filters mounted to the cage wall. Indeed, in the past two decades the currents induced by lightning strikes had never damaged the fourteen receivers (frontends), and the new designs had to be at least as robust as the old ones.

In 1996, the systems group at the WSRT looked into the EMC situation of the WSRT as a whole, including the telescope structures, power grid, the control building grounding, and cabling connections to the telescopes. Looking at the relevant EMC norms it all seemed compliant. With the upcoming major changes, and also after a warning shot by a recent lightning strike in a tree near telescope number 7 destroying optical coupling diodes of the telescope control systems, we decided to ask an external expert, DARE Electronics in Woerden, to screen the WSRT and provide EMC advice.

The EMC site survey concluded that the control building lightning protection was ok, that the grounding of the individual telescopes could be improved by adding grounding strips at a few places in order to avoid large lightning-induced currents running over the cabling shields. It was also noted that external cabling entered the control building from different directions. From an EMC point of view it would be best to re-route them to enter at one spot, but as that was not practical, the expert advised to connect the cabling shielding to one common grounding strip. All this and some other related advice was relatively easy to implement, so there was ample time for Pieter Donker, Hans Weggemans, Harm-Jan Stiepel and the rest of the crew to do this, well before the new systems were expected to arrive from the Dwingeloo laboratories.

The company also advised to transfer computer equipment from the console room into the Faraday cage of the control building, as these systems were generating radio 'noise' that leaked into the two telescopes closest to the control building. This we already knew, and was part of our planning in extending the Faraday cage for the new equipment.

The modifications turned out to be a great success, allowing a seamless integration of the upcoming upgrade equipment. In addition, this EMC work also helped Prof. Howard Reader and Gideon Wiid to prepare recommendations for making the South African MeerKAT radio telescope lightning proof and RFI robust.

Thanks to its advanced design, for which a Reliability, Availability, Maintainability (RAM) analysis was done, it could now safely be said that the knowledge of building receivers at ASTRON culminated over tens of years in the extremely reliable and agile MFFE which required very low maintenance and had a correspondingly observing efficiency.

Two Phases

Around 1997 a little ceremony was held to celebrate the first phase delivery of the MFFE (UHFlow / UHFhigh) system. All present remember the act performed by our Board member Renzo Sancisi in ceremonially placing a frontend into the telescope frontend box using the cherrypicker hoisting platform. Renzo's apparent reluctance to join Gie Han Tan and Harm-Jan Stiepel on this high act was however solved. An apparent problem prevented the whole heavy load to bridge the 12 m up and a load reduction was required. As it happened, Renzo was so kind as to give up his place and to step off the platform to watch the scene from solid ground.
After that, the UHF commissioning phase was successfully done by Richard Strom and reported in Note 654 in 1997.

Work continued in the second phase of finishing the whole set of receivers. The picture (Figure 5) at the NAC (Dutch Astronomy Conference) in 1997 shows Lodie Voute, Gie Han Tan and Arnold van Ardenne discussing the prototype MFFE next to the rotatable model. On this occasion, the exhibition was on the first floor accessible by stairs and a small elevator. Going by the stairs was not an option so the prototype was fitted into the elevator by dismounting elements from both its sides!

Figure 5: Discussions during the NAC in 1997 in Dalfsen. Lodie Voute, Gie Han Tan and Arnold van Ardenne are discussing the prototype of the real thing while the rotatable model is on the right.

In the end of the second phase, Gie Han, after a seconded stay at the German Company Rohde and Schwarz to develop the prototype LOFAR LBA antenna, left to join ESO. The last project phase was then capably lead by Yde Koopman and in 2001, the complete set of 12+2 spare MFFE receivers were finished including their full cryogenic capability, and they were shipped to Westerbork. There, they were generally serviced under supervision of Harm-Jan Stiepel who mostly on his own, kept the WSRT receiver suites including the MFFE, alive and kicking. The picture (figure 6) shows Harm-Jan in the Westerbork electronics maintenance and support lab.

Figure 6: Harm-Jan Stiepel in the Westerbork electronics maintenance and support labs around 2005.

It is interesting to note that Bert Woestenburg who was responsible for the many Low Noise Amplifiers and the cooled frontends throughout his career at ASTRON, identified about 70 ASTRON R&D persons who contributed to the development of all WSRT receivers up to and including the MFFE. Over that period of close to 35 years, many people from other countries came to ASTRON's receiver lab to learn and collaborate, notably many from China's NAO for furthering Chinese radio astronomy.

While some of the MFFE still remain to be in use after almost 20 years, mostly for VLBI and geodetic observations, it can be said that in ASTRON the MFFE mark the end of an era and the start of the software receivers like Apertif and LOFAR.

The Life of the MFFE cryostat, from WSRT to ELT

Johan Pragt, Jan Idserda, Eddy Elswijk

Temperature

Temperature for humans is often subjective and measured in relation to freezing water and boiling water. For instruments, temperature is absolute and starts at zero Kelvin or -273.15 degree Celsius. Physical behaviour and technical performance are completely different at extreme low temperatures. For the WSRT, one crucial performance parameter affected by temperature is the noise of the system that should be as low as possible. Theoretically, the noise of receivers, antennas, filters and amplifiers is zero at zero Kelvin. Any higher temperature will produce noise. Building receivers, in particular low noise amplifiers, at that minimum temperature has an important drawback. It would take huge amounts of energy and still the amplifier will not reach zero Kelvin.

In the total observing system, the atmosphere above the WSRT has a temperature of, say, 213 to 300 Kelvin (about -60 to 27 degree C). Fortunately, it is transparent to lower frequency radio waves so the effective "noise temperature" is only around 10 Kelvin (depending on altitude, wavelength, season, observing angle, rain, etc.). The reflector in the receiving system (the 25 meter diameter prime mirror) is also quite warm, from 273 to 300 Kelvin (0 to 27 degree C), but given its good reflectivity the effective noise temperature is also around 10 Kelvin. The receiver noise temperature however should be even lower so that it contributes relatively little to the overall noise of the telescope system.

The Life of the WSRT testcryostat

Our first experience at WSRT with cryogenically cooled front ends was during the 1980's and by the end of the 80's two telescopes were operating with helium cooling fridges and cold amplifiers. During the development of the Multi Frequency Front End (MFFE) for the WSRT in the 1990's, cryogenic systems were installed in all 14 telescopes. A test cryostat was designed and built to test receivers, LNA's, antennas, and filters intended for the MFFE. The box type cryostat had a large transparent entrance window from thin KAPTON foil supported by polystyrene foam, fully aluminium casing and as described in detail by Jaap Bregman in Internal Technical Report 215, it worked great. However, at the end it was still a bit too heavy and an update design based on honeycomb structure glued to aluminium plates was implemented to match the mass limits of the MFFE. These new cryostats were implemented 16 times for all of the MFFE receivers (14 dishes, 2 spares). With MFFE up and running, the MFFE test cryostat went out of service.

Figure 1: Box cryostat with MIRI grating wheel TVC test

The Second Life:

A second life for the test cryostat came soon after its service to the development of the MFFE. It would be used as a test system for an instrument destined for the Very Large Telescope (VLT) in Chile. The VLT Imager and Spectrometer for mid-Infrared (VISIR) was being developed at ASTRON. VISIR operates at mid Infrared wavelengths (humans feel this wavelength as warm radiation) and it needs to be cold (<40 Kelvin or -233 degrees C) so that the instrument structure and optics don't act like a sort of infrared lamp and over expose the detectors. The box cryostat entrance window was modified from the radio transparent thin Kapton foil to a thick flat transparent piece of Glass (Fused Silica). It was then used to test aluminium mirrors, rotating mechanisms, and also the extremely long (350 mm) aluminium reflective grating (echelle) for the high resolution spectroscopic mode of VISIR. The unique huge entrance window of 200 mm and the deep structure of the cryostat box made it possible to install the echelle at its working angle. The box cryostat worked great! It was a relatively light weight unit, easy to position in front of various optical test equipment such as the optical interferometer. The resolution of the aluminium optical unit could be tested while cooling. Even down to 40 Kelvin where we verified that it achieved the 30 nanometer resolution requirement.

The Extended Life

After the success of the VISIR tests, the test cryostat was modified again, this time to allow for a range of testing for other instruments. The MID-infrared Interferometric instrument (MIDI) is a two channel interferometer instrument for the VLT Interferometer (VLTI). We tested motors, special filters and grisms. For the VLT spectroscopic camera called SPIFFI 2K, the test cryostat was used to test shrinkage of plastic and glass down to 40 Kelvin while mounted in a very stiff cryogenic lens mount shown in Figure 2. This determined the design of a large glass lens (185 mm) in its aluminium housing. A test lens assembly was cooled and based on the positive results, the principal was applied to all five lenses of the SPIFFI 2K camera [ref 1] and worked great. It is still operational at the VLT! This successful principal design was applied in several other cryogenic instruments to hold glass lenses and prisms in aluminium structures. The cryostat is used for the space instrument JWST-MIRI (JWST is the successor of the Hubble Space telescope) to test optics. Ultimately for MIRI, a larger testcryostat is necessary to qualify the full instrument. This may look like the end for the box cryostat, but after 25 years of operation, it can still compete because of its easy handling and large entrance port.

The story continues with planned tests of the mirror for the METIS instrument and the MICADO ADC prototype both for the ELT and now in pre-design phase at NOVA-ASTRON.

This amazing test cryostat from our first experience with cryogenics on the WSRT in the 1980's has been used for testing 10 instruments over the years, and still counting!

ref 1: G. Kroes, et al., "Opto-Mechanical design for transmission optics in Cryogenic IR instrumentation," Proc. SPIE 7018, 70182D (2008).

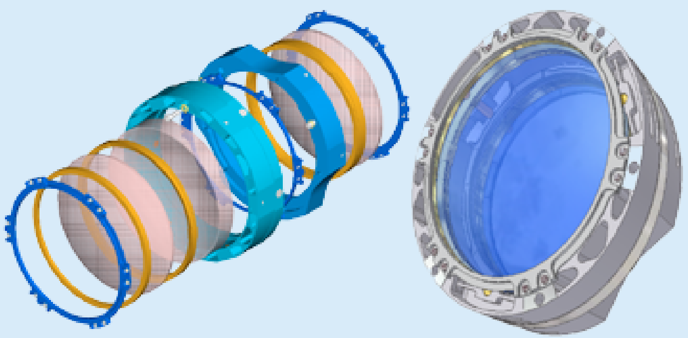


Figure 2: SPIFFI 2K Camera lensmount, typical size 185mm

Acknowledgements

Collaborations developed with all three Dutch Technical Universities for example regarding the triple band feed and the superconducting RFI filters. Some references are mentioned below but surely the MFFE could only be developed with many other colleagues not all mentioned here. The picture (Figure 7) shows the team of which most with some effort can be recognized. The commissioning phase had the involvement of many others from the Labs and Observatory staff.

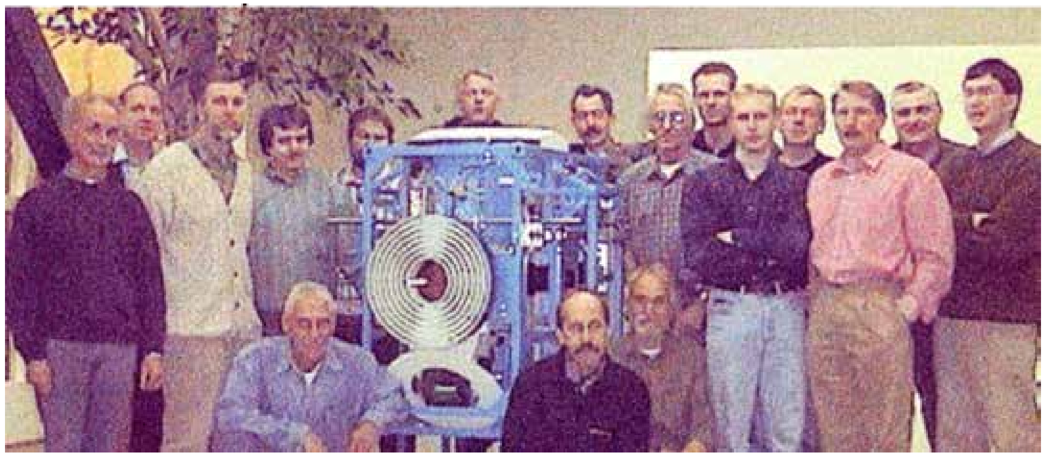


Figure 7: The MFFE team at the turn of the century in the last project phase, (left to right) Leo van der Ree, Yde Koopman, Paul Riemers, Jürgen Morawietz, Sieds Damstra (almost hidden), Anne Koster, Kees Brouwer, Martin Bakker, a student, Henk Heutink, Gie Han Tan and in the back row Menno Schuil, Lambert Nieuwenhuis and George Koenderink. Sitting in the front row: Jaap Bakker, Jan Idserda and Jan Dekker

Note (eds.): Gie Han Tan received the prestigious Dutch Veder Award in Jan. 2000 for his role in the MFFE development.

References from Internal notes and reports:

NFRA Notes

(http://www.astron.nl/r-d-laboratory/resultspublications/publications-pre-2009/notes/notes):

-532 "Microstripsubstraten" (in Dutch) by A. Koeling

-559 "MFFE Opzet LO1" (in Dutch) by J.F.N. Roosjen

-500 "Brief outline of calibration system for new frontends" by A. van Ardenne

-572 "Noise source determination of X- and Y-dipole phase difference at 18 cm" by R.G. Strom

-640 "Calibratie voor de dubbele LNA-configuratie van de UHF-banden in het MFFE" (in Dutch) by E.E.M. Woestenburg / A. Gunst

-521 "Metingen verricht aan een afstembare ontvanger voor de WSRT" (in Dutch) by G.H. Tan

-523 "Een nieuwe gecombineerd 18 cm/21 cm-feed" (in Dutch) by G.H. Tan

-618 "Beschrijving MFFE Controle Systemen Multi Frequency Frontend" (in Dutch) by A. Doorduin / R. Kiers

-595, 597 "EMC/Lightning protection" resp. "EMC/System design MFFE" by G.H. Tan

-654 "Report of the UHF test period" by R.G. Strom

NFRA ITR's

(http://www.astron.nl/r-d-laboratory/resultspublications/publications-pre-2009/itrs/itrs):

- 205 "A 230 - 460 MHz HEMT- Amplifier with extremely Low Noise at Room Temperature" by E.E.M. Woestenburg

-206 "Cryogenic Noise Performance of HEMTs and MESFETs between 300 and 700 MHz" by E.E.M. Woestenburg

-214 "Design Procedures for Long Endurance Cryostats with Large Microwave Windows." by J.D. Bregman

-219 "LNAs for the Multi Frequency Frontends" by E.E.M. Woestenburg

Other publications:

G.H. Tan, "Upgrade of the WSRT: The Multi Frequency Frontends", Proc. 26th European Microwave Conference, pp59-64, Sept. 1996, Prague, Czech Rep.

G.H.Tan, "A Highly Stable, Phase Coherent, Wideband Microwave Synthesizer for Radio Astronomy Applications", Proc Joint EFTF-IEEE IFCS Meeting, pp 607-610, 1999

S. Wallage, J.B. Tauritz , G.H. Tan , P. Hadley & J.E. Mooij, "High Tc superconducting CPW bandstop filters for radio astronomy front ends", IEEE Tr.on Appl. Supercond., Vol7, 2, pp 3489-3491, June 1997

Ever growing sensitivities

Chapter 10.3 WSRT surfing the digital wave

André Gunst *

The WSRT remained at the scientific foreground of discoveries by a process of enabling continuous improvements over its long history. One of the driving forces of these improvements was the understanding and application of the rapid advancements in digital technology. The digital electronics technology trend was nicely captured by the well-known "Moore's law" formulated already in 1965 by Intel founder Gordon Moore. It predicted the doubling of the amount of transistors within an integrated circuit every two years. Until recently, this "law" was followed by industrial developments. The WSRT digital instruments reaped all the benefits from that as shown in a plot by Arnold van Ardenne at the end-nineties in preparation for the SKA R&D. The plot clearly shows a close connection between the ASTRON/JIVE and other digital correlators for radio astronomy and Moore's law. The graph also put plans for, at that time, future projects into perspective.

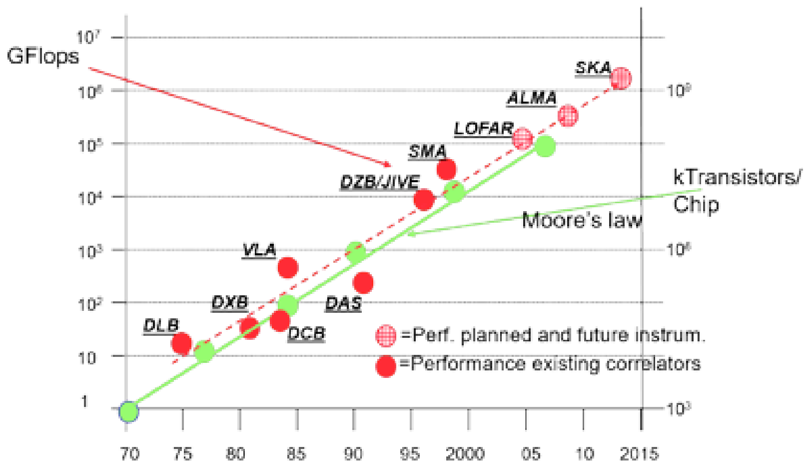


Figure 1: An early plot (end nineties) showing the nice fit of the capability trend of digital correlators to "Moor's Law" for current and planned projects (LOFAR, ALMA, SKA).

The digital electronic revolution started with Transistor-Transistor Logic (TTL) operating at 5 Volt. A the heart of this technology are transistors which are used as switches representing a "0" or a "1". In the mid-seventies ASTRON's first digital correlator, the Digital Line Backend (DLB), used TTL circuitry with some functions integrated in an Application-Specific Integration Circuit (ASIC). The ASIC developed for the DLB remained on the commercial market for some years. In the early eighties, the follow-up technology was low power Schottky TTL logic (LS-TTL), characterized by up to three times higher switching rates. This LS-TTL was used extensively and successfully in the Digital Continuum Backend (DCB). As with the DCB, an ASTRON designed ASIC was used (see page 177 [Mr Correlator]).

The general need for a lower power solution gave birth to Complementary Metal Oxide Semiconductor (CMOS) technology, still used as workhorse technology today with increasingly smaller line definitions. In the DZB correlator, CMOS technology with a feature size of 800 nm is applied. The "Z" in the name DZB, was chosen because it was the last correlator that Albert Bos (lead architect of all digital backends) designed for Westerbork. The CMOS technology in the DZB was integrated in a much more complex ASIC chip as well. The Haystack Observatory in Boston designed the overall ASICs, while using the correlator cell conceived by Albert Bos as a core. A total of 32 of these chips are integrated on boards and became operational in the nineties for both ASTRON, JIVE, MIT and the Submilimeter Array of the Smithsonian Institution in Hawaii.

As the computer industry required more processing per unit area, the transistor size in the CMOS technology was reduced. However, this led to increasing the nonrecurring costs for the masks which defined the pattern on the silicon chip, and hence the costs for the ASIC chips increased dramatically. For cost reasons it therefore was only attractive in cases where many chips were required. The industry solved this by the introduction of Field Programmable Gate Arrays (FPGA). An FPGA is an integrated circuit which is configurable after manufacture making it useful for many different applications.

Small FPGAs were already used in previous systems of the WSRT for auxiliary functions, but its first main use was in the Tied-Array Distribution Unit (TADU). In TADU, which became operational in 2006, the functional density and performance was much increased by the use of the 130 nm FPGA from Altera.

The current Apertif system also uses FPGA with a CMOS technology of only 40 nm. In total 8 FPGA's are integrated on a board: The UniBoard. Apertif is a very complex system with close to 1000 FPGA's in total.

The many generations of digital technology used in the WSRT inspired Sjouke Zwier to build a robot (see Figure 2). Actually, it was a robot statue, which is presently on display in front of the digital lab of ASTRON.

* ASTRON, The Netherlands

Figure 2: On the right the robot statue built by Sjouke Zwier (on the left) together with Gijs Schoonderbeek from many generations of left-over digital boards used in the WSRT (courtesy AJDI Dec. 2016).

The robot was presented to the lab at the occasion of the retirement of Sjouke in December 2016.

Figure 3: Various proud digital designers. On the left, the digital hardware designers Sjouke Zwier (l) and Gijs Schoonderbeek (r). The right panel picture shows the digital firmware designers Daniël van der Schuur (l) and Eric Kooistra(r). They all are displaying the first UniBoard from different viewpoints.

The flexible FPGA processing Board (18 layers!) shown in Figure 3 reached an impressive 1 TBit/sec Input/output rate and consumes 200 W. It is used in Apertif and for JIVE. A newer version with 3-4 times more processing power is used for ARTS (see Chapter 4). This successor, Uniboard 2 was developed in a 7partner collaboration in the Radionet EC-FP7 program.

The lessons learned from all these developments in their different applications, will be applied to the development of the SKA processing machines.

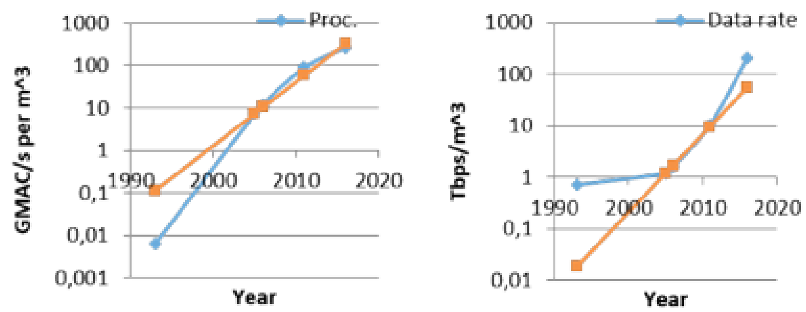


Figure 4: (left) Processing capability of hardware developed by R&D (blue) and Moore's law (red) over the years, expressed in Giga Multiply and Accumulate per second and per m³ volume density. (right) Data rate capability of hardware developed by R&D (blue) and Moore's law (red) over the years, expressed in Tera bit per second and per m³ volume density. Strictly speaking, Moore's law was meant for processing only.

As illustrated through Figure 4, many generations of digital electronics developed in-house have been used in the WSRT. This has been accomplished by applying the latest technology available by ASTRON and in collaborations. Hence, it is safe to say that this resulted successfully in surfing the digital waves, contributing to the radio astronomers quest to unveil the mysteries of the Universe.

As always it is not possible to acknowledge contributions of all of those who made this possible, but we acknowledge in particular Anne Koster, Arie Doorduin, Rob Millenaar, Albert Bos, André Kokkeler (now working at Twente University) and Hajee Pepping.

Cosmology with the WSRT

Chapter 11.1 Radio Continuum Surveys and Cosmology

Hans Rudolf de Ruiter*

At the time the Westerbork Synthesis Radio Telescope started observing, in June 1970, the memory of a vivacious and sometimes bitter dispute among astronomers was still fresh. This debate had to do with one of the most profound philosophical questions: what is the origin and the structure of the Universe? An important group of astronomers, among whom the famous Fred Hoyle, Hermann Bondi and Geoffrey Burbidge, had developed the "Steady State" cosmology, as an alternative for the "Big Bang" (a term coined by Hoyle, intended to be disparaging). In the "Steady State" view the Universe had always existed and would exist, unchanging, forever. Radio astronomy turned out to play a fundamental role in the eventual confirmation of the big-bang cosmology as the most favoured theory of the origin of the Universe. In the late fifties and early sixties astronomers started to map the radio sky. English has a very handy word for this kind of activity: *survey*. It is amusing to think that we would have used the German word "Durchmusterung" if radio astronomy had been developed a hundred years earlier, when stellar catalogues were constructed like the Bonner Durchmusterung. Somehow the 3C Durchmusterung sounds a bit odd...

Radio source counts in the first radio surveys (e.g. the 3C) caused a great deal of excitement, because it was immediately clear that the number of fainter sources was more than one would have expected in a static universe. Many of the radio sources were associated with galaxies and with "radio stars". Maarten Schmidt established in 1963 that the latter objects had high redshifts and were thus presumably located at large distances. Certainly, they were not normal stars in our galaxy. Maarten Schmidt coined the term quasars (from quasi-stellar objects) for them. They were quickly interpreted as the active nuclei of galaxies, in which highly energetic processes produce enormous quantities of energy, expelled in the form of matter and electromagnetic radiation. Gigantic black holes in galactic nuclei are the only feasible way of causing such energetic events.

The radio source counts, together with the discovery of the cosmic microwave background, were so compelling that the Big Bang model was now generally accepted.

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Radio astronomy had contributed to a breakthrough in cosmology, making it possible to study the evolution of known and perhaps unknown classes of radio source populations (galaxies and quasar and objects still to be discovered).

Such was the state of affairs when the WSRT entered the stage. A serious problem had always been the rather limited accuracy of radio source positions. Redshifts can almost exclusively be measured in the optical range of the electromagnetic spectrum thanks to the presence of well-known spectral lines characteristic of elements like hydrogen, oxygen, and so on. Since a radio source by itself does not give information on the distance, precise positions are necessary to know what, or rather where, exactly you are looking at. The new generation of interferometric radio telescope arrays, in particular the WSRT, could deliver a positional accuracy that was sufficient for this purpose: the WSRT was a unique and revolutionary instrument in the decade between 1970 and 1980. Even after the advent of the VLA, around 1980, the cosmological studies based on the WSRT remained important. The distribution of tasks between the two Dutch universities involved in WSRT observations, Groningen and Leiden, turned out to be very successful and fertile. Groningen specialized in neutral hydrogen observations (the famous 21 cm spectral line of hydrogen) and would produce ground-breaking results.

Leiden concentrated on continuum studies (both surveys and individual galaxies). The dynamic Prof. Harry van der Laan supervised a number of PhD students–including myself–doing this kind of cosmological study, during the 1970s and 80s. A selection of some of the theses is given at the end.

A harbinger was Jet Katgert-Merkelijn, who got her PhD degree in 1970 (see Thesis [a]). She determined the radio luminosity function of radio galaxies, using the Australian Parkes telescope. Her work was the beginning a series of similar studies at Leiden Observatory.

Among the first persons carrying out continuum radio surveys, right after the inauguration of the WSRT, were Rudolf Le Poole and Peter Katgert (Thesis [b]). They spent much time to get to know the WSRT properties, the calibration and the software, which helped successive observers in understanding in detail how to treat the WSRT data.

In 1973, Claas Oosterbaan, Tony Willis and I started to work with data obtained with the WSRT. Our aim was to construct a catalogue of faint radio sources and identify them optically with galaxies and quasars. We therefore tried to use optical plates that could detect the faintest possible objects. By the way, this was long before the now universally present CCD detectors had been invented.

Two years later Tony Willis and I spent a few months in Pasadena, because we could use the beautiful optical material owned by Halton C. Arp, an astronomer who worked at the Mount Wilson and Palomar Observatories. Arp had a vast

archive of thousands of optical plates; most of these (Kodak) plates used the then hypermodern IIIa-J emulsion, which was capable of registering very faint objects.

The demise of the steady-state theory was hard to swallow for some. Although the support for it dwindled to a trickle, a number of hard-core adversaries of the Big Bang now started to question the cosmological nature of quasars; in particular, they maintained that the redshifts of quasars were not an indication of their distances, unlike the redshifts of galaxies.

I was only vaguely aware that Arp was perhaps the most vociferous of the "dissidents", who were against the common interpretation of quasar redshifts. Arp would stick to his convictions right until his death in 2013. Arp had a pleasant and open character, but I quickly found out that he had a quasi-emotional problem with statistics, not so much with the mathematics but with the general acceptance of certain concepts like probability and likelihood. Although I investigated some of his claims in detail later on, I could see no reason at all to abandon the conventional view of the redshift as an indicator of distance.

The optical identification of radio sources, that is, finding optical counterparts at the radio position, was a laborious, time-consuming process, especially compared to the modern computer-based cross-correlations between radio, optical, X-ray or any other wavelength data sets. Once you have the data sets available, linking these sets is a matter of seconds, even if many thousands of objects are involved. Tony Willis, Claas Oosterbaan and myself–see Thesis [c]–carried out a survey of radio sources, found as background sources in observations that were done for specific sources, mostly nearby radio galaxies. This is, by the way, the reason why there was so much optical material collected by Arp: he was interested in bright and possibly disturbed galaxies many of whom had been observed with the WSRT as well.

Jet Katgert-Merkelijn[1] gave, on behalf of the people who had done surveys with the WSRT in the early days, a summary of the work done so far, and presented this at the IAU Symposium 74 (1977). I reproduce her table in Figure 1.

Of course, there is not enough space here to discuss the many, many studies based on all the WSRT surveys done in the past years. The analysis of the cosmological evolution of power and size of radio sources is beyond the scope of this short article.

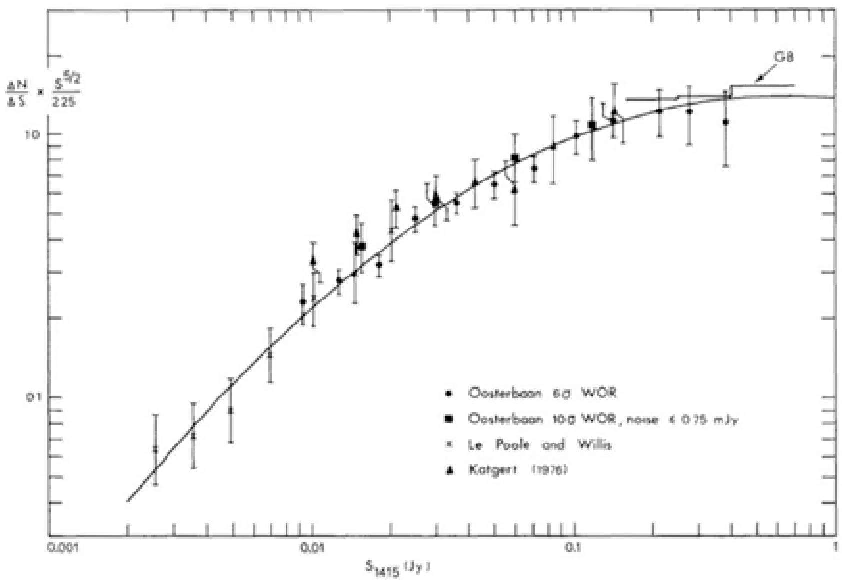
The positional accuracy of the WSRT turned out to be very well matched with the optical material like the III a-J plates. As shown in Figure 1 about one third to one quarter of the radio sources had an optical counterpart, often an elliptical galaxy, or a candidate quasar. The true nature of the latter had to be confirmed later by spectroscopical means. The deep plates were far superior to the Palomar Sky Survey, but did not cover the whole (northern) sky. Tony Willis[2] (always at the same IAU Symposium 74) summarized the WSRT radio continuum surveys.

Authors	Freq. (MHz)	N	S_{lim} (mJy)	Plates	m_{lim}	ID %
De Ruiter et	1415	462	3 - 9	III a-J	22.5	27
al., 1976		39	6 - 9	III a-J	24.0	49
Katgert & Spin-	1415	53	7	PSS	20.5	26
rad, 1974		32	7	098-02	22.0	43
Jaffe & Perola,	1415		4 - 5	III a-J	22.5	
1975 δ > 20		40				28
δ < 20		34				29
Katgert et al., 1973	1415	166	6 - 10	PSS	20.5	18
Valentijn et	610	88	6	III a-J	22.5	35
al., 1977		38	16			26
Katgert, 1977	610	226	16 - 29	PSS	20.5	17

Figure 1 WSRT continuum surveys until 1977. Although many surveys used an observing frequency of 1415 MHz, some were done at 610 MHz. Limiting flux densities were typically in the range 1-10 mJy (with modern telescopes and detectors we can easily go down to a thousand times fainter fluxes). The optical data normally used came from the Palomar Sky Survey, but the much more sensitive III a-J had become widely available (see columns 5 and 6). Also given is the percentage of radio sources for which an optical counterpart had been found. Roughly two thirds of the sources remained unidentified, presumably because the optical objects was so faint as to be below the plate limit (see the identification percentage in column 7). Note that the strength or brightness is expressed in mJy (millliJansky), which is equal to .

Since all surveys covered only small parts of the northern sky, very few of the strongest sources (which are quite rare), were present, and one finds sources only below 1 Jy, which happens to be at the maximum of the normalized source counts (see Figure 2). For historical reasons the source counts are "normalized"

Figure 2 WSRT normalized radio source counts at observing frequency 1.4 GHz, before 1977.



with what is called the Euclidean count. This is actually much simpler to understand than it might appear. Counting the sources found and dividing them in intervals of strength (flux density) the resulting distribution is divided by the one expect if the sources were uniformly distributed. As seen in Figure 2 the WSRT could cover the range between 1 mJy and 1 Jy. Not seen (as there are no strong sources above 1 Jy) is the part of the source count that was the death blow to the steady state theory. The shape of the counts for fainter sources is exactly what you would expect: it not a horizontal line due to the expansion of the universe and other well-known cosmological effects.

In a way, our 1970-1980 Universe was reassuringly simple. "Dark matter" and "dark energy" were unknown, even though there were some early indications of dark matter, as Fritz Zwicky had pointed out already in the 1930s. We had stars and stellar systems (which were called collectively galaxies), and presumed that quasars were nothing but the highly active nuclei of galaxies. In such a nucleus we imagine that a gigantic black hole is lurking, spitting out energy in various forms (like for example radio waves). An active galactic nucleus often enters the literature under its acronym AGN and this could comprehend both galaxies and quasars. Much theoretical work followed and a qualitative model consisting of a central black hole emitting double-sided radio jets, which might travel to enormous distances from the nucleus (up to many millions of light years), was accepted by most astronomers. In addition, the mechanism of the radio radiation (synchrotron emission) was known in detail since the 1950s.

The first studies about samples of radio sources dealt with their composition: how many galaxies were present? How many were quasars? Did the ratio change going to fainter sources? It became clear that bright (optically as well as in the radio) quasars must have evolved strongly: in early stages of the universe, there were far more of such bright quasars than at the present epoch. This was about the extent of our knowledge in the early 1970s. The PhD theses of Jet Katgert-Merkelijn, Peter Katgert, and myself (see Figure 3), tried to give an inventory of the then known populations of radio sources, their luminosity

Figure 3 From left to right: Jet Katgert-Merkelijn, Peter Katgert, Hans de Ruiter.

functions (that is the distribution of their radio powers) and the cosmological evolution of the various constituents like elliptical radio galaxies and quasars).

Perhaps the most serious limitation of these early studies was the lack of spectroscopic data. Since the redshift of spectral lines is the only way to determine the distance, only some of the most nearby and brightest galaxies and quasars had spectral data available. Fortunately, radio galaxies were often found in the brightest and most massive elliptical galaxies, these had always very similar optical luminosities. For that reason, one could get a rough estimate of their distance notwithstanding the lack of spectral data.

Strong radio sources associated with such elliptical galaxies and with quasars in general were found to evolve very strongly in the sense that they were much more common in the early epochs of the Universe. These studies based on indirect methods were very uncertain and only in recent years there is significant progress in the collection of spectroscopic data, thanks to important projects like the SDSS (Sloan Digital Sky Survey).

It would take another 5-10 years, before a new batch of PhD students (Windhorst, Thesis [d], and Marc Oort, Thesis[e]), would explore the sub-mJy level (0.1-1 mJy). A simple model of a hypothetical population of objects could easily reproduce the shape of the radio source counts, as had been demonstrated by Longair already in the 1960s, if one includes cosmological evolution of the population. At lower flux levels, also non-evolving or only mildly evolving population should be present, like for example spiral galaxies, but these would enter our sample only below 1 mJy and perhaps even much lower.

Figure 4 Rogier Windhorst and Marc Oort.

From 1980 onward, the WSRT carried out some deep surveys, and these were studied by Rogier Windhorst and Marc Oort (see Figure 4). Their work would lead to “definitive” source counts at 1.4 GHz, down to 0.1 mJy, in large part based on WSRT observations.

The pictures (Figures 3 and 4) of the five Leiden PhD students are more recent than their PhD theses...

The most important and beautiful figure is, no, not Figure 3 or 4, but Figure 5, taken from an article by Rogier Windhorst[3] and his collaborators. There you can see in every detail all the properties of the radio source counts starting at about 0.1 mJy (100 times fainter than in the studies of the 1970s!) going upwards to the strongest sources at 10^4 mJy or more. VLA and Cambridge surveys confirmed the results of Windhorst and Oort.

Note that the counts at the high end (at about 1000 mJy, corresponding to 3 in the logarithm) go down again towards the brightest flux densities. In Figure 2 strong sources were absent due to their paucity.

Perhaps equally interesting is the *flattening* of the source counts that starts just above a mJy and becomes more pronounced towards the faint end at 0.1 mJy. Windhorst and later Oort found that a new (in the sense of a hitherto unknown) population of *blue* radio galaxies was responsible for the flattening of the counts, and not the usual *red* elliptical galaxies, which abound at the higher flux densities together with the quasars.

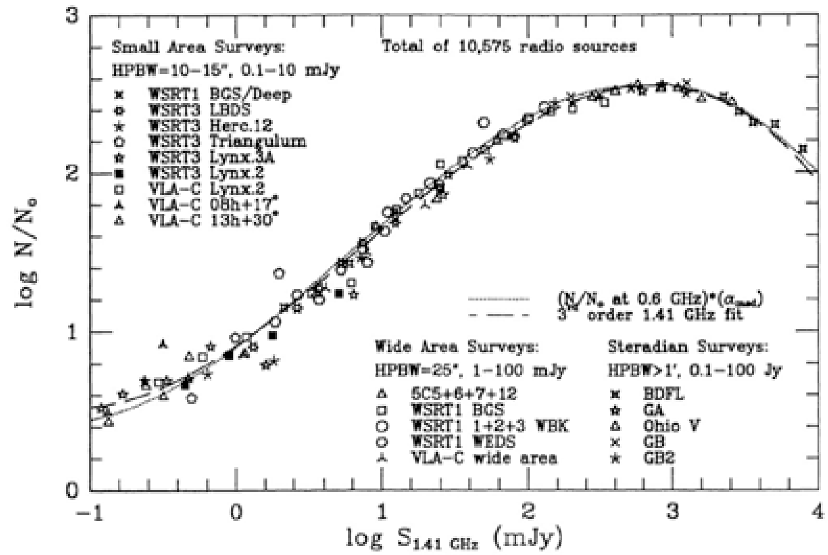


Figure 5 The normalized definitive radio counts at 1.4 GHz. Note the flattening below 1 mJy (log S = 0), which is due to a new population of blue radio galaxies.

It remains unclear, even until the present day, what these galaxies really are, but most astronomers consider them to be “starburst”, or star forming, galaxies. The radio emission is then not, at least not predominantly, due to an active nucleus, but to an anomalously strong burst of star formation. Of course, a phase of strong activity in the galaxy nucleus may indirectly have caused strong star formation, a possibility that shows how simple and naïve our ideas about source populations were: reality may be much more complex.

There may be sub-populations of radio galaxies, which sometimes partly overlap. Classifying them all may be a hard task. We find a bewildering zoo of different classes of objects in modern literature. For example, Padovani[4] gives the following list: FSQ (flat spectrum quasars), SSQ (steep spectrum quasars). FRI (Fanaroff_Riley type I radio sources), FRII (type II radio sources), BL Lacs (a kind of quasar-like objects without clear spectral lines), radio-quiet AGNs, and elliptical galaxies with active star formation. It is by no means clear how and to what extent all these different but partly overlapping classes of objects contribute to the source counts. In any case we know that the presence of an Active Galactic Nucleus may or may not be accompanied by strong star formation (and vice-versa).

Below 1 mJy star forming galaxies start to appear, but the classical AGNs we see among the strongest radio sources still make up about 50 % of the radio sources. This may even be so at µJy levels, i.e. at levels a thousand times fainter than the mJy sources. De Zotti[5] and collaborators discuss this in detail. Considering the confusion that still reigns it is wise to keep the models as simple as possible, for the moment at least.

Very deep surveys (going down to a few µJy), were carried out mainly with the VLA, but even the WSRT (with its modern instrumentation) can reach these levels. The improvement in sensitivity by a factor of about 1000 in about 30 years is impressive indeed. A number of studies were done with the VLA, in the region of the *Hubble Deep Field (HDF)*. Worth mentioning are the studies by Richards et al.[6] at 8.5 GHz down to a limit of 9 µJy, Fomalont et al.[7] at 8.5 GHz down to 7.5 µJy and Richards[8] at 1.4 GHz with a limit of 40 µJy. The WSRT cannot stand up to such a firepower, one might say, but this is only partly true.

In the same period, a group of astronomers led by former ASTRON director Mike Garret[9] made very deep observations with the WSRT of the *HDF* region, which reached the unprecedented level of 40 µJy, without too much effort. The observing time (six 12-hour periods) was very similar to the times used for the extensive surveys in the early 1970s. In Figure 6, we show the field observed by the WSRT in the form of a contour plot.

Since the planning of the biggest radio telescope ever, the Square Kilometer Array (SKA) has started, modelling radio source counts down to very faint levels (nano Jansky–a thousandth of a µJy) has become a popular pastime. Many articles have discussed the possible populations that might be present and at what level they would enter the counts. All astronomers appear to agree about one thing: if you arrive at the level of 1 nanoJy, you have seen virtually everything there is to see. In fact, Condon et al.[10] assert that at that level about 95 % of all the radiation, originating in known types of radio sources, as briefly sketched above, is detected. The remainder should come from the billions of stars, planets (whether populated by aliens or not) and perhaps some extremely weak populations of sources we have no inkling about (yet). Indeed, some in-

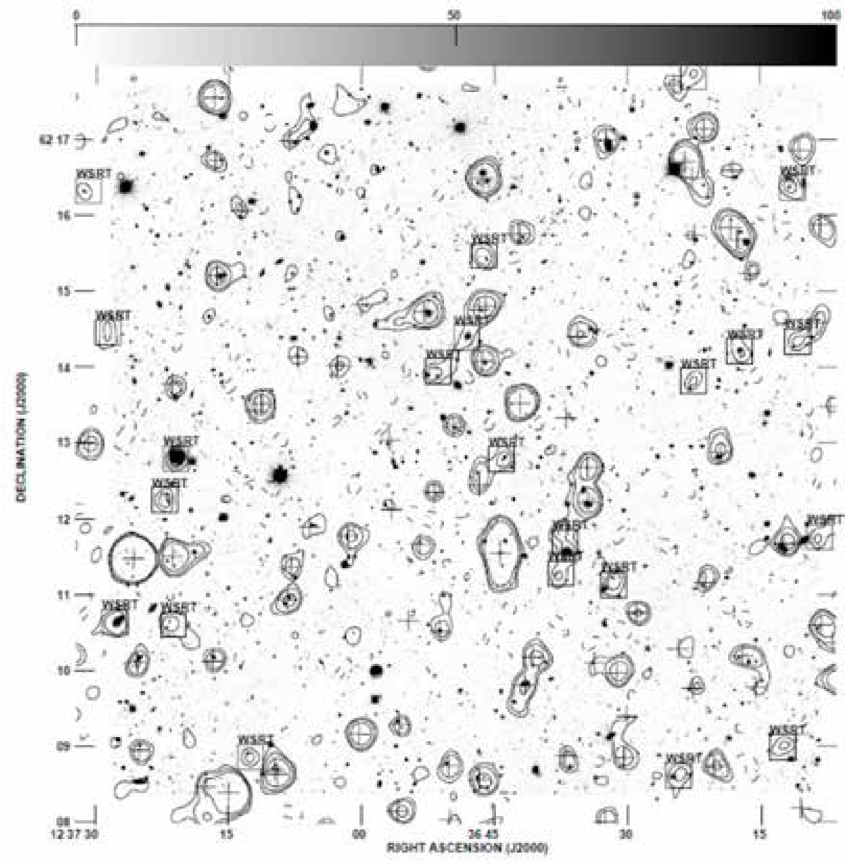


Figure 6 WSRT Contour-plot of a 10 by 10 arcminutes field, centered on the HDF region (the inner 2.5 by 2.5 arcmin). The radio image is overlaid on an optical image (I band picture made with the Canadian-French Hawaii telescope). The first contour is at 27 µJy; crosses indicate the position of sources found also in VLA observations. Squares denote WSRT sources not detected by the VLA.

direct evidence points to the latter possibility. It turns out that the temperature of the extragalactic background radiation in the range 3-90 GHz is higher than one would expect based on the known populations of radio sources (ARCADE 2 measurements, see Fixsen et al.[11]). Condon[10] concludes from this that there is room for some new, still unknown populations. Since real data at the nanoJy level are lacking, his conclusion is obviously pure speculation, but no doubt, there is lots of interesting work to be done with SKA.

Now that we have entered the era of "overwhelmingly large" telescopes, fast computers and terabytes of memory even in small PCs, astronomy has started to produce ever-bigger data sets of objects at all imaginable wavelengths, and surveys have taken on a new meaning. Especially the *all sky* surveys are all the rage, and the possibility to access such the data sets online is changing astronomical research dramatically. Already more than 20 years ago, a WSRT *all sky* survey was performed; well, not really all sky, but that part of the sky visible from the far north of the Netherlands. To be even more precise, the part of the sky above a declination of 30 degrees, for which high quality mapping is possible. While the VLA mapped a large part of the sky at 1.4 GHz (FIRST and

NVSS, both directly accessible from the NED Website, at ned.ipac.caltech.edu), WENSS surveyed the northern sky at lower frequency, 325 MHz. WENSS is described in Rengelink et al.[12].

Anybody, astronomer or non, can easily access Westerbork data, a genuinely democratic operation: just go to Westerbork on the Web (at wow.astron.nl), read the (very simple) instructions and type in the position or the object name and get your own piece of the radio sky at your home computer. As an example I show the field obtained by requesting the data of 3C238; the resulting map is given in Figure 7. The file sent to you is in FITS format (used extensively by the astronomical community). The only thing you need is a *viewer* for FITS files (for example SAOimage, which can be downloaded freely). If you wish, SAOimage can save the FITS file in more common photographic formats like GIF or JPG.

The importance of the modern radio surveys is enormous, not in the least because similar developments in other wavelength ranges (including truly *all sky* surveys done with satellites, like GALEX–ultra-violet–and 2MASS–infra-red), have revolutionized studies based on the use of these big data sets. The low observing frequency of the WSRT (325 MHz) opens up the possible to hunt for specific types of radio sources, by combining the WSRT with the higher frequency data of the VLA surveys at 1.4 GHz, and studying the spectral properties. Wieringa & Katgert[13] used partial 327 and 608 WSRT data (WENSS had not been completed at that time) to select sources with steep spectra, i.e. sources much stronger at the lower frequency. It was known that many sources with steep radio spectra are at very high redshifts, so that selection based on spectrum is an efficient way for finding the most distant sources. This kind of study has been repeated on a much larger scale, by combining all available all-sky surveys (WSRT, VLA, others) and having the computer select the sources with steep spectra. This can be done in a fully automated way, saving time and effort. Carlos de Breuck[14] and collaborators have done such a study, with great success.

How successful was the cosmological research done with the WSRT? This kind of question is hard to answer of course, and perhaps is rather meaningless. Nevertheless, in my opinion the strategy to mix deep surveys in specific small parts with less deep surveys over larger parts of the sky worked quite well. In the first years one could not reach the sub-mJy level yet, but on the other hand one could take advantage of the simple fact that all WSRT observations contributed "for free" to a background of radio sources in fields observed for quite different purposes. An example is the Background Survey used in my own thesis (Thesis [c]). Much later Windhorst and Oort could concentrate on small fields and dedicated themselves to extended observations at different radio frequencies, which reached levels close to 0.1 mJy. Even without the fast computing facilities of today and without the huge databases at optical, infrared, UV and X frequencies existing now, they were able to carry out extended optical observing campaigns. This work turned out to be very successful.

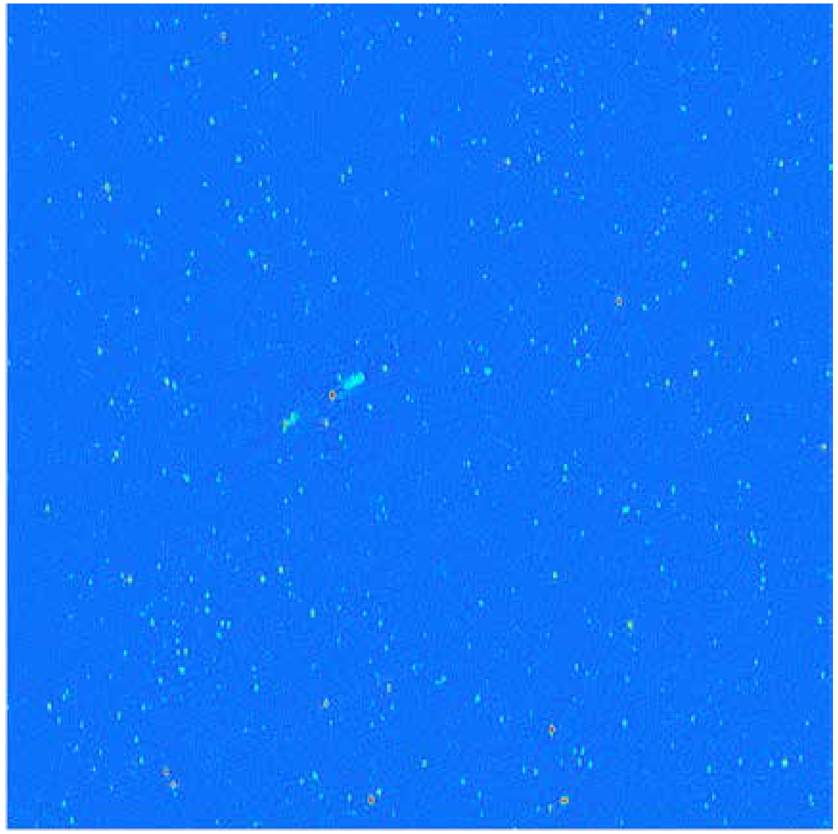


Figure 7 A Wenss field, obtained online, using the search name 3C 238, which is the extended radio source left of the centre. The observing frequency is 325 MHz.

My final opinion is therefore positive. The WSRT has performed a logical sequence of cosmological studies dedicated to the exploration of the various constituents of the early universe and their evolution over time. The possibilities of the WSRT have been exploited as much as was possible in the 1970s and 1980s, until the role of the WSRT was mostly–but by no means entirely–taken over by the VLA, and Australia Telescope in the Southern Hemisphere. The future cosmological studies with the SKA will be a direct continuation of much of the work for which the WSRT has laid the foundation.

WSRT Surveys: Leiden PhD Theses in the period 1970-1990

[a] Jet Merkelijn 1970: *A determination of the Luminosity Function of radio galaxies at 400 and 2700 MHz.*
[b] Peter Katgert 1977: *populations of weak radio sources.*
[c] Hans de Ruiter 1978: *faint extragalactic radio sources and their optical identifications.*
[d] Rogier Windhorst 1984: *faint radio galaxy populations.*
[e] Marc Oort 1987: *radio galaxies at very low flux levels.*

References

1 Katgert-Merkelijn et al. 1977, IAU Symp. No. 74 "Radio Astronomy and Cosmology"
2 Willis et al. 1977, IAU Symp. No. 74 "Radio Astronomy and Cosmology"
3 Windhorst, Mathis en Neuschaefer 1990, ASPC, 10, 389
4 Padovani 2010, MNRAS, 411, 154
5 De Zotti et al. 2010, Astron. Astophys. Rev, 18, 1-65
6 Richards et al. 1998, AJ, 116, 1039
7 Fomalont et al. 2002, AJ, 123, 2402
8 Richards 2000, ApJ, 533, 611
9 Garrett, M.A. 2000, AA, 361, L24
10 Condon et al. 2012, ApJ, 758, 23
11 Fixsen et al. 2011, ApJ, 734, 5
12 Rengelink et al. 1997, AAS, 124, 259
13 Wieringa en Katgert (1991, AA, 248, L31)
14 Carlos de Breuck et al. 2000, AAS, 143,303

Cosmology with the WSRT

Chapter 11.2 WSRT observations of ultra-steep spectrum sources

Pointing the way to the most massive forming galaxies and clusters and to LOFAR

George Miley*

Distant luminous radio galaxies are unique laboratories for studying the formation of the most massive galaxies and clusters in the early Universe (redshifts $z \sim 2$ to $z \sim 5$). During its first decade, the WSRT played an important role in laying the groundwork for such studies. This topic was also one of the main scientific applications that motivated the original LOFAR proposal to ASTRON in 1997.

Most radio sources detected in low-frequency surveys have "normal" steep radio spectra, with indices $-0.6 > \alpha > -0.9$. Only about 10% of all sources have "ultra-steep" spectral indices with $\alpha < -1.0$. In the early seventies very little was known about these ultra-steep radio (USS) sources. The limited studies that had been carried out with Cambridge telescopes in the sixties indicated that bright metre-wave USS sources occurred exclusively in nearby rich clusters of galaxies, but the statistics were sparse. In the early seventies Tony Willis and I thought that it would be interesting to use the WSRT to study a significant sample of decametre USS sources from the 4C Catalogue. The 4C Catalogue provided a relatively large database for such investigations. In 1973 and 1974 we therefore made several short "cut" observations on 46 4C USS sources having USS spectral indices (< 1.0 between 178 and 1400 MHz). We would compare our results with a similar study that was being carried out on sources with normal radio spectra (Padrielli and Conway et al. 1977, Astron Astrophys. Suppl. 27, 171).

The reduction and analysis was suited for an undergraduate research project and we found a young student who was looking for such a project and was willing to do it. His name was Xander Tielens. Xander later went on to become one of the most important world players in interstellar molecule and astrochemistry research and a professor at Leiden. Our analysis of the WSRT

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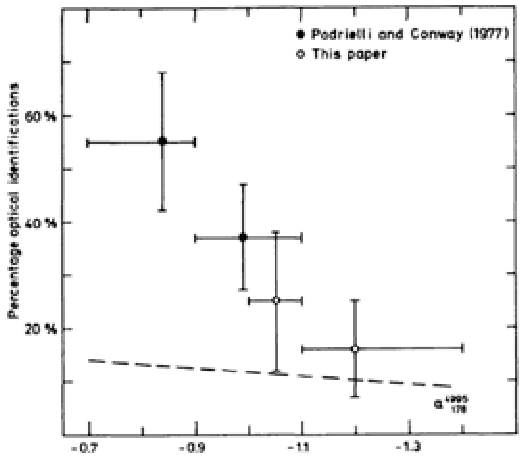


Figure 1. Percentage sources whose WSRT positions resulted in definite optical identifications on the Palomar Sky Survey plotted against spectral index. The plot showed for the first time that radio sources with ultra-steep spectra are located at significantly greater distances than sources with normal spectrum sources (Tielens Miley and Willis, 1978, Astron. Astrophys. Suppl. 35, 153-162). When this paper was published the most distant known radio galaxy was 3C343.1 at redshift z = 0.344 (Spinrad et al. 1977, Ap J Lett, 216, L87 – L89). Most of the 4C USS sources surveyed by the WSRT were later found to be associated with massive forming galaxies with redshifts 2 < z < 5.

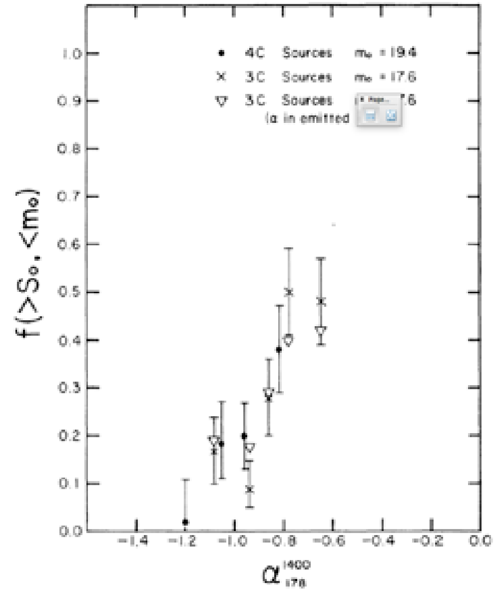


Figure 2. Fraction of radio sources with counterparts brighter than a given optical magnitude, m_o, plotted against spectral index (Blumenthal and Miley, 1979, Astron. Astrophys. 80, 13 – 21).

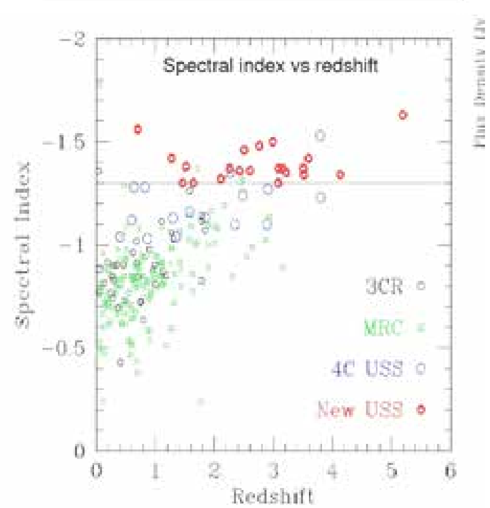


Figure 3. Plot of radio spectral index versus redshift, showing that more distant sources have steeper spectra (De Beuck, van Breugel, Miley, Rottgering, Stanford and Carilli, 2000, Astron. Astrophys. Suppl 143, 303-333).

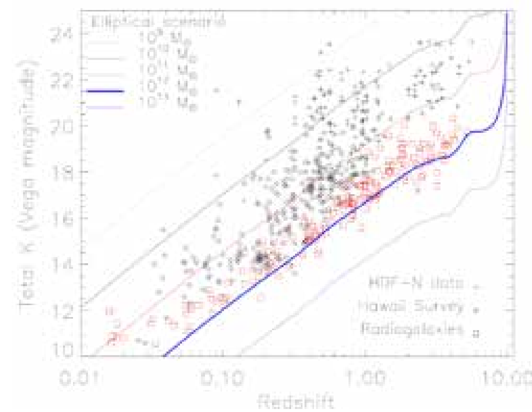


Figure 4. USS radio sources pinpoint the most massive galaxies in the early Universe. Hubble K-z Diagram of radio and optically selected galaxies. Radio galaxies. denoted by the red squares occupy a bright upper envelope. Prepared by Brigitte Rocca and taken from Miley and De Breuck 2008, Astron. Astrophys. Rev. 15, 67 – 144.

sample showed that USS 4C sources differed significantly from normal spectrum 4C sources (Tielens, Miley and Willis, 1978, Astron. Astrophys. Suppl. 35, 153-162). Many more USS sources were unresolved (< ~ 20"), indicating that they were smaller than normal sources. However, the most startling difference was apparent when we tried to identify the USS sources with optical objects on the Palomar Sky Survey. Most of them were blank fields (see Figure 1), indicating that USS sources are located at systematically much greater distances than normal spectrum sources.

While on sabbatical at the U. Cal. Santa Cruz, I looked into the implications of this result with cosmologist, George Blumenthal. Our conclusion (Figure 2) was that USS radio galaxies and quasars followed the same behaviour. From the available data it was difficult to distinguish between a spectral index dependence of radio source luminosity and redshift.

The implications of this result was not followed up until the mid-eighties, when I spent a 4-year leave of absence from Leiden at the Space Telescope Science Institute. The tragic Challenger accident and the postponement of the Hubble launch created unexpected time for research. I devised a PhD project for Ken Chambers a gifted Johns Hopkins student and contacted Wil van Breugel at the University of California, who had access to the Keck Telescope. We started a programme of optical and infrared imaging and optical spectroscopy of the WSRT USS sample, using any telescope we could get our hands on. The result surpassed our wildest dreams. We broke the distance record for a radio galaxies several times, with objects such as 4C40.36 at z = 2.3 and the monster radio galaxy 4C41.17 at z = 3.8.

The USS detection technique for finding distant radio galaxies developed with the WSRT has since been extremely successful. Most of the several hundred known z > 2 luminous radio galaxies were found by targeting small USS radio sources (Figure 3). Massive galaxies and protoclusters detected using the USS technique have been the topic of dedicated ESO Large and Key projects, many observing hours with the Hubble Telecope and intensive study by other large telescopes throughout the electromagnetic spectrum. They have also been food for many Leiden PhD theses, including those of Huub Röttgering, Rob van Ojik, Laura Pentericci, Carlos De Breuck, Roeland Rengelink and Huib Intema.

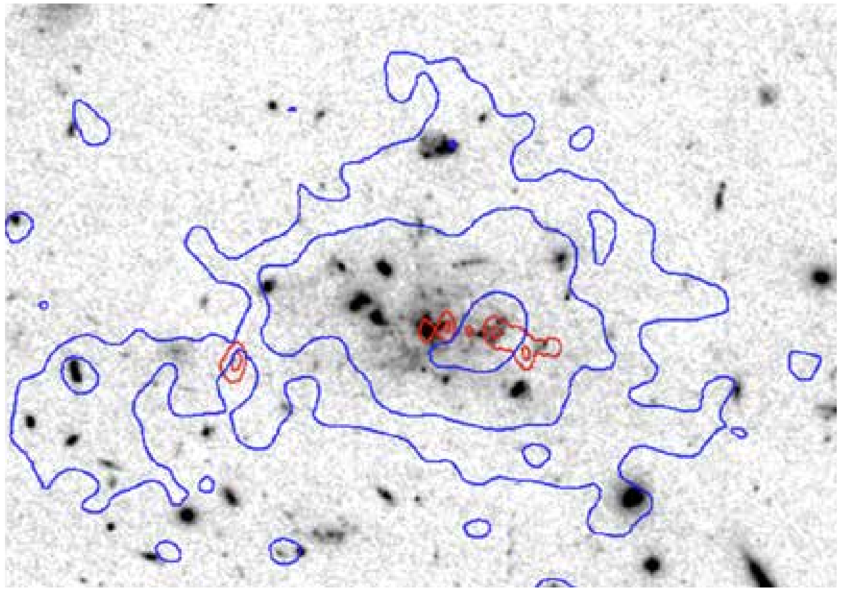
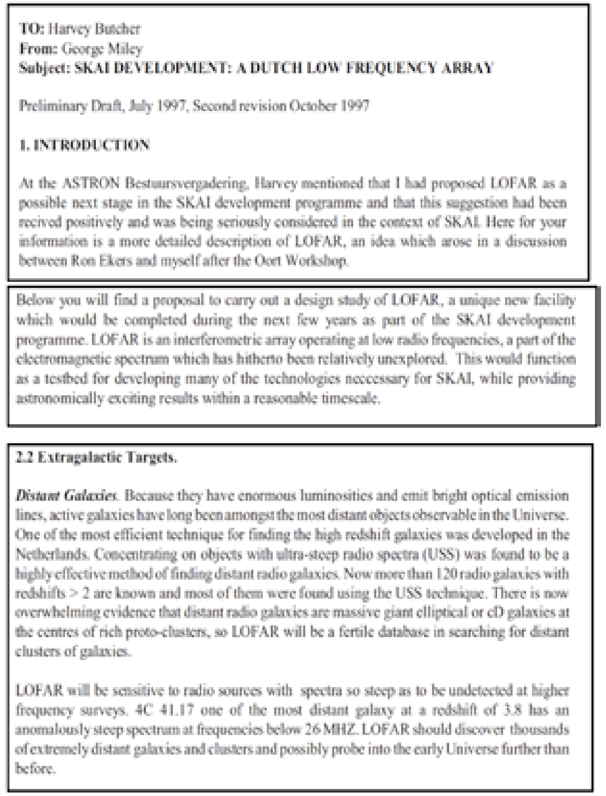


Figure 5. Deep Hubble ACS mage of the Spiderweb Galaxy at z = 2.2. This is one of the most spectacular distant and massive galaxies found using the WSRT-developed USS technique. The blue contours from the VLT show the giant 150kpc halo that surrounds it and the red contours from the VLA shows the radio source (Miley et al. 2008, Ap J Lett 650, L29 – L32). The galaxy complex is embedded in a forming protocluster. The Spiderweb and similar objects are excellent laboratories for studying the formation and evolution of the most massive galaxies and clusters and black holes in the early Universe and processes such as galaxy merging, AGN feedback and galaxy downsizing.

A detailed description of the properties of distant luminous radio galaxies and their environment is outside the scope of this contribution (e.g. review by Miley and De Breuck 2008, Astron. Astrophys. Rev. 15, 67 – 144). Their properties indicate that they are the progenitors of brightest cluster galaxies in the local Universe. The various building blocks of high-redshift USS radio galaxies (relativistic plasma, gas in various forms, dust, stars and a powerful AGN) are relatively bright and provide unique diagnostics about the early Universe. The Spiderweb Galaxy (Figure 5) and similar objects are laboratories for studying the formation and evolution of the most massive galaxies and clusters and black holes in the early Universe and processes such as galaxy merging, AGN feedback and galaxy downsizing.

Distant USS radio sources and their "monster" galaxy counterparts also played an important role in motivating the 1997 proposal to ASTRON for a low-frequency array called LOFAR (Figure 6). In the late nineties, the WSRT was almost 30 years old and ASTRON were devoting all their future efforts into developing a do-all mega-facility the Square Kilometre Array Interferometer (now SKA). It was generally expected that SKAI would be finished in 10 – 15 years, so the suggestion of building a less ambitious facility to fill the gap was under-



TO: Harvey Butcher
From: George Miley
Subject: SKAI DEVELOPMENT: A DUTCH LOW FREQUENCY ARRAY

Preliminary Draft, July 1997, Second revision October 1997

1. INTRODUCTION

At the ASTRON Bestuursvergadering, Harvey mentioned that I had proposed LOFAR as a possible next stage in the SKAI development programme and that this suggestion had been recived positively and was being seriously considered in the context of SKAI. Here for your information is a more detailed description of LOFAR, an idea which arose in a discussion between Ron Ekers and myself after the Oort Workshop.

Below you will find a proposal to carry out a design study of LOFAR, a unique new facility which would be completed during the next few years as part of the SKAI development programme. LOFAR is an interferometric array operating at low radio frequencies, a part of the electromagnetic spectrum which has hitherto been relatively unexplored. This would function as a testbed for developing many of the technologies neccessary for SKAI, while providing astronomically exciting results within a reasonable timescale.

2.2 Extragalactic Targets.

Distant Galaxies. Because they have enormous luminosities and emit bright optical emission lines, active galaxies have long been amongst the most distant objects observable in the Universe. One of the most efficient technique for finding the high redshift galaxies was developed in the Netherlands. Concentrating on objects with ultra-steep radio spectra (USS) was found to be a highly effective method of finding distant radio galaxies. Now more than 120 radio galaxies with redshifts > 2 are known and most of them were found using the USS technique. There is now overwhelming evidence that distant radio galaxies are massive giant elliptical or cD galaxies at the centres of rich proto-clusters, so LOFAR will be a fertile database in searching for distant clusters of galaxies.

LOFAR will be sensitive to radio sources with spectra so steep as to be undetected at higher frequency surveys. 4C 41.17 one of the most distant galaxy at a redshift of 3.8 has an anomalously steep spectrum at frequencies below 26 MHZ. LOFAR should discover thousands of extremely distant galaxies and clusters and possibly probe into the early Universe further than before.

Figure 6. Excerpts from the original proposal to ASTRON in mid-1997 for a low-frequency array called LOFAR. The detection of USS sources at low frequencies and the importance of this for studying forming massive galaxies and clusters in the early Universe was an important motivation for the LOFAR science case.

standably not received "with open arms" by everybody concerned, particularly a low-frequency facility in the RFI environment of the Netherlands. However, there were other arguments that emerged to justify building a low-frequency facility. First, LOFAR would provide an opportunity to develop several of the techniques that would be needed for SKA and trying them out in a hostile RFI environment. Brilliant ASTRON engineers, such as Jaap Bregman using revolutionary technology, developed LOFAR into a sophisticated software telescope and technology platform. Secondly, Ger De Bruyn became passionately involved in searching for HI emission from the Epoch of Reionisation, that became another prime motivation for LOFAR. Thirdly, Harvey Butcher ensured that LOFAR was more than just a radio telescope. It became a "multidisciplinary sensor array" with geophysical and precision agriculture applications, eligible for ICT funding. Finally, Harvey and Eugene de Geus and the Dutch province of Drenthe conducted a masterly campaign to persuade policy makers that building LOFAR would benefit the Netherlands. The rest is history!

Cosmology with the WSRT

Chapter 11.3 WSRT and VLBI observations of the Hubble Deep Field (HDF-N)

Michael Garrett*

Introduction

In early 1999, the WSRT upgrade was transitioning towards completion. Although the broadband IVC-DZB system was fully available yet, a new suite of very sensitive Multi-frequency Front End (MFFE) receivers were already achieving ~30K noise levels on the telescope. Dr. Willem Baan, Radio Observatory director, was looking around for projects that would demonstrate the new capabilities of the WSRT to the international community. Around the same time, I had become very interested in the Hubble Deep Field North (HDF-N) – a small patch of sky only a few arcminutes across, that had been observed by the Hubble Space Telescope (HST) for a then unprecedented integration time of 10 full days! I was not the only astronomer to be very excited by these very deep but high resolution optical images, and soon every ground and space-based telescope was investing huge amounts of observing time on the HDF-N and the surrounding Hubble Flanking Fields (HFF). It became clear that with the new MFFE systems installed on the WSRT, exploring large areas of the faint radio sky was now eminently possible. It struck me, that it would be interesting to see what this μJy radio sky looked like on the largest angular scales – perhaps the WSRT could pick up extended objects missed (resolved) by the higher resolution VLA and e-MERLIN observations (Muxlow et al. 2005). The HDF-N (and HFFs) therefore became an obvious target for the WSRT - a nice opportunity to show case the improved performance of new MFFE systems. After submitting a proposal with Ger de Bruyn, Willem Baan and Richard Schilizzi, we were happy to receive 72 hours of observing time spread across the various array configurations in chunks of 6 x 12 hours.

During this period, I was also deeply involved in demonstrating and developing the concept of "wide-field VLBI". This had started in the late 1980s while working with Dr. Richard Porcas on VLBI imaging of gravitationally lensed systems in which the lensed components could be separated by up to 10 arcseconds (or 10,000 synthesised beams). Richard had mentioned during my first visit to Bonn as a young PhD student, that one day it would be nice to image out the full field of view around each lensed systems, rather than target the lensed components individually via the tedious (and somewhat fraught) process of multiple-pass correlation. In particular, with multiple passes, the response of one lensed component could not be totally isolated from each other, leading to all sorts of problems on the shortest EVN baselines. In the early 1990s, I successfully applied wide-field techniques to several lensed systems (e.g. Garrett et al. 1994), mapping out large areas of the sky (at least in terms of VLBI) that encompassed the locations of all the lensed components in a single correlator pass. I extended these methods to the nearby nuclear star-forming galaxy M82, detecting several widely separated SNRs, located across the central region of the galaxy, a distance spanning several arcminutes on the sky (or ~ 400,000 beams!). Applying these wide-field techniques to other potential targets, I became almost evangelical about the promise of wide-field VLBI (Garrett et al. 1999), and bored people greatly about the evils of data averaging.

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I think it's fair to say that not everyone fully shared my enthusiasm for this new approach! At that time, only a handful ofspecial targets could benefit (chiefly lenses, binary QSOs, and nearby galaxies), and the requirement to keep all the data in its raw, un-averaged form was a stretch for the compute and storage systems of the day.

The HDF-N would change all of that!

WSRT data analysis

It will come as no surprise to most readers, that Ger de Bruyn was very much involved in the analysis of the WSRT HDF data. He was very keen to see if the new MFFEs were as good as the ASTRON engineers claimed. Ger was so familiar with analysing WSRT data, and adept with the manipulation of the home-grown *Newstar* software analysis package (see Chapter 6), that there was no need to spend too much time inspecting or editing data. The diagnostic output of the *Newstar* calibration and imaging tasks told Ger everything he needed to know about data quality. This approach also suited me quite well – experienced in handling the huge data sets generated by wide-field VLBI projects (a then staggering 120 GB!), I had long given up on the plodding approach to VLBI data processing that still absorbed most of my colleagues. Watching VLBI

Figure 1: The Hubble Deep Field North (Williams et al. 1996) – a patch of sky no bigger than a grain of sand held out at arms length, yet encompassing thousands of distant galaxies.

astronomers editing individual visibilities by hand, and agonising over every point, was amusing but not very productive. It was naturally a challenge to keep up with Ger. Newstar was opaque to almost any normal mortal, save for a few astronomers that had used it in Dwingeloo, and perhaps the package's chief architect and advocate, Wim Brouw and Jan Noordam respectively.

In any case, the total intensity images produced by *Newstar* reached a noise level of ~9 μJy (See the interior of Figure 2), and despite my best efforts, I could never get better than 10 μJy with AIPS. The Newstar images also looked better, and the linear polarisation images went deeper - to 7.5 μJy – this came as a surprise to me, and I assumed it was a dynamic range effect in stokesI but Ger rightly understood that this was a sure sign that the r.m.s. noise level of the total intensity maps included a contribution from not only thermal noise but also source confusion (~5 μJy) adding in quadrature. Ger was greatly encouraged by this result – it basically meant that the sensitivity of the MFFEs, and the rest of the new WSRT system, worked pretty much "as advertised". Personally, I found it a bit disappointing – it seemed to me that the WSRT was now quickly confusion limited with maximum baselines of only 3 km and very sensitive receivers. This could only get "worse", as the total bandwidth expanded from

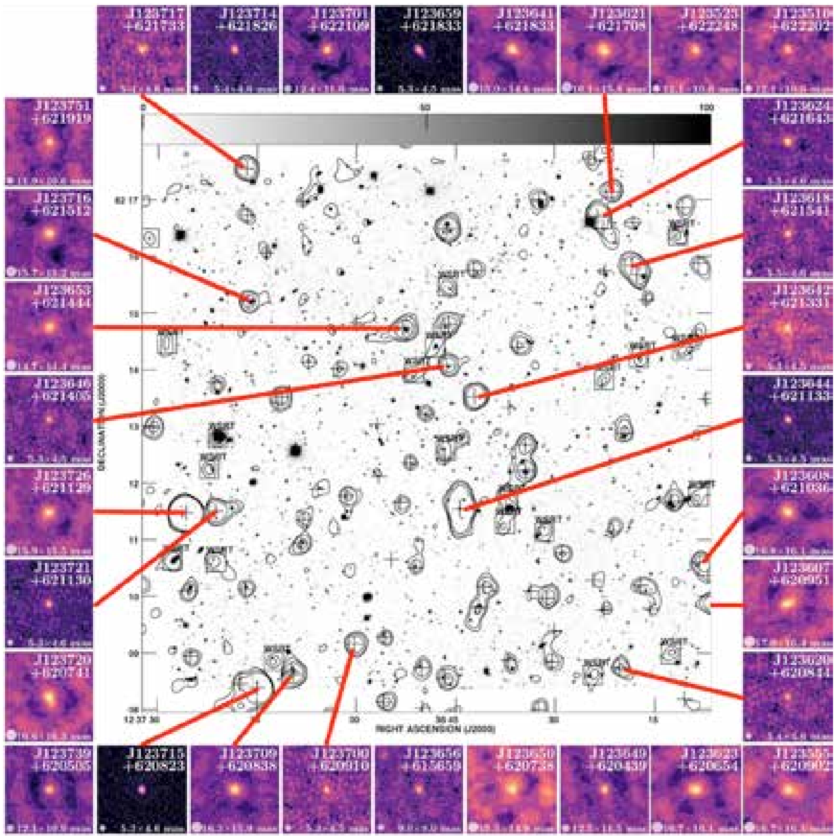

Figure 2: EVN detections of faint radio sources in the HDF and HFFs frame the original WSRT contour map, superimposed on an CFHT I-band image of the field (Berger et al. 1998). Image courtesy of Jack Radcliffe.

80 MHz to 160 MHz with the introduction of the new IVC-DZB system later in the year. But looking to the future, it also meant that personally, the reduced "raw" sensitivity of the future Apertif L-band PAF system, was never to be a major issue for me.

I learned a lot from Ger during this period. My own background and expertise was very much rooted in high resolution radio astronomy, and in particular VLBI. First of all, I was shocked by the stability and quality of the WSRT data, as compared to VLBI! While the concept of filled apertures, redundancy and a 1-D East-West array seemed absolutely pre-historic to me (being raised, on a diet of sparse 2-D arrays, self-calibration and hybrid mapping), I noted that Ger made good use of these attributes, and by the end of the project I could appreciate their own merits. Some of these concepts have become of interest again, as the SKA1 with hundreds of antennas also offers superb aperture coverage. I was also surprised to find out that short baselines were not only a problem for VLBI but also the WSRT, with a mix of RFI, foreground emission and the response of the Sun being blamed. I was also very happy to see that the synthesised field-of-view of the WSRT was so large that the map we produced was literally "teaming" with sources – they were all over the place, and to me this was how all radio astronomy should be, including VLBI. The fact that there was always enough sources in the field to self-calibrate the data was also pleasing, and I became more convinced than ever, that VLBI need not be any different in this respect, with in principle the primary beam being the only real limit to the field-of-view.

WSRT Science Results

The WSRT observations produced some fantastic images of the HDF and associated HFFs. Scientifically it was clear that the very deep but much higher resolution VLA and MERLIN observations were missing a substantial number of extended sources, providing a somewhat filtered view of the μJy sky. The NRAO completion mumbled about confusion effects... but the upgraded WSRT detected many sources that the other arrays did not, and there was also evidence for AGN variability. Some of the new WSRT sources were also clearly associated with nearby star-forming galaxies, resolved across their disks in the higher resolution VLA maps. But perhaps the most important outcome was that a combination of the HDF-N 20 cm WSRT and 15 μm ISO data demonstrated the surprising result that the FIR/MIR-Radio correlation held not only for galaxies in the local Universe but also for galaxies located at cosmological distances (Garrett 2002).

EVN results

The EVN observations of the HDF-N and the HFFs were made almost in parallel with the WSRT observations. They combined two techniques – a wide-field analysis of the data, combined with the employment of phase-referencing (Beasley & Conway 1995). Together this approach extended the coherence time of the array across the entire observing run, so that in principle the detection of submJy sources (and even µJy sources) became possible across the entire field. The only question was what fraction of these faint sources would be compact on VLBI scales – at this point no one could be sure. It was therefore incredibly brave of the EVN Programme Committee (PC) to award a total of 32 hours of observing time dedicated to the HDF-N – the ultimate blank field (the HDF-N was specifically chosen to be devoid of bright radio sources). The observations were made in November 1999, correlated in Socorro and I analysed them on a working visit to Jodrell Bank in February 2000. I still remember the feeling of elation when the first three central sources popped up above the noise level, the faintest being only 180 µJy. Figure 2 shows a more recent VLBI observation (Radcliffe et al. 2018) that achieves a central r.m.s. noise level of 5 µJy, and detects over 30 sources.

I was incredibly excited by the EVN results – in addition to revealing the existence of very faint but compact sub-mJy and µJy radio sources, it became clear from source brightness temperature arguments that the radio emission must arise from an AGN or be AGN dominated. This meant we could use VLBI to directly discriminate between emission generated by star formation and AGN processes in distant galaxies – a tricky business by other means. But I was actually more excited by the fact that at Lband we could now point the EVN anywhere on the sky, and detect multiple sources in the field – not only that but we later demonstrated that the accumulated response of all of these sources could permit self-calibration to be used (just like the WSRT) – even in a so-called "blank field" (e.g. Garrett et al. 2005, Radcliffe et al. 2017).

Final thoughts

My involvement in the WSRT observations of the HDF had many positive aspects. I got a chance to work with Ger, and to see at first hand a master craftsman at work. Although I was still working for JIVE at that time, leading a highly visible and successful WSRT project gave me the opportunity to engage with ASTRON staff and understand more about the organisation. It was an opportunity that eventually led to an interesting career path in which ASTRON would figure prominently.

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Chapter 12

The Westerbork Telescope and Neutral Hydrogen (HI) in the Universe

Thijs van der Hulst[1], Tom Oosterloo[2], Raffaella Morganti[2]

In 1944 Henk van de Hulst made the pioneering discovery that radiation from neutral hydrogen atoms in the universe is observable at a wavelength of 21.11 cm, i.e. with a radio telescope. This discovery fundamentally changed astronomy in the Netherlands. After the important early work with the Kootwijk and Dwingeloo telescopes, focused on mapping the HI in our own Galaxy, the Milky Way, the WSRT followed this lead and showed that not only the Milky Way and its neighbour the Andromeda galaxy, but the majority of the galaxies in the universe are full of neutral hydrogen with similar distributions and kinematics. Neutral hydrogen (HI) observations throughout the following decades has taught astronomers a lot about the structure and evolution of galaxies from observing the HI. Work with the WSRT has been world-leading from the start and, because of a series of improvements of the telescope over the years, is continuing to play an important role in the field of extragalactic HI astronomy.

The WSRT was originally designed for measuring wideband radio radiation from radio-galaxies and quasars and from star formation in galaxies. Thanks to a clever modification of the system, engineers and astronomers made the WSRT suitable for measuring the 21-cm line radiation of neutral hydrogen in the early seventies. It was important to do this at the time because it gave the WSRT a unique advantage over other telescopes. Around 1980 the VLA (Very Large Array in New Mexico, USA) would be put into operation. Having spectral line capabilities before this date gave the WSRT a unique position regarding kinematical studies of nearby galaxies. Later also the VLA obtained spectral line capabilities, but the WSRT stayed ahead again by deploying very stable, broadband correlators, first the DXB and then the IVC.

The WSRT hardware had 80 analog channels, which were used for broadband work and allowed for measuring the 80 signals from all four possible combinations of the two receivers per telescope for 20 baselines (telescope pairs). The change to the existing hardware was a modification to these 80 channels to simultaneously measure the signal of 10 baselines in 8 narrowband filters (27 km/s wide and separated by 40 km/s) instead of 40 broadband signals from 20 baselines. A full sampling of a spectrum with 20 baselines required

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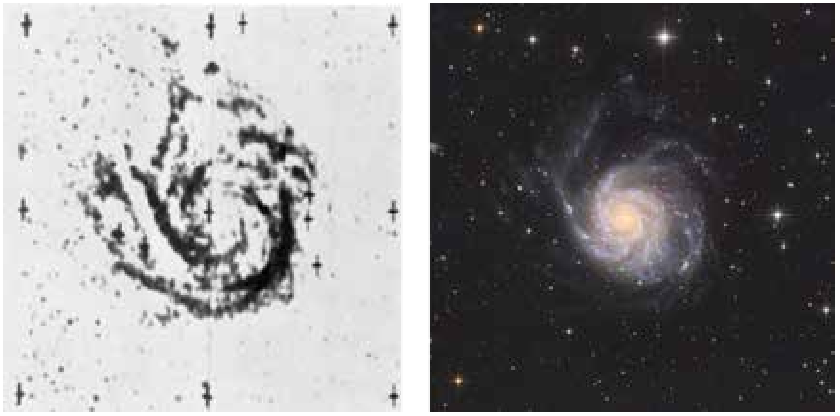


Figure 1: The first Westerbork image of neutral hydrogen in a spiral galaxy, in this case the large nearby spiral Messier 101. The left panel shows the hydrogen distribution, the right panel the light distribution on the same scale. The optical image is from the Sloan Digital Sky Survey (www.sdss.org) . The WSRT image is from Allen, Goss & van Woerden, Astronomy & Astrophysics, 29, 447, 1973.

4 measurements in practice. Slow compared to the broadband work, but sufficient for establishing a number of scientific breakthroughs. This was possible because, despite the long observing time for a fully sampled observation with the WSRT, there was actually no competition. The sensitivity and spatial resolution of the WSRT were much better than any other interferometer at the time.

With this 80-channel receiver, it was possible for the first time to map in detail the structure and kinematics of the neutral hydrogen gas in galaxies and this actually opened up a whole new area of research. Because of the unique capabilities offered by the WSRT, each observation immediately yielded new and interesting results. What became clear first was that the neutral hydrogen in spiral galaxies shows the same kind of spiral structure as thought to be present in the Milky Way and that the distribution of the gas follows in particular that of the bright young stars. Figure 1 shows the first Westerbork image of the neutral hydrogen (HI) distribution in the large nearby spiral galaxy Messier 101. This clearly demonstrated that the HI in galaxies also exhibits spiral structure. The early HI observations also showed that the gas disks of galaxies are larger than the stellar disks (on average one and a half times) and that the outer parts of the gas disk often have a different orientation, the so-called 'warps'. One of the largest warps to date has been found in the galaxy NGC 4013 and is shown in figure 2. The precise origin of such warps is still under investigation. The main cause is thought to be external, either a steady inflow of fresh gas or the capture of small satellite galaxies.

The most important work that has been carried out with the 80-channel receiver is undoubtedly the use of neutral hydrogen to measure the rotation of galaxies at much larger distances from their centres then possible optically, and hence derive from the rotation the total mass distribution in spiral galaxies out to these large radii. Astronomers use the Doppler effect to measure the velocity of the neutral hydrogen along the line of sight, and in this way the rotation of the gas disk around the centre of a galaxy can be measured. This measurement can be used to estimate the total mass, just as the mass of the sun can be de-

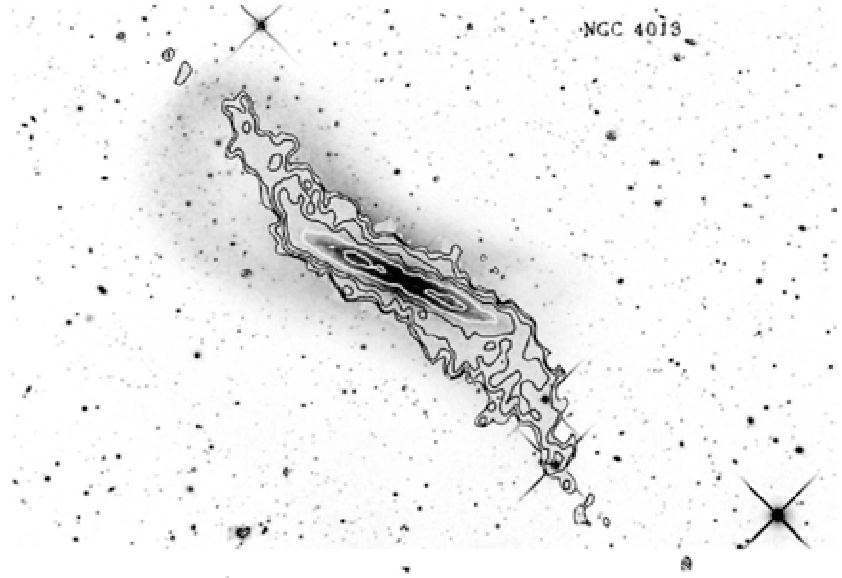


Figure 2: The giant warp of the hydrogen disk in the galaxy NGC 4013. Contours represent the hydrogen column density distribution (taken from Bottema, Astron. & Astrophys., 295, 605, 1995) and are superposed on the light distribution of the galaxy taken from Martınez-Delgado et al., Astrophysical Journal 692, 955, 2009. The black inner part is the stellar disk. The grey faint extensions outline the so-called stellar rings, probably the remnants of a satellite galaxy.

termined from the orbital speed of the earth and the other planets around the sun. The orbital speed is a measure of the mass: the mass, that is to say gravity, pulls the gas clouds inwards but a sufficiently high orbital speed prevents this from happening. The larger the mass, the faster the gas must move so as not to fall to the centre. So in other words, if we know the speed and the distance to the centre we can determine the mass within that radius.

Bosma first showed (PhD thesis 1978, and Astronomical Journal 86, 1825 & 1981) that the majority of galaxies show flat rotation curves out to the largest measured radii, indicating that the total mass keeps increasing with radius, other than the distribution of light in galaxies suggest. This is illustrated in Figure 3. This led to the notion of the so-called 'dark matter', as the rotation indicated that there must be more matter present than is observed in the form of gas and stars. This 'dark matter', whose nature has not yet been determined up to this day, plays a fundamental role in modern astronomy and cosmology. In the 1980s, opinions were divided on how exactly the dark matter in galaxies was distributed. "How much is there?" and "where exactly is it?" were important and unanswered questions. Because the neutral hydrogen in galaxies extends much farther than the observable distribution of stars, the WSRT measurements of the movements of the gas in galaxies yielded the best determinations of the mass distribution in these systems. It became clear that there is significantly more matter in galaxies than the sum of all stars, dust and gas and that most of the dark matter resides in the outer parts of galaxies. This led to more detailed modelling of the rotation of galaxies taking into account both the visible and the dark matter. Of these studies the one of NGC 3198 has become the classical example and is shown in Figure 4.

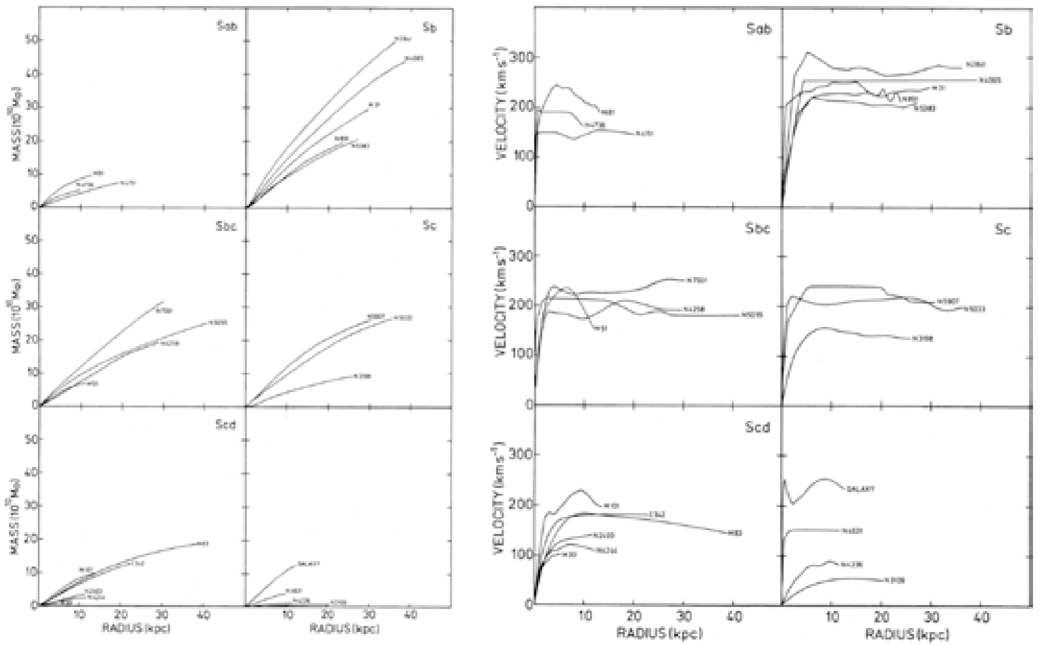
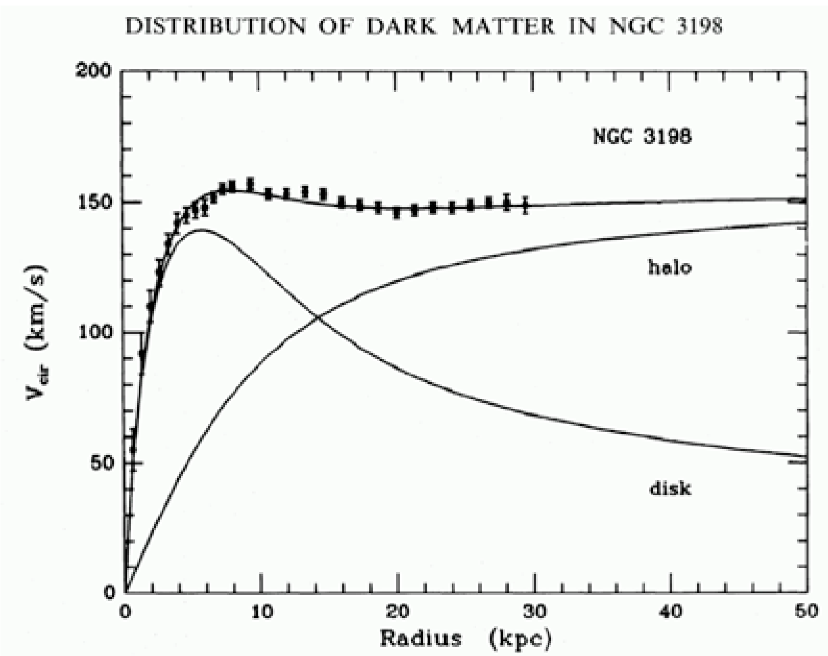


Figure 3: Rotation curves (right panel) and cumulative total mass distributions of 25 galaxies studied by Bosma (Astronomical Journal, 86, 1825, 1981). It is clearly demonstrated that extended rotation curves remain flat and that the corresponding cumulative total masses continue to increase and do not converge to a constant value.

Figure 4: The extended and flat HI rotation curve of the spiral galaxy NGC 3198, illustrating the discrepancy between the measured rotation and the rotation expected on the basis of the measurable mass in the disk, requiring a dark matter halo component. (van Albada, Bahcall, Begeman & Sancisi, Astrophysical Journal 295, 305, 1985)



Another nearby galaxy observed in detail in HI in those early days is Messier 81, a spiral galaxy with three close companion galaxies Messier 82, NGC 3077 and NGC 2976. The studies of Messier 81 showed not only the complexity of rotation curves (its rotation curve is asymmetric) but also the presence of strong non-circular motions in the gas orbits around the spiral arms, caused by so-called density waves, and it became the first galaxy in which the density wave theory was properly tested by Visser (Astron. & Astrophys. 88, 149/159, 1980, Bash & Visser, Astrophysical Journal 247, 488, 1981). In addition, it appeared that there is a lot of filamentary HI in between Messier 81 and its companion galaxies, clear signs of the effects of gravitational interaction (like the ocean tides on the earth caused by the presence of the moon) between Messier 81 and its satellite galaxies. We now know that such HI structures exist in many groups and can be used to probe whether galaxies in a group have strong tidal interaction or not. Figure 5 shows Messier 81 and the first images of the intergalactic HI.

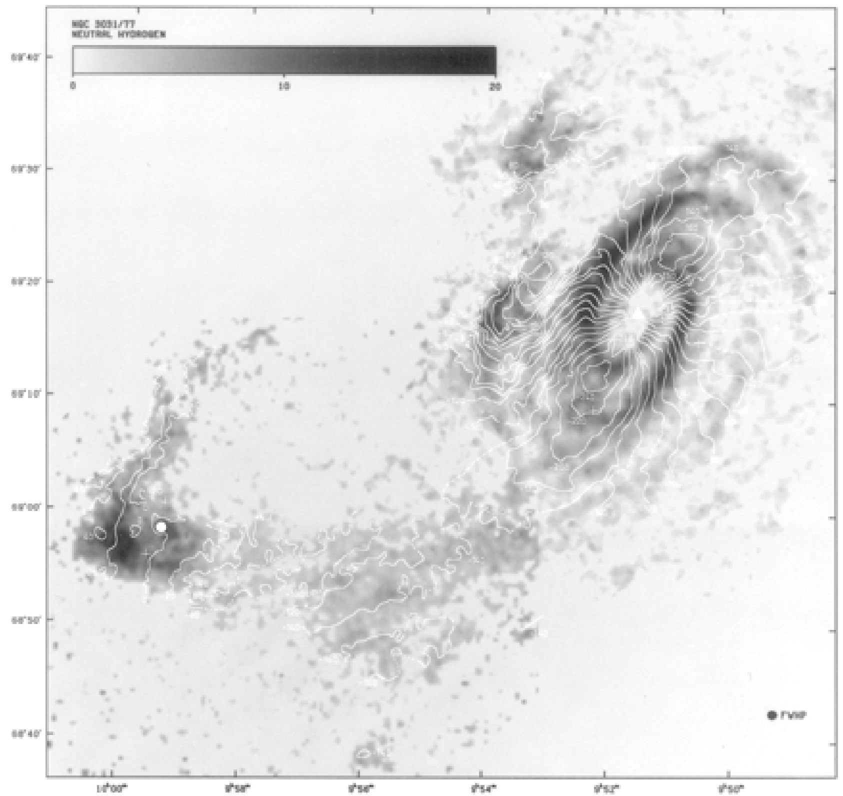


Figure 5: Early HI observations of Messier 81 and NGC 3077 showing both the streaming motions in the isovelocity contours crossing the spiral arms of Messier 81 and the HI bridge and other intergalaxtic HI features between Messier 81 and NGC 3077 to the lower left (van der Hulst, Astron. & Astrophys., 75, 97, 1979). The white triangle and white dot indicate the optical centres of Messier 81 and NGC 3077 respectively.

Roughly every 10 years a significant improvement in the capabilities of the WSRT has led to new breakthroughs. The first was the construction, in the late seventies, of a digital correlator that could handle significantly more than 80 channels: no less than 5120. This increased the observing speed for emission by neutral hydrogen by a factor of four and also enabled a single observation to cover a larger range in velocity coupled to a much higher velocity resolution than before. This made it possible to observe not only the hydrogen in large groups and clusters of galaxies, but also to detect the neutral hydrogen absorption of strong continuum radiation in radio galaxies and active galactic nuclei (so-called AGN) over a wider range of velocities. At the same time, the WSRT was expanded with two more telescopes, placed 1.5 km eastward of the existing array, thereby increasing the angular resolution of the radio images by a factor of two. This was of great importance to a wide range of research areas, including HI research. The number of galaxies for which HI observations were available increased from about a dozen to several tens, slowly enhancing our knowledge of the distribution of HI and via the rotation curves the distribution of all matter in many types of galaxies. Figure 6 gives a quick overview of theses that have as a main component the study of rotation curves and dark matter in galaxies.

Figure 6: A selection of PhD theses that have used WSRT data to study rotation curves, dark matter and the Tully-Fisher relation in galaxies.

In the period 1992 to 2002 an ambitious observing program started entitled WHISP (the Westerbork HI Survey of SPiral galaxies, van der Hulst, van Albada & Sancisi, 2001 ASP Conf. Proc. 240, 451). The aim was to observe 1000 galaxies in the nearby universe, covering a wide range of galaxy types and luminosities with as its main goal to study the systematics of the dark matter (and

the Tully-Fisher relation) in galaxies of different type and mass and in different environments. When the WHISP program ended just after the turn of the century some 290 fields had been observed. The data were used for a number of theses on dark matter in galaxies, warps in galaxies, and to date the data are still widely used for many different projects, ranging from studying the relation between star formation and the gas density in galaxies to studies of the HI diameters in galaxies. The WHISP data continue to be an important resource until in a few years the blind surveys with Apertif and other instruments will have produced similar data for many more galaxies.

Halfway through its long observing period the WHISP project profited from a third major upgrade of the WSRT, the installation of the so-called multi-frequency-front-ends (MFFEs). For 21cm line work these brought a significant increase in sensitivity as with the MFFEs not only the movable telescopes had cooled receivers, but also the ten fixed telescopes were now equipped with 30K systems, increasing the sensitivity by a factor two. In addition the first digital correlator was replaced by a new system that has no less than a quarter of a million channels and is also equipped with adequate analogue hardware that can measure a total bandwidth of 160 MHz. This corresponds to a speed range of about 32000 km/s, or one can measure galaxies at distances between a few thousand and more than a billion light-years away. Detecting the weak hydrogen signal in such distant systems requires long observations to acquire sufficient sensitivity. This has been done for a small number of select areas.

Though WHISP had mostly focused on gas rich galaxies (and therefore mostly spiral and irregular galaxies) this now opened the way for observing gas poor systems, such as the elliptical and S0 galaxies, much more effectively. This led to the successful programs of first observing a modest sample of such galaxies taken from the SAURON project and then to the much larger program called Altas3D, described below.

In 2004 the WSRT Programme Committee decided to allocate a considerable amount of observing time to observe neutral hydrogen in a large sample of early-type galaxies, until then believed to be depleted of gas. The increased sensitivity and capabilities of the (then) new MFFE receivers offered an ideal opportunity to begin studying this class of galaxies in detail. So called early-type galaxies, in particular the elliptical galaxies are different from spiral galaxies in that their light distributions are smooth, do not form new stars and, therefore, consist mostly of old stars. Therefore they are often referred to as red-and-dead! Optical images of spiral galaxies on the other hand clearly show that they consist of a mix of stars, gas and dust and that many new stars are continuously formed. The reason for this difference is thought to be the lack of gas in early-type galaxies, inhibiting the production of stars. Early work with the WSRT (e.g. van Driel & van Woerden, 1991 Astron & Astrophys. 243, 71) showed that some early-type galaxies do have gas, except that the densities of the gas are too low for star formation. Obtaining a complete view of the gas content of early-type galaxies was, however, limited by the sensitivity of the available radio telescopes until the MFFE upgrade of the WSRT.

The first group of elliptical galaxies for which deep HI observations were obtained, was the so-called SAURON sample, earlier studied in detail using the innovative optical integral field spectrograph SAURON on the *William Herschel Telescope* (WHT), providing the complete view of the stellar component and of the ionised gas. The deep HI observations from the WSRT complemented this and showed that the picture regarding gas in early-type galaxies is much more complicated than expected.

The first surprise was the high detection rate: HI was detected in about a quarter of galaxies, a much higher fraction than expected. Another surprise was that in many cases the HI was distributed in a regular disk. Figure 7 shows NGC 4278, where a regular HI disk can be seen, twice as large as the optical body of the galaxy. Like in NGC 4278, the majority of the cases show a strong similarity between the kinematics of the HI and that of the ionised gas, suggesting a similar origin of the gas, while the gas kinematics can be quite different from that of the stars (as in Figure 7). In some cases, the gas is even counter-rotating to the stars suggesting that the gas has an external origin.

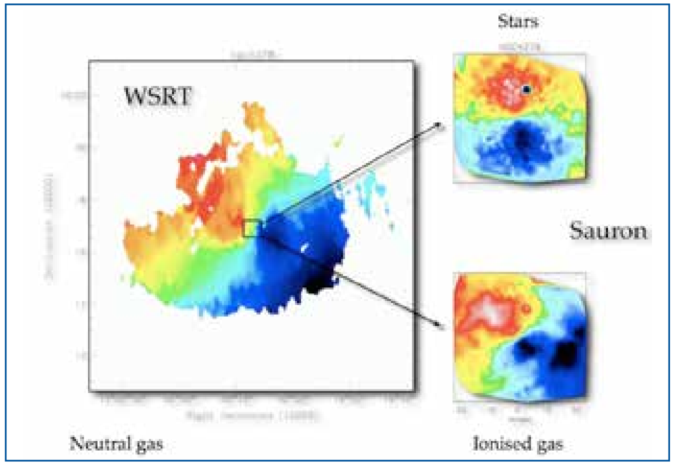


Figure 7: Images representing the motion of gas and stars in the galaxy NGC4278. The red regions are moving away from us, the blue are approaching us. The figure represents a nice example of the complementarity of the data. On the left the neutral hydrogen as measured by the WSRT, on the right the ionized gas (bottom) and stars (top) as measured by the integral field spectrograph SAURON on the William Herschel Telescope on La Palma. Note the different scales that the two instruments can image: the SAURON data cover the very inner part of the HI image (black box).

Figure 8 shows NGC 4203, a good example of the (huge) extent of the HI disks found in some of the early-type galaxies. The amount of HI in early-type galaxies is often similar to what is found in spirals, but because of the huge extent, the typical surface density of the gas is much lower, too low to form stars. This illustrated that the difference between early-type galaxies and spirals is not so much that early-type galaxies do not have gas, but that the density of the gas is too low for active star formation. The results of this study have been presented in Morganti et al. Monthly Notices RAS 371, 157, 2006 and Oosterloo et al. Monthly Notices RAS 409, 500, 2010.

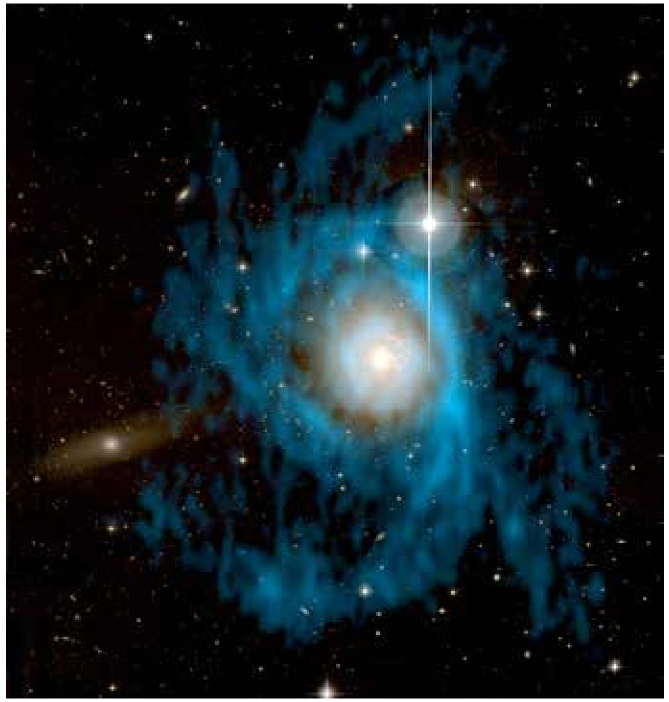
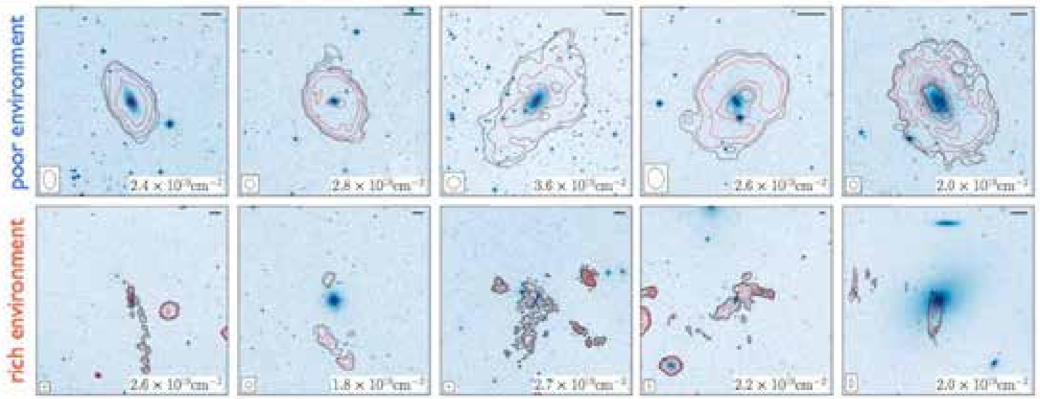


Figure 8: HI emission in NGC4203 (blue in the image) observed by the WSRT (Yildiz, M.K et al. 2015, Monthly Notices RAS, 451,103). They find that the gas system (shown in blue) consists of two separate components: an inner regularly rotating ring and an outer irregular HI structure which likely has an external origin.

This study led to a larger project aimed at observing more than 100 early-type galaxies part of a volume-limited, complete sample: the Atlasd3D survey (Cappellari et al. 2011 Monthly Notices RAS 413, 813). The WSRT observation of this much larger sample (Serra et al. 2012 Monthly Notices RAS 422, 1835) not only confirmed the previous results, but also showed that the distribution of the HI (regular disks versus compact disks and HI tails) depends strongly on the environment of the galaxy. This is demonstrated in Figure 8. Early-type galaxies in poor environments (top row in Figure 9) typically host giant HI disks with radii up to many tens of kpc. The disks are very regular, indicating that the host galaxy has been undisturbed for a very long time.

Figure 9: Examples of HI in early-type galaxies in different environments (Serra et al. Monthly Notices RAS 422, 1835, 2012)



The situation is very different in richer environments like galaxy groups and at the outskirts of galaxy clusters (bottom row in Figure 9). Here the HI typically has a very disturbed morphology. In many cases long HI tails stretch from the host galaxy into the surrounding space, demonstrating that some gas may have recently been removed from (or accreted onto) the galaxy. Early-type galaxies in these environments are evolving because of the interaction with what is around them. At even denser environment densities, in the very centre of clusters, hardly any HI is found in galaxies. These galaxies have moved through the hot cluster medium and were stripped from their HI on their way to the cluster centre where the intra-cluster medium is most dense.

The elliptical galaxies described above have been favourite targets for another reason. The super-massive black holes (SMBH) hosted in their centres can emit spectacular collimated radio jets shining bright at radio wavelengths and interacting with the surrounding medium. Because of the strong radio continuum emission it becomes possible to study the gas in these very central regions because it reveals its presence by absorbing the continuum emission. This allows us to trace the presence of even small amounts of gas: The stronger the radio source, the easier it is to detect even a small HI cloud. The initial studies of HI absorption (also done with the WSRT) focused on tracing HI gas with velocities within a few hundred km/s of the systemic velocity of the host galaxy, i.e. looking for gas from circumnuclear disks or similar structures around the SMBH.

The expansion of the WSRT backend to broader bandwidth (with the IVC) offered the unique opportunity of tracing the HI gas over a much broader range of velocities. This technical capability led to a major surprise when in 2003 HI absorption observations of the nuclear region of the radio galaxy 3C293 showed that, in addition to a narrow absorption component associated with a circumnuclear HI structure, a very broad, blueshifted and very shallow wing of absorption was detected, extending to velocities more than 1000 km/s lower than the systemic velocity. Figure 10 shows a cartoon illustrating the HI absorption profile and the location of the narrow and the broad velocity component. This has now been seen in a number of other AGN (e.g. Morganti et al. 2005 Astron. & Astrophys. 444, L9). The first inventory of how common these HI outflows are, has also been done with the WSRT. A large HI absorption survey, comprising observations of more than 250 radio galaxies, has been done in preparation for larger surveys with Apertif, the new Phased Array System on the WSRT). This was, in fact, the last survey of the old Westerbork Synthesis Radio Telescope. The project (see Maccagni et al. 2017, Astron. & Astrophys. 604, 43) went on until the WSRT was gradually refurbished for the installation of the Apertif 'Phased Array Feeds' (PAFs) on the WSRT.

In some radio galaxies, the HI outflow has been further studied at higher spatial resolution using Very Long Baseline Interferometry reaching even parsec scales (Morganti et al. 2013, Science 341, 1082; Schulz et al. 2018). These observations have given direct proof that, at least in some cases, the outflowing gas is accelerated by the interaction with the expanding radio jets. The data have shown that the outflows appear to be relatively massive, therefore likely playing a relevant role in the feedback.

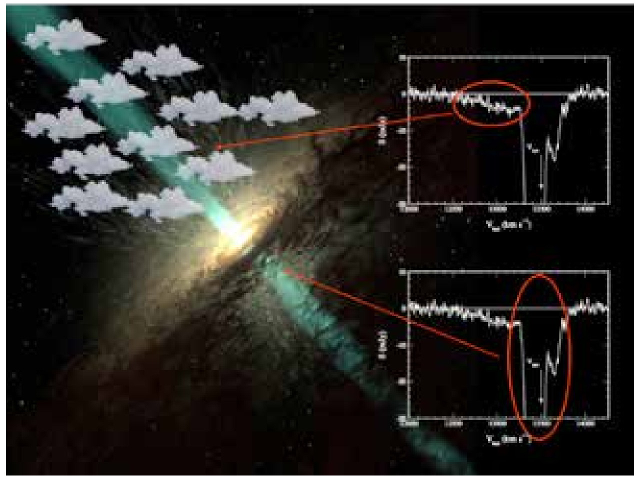


Figure 10: Cartoon (taken from Morganti & Oosterloo 2018, Astron. & Astrophys. Rev.) showing the HI absorption observed in 3C293 obtained with the WSRT (Morganti et al. 2003 Astron. & Astrophys. 593, L69) and the components of gas that can produce the various parts of the absorption profile.

In the nineties, another discovery had drawn attention: The first clear observational evidence for gas with anomalous velocities in galaxies. The most impressive high velocity complex found thus far in any galaxy is the large complex in M 101 shown in Figure 11. This discovery and the improved sensitivity of the WSRT with the MFFEs stimulated projects aimed at deep observations of a small number of galaxies in order to reveal the low column density HI in and around galaxies, in particular gas with anomalous velocities. This allowed hydrogen with low density to be well mapped and has led to a number

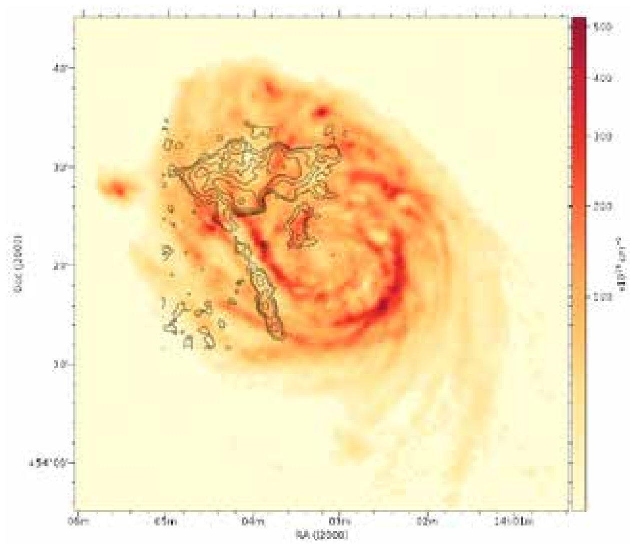


Figure 11: The high velocity gas complex in Messier 101 shown in black contours superposed on the HI column density distribution in orange. The image has been made from recent WSRT observations of Messier 101 by Oosterloo et al.

of interesting insights that are directly related to the influx of fresh gas from the surrounding area as well as the redistribution of gas in a galaxy as an ultimate result of the formation of especially massive stars. They produce powerful stellar winds at the end of their short (100 million years) existence and then explode as supernova. Both processes drive hydrogen gas out of the plane of the system and form the so-called 'Galactic Fountain'. This gas circulates above the surface for some time and then falls back under the influence of the gravity of the disc. This concerns a small part of the total hydrogen in a system, but this process has now been convincingly demonstrated on the basis of sensitive measurements. All this has led to an image in which galaxies are constantly in a dynamic balance in terms of their gas disk: a part of the gas leads to the formation of stars, these drive out and in turn displace part of the gas and in addition 'fresh' gas into the galaxy from the intergalactic space.

A prime example illustrating such phenomena is the edge-on galaxy NGC 891, shown in Figure 12. Its gas disk is clearly 'fatter' than the stellar disk and in addition it shows long filaments that witness the infall of fresh gas into the galaxy. NGC 891 is a remarkable object. Its hydrogen distribution was observed many times with the WSRT throughout the fifty years of its existence and rather than becoming more extended radially the increased sensitivity revealed this galaxy to get 'fatter' and 'fatter' in HI and revealed the vertical distribution of HI to very low levels, also uncovering the ~20 kpc long filaments in the northwest. These observations showed that the bulk of the gas above and below the disk is corotating with the disk, though at a somewhat lower velocity. There is no information on the velocities perpendicular to the disk because NGC 891 is seen edge-on and the Doppler motion only measures velocities along the line of sight. Deep observations of the face-on galaxy NGC 6946 (Boomsma et al. Astron. & Astrophys. 490, 555, 2008) did, however, reveal that over the entire HI disk there is gas with vertical motions that can be interpreted as gas flowing out of the disk into the halo as a result of a 'Galactic Fountain' like process.

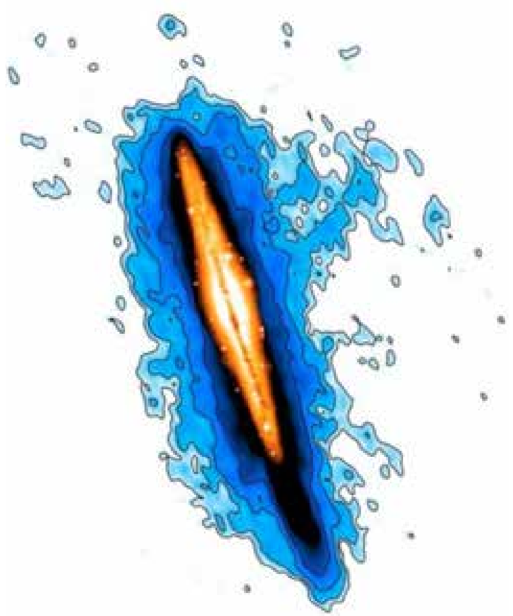
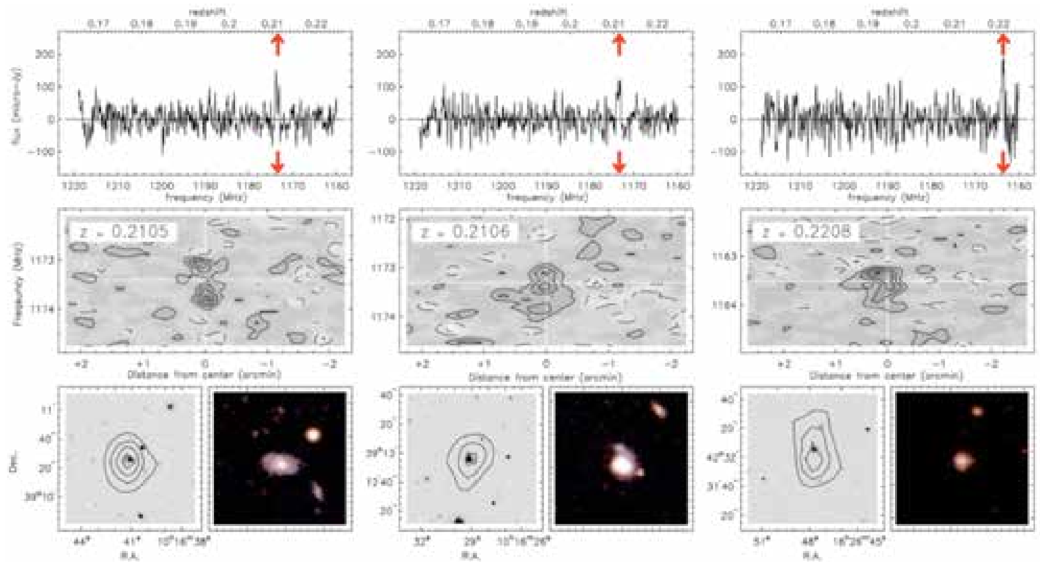


Figure 12: The neutral hydrogen distribution in the edge-on galaxy NGC 891. The contours and blue shades represent the neutral hydrogen emission. The orange figure in the center illustrates the light distribution. The neutral hydrogen data are taken from Oosterloo, Fraternali & Sancisi, Astronomical Journal 134, 1019, 2007). Image courtesy T.A. Oosterloo.

These discoveries led the the "HALOGAS' project (Heald et al. 2011, Astron. & Astrophys. 526, A118) which obtained deep WSRT observations (120 hours per object) of 24 galaxies of various type and mass to study these phenomena. The project still is ongoing, but constitutes the most sensitive collection of high-resolution HI observations of galaxies for a while to come.

The increased sensitivity and bandwidth of the WSRT have greatly helped the study of HI in distant galaxies. Ultra-deep (in this case 1000 hours) observations of two distant clusters of galaxies Abell 963 and Abell 2192 (z ~ 0.2 or a distance of ~800 Mpc or a look-back time of 2 x 10^9 year) managed to detect more than a hundred galaxies at this distance (epoch) and allow a characterization of the HI properties of galaxies not only in the range of environments that are present around these clusters, but also at a time when the universe and hence the galaxies were of 2 x 10^9 year younger than in the local universe. Figure 13 shows three of the detections in Abell 963. These observations, combined with similar studies of clusters and groups in the nearby universe begin to show that a number of physical processes are at work: Gas stripping by an external medium, gas removal by gravitational interactions, increased start formation and its consequences (winds, gas removal) by stripping and interactions, and in addition the continuing accretion of gas from the cosmic web and re-accretion of material removed in an earlier phase. The precise balance of these processes, many of which can only be diagnosed by observing the HI in and around galaxies, is yet unclear and requires observations of many more objects in many different stages of their evolution and different environments. New surveys, as with Apertif (see below), will provide such information.

Figure 13: three detections in the deep observations of the cluster Abell 963 at z~0.2. Courtesy Marc Verheijen, see also Verheijen et al. Astrophysical Journal, 668, L9, 2007



The story of what the WSRT has contributed to our understanding of HI in galaxies will be incomplete if we let the smallest galaxies and galaxies in the emptiest corners of the universe unmentioned. The most effective way to find galaxies with extremely low HI contents is with a telescope with a large collecting area, single dishes such as the Arecibo telescope, the Parkes telescope or the

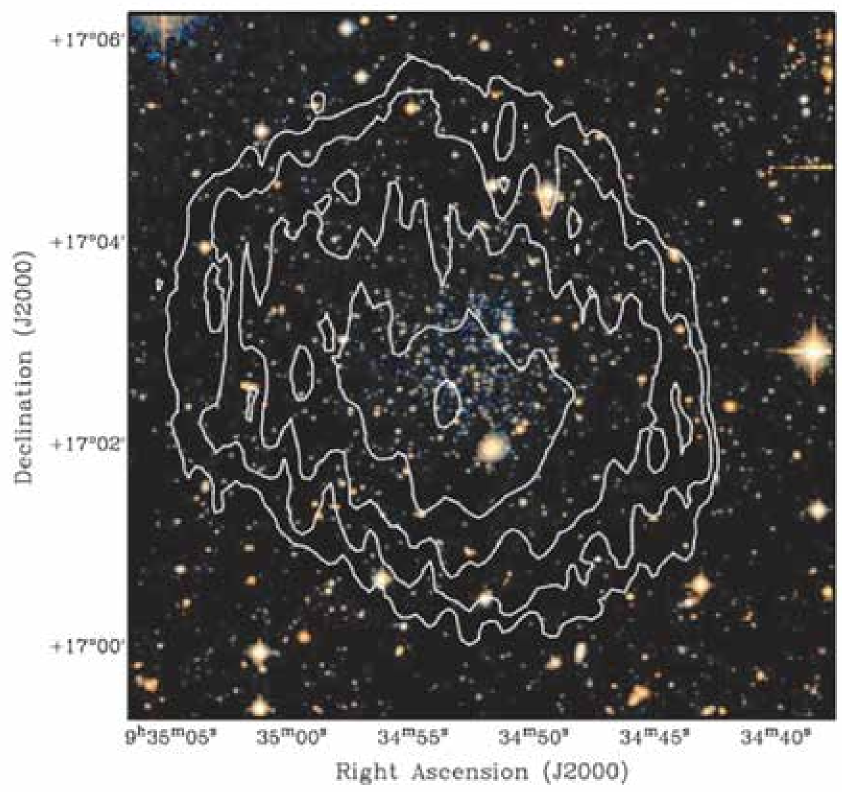


Figure 14: The neutral hydrogen distribution in dwarf galaxy Leo T, superposed on an optical image of the galaxy. Note that the optical galaxy is barely visible and hardly larger than the fourth hydrogen column density contour. Data from Ryan-Weber et al. Monthly Notices of the Royal Astonomical Society, 384, 535, 2008.

Green Bank Telescope. Surveys with the former two have indeed found objects with very low HI mass, but only follow up observations with instruments such as the WSRT have been able to confirm that the HI is in an extended, low surface brightness, rotating disk. An interesting and perhaps prototypical example, found first in the Parkes HIPASS survey and later confirmed optically and observed in detail with the WSRT, is Leo T (Figure 14), an optically insignificant galaxy, extremely rich in HI, albeit several orders of magnitude less in HI mass than typical spiral galaxies. These HI rich, dwarf galaxies have very low mass and thick HI layers, with very little rotation, though also here estimates of the total mass indicate that they are dominated by gas but also have dark matter.

The emptiest areas in the Universe are the so-called voids, huge regions, still expanding with the general expansion of the Universe, where the galaxy density (and general matter density) is at a record low. These voids are not completely devoid of galaxies and are populated by on average smallish galaxies, which do have very similar properties to their counterparts in denser environments. HI observations with the WSRT have contributed to this notion from the point of view of their HI properties. The earliest such observations were done already in the nineties, in the Boötes void, but superseded by more recent observations (carried out in 2008-2009) of galaxies in 60 carefully selected voids. Many of

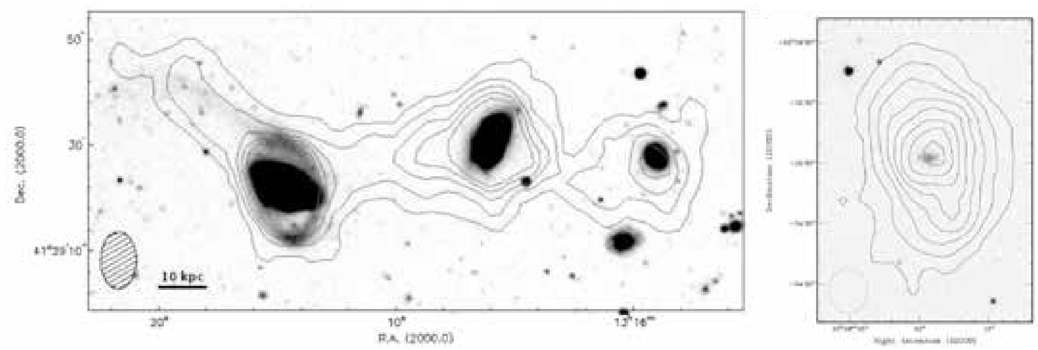


Figure 15: Two examples of galaxies in voids. The right panel shows a huge hydrogen disk around a small galaxy, misaligned with the stellar body as the gas was accreted from a wall between voids. The left panel shows three galaxies, connected by a hydrogen filament, perhaps the residual gas of the structure from which the galaxies formed in the void. Data from Beygu et al. Astronomical Journal, 145, 120, 2013,

the small galaxies in voids appear to have companions, show signs of gravitational interaction and there may be at least two examples of galaxies in formation: The case of a galaxy with a huge polar disk which aligns well with a thin large scale structure wall between voids from which gas may have been accreted, and the case of three galaxies apparently connected by an HI structure which could be the remnant of a large scale structure filament from which these galaxies formed. Figure 15 shows these examples.

The various improvements in the WSRT system made it possible to map the hydrogen in and around a large number of galaxies, and in the last 20 years, about five hundred galaxies have been systematically observed. This does not give a complete but it's a very good overview of the properties of galaxies, both in terms of the distribution of the hydrogen in and around the systems and the distribution of the total mass on the basis of the movements of the gas. These studies form the basis for the knowledge of hydrogen in and around galaxies and are a guideline for large surveys with future radio telescopes.

The last big change for the WSRT is to equip 12 of the 14 telescopes with so-called 'phased array feeds' (PAFs). A PAF is a system of several closely spaced antennae that each sample the incoming radiation field. The signals of the elements can be combined with each other coherently to cover multiple positions in the sky. The WSRT PAF system (called Apertif, www.apertif.nl) consists of a matrix of 11 by 11 antennae that together sample 39 positions in the sky and give the WSRT effectively a 25 times larger field of view. This means that in one day an area in the sky can be measured that previously took 25 days. The realization of this technique is based on years of experience in dealing with complex radio interferometry techniques, combined with the gigantic increase in computing power of modern processors. Apertif will be ready by the end of 2018 and the WSRT will then start a large-scale survey of a significant part of the northern sky. With this, our knowledge of neutral hydrogen in and around galaxies will advance significantly, not only because we will have hydrogen images of many more galaxies, but also because a large number of different environments in the nearby universe will be mapped, both empty and densely populated areas. The latter is very important as the environment also determines which

Figure 16. Recent hydrogen image of Messier 101, made with the WSRT and its sensitive MFFEs. The blue emission is the hydrogen in this galaxy, superposed on the optical image shown in orange colours. The large extent of the hydrogen as compared to the light distribution from stars and nebulae is very clear from this image. Image made from recent WSRT observations, courtesy Tom Oosterloo.

processes of gas accretion and gas removal dominate galaxy evolution, as described above. So with Apertif the WSRT will enter its fifth youth even before the respectable age of 50 is reached and will routinely be able to image large areas of sky and produce images such as the recent HI image of Messier 101 (Figure 16). A comparison with the very early WSRT image shown in Figure 1 demonstrates the degree of improvement the WSRT has undergone since the opening in 1970.

The development of even more sophisticated software to enable proper and careful analysis of the neutral hydrogen data has also been very important during the past several decades. The Groningen Image Processing System (GIPSY, www.astro.rug.nl/~gipsy) still is a primary platform for the analysis of neutral hydrogen observations. It has been designed in the seventies and eighties with a keen eye for new software techniques incorporating novel ideas, in particular for image processing applications. It has been developed further over the years, has been transferred to new hardware and computing platforms and is now used by hundreds of astronomers around the world for the analysis of neutral hydrogen data from not only the Westerbork telescope but also from various similar instruments.

Chapter 13 HII region studies with the WSRT[1]

Frank Israel*

1. Making plans

Well before the official opening of the WSRT, astronomers in The Netherlands were already considering how to put the powerful new telescope to good use. Many of them, with Oort in the forefront, were eager to expand their observing horizons beyond the boundaries of the Milky Way galaxy, until then the effective limit of almost all Dutch astronomical research.

These early ideas can be traced in a number of Synthesis Radio Telescope Project internal technical reports (ITRs). In the years 1967 and 1968, five of these[2] deal with possible observing programmes, and Oort provided an inventory of 15 worthwhile programmes in ITR-74, only four of which were Galactic. In part of ITR-65, Van Woerden briefly discussed HI line measurements of Galactic clouds and globules, but the only one specifically focusing on Galactic objects is ITR-48[3] by Brouw, Habing, Pottasch, Tolbert, and Van Woerden. The authors were all located at the Kapteyn Lab in Groningen, except Brouw who together with Habing was yet to obtain his PhD. The five topics were polarization, supernova remnants, planetary nebulae, HII regions, and the Cygnus-X region. Remarkably, Habing did not write the section on HII regions (which he later studied with the WSRT) but supernova remnants (which he did not). Instead it was Tolbert who discussed three lines of investigation: mapping of individual HII regions and studying early star formation; tracing Galactic structure using recombination lines, and mapping the HII region population in other nearby galaxies (among them M 33 and M 101). Before 1975, all three had been carried out with the WSRT.

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1 This is a personal account of work with the WSRT in the first five years of its operation. A detailed overview of these results and their scientific context can be found in Habing & Israel, 1979 Annual Review of Astronomy and Astrophysics, Vol. 315, p. 345. A much more complete and broader treatment of how we came to learn about star formation and the role of HII regions can be found, among other places, in the book by H.J. Habing, 'The Birth of Modern Astronomy 1945-2015' published by Springer, New York, 2018/2019.

2 ITRs 44, 48, 49, 65, 73

3 Undated, but must be second quarter of 1967

2. Flags on stellar construction sites

HII regions were of particular interest because they flagged sites of recent star formation, and thus might provide a clue as to how stars form. The most massive and luminous stars so rapidly consume their nuclear fuel that they never grow old and are always young, so to speak. As they are also very hot, they radiate intense ultraviolet (UV) light in all directions and thereby ionize the surrounding HI into ionized hydrogen (HII). This process had been elucidated many years earlier by Strömgren (1939) in a classical paper that established the fundamental relationship of HII regions to massive young stars. The ionized volume, hence the size of the HII region, depends on the flow of UV photons from the star that maintains the ionized state of the gas. In a homogeneous HI gas, the isotropic UV photon flux should create a spherical HII region, the so-called Strömgren sphere. As foreground dust clouds absorb nebular light, observed nebular shapes could be quite different. This all made a lot of sense and the only thing left to do was to determine how dense stars form out of tenuous HI gas.

This was still very much a mystery at the time. Observations in the 21-cm line readily established that the Galaxy was full of neutral hydrogen (HI) clouds. Cores in these clouds would somehow contract into stars. For a while, it was speculated that the so-called Bok globules, seen silhouetted against distant stars or bright nebulae, were isolated cores ready to collapse into stars. When looked at more closely, they seemed to be very stable, however. HII regions were more promising, albeit in an indirect way. Wasn't it reasonable to expect stars to be also forming today where they formed yesterday? Shouldn't the present-day properties of HII regions tell us about yesterday's formation of their exciting stars?

Such HII region studies were rather few and limited in scope. Dust extinction impeded global structure studies. Most attention had been lavished on eye-catching luminous nebulae many of which had already been noted by Messier two centuries earlier, such as the Lagoon nebula (M 8), the Omega nebula (M 17) and the Orion nebula (M 42). In his Galactic Plane survey, Westerhout (1958) had measured the radio emission from these and other nebulae. The radio observations were not hampered by extinction, and some of the nebulae he found, such as W49 and W51, were completely obscured by dust and optically invisible. Unfortunately, the half-degree beam of the Dwingeloo telescope showed only the largest nebulae and did not provide any useful detail. Some ten years later, just before the advent of aperture synthesis telescopes such as the WSRT, the state of the art in HII region radio research was contained in a series of papers published in 1967 by Mezger and colleagues using the newly built NRAO 140-ft telescope. At a frequency of 5 GHz, they obtained a resolution of 6'4, six times better than Westerhout's survey at 1.4 GHz. They were primarily interested in hydrogen recombination line measurements, but in their first paper (Mezger & Henderson, 1967) they provided the template for the analysis of subsequent HII region radio continuum observations, including the detailed equations for numerical analysis of thermal radio emission. Even with a six-fold increase in resolution, their maps of the thirteen Westerhout sources were still decidedly 'blobby', although they did reveal multiple components. Most importantly, they inferred the presence of 'compact' HII regions (size less than 0.5 pc, electron density typically 10^4 cm^{-3}) from fits to the multi-frequency radio continuum, even though these compact HII regions were not obvious in the radio maps. Mezger et al (1967) suggested that this new class of HII regions might be associated with known sources of OH-maser emission, and speculated that they were the ionized insides of 'cocoons' of gas and dust out of which the embedded O-star had recently formed.

3. Start a new field of research ...

This was the situation when the WSRT became operational in June 1970 with a clear focus on galaxies and distant radio sources. Among the first two dozen WSRT proposals only three targeted Galactic objects: the confused Cygnus-X region (W7: Baars & Wendker), X-ray sources (W13: Braes & Brouw), and indeed HII regions (W24: Israel, Habing, and De Jong). This was to be the topic of my Ph.D. program, supervised by Habing. We believed that the superior resolution of the WSRT (initially 24" at 1.4 GHz, soon followed by 6" at 5 GHz) would reveal the HII region structural detail necessary to infer how their stars formed in the first place.

When we started the project, the three of us were far from being expert in the field. Habing quickly set about to repair this, first by travelling to Bonn to meet Mezger who had become one of the MPI-directors in charge of the 100-m Effelsberg telescope at the occasion of a visit by Wynn-Williams who in turn had just finished his PhD. at Cambridge University. Using the new Mullard Radio Astronomy Observatory's One-Mile Telescope, the first operational aperture synthesis telescope, he had produced the first wonderful maps of HII regions concentrating on Westerhout sources like those before him. His *pièce de résistance* was a spectacular map of the obscured radio source W3, situated next to the optical nebula IC 1795 (Wynn-Williams, 1971) at a resolution of 6.5". This was fully 60 times better than Mezger's single-dish maps, and still almost a factor of four better than we could then accomplish with the WSRT. Green with envy we learned what could be done.

As it turned out, Mezger was more interested in recombination line studies, still beyond the WSRT capabilities, than in the continuum work we were about to embark on. Wynn-Williams was about to start a post-doc with Neugebauer and Becklin in California and redo his radio maps in the mid-infrared (Wynn-Williams et al., 1972). There appeared to be little scope for collaboration. After our return to Leiden, Habing cleverly invited some 35 experts

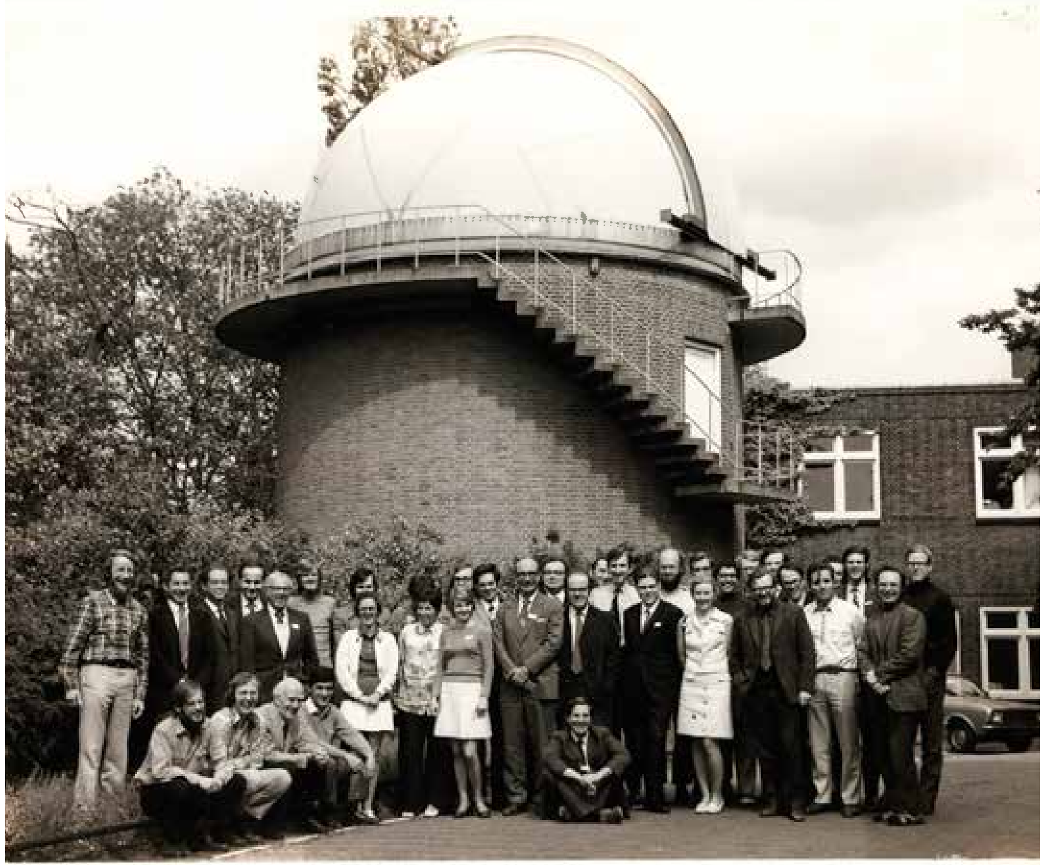

Figure. 1: Leiden, June 23, 1974. Participants of the Workshop 'The Nature of Dense Condensations in HII Regions', held at the Sterrewacht.

Front row, left to right: Frank Israel, Thijs de Graauw, Jan Oort, Nino Panagia, Lanie Dickel, Marie-Claire Lortet, Lise Deharveng, Donald Osterbrock, Franz Kahn, John Shakeshaft (seated) Heinz Wendker, Lindsey Smith, John Dyson, Peter Mezger, Stuart Pottasch.
Back row, left to right: Jaap Baars, E. Capriotti, C.C. Lin, Harm Habing, Mayo Greenberg, Vincent Icke, David Flower, unidentifiable, Piet Bedijn, Jorn Wink?, Wilhelm Altenhoff, Michael Grewing, Teye de Jong, David Hummer, Peter Biermann?, unidentified, T. Cato, unidentified, Malcolm Walmsley, unidentified, Woody Sullivan, Harry van der Laan.

Photo credit: Sterrewacht Leiden/J.F. Planken

to attend a three-day workshop on 'The Nature of Dense Condensations in HII Regions' at the Leiden Sterrewacht in June 1972. This brought us up to speed and also provided us with very useful contacts. It was the beginning of a very productive collaboration with the French optical astronomers Lortet-Zuckerman, Deharveng, and Caplan, who provided us with detailed information on nebulae and exciting stars in exchange for our radio results.

4. Intricacies of carrying out the Sharpless HII region program

Although the WSRT was not the first synthesis array telescope to take a detailed look at HII regions, it did have the advantage over the Cambridge One-Mile Telescope that it was much faster and more sensitive thanks to it having four times as many dishes, each with twice the collecting area, and seven times as many instantaneous baselines. We thus could start a program much more ambitious in terms of numbers of HII regions than our colleagues in the UK. Right at the beginning, we decided to avoid most of the Westerhout sources whose sizes are comparable to or exceeding the primary beam of the WSRT and extend well beyond the first grating response in a single 12-hr synthesis measurement. Instead, we turned to the very extensive catalog of large and small optical HII regions by Sharpless (1959). With this catalog as a guide, I spent days selecting suitable candidates (bright, and smaller than 10' in size) for observation on Palomar Sky Survey (PSS) prints. These came in two varieties: prints from red plates and from blue plates. The former highlighted HII regions as their H-alpha emission fell within the band, and the latter predominantly showed the blue exciting stars. For decades, the PSS prints and plates were among the most indispensable tools of observational astronomy. In the end, we chose about three dozen out of 313 Sharpless HII regions for observation with the WSRT.

Enthusiastic but inexperienced, we did not get off to a smooth start. It had not yet fully dawned on us that an interferometer is a great way of losing source flux, and we had failed to specify that the shortest interferometer spacing should be really short, i.e. that we required the shortest available spacing of 36 m (170 wavelengths). As the telescope group had scheduled our extended source observations for some unfathomable reason at baselines starting five times longer, the radio maps we got out of the reduction pipeline showed a lot of noise and next to no flux. In one object, we did see an intriguing chain of very weak compact sources, but later re-observation with better baseline coverage revealed that these were merely insignificant brightness fluctuations in the extended emission.

Right among the first few usable observations was a map of Sharpless 158 (S 158, also known as NGC 7538). We still missed most of the flux with a shortest baseline of 90 m but what we did see was similar to the optical brightness distribution, with the notable exception of a completely obscured, unresolved source at the southern edge of the optical nebula. An accurate position for the OH maser source detected earlier had just become available, and we found that it coincided precisely with what we imaginatively called an ultra-compact HII region (size less than 0.15 pc, electron density 10^6 cm^{-3} or higher). Combing the literature, we came up with several other cases where an OH maser was precisely coincident with a compact thermal source (Habing, Israel, & De Jong, 1972). The close association of (ultra)compact HII regions with powerful OH masers argued strongly in favor of Mezger's speculation that these objects were the actual birthplaces of young and luminous massive stars.

Almost as a curiosity, we noted a discrepancy between the radial velocity determined by optical and radio methods by as much as 10 km s^{-1}, which we did not understand, but paid no further attention to. It should have reminded us of the even larger velocity discrepancy of 16 km s^{-1} between the stars and the gas of the Orion nebula, that I had noticed as a student more than two years earlier, but we didn't realize it at the time. I remember thinking this was peculiar but nobody else seemed to think it was a big deal and I did not pay further attention to it. As it turned out, that was a mistake: never ignore discrepancies you don't understand. It should also be noted that the prototypical emission nebula, the Orion Nebula, was among the poorest possible prospects for WSRT observing. Its declination is close to zero, which means that the WSRT observing beam is extremely elongated in a north-south direction and that up to half the time individual dishes are shadowing one another. We did observe Orion A in 1973, but the map was useless even though the emission from the bright Huygens part of Orion is compact enough. A decent map was obtained only in 1976, when Martin and Gull (1976) managed to combine E-W spacings observed with the Cambridge One Mile Telescope with those from the N-S arm of the Owens Valley interferometer, and successfully clean the resulting 'dirty' map.

Figure 2: Leiden, August 22, 1974. Jan Oort introduces the last ever astronomical colloquium in the Sterrewacht lecture room where Alar Toomre was attempting to convince a skeptical audience that galaxies really do interact and merge. Many of the of the people depicted were actively involved in Westerbork operations and observing programs.

Front row: Luc Braes, Ernst Raimond, Harm Habing, Walter Jaffe, Edwin Valentijn.
Second row: Jean Casse, Richard Strom, Ger de Bruijn, Hans van Someren Greve, Xander Tielens.
Third row: Roelf Marten Duin, Frank Israel, Johan Degeweij, Steve Bajaja.
Fourth row: Gerard Uiterwaal, Wil van Breugel, unidentified, George Rossano. The person way in the back behind Uiterwaal might be Ron Harten.

Photo credit: Sterrewacht Leiden/L.A. Zuiderduin

My sometimes shaky technical knowledge was compensated by the generous help of Leiden colleagues such as Le Poole, Harten, and Van Someren Gréve who knew a lot more about aperture synthesis methods and reduction techniques and never tired of pointing this out. Van Someren's daily return from the university's central computing facility (CRI) with the latest Westerbork computer output never failed to fill me (and others) with apprehension. The Westerbork reduction pipeline made use of several reduction programs on thick packs of punch cards, to be run one after the other, and each to be controlled by so-called 'stuurkaarten', punch cards with instructions about map sizes and scales, contour levels, etc., provided by the user (me). I found it easy to make mistakes and hard to catch them by reading the smudgy print at the top of the cards. Van Someren had a strong sense of drama when, in front of everybody gathered for coffee, he handed out a minuscule contour map ('your postage stamp'), slowly unrolled a plot that stretched for meters because of a decimal error (`your wall-paper'), wondered publicly about the meaning of a plot containing only a single contour, or conversely, a plot with many contours squeezed together in the noise. Each of these unique products had, of course, taken up lots of computer or plotter time at the CRI.

5. Not so easy ...

Notwithstanding such minor mishaps, a significant HII region database was built up in a few years, including not only 1.4 GHz measurements but also observations at frequencies of 0.6 GHz and 5.0 GHz that in the meantime had become available, published in a number of papers, some together with other authors such as Felli, Harten, Deharveng, most of which formed the bulk of my 1976 PhD thesis. By that time it had become clear that these detailed radio maps told us a lot about HII region structure, but not so much about star formation. Clearly, when one or more luminous stars turned on and rapidly ionized their surroundings, the sudden injection of energy would wipe out almost all clues to the formation process. When fire burns down the house, not much is left of the furniture ... From HII regions we could learn how stars and gas interacted, but not what went on before. Even the obscured ultra-compact HII regions, interpreted as cocoon stars, did not reveal much about their origin.

However, this was not the end of the story. The structure of the very first HII region we closely looked at, S 158 (NGC 7538) was peculiar. Even though the radio nebula was extinction-free, and apparently excited by a single central star, it did not look like a Strömgren sphere at all. We did try to model the very asymmetrical shape by a sphere of gas containing an off-center spherical cavity. The fit was not particularly good. Moreover, we quickly found several other, mostly small, HII regions to be similarly asymmetrical and have a central brightness minimum partly surrounded by a relatively broad shell. While some of these were true windblown shells (most notably NGC 7635: Israel, Habing, De Jong, 1973; Icke, 1973; NGC 6888: Wendker et al. 1975), such an explanation was clearly not feasible for the bulk of these objects: wrong shell shape, wrong energetics. In

Figure 3

Figure 3.1: H-alpha image S 158 (NGC 7538), a small bright emission nebula. The ultra-compact HII region to its south is completely obscured.
Photo credit: Fred Calvert/Adam Block/NOAO/AURA/NSF

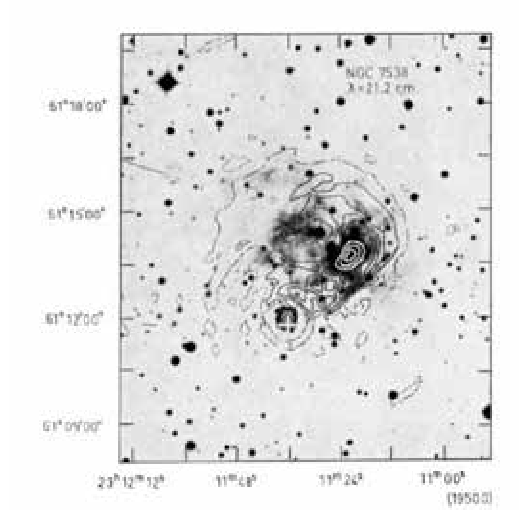

Figure 3.2: S158, WSRT 1.4 GHz, 24" resolution, shortest spacing 90m Habing et al. (1972). The extended emission of the main nebula is only partly recovered. The ultra-compact HII region is prominent. The cross marks the position of the OH maser.

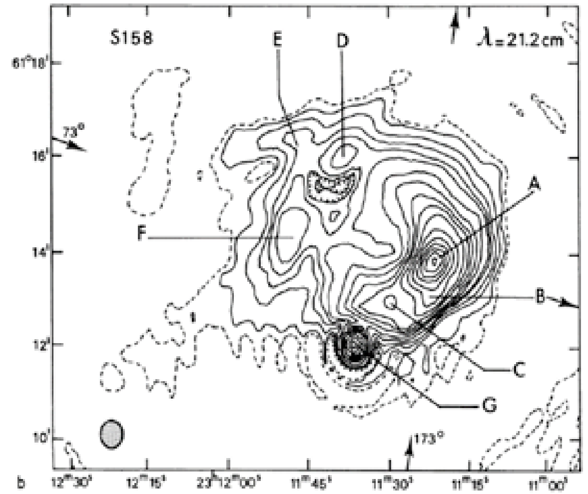

Figure 3.3: S158, WSRT 1.4 GHz, 24" resolution, shortest spacing 36m Israel (1973). The extended emission of the nebula is now fully recovered. The asymmetrical shape, relatively sharply bounded on the right, and diffuse on the left, is characteristic of a blister HII region seen more or less edge-on

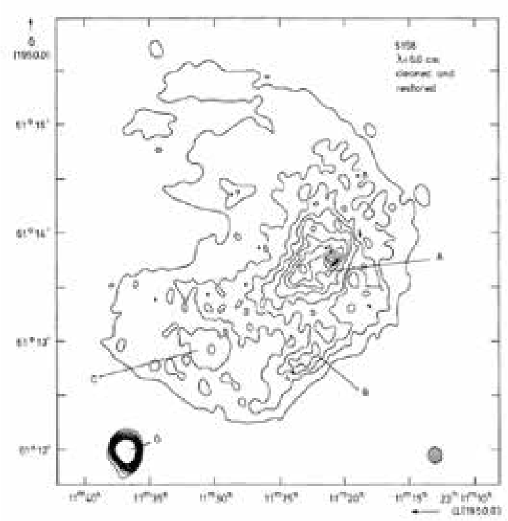

Figure 3.4: S158, WSRT 5 GHz, 6" resolution, shortest spacing 36 m. Israel (1976). The image shows more detail, but the extended diffuse emission is mostly lost. The ultra-compact HII region is still unresolved.

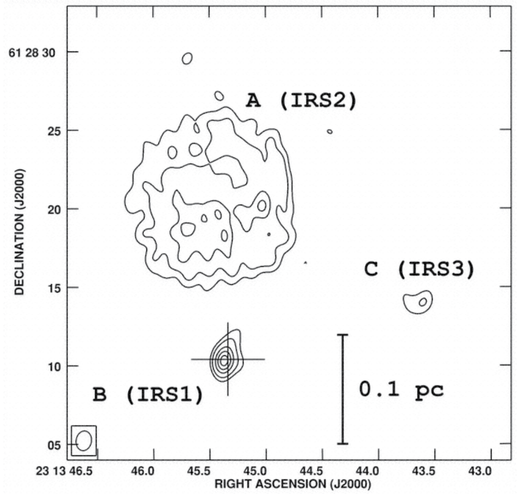

Figure 3.5: VLA B array image (resolution about 1 arcsec) of the ultra-compact object, which turns out to be a group of nebulae each surrounding a newly formed star. From Hoffman et al., 2003 ApJ, 598, 1061

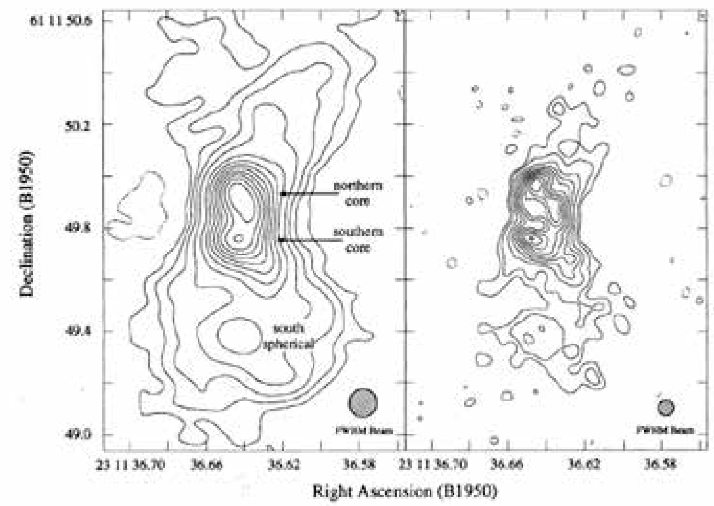

Figure 3.6: Gaume et al. 1995 ApJ 438, 776. 22GHz VLA A configuration (resolution 0."11) image of the brightest ultra-compact object component IRS-1. Even this very small object shows characteristics of a blister.

fact, also the Orion nebula has such a structure, as does Wynn-Williams' source W 3A. Although Strömgren's physical model was beyond reproof, his geometry was way off. HII regions were clearly more complex than a simple Strömgren sphere and this turned out to be true even for the ultra-compact HII regions when these were finally resolved by long baselines at short wavelengths.

This was a very puzzling phenomenon, but all attempts to get colleagues working on HII region models interested frustratingly failed. The answer came in 1974, unexpectedly, as I was leafing through a stack of preprints (no internet preprint server in those days) during a visit to NRAO in Charlottesville, USA. In one of these, Balick et al. (1974) suggested that Orion consists of flows emanating from stars embedded in a small, contracting molecular cloud behind the HII region. They also referred to an earlier paper by Zuckerman (1973) that I had overlooked, in which the Orion nebula was seen as a protrusion on a likewise small molecular cloud. These two papers hit me like a flash of lightning. Here was the vision I was looking for! Clearly, I should have paid more attention to the work of others, having ignored Orion which I wasn't studying, and rather having missed the relevance of the newly (1970) discovered molecular gas. Although Zuckerman and Balick et al. were the first to propose the connection between the ionized nebula and a previously unseen reservoir of molecular gas, they still underestimated the importance of the latter. It took three more years before the overwhelming size and mass of the Orion Molecular Cloud complex (OMC-1) was recognized by Kutner et al. (1977). Nor did the authors dare more than hesitatingly suggest that other HII regions might be similar.

6. Burning blisters

This was a major change of paradigm. The Orion nebula taught us that we had thus far tried to form stars and HII regions completely missing the major ingredient: molecular gas (H_2). In fact, nowadays H_2 has almost completely taken the place of HI, which is considered to be mostly irrelevant to the star formation process. Its inclusion solved the problem of Orion's kinematics that had always been problematical as they never could be made to fit expansion, contraction or rotation in a satisfactory manner. For me, they provided the solution to the observed HII region structures, if I could prove that they were all Orion-like. The opportunity came in 1975 when Habing had arranged that I should visit Thaddeus in New York City for a few months. At the same time that Blair, Peters and Vanden Bout (1975) established that Sharpless HII regions more often than not showed CO emission, I used Thaddeus' Columbia millimeter-wave dish and Vanden Bout's larger millimeter dish at McDonald Observatory in Texas to systematically measure the velocity difference between the ionized gas and the associated molecular cloud. The available morphological and kinematical data so obtained convincingly showed that almost all HII regions fit a configuration that we compared to a blister on the human skin: well-defined very bright ionization fronts eating into a very much larger molecular cloud from which gas is streaming away into interstellar space, becoming more and diffuse

with increasing distance (Israel, 1976). Only very large, highly evolved HII regions, often resulting from the merger of overlapping HII zones do not fit this description any more. It is interesting to note that this entire insight was but the last in a chain of steps, and that required the combination of two different techniques: aperture synthesis mapping of centimeter-wave radio continuum mapping and single-dish millimeter wave molecular line measurements.

An important consequence of the blister model was that the exciting stars should have formed inside the molecular clouds, but near the edge and not at the center. Subsequently, the gas dynamics were successfully modelled in Tenorio-Tagle's (1979) Champagne model. This state of affairs seemed so obvious that it did not occur to me that it was not common knowledge in the HII region community. In the summer of 1977, I discovered to my surprise that this was nevertheless the case, when I was participating in a workshop on Giant Molecular Clouds. This led me to turn the relevant but unpublished part of the thesis into a separate paper (Israel, 1978) that is occasionally still being cited. For the first but not the last time, it made me realize that whatever familiarity has made obvious to one can be entirely new to others. I still find it amazing that it took everybody, including myself, so long to discover the importance of molecular gas clouds and the nature of HII regions when it was staring us in the face.

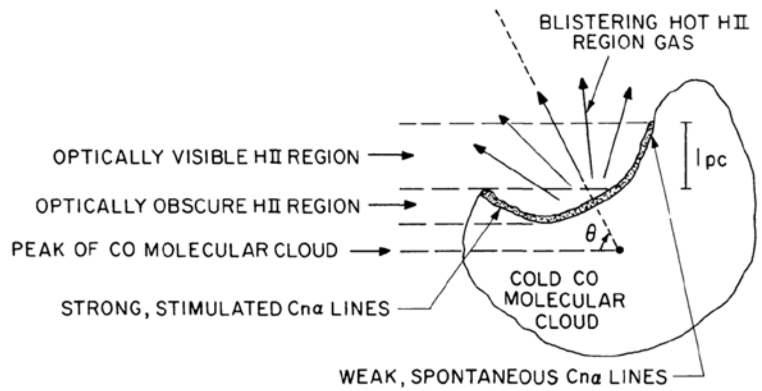

Figure. 4: Schematics of a blister HII region. From Rodney & Reipurth (2008).

7. Slowly, slowly

Missing the obvious kept on occurring. We had no answer to the question why massive stars would preferentially form near molecular cloud edges rather than the center where densities were supposed to be higher. Was star formation always caused by molecular clouds colliding? Observational evidence did not support that. Were molecular clouds perhaps flat and two-dimensional like sheets or pancakes? That did not appear very likely, either. Yet, these suggestions were very close to the solution that once more kept staring us in the face for years. If one looks, for instance, at the very nearby Ophiuchus cloud complex, multiple streamers of gas and dust are immediately obvious. Yet it took the far-infrared maps of the Herschel Space Observatory, launched in 2009, to establish that filaments are ubiquitous, and that molecular clouds are not bulky entities but almost entirely consist of filaments which themselves may consist of tightly wound fibers. Star formation is now thought to take place where filaments interact, and the scales of action approach those where magnetic fields might come into play.

The very one-dimensional structure of filaments makes it unavoidable that stars always form near a cloud edge: there is no other place. It took us over 40 years to see this obvious truth.

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The Solar System

Chapter 14.1 1980: Jupiter's Radiation belts

Imke de Pater*

In 1977, a few days before Christmas, graduate student Imke de Pater spent 5 consecutive 12-hour nights at the Westerbork telescope, anxiously watching the red flickering lights in the dark operating room. She was observing Jupiter, and the telescope array had to work smoothly without any interruptions for 5 nights straight, since she wanted to map every rotational aspect of a planet that rotates in 10 hrs. With Westerbork's east-west array you need to observe an object for 12 hours to build-up a 2-dimensional map, since one short ½ hour observation would give you in essence only a scan through the planet, i.e., shows structure (resolution) only in one direction. The rotation of the Earth during a 12-hour observation provides resolution in both east-west and north-south directions. Using five 12-hour observations, de Pater combined six 25-min snapshots at each rotational aspect of the planet (every 15 deg.) to construct 24 maps to get a full picture of the planet from all viewing angles.

She was not focused on the planet itself, but observed the synchrotron radiation at a wavelength of 20 cm, emitted by energetic electrons trapped in Jupiter's radiation belts (analogous to the Earth's van Allen belts). She used the emission from these electrons to derive the structure of Jupiter's magnetic field and the electron distribution within it, and developed full radial diffusion models for the electrons in a multipole magnetic field for this work. In order to best map out the magnetic field structure, she arranged the dipoles at the telescope in the parallel configuration to optimize sensitivity to circular polarization. This was an innovation at the time! The combination of linearly and circularly polarized emission was optimal to derive the magnetic field structure in Jupiter's radiation belts.

Maps of Jupiter's total and circularly polarized flux density at three rotational aspects of the planet are shown in Figure 1. Most emission comes from electrons near Jupiter's magnetic equatorial plane. In the top figure, the magnetic north pole was directed towards us (longitude 200 deg), and the bottom one away from us (longitude 20 deg), and the middle figure shows a map at an aspect in between (305 deg). The orientation of the magnetic dipole field can be derived from the maps of the circularly polarized flux density (figures on the

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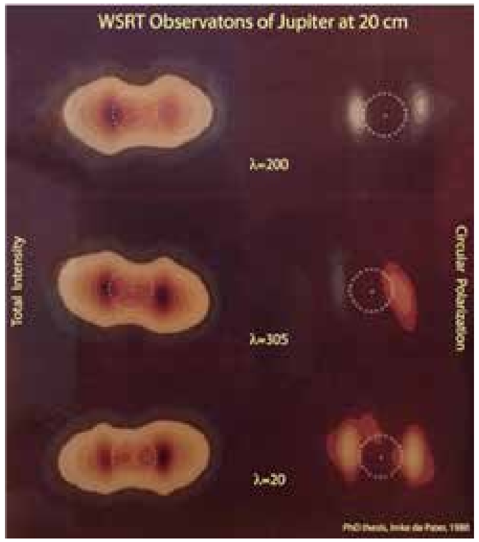


Figure 1. Maps of Jupiter's synchrotron radiation at three rotational aspects, from top to bottom: 200 deg, 305 deg, and 20 deg. The magnetic north pole is facing earth in the top figure. On the left side the total intensity is shown, and on the right side the circularly polarized flux density.

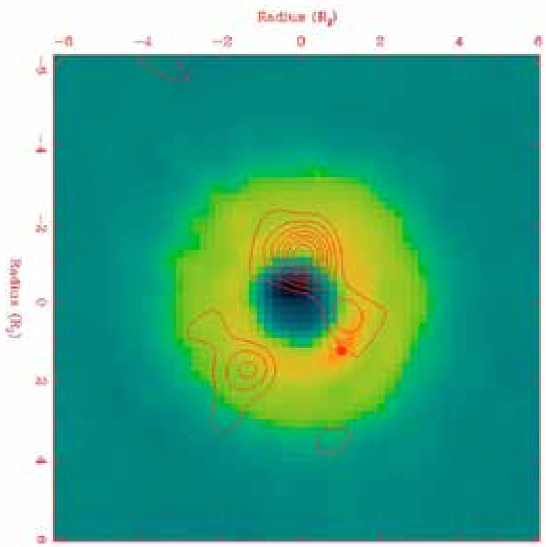


Figure 2. Observations taken with the WSRT telescope on 20 July 1994 during the week that comet ShoemakerLevy 9, a string of 2 dozen comet fragments, crashed into Jupiter. In this figure we look down onto the magnetic equator. The magnetic pole is in the center. The coloured background shows the emissions about 2 weeks before the impact, while the contours show the excess in emission after several fragments had impacted the plan

right side). The simultaneous red and blue colors at the rotational aspect of 305 deg is a clear indication that Jupiter's field is not a simple dipole magnetic field, like that of a bar magnet, but has a multipole character, such that the magnetic equatorial plane, where most radiating electrons reside, is warped like a potato chip. These circularly polarized maps are still now, 40 years later, the best maps ever produced from Earth!

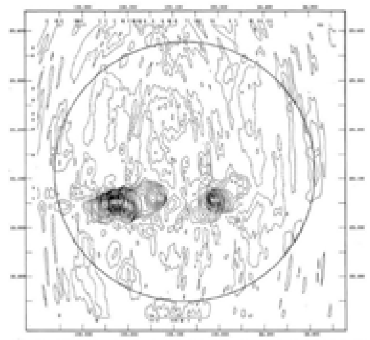
Follow-up observations of Jupiter's synchrotron radiation in 1994, when comet ShoemakerLevy 9 crashed into the planet, reveal a quite distorted view of the radiation belts. Figure 2 shows a view of the magnetic equator seen from above: The colour view shows the emission before the impact took place, while the superposed contours show the excess emission caused by impacts of various comet fragments.

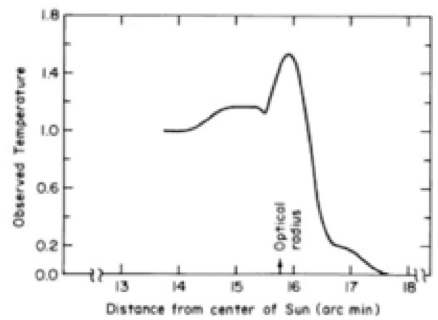
The Solar System

Chapter 14.2 Participating in Solar Maximum Year 1980

Jaap Bregman*

The first solar observations with the WSRT at 21 cm and 6 cm wavelength date back to 1974 and suffered from saturation effects in the receiver chain, for which reason it was necessary to implement a 20 dB solar attenuator in (potentially all) later frontend upgrades. The first solar image with the WSRT by Bregman and Felli published in 1976 is shown in the left figure. The circle marks the white light disk of the Sun with ~0.52° diameter that fills the 21 cm beam of ~0.6° FWHM.





In 1976 Kundu et al observed the quiet Sun at 6 cm with 6 arcsec resolution. The right figure from the 1979 paper shows the limb brightening obtained by model fitting. Auto correlation of a 10 arcmin x 10 arcmin field indicated the first radio supergranulation "network" width ~11,000 km and a radio "cell" spacing of 32,000 km. The brightness temperature of typical network elements is ~2.5 x 10^4 K, while that of the radio cells is 1.5 x 10^4 K.

The solar astronomy group at Utrecht University participated through SRON in the HXIS experiment aboard the Solar Maximum Mission Satellite. This X-ray imager would provide data that needed complementary radio data. Therefore, ASTRON was approached in 1978 whether the new Digital Line Backend (DLB) would be suitable to provide one-dimensional snapshot images at timescales shorter than one second at 6 cm and 50 cm wavelength. A fast readout cycle of 0.1 s was feasible only when one data block with zero time lag cross-correlations was read. In practice it meant that only a single polarization output of the

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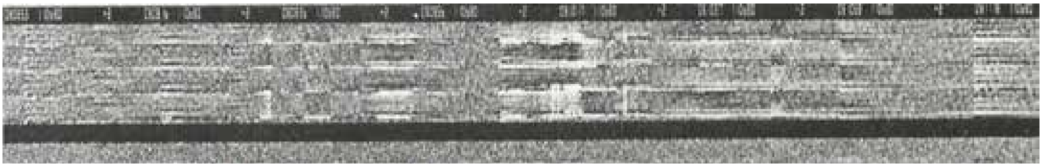
fixed telescope receivers could be used which had to be duplicated to the other polarization input at the DLB to receive there an additional 90 degree phase shift. Then, every fixed movable combination got a sine and a cosine channel for a complex output, just as in the old analogue backend.

Radio emission from the Sun has hardly any linear polarization, so only one orthonormal and one orthogonal linear cross-polarization is sufficient to provide the total intensity and the circular polarization state. Digital cross-correlation in 1bit mode can handle high correlated fractions as could occur when radio bursts provide more power than the background of the quiet Sun. Apart from additional software for fast data block reading and sorting of the data, special calibration procedures provided accurate amplitude, phase and polarization settings for on-line imaging.

In addition to Utrecht University, solar physicists at Maryland University in the USA and Arcetri Astrophysical Observatory in Florence expressed interest in using the WSRT in its new solar mode. Three observing sessions of respectively 8, 10 and 6 days were allocated, mainly at 6 cm, and some observation switching between 6 cm and 50 cm. Utrecht received the 0.1 s data and the other institutes received data integrated longer to 10 s for synthesis imaging.
The Real-time Display System (RDS) provided by Utrecht used an HP 21MX computer that shared the hard disk controller with the 21MXE for data sorting and control of all WSRT subsystems, and the 21MXF for monitoring and tape writing. The RDS Fourier transformed every 0.1 s the total intensity and the circular polarization correlations from the 40 interferometers into fan beam patterns and put them on three display screens, with one for recording on film and two for real time monitoring. This real-time monitoring was essential to prolong an observation when bursting activity had started.



In the figure, we just see time markers at the top and two time series: The top one for total intensity and the other for circular polarization. At meridian transit, each band extends 11.5 arcmin in East West direction and its brightness gives the strength relative to a running mean. Each signal spot on the sun gives four tracks, one being the main lobe of the point spread function, and the other three give the grating lobes each with a different shape (in vertical direction).

Kattenberg et al observed a particular sub-flare on June 13 1980 with the Hard X-ray Imaging Spectrometer (HXIS) and the WSRT in 0.1 s mode at 6 cm and with 3 arcsec highest resolution. A full synthesis image of the flaring region was compared with optical images for proper position alignment. Citing the important scientific result from their paper summary is as follows. “The fast electrons causing the X-ray and microwave impulsive bursts had a common acceleration source, but the bursts were produced at the opposite foot points of the loops involved, with microwaves emitted above a sunspot penumbra.”

Apertif; the next stage

Chapter 15.1 Observing Perspectives with Apertif

Tom Oosterloo*

Radio astronomy has made several fundamental contributions to science. Among these are the detection of the cosmic microwave background, the discovery of pulsars, revealing the existence of active galactic nuclei, and detailed spectroscopic studies of the kinematics of the gas in galaxies which played an important role in the discovery of dark matter. In order to maintain this momentum of discovery, the performance of radio telescopes has to be improved continuously. One of the main limitations of current radio telescopes is their relatively poor performance for doing deep, high spatial resolution surveys of large regions of the sky. In many other wave bands, very large data sets resulting from large surveys covering large fractions of the sky are now available. These data sets have a large impact because they enable statistical studies on a scale not possible before, while they also are, because of their scale, rich sources of rare (and thus interesting) types of objects. The fact that the data from these surveys are publicly available is an important additional factor contributing to their success. This has, to some extent, made astronomy more democratic. Instead of data being available to only those who have access to a telescope, everybody can just take the data from a public archive.

So far, radio astronomy has played a relatively limited role in this 'new' astronomy which is based on large public surveys. A number of important radio surveys are available (e.g., WENSS, NVSS, FIRST, HIPASS, Alfalfa) but they are, compared to the quality and depth of the large surveys in other wave bands, of limited sensitivity and/or spatial resolution. This will change, of course, with the advent of the Square Kilometre Array (SKA), but in the mean time significant improvements can already be realised. One of the main reasons radio surveys are lagging behind those in other branches of astronomy is that, given the sensitivity and field of view of current radio telescopes, it is very expensive in terms of amounts of observing time to survey large volumes of space with sufficiently high sensitivity and resolution. Hence, the available radio surveys are either relatively shallow or have very low resolution, or both. An obvious solution to this problem is to enlarge the field of view of a radio telescope so that large areas can be surveyed much faster. ASTRON has been leading such

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efforts with LOFAR at low frequencies and with Apertif in the 1-2 GHz band. Both instruments will produce very large datasets covering much of the sky and it is likely that these data sets will have a major impact on how radio astronomy is done, as well as on the role of radio data in modern survey astronomy. Given the large frequency range the combined data sets from LOFAR and Apertif will cover, there is, in fact, a very useful and unique synergy between both instruments. They will also play an important role in preparing radio astronomy for the era of the SKA. Below, we briefly describe the main science topics of Apertif in the context of the issues discussed above.

1. Gas and galaxy evolution

One of the main scientific applications of Apertif is to observe large volumes of space in order to make a full inventory of the detailed properties of the neutral hydrogen (HI) in galaxies and see what these can tell about the structure and evolution of galaxies. Detailed spatially resolved studies of the HI in galaxies has been one of the key science areas of the WSRT since the 1970s and these have greatly contributed to improving our understanding of galaxies. However, although these studies have been very successful, these HI surveys, because of the characteristics of the WSRT, have been limited to relatively small samples of galaxies in the nearby Universe (e.g. the WHISP and ATLAS^{3D} surveys) and do not match the large surveys in other wavebands. A few large surveys of the HI content of galaxies have been done with other instruments (HIPASS with Parkes and Alfalfa with Arecibo), but these are based on observations with single-dish telescopes which do not spatially resolve the objects and hence give much less information on the internal distribution and kinematics of the HI in galaxies. They only provide the global HI properties, such as total HI mass and overall rotation velocity. Interesting science can be done with such data and many interesting results have been obtained, in particular concerning global scaling relations such as how the gas content varies with galaxy mass and other global galaxy properties. But these data are less suitable for studying which phenomena drive the existence of these scaling relations because one cannot see what is going on in the galaxies. The key improvement Apertif will bring is that it will provide a very large database of *spatially resolved information* on the HI in galaxies instead of on global properties only. Hence, not only can the scaling relations be investigated, but in addition also the mechanisms responsible for these scaling relations because the processes occurring in the galaxies can be imaged. This huge improvement will bring extragalactic HI studies to a different level and makes it possible to much better understand the scaling relations. Figure 1, taken from a project done with the old WSRT to prepare for Apertif, illustrates what a typical Apertif HI detection will look like and the kind of information Apertif will give on a very large number of galaxies.

With such information, the properties of the neutral hydrogen in galaxies as function of mass, type and environment can be studied in much better detail. For example, analysis of the Alfalfa survey has shown that larger galaxies (i.e. galaxies with more stars) have relatively less gas and also that galaxies in dense environments (i.e. many galaxies per unit volume) also tend to have less gas. The imaging capability of Apertif will allow us to understand the mechanisms driving such trends. Figure 2 shows an example of the processes that influence the gas content of galaxies, based on a WSRT observation of the HI in and around a group of galaxies in a relatively dense environment. Apart from detecting the gas in the galaxies, the data also show a large cloud complex of gas in between the galaxies. This complex resulted from tidal interactions between some of the galaxies, leading to the removal of gas from these galaxies. If such interaction occur often, this may explain the lower gas content of galaxies in environments such as galaxy groups. Apertif will reveal a large number of such cases which will make it possible to obtain a complete overview of the mechanisms that control the gas content of galaxies.

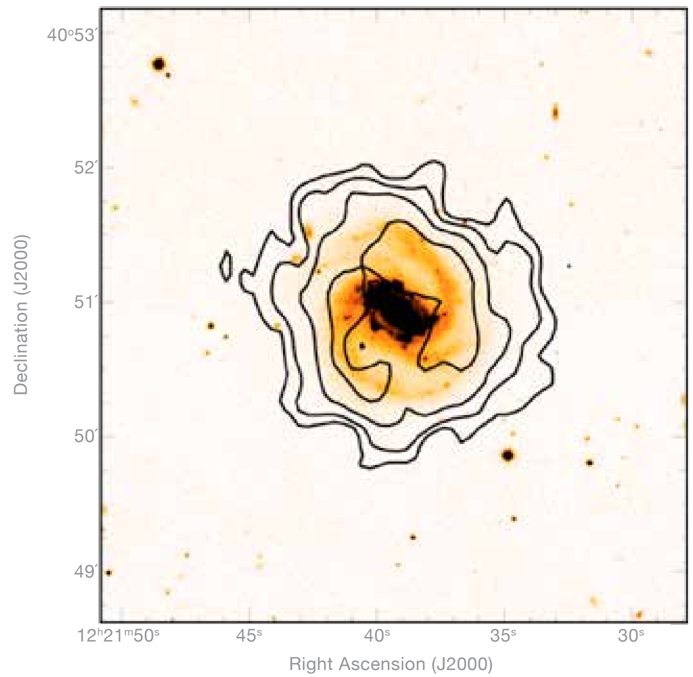


Figure 1. Illustration of what a detection will look like at the typical distance of a galaxy in the shallow HI survey. on top of an optical image taken from the Sloan Digital Sky Survey. The HI data were taken with the 'old' WSRT as part of a project to prepare for the Shallow Apertif HI survey (Wang et al. 2013, MNRAS, 433, 270). The spatial resolution of the HI image is 30 arcsec. Contour levels are 8, 16,32, 64 10^{19} cm^{-2}.

In addition, the broad observing band of Apertif allows, for the first time, to detect large samples of distant (and hence younger) galaxies. This means that the *evolution* of gas in galaxies with redshift can be addressed. The improvement offered with Apertif will be dramatic. Currently, we know about the HI in about 40,000 galaxies, of which 99.9 % are from single-dish observations of galaxies in the relatively nearby Universe out to look-back times of at most 0.5 Gyr. Hence we can only study how galaxies have evolved over such a relatively short period compared to the age of the Universe (which is about 13.7 Gyr). The surveys done with Apertif will result in more than one hundred thousand spatially resolved detections, most of which will be of galaxies above $z = 0.05$, i.e. up to look-back times of 3 Gyr. Hence the evolution of the gas properties of galaxies can be studied over a much larger time span.

One of the main issues in this context is the role gas and gas accretion plays in the evolution of galaxies. In general, all stars in a galaxy form from the gas in that galaxy. The observed levels of star formation in galaxies is such that the time scale on which all gas in a galaxy should be completely consumed by star formation is typically of order of 1 Gyr, i.e. much shorter than the age of the Universe. Therefore one would expect to see a fast decrease with time of the average gas content of galaxies. In the past, the levels of star formation in galaxies were even higher, leading to even shorter depletion time scales for the gas in distant galaxies. However, this is not observed: the typical gas content of galaxies is almost constant with time, also on time scales longer than 1 Gyr. This is very puzzling and clearly something is missing in our understanding of how galaxies evolve. Apparently the decrease of the gas reservoirs in galaxies is offset by some mechanism, for example the accretion of new supplies of gas.

One possibility is that galaxies accrete gas from the inter-galactic environment. Interestingly, most of ordinary matter in the Universe is not located in galaxies, but is still 'freely floating' in the large spaces in between galaxies in the form of warm, ionised gas. Modern numerical simulations predict that, given the right conditions, part of this intragalactic gas cools and falls into galaxies, providing a channel by which galaxies can acquire fresh gas and thus keep their gas supply to higher levels. In the last decade, several deep WSRT studies have been done to try to detect this gas accretion and some very interesting results have been obtained. Figure 3 shows an example from a deep WSRT observation of the edge-on disk galaxy NGC 891, a galaxy very similar in size and type as our Milky Way. Given that the galaxy is seen edge-on, one can study the vertical extent of the HI. Figure 3 shows that large gas reservoirs are detected outside the galaxy. Part of this gas is connected to a gas cycle which exists in disk galaxies in the form of gas being blown out of the galaxy by supernovae connected to the star formation in the galaxy. At later times, this gas will rain back onto the galaxy. However, another part of the gas has kinematics which is not consistent with this gas cycle and is possibly gas that is being accreted from outside. Due to the large amount of observing time needed to make images like the one in Figure 3, only very few galaxies have been studied for the presence of such gas accretion and our picture of the role of accretion is very incomplete. The Apertif surveys will reveal many cases of this gas accretion and will provide crucial information on how galaxies can acquire gas and will contribute to understanding this fundamental aspect of how the gas content of galaxies evolves with time.

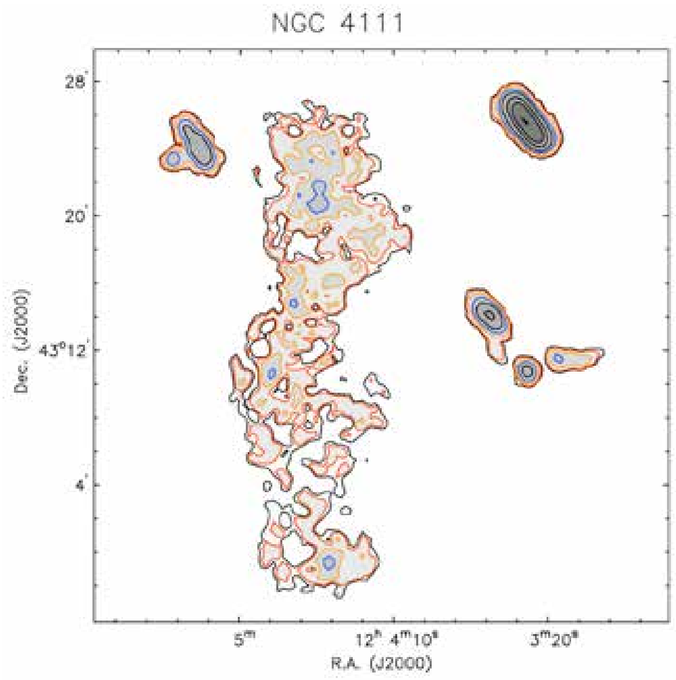


Figure 2. HI image of a large intra-galactic HI cloud in a group of galaxies, illustrating one of the type of features the Medium-Deep Survey will reveal in large numbers. This cloud shows that interactions between the galaxies have occurred which is relevant information for studying how the galaxies evolved. Contour levels are 2 (red), 5 (orange) and 10 (blue) x 10^{19} cm^{-2}. The faintest contour corresponds to the detection level of the Medium-Deep survey.

2. The smallest galaxies, and smaller.

One other key topic for Apertif is to investigate the limits of galaxy formation. The very smallest galaxies are very vulnerable objects. Their gravitational field is very weak and it does not take much to disturb such galaxies, or even to destroy them. In addition, the gas densities in these small galaxies is so low that the gas is not able to cool anymore into dense gas clouds, something which is necessary to form stars. Hence, it is expected that below a certain mass, galaxies cannot exist anymore, either because they have been destroyed by larger neighbouring galaxies, or because they were so small that no stars can have formed. It is not known what this lower limit to galaxies is. Knowing this limit is important because it gives vital information on the conditions occurring in the very early Universe when galaxies first form and which inhibit the formation of the smallest galaxies.

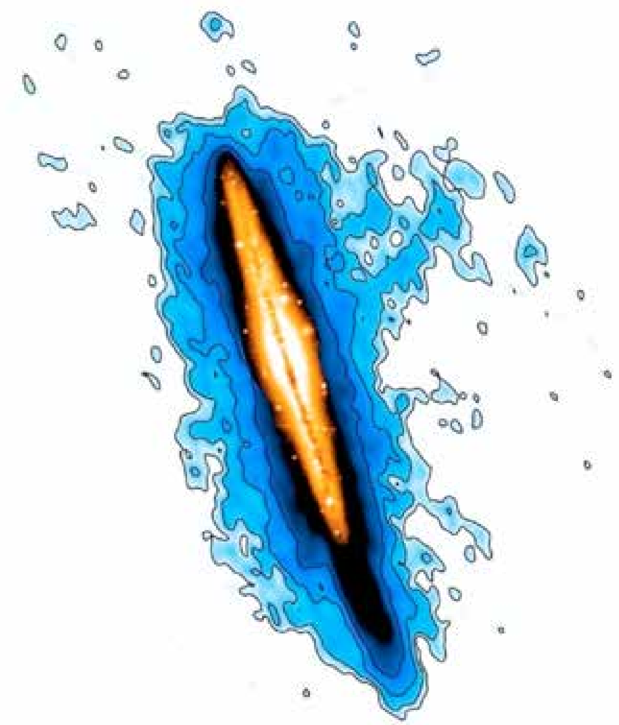
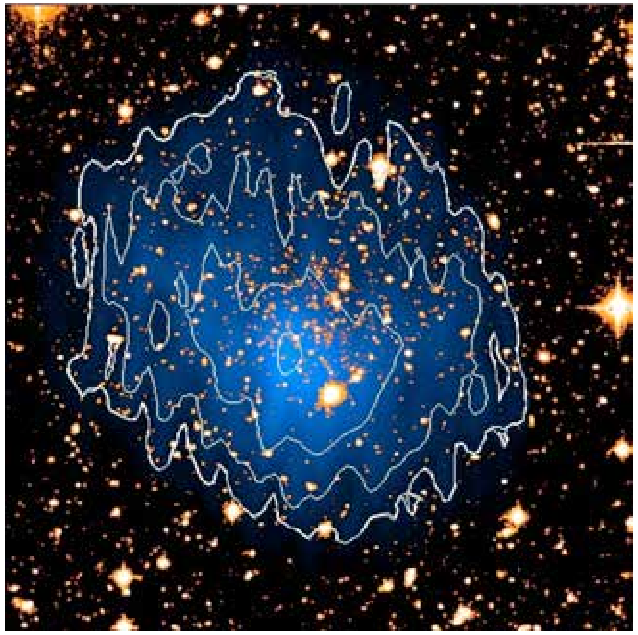


Figure 3. Image of HI in the edge-on galaxy NGC 891 as obtained from a deep WSRT observation (Oosterloo et al. 2007). The orange depicts the stars in this galaxy, the blue the HI. The data clearly show that the HI extends well above and below the stellar disk of NGC 891 with, in particular in the NW, large streamers of gas. Detailed study of the kinematics of this gas shows that a large fraction of this extra-planar HI corresponds to HI blown out of the disk by supernovae connected to the star formation in the disk. This gas will rain down on the disk at later times. Another large part of the gas (e.g. the NW streamer) cannot be part of this gas cycle because its kinematics is not consistent with it. Possibly this 'anomalous' gas is gas that is being accreted from intergalactic space

The smallest galaxies are expected to be very gas rich (i.e most of the ordinary matter is in the form of gas, not in stars). This is because gas may exist in the galaxy, but it is not dense enough to form stars because the gravitational potential well is not strong enough to create densities high enough for star formation. Only one or two examples of such very small, very gas rich galaxies are known. One example is shown in Figure 4 which shows Leo T as observed with the WSRT. Leo T, located about 400 kpc from the Galaxy, has an HI mass of just above 105 Msol and a stellar mass about 1/5-th of the HI mass, so it is gas dominated. In the optical, Leo T is hardly visible, but in HI the galaxy is very bright. Several cosmological models predict that objects like Leo T should not exist because the conditions in the early Universe were such that star formation in objects of the size of Leo T was not possible. Yet, Leo T does exist indicating that our understanding of the early Universe is not complete. It is clear that we have to know much more about how many objects like Leo T, or even smaller, exist and in which galaxy environments they are more likely to be found. In this way we obtain important constraints on what the early Universe looked like.

Because these small galaxies are small and therefore faint, they can only be detected in the very local Universe, up to distances of a few megaparsec. Hence, to survey a cosmic volume large enough to be able to detect a reasonable number of such small galaxies, the only viable strategy is to survey a large region of the sky. This will be made possible thanks to the large field of view of Apertif and it is expected that Apertif will discover a large number of systems like Leo T, providing important input for cosmological models.

Figure 4. Image of Leo T, the smallest gas bearing galaxy known. The grey scale depicts the optical image of Leo T, visible as the small concentration of stars in the centre (most stars in the image are Galactic foreground stars). The contours show the HI distribution as observed with the WSRT.



3. AGN and AGN feedback

All large galaxies have a super-massive black hole (SMBH), typically a 100 million times more massive than the Sun, in their centre. Such a SMBH will accrete material from its immediate surroundings, making it even more massive. This is a very violent process, creating extreme physical conditions around the SMBH. As a result, not all the accreted material falls in the SMBH, but a significant fraction is ejected away from the SMBH, often in the form of narrow jets of plasma at very high speeds (close to the speed of light). If this happens, the object is called an Active Galactic Nucleus (AGN). The plasma jets interact with the interstellar medium of the galaxy, creating massive, fast galactic outflows of gas by which galaxies can lose a significant fraction of their gas supply. This has a large impact on the ability for the galaxy to form stars because less gas means less stars can form. In particular for large galaxies, this process is thought to play an important role in their evolution.

Given the enormous amount of energy involved, one would expect that these outflows consist of hot, highly ionised gas. However, one of the surprises in the last decade, and to which the WSRT has made important contributions, has been that in many objects these fast outflows are instead mainly composed of cold (10-100 K) gas. Such cold gas outflows are detectable as very broad HI absorption profiles in the spectrum towards a bright radio continuum source (see Figure 5 for an example). It is not well understood why the outflows are predominantly cold. Given the relevance of fast gas outflows for galaxy evolution, it is important to understand this and so improve our understanding of these outflows.

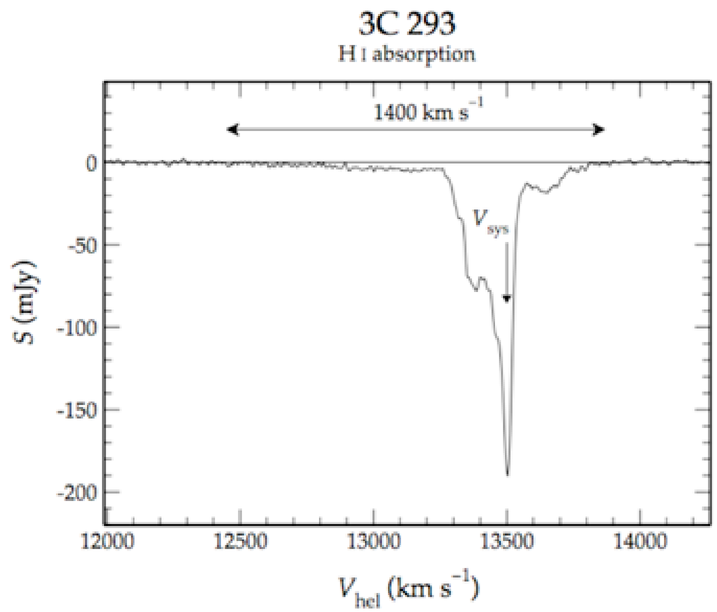


Figure 5. Detection of a fast, cold outflow in the radio galaxy 3C293. HI absorption is detected over a very large range of velocities. The deep component is caused by the normal interstellar medium in this galaxy. The broad, shallow component toward lower velocities is due to the fast outflow of atomic hydrogen, driven by the AGN in the centre of NGC 293.

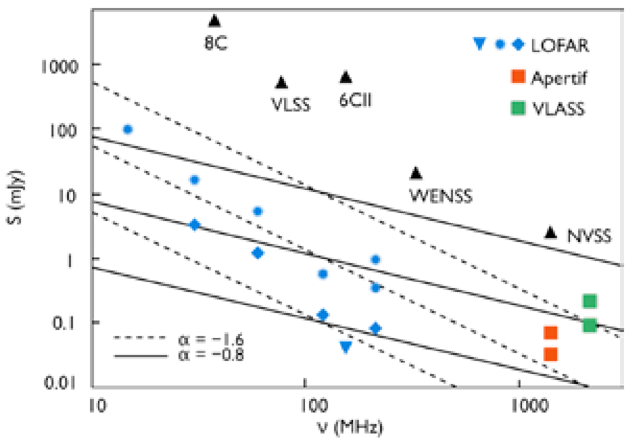


Figure 6. Comparison of the various existing and planned continuum surveys. The lines illustrate the slope of the spectrum of typical radio sources

Only a few dozen cases of cold gas outflows are known. Progress has been made in understanding them, but there is a very large variety in the possible conditions around the SMBH. For example, some AGN are much more powerful than other AGN (by many orders of magnitude) and the conditions (temperature, density) of the gaseous medium around the AGN can also be very different from galaxy to galaxy. Currently available observations have not covered yet the possible parameter space, limiting a full study of these fast outflows.

Obviously, the large Apertif surveys will allow to inspect the HI spectrum towards every radio continuum AGN in the survey volume. It is expected that several hundred cold outflows will be discovered, covering a much larger parameter space than available currently. This will greatly help in making better models of the mechanisms driving these outflows. Moreover, this survey for cold outflows will be blind, i.e. not only of pre-selected subsamples of sources but of every source in the survey. This will reduce selection effects.

4. Radio continuum and the synergy with LOFAR

Because of the broad observing band, every Apertif observation can be used for HI science as well as for studies of the radio continuum of galaxies. This means that the Apertif HI surveys will also result in a deep, high-resolution continuum survey over the same area. The information from this continuum survey can be used to address many topics relating to galaxy evolution. For many galaxies, the radio continuum emission is caused by the star formation in these galaxies. Hence, the Apertif continuum data forms a nice complement to the HI information on the gas properties and will help address the issues discussed above.

The improvement offered by the Apertif continuum survey is very significant. For example, compared to the NVSS (the main continuum survey done with the VLA), the Apertif survey will be about a factor 50 deeper and will have a spatial resolution a factor 3 better (see Figure 6). But an important and unique strength of the Apertif continuum surveys is the synergy with the LOFAR surveys and this will remain an important advantage over any other instrument until SKA1-Mid and SKA1-Low will become available. The relative sensitivities of LOFAR and Apertif match the spectrum of the typical radio source.This implies that most sources will be imaged by both instruments with similar signal-to-noise and resolution. This, for sources detected in both surveys, flux density measurements at 60, 120 and 1400 MHz will be obtained, thus spanning more than a factor 10 in frequency range. This wide frequency coverage is extremely valuable for understanding the nature of the detected sources.The resulting radio colour-colour diagrams will be a powerful tool to spectrally discriminate between radio sources with extreme radio spectra such as diffuse emission from clusters, very distant radio galaxies and GPS/CSS sources. For nearby resolved sources it will instantly yield spectral index and spectral curvature maps, a very rich source of information to constrain many physical parameters and processes.

Exploring the time-varying Universe

Chapter 15.2 ARTS, the Apertif Radio Transient System

Joeri van Leeuwen*

Compared to the pre-2017 Westerbork SRT, the factor 40 increase in field-of-view enabled by Apertif allows for all-sky surveys with unprecedented sensitivity and speed. ARTS, the Apertif Radio Transient System, extends this wide-field Apertif system to both high time and angular resolution, enabling precision neutron-star timing, unique searches for fast transients such as pulsars and Fast Radio Bursts (FRBs), and extremely sharp imaging through VLBI. ARTS is a tied-array beamformer and a time-domain back end that turns these new receivers into high-speed and very high resolution cameras.

Apertif on WSRT, 2018

Looking for new pulsars and FRBs

Throughout the Universe, many short bright radio bursts go off. Some of these are emitted by pulsars, acting as Galactic radio lighthouses. Others originate from far outside our Galaxy, and appear to represent enormous explosions.

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Such Fast Radio Bursts (FRBs) are extremely bright flashes of radio light that travel billions of light years to reach Earth. They were discovered a decade ago, but their nature continues to be largely unknown. Given the energies involved we expect that both the pulsars and the explosive bursts can provide fundamental insights into matter and gravity, which permeate our Universe. Thousands of FRBs must go off in the sky every day, but only a few dozen have been seen (Petroff et al. 2017).

To improve our understanding of pulsars and FRBs, we need find more and study these better than before. Given their unpredictability and short duration, millisecond bursts, these new discoveries can only happen with instruments that have high sensitivity, a wide field of view, and can measure fast, fleeting events.

ARTS is such an instrument: it combines the revolutionary new Apertif front ends (the eyes), with an exceedingly powerful hybrid supercomputer (the brain), operating using new firmware and software algorithms (the thoughts). To find FRBs, ARTS continuously makes a high-speed movie of the radio sky, at 20.000 frames per second. Using that technique, we will search the entire Northern Sky to determine the origin of some of the most powerful flashes and explosions in the Universe.

Successor to PuMa and PuMaII

ARTS is a hybrid FPGA-GPU machine, which serves as a cutting-edge transient survey instrument, and as a pulsar-timing and VLBI backend for all WSRT users. New firmware for the Apertif Uniboards to produces up to 468 (!) simultaneous tied-array beams -- already approaching SKA requirements, now. These can fill out the entire Apertif field of view for dedicated transient searching. Furthermore, a new Uniboard^2-based second beam former that runs the same firmware will operate in parallel to any imaging that Apertif does. This truly commensal system thus provides the first ever 24/7 pulsar/FRB search machine in the world at this sensitivity and depth. Based on the system parameters and the all-sky rate, ARTS could discover one FRB per week (Maan & van Leeuwen 2017).

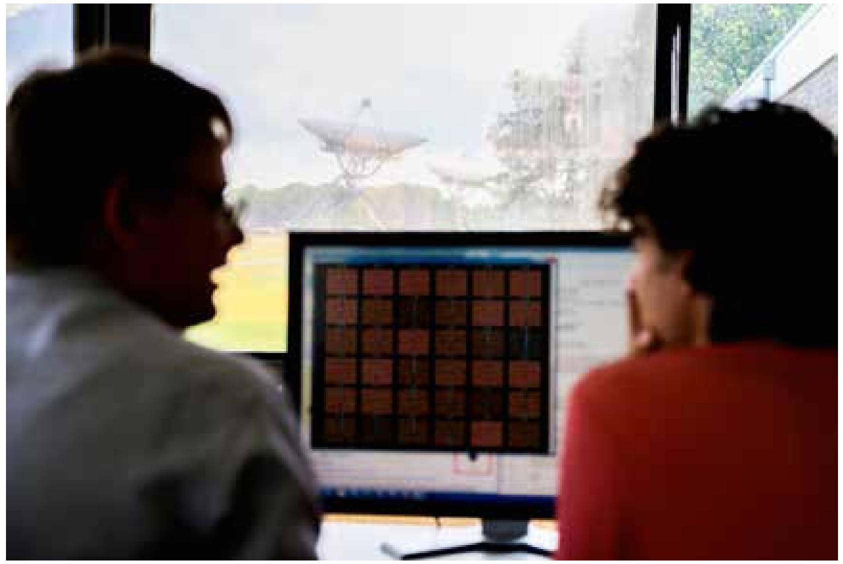
After this FPGA beamforming, signals for all these applications are further processed on a large GPU cluster. This versatile back end, the successor to PuMa and PuMaII, covers the coherent dedispersion for timing, and the full-field fast-transient search. That FRB dedispersion and search on almost 500 beams needs an amount of computing power that only the fastest supercomputers in the world can produce. Thus we designed and built a GPU supercomputer, which is completely powered by image processing chips from the gaming industry. Gamers use very powerful processors for video tasks: the Graphical Processor Units (GPUs). In ARTS we now use these chips to process the high-speed time-domain streams from Apertif. The supercomputer consists of 200 GPUs, which process 4 terabits of data per second: more than the en-

More data than the internet of the entire country.

The ARTS GPU supercomputer.

tire internet of the Netherlands. With a peak compute capacity of 2 petaflops it is the most powerful GPU supercomputer in the Netherlands.

After training, the software on ARTS has the ability autonomously find FRBs amongst the millions of candidates signals. In the past much of this was done manually, but for a 24/7 telescope that produces 100s of beams, it is impossible to keep up manually with the data rate. A neural-net "deep learning" pipeline now does the candidate sifting (Connor & van Leeuwen 2018). As we detect more FRB and re-train the algorithms, ARTS will continuously learn to distinguish the flashes better and better from e.g. interference.



Looking at first ARTS data.

FRB Localisation

Most FRB searches are carried out using single-dish instruments, which can only provide limited localisation, preventing detailed follow-up. ARTS has the huge advantage that it employs a fully real-time interferometer, than can immediately determine the precise location of the FRBs. We know they come from other galaxies, but for one-off bursts, we have not been able to pinpoint the exact location. And so it is unknown whether e.g., all FRBs are bright bursts from neutron stars; or that exploding stars or black holes also send out these radio flashes.

In a second step of localisation, the bursts position is further refined. The FPGA-GPU supercomputer will determine where FRBs go off within a handful of seconds. Because of the dispersive delay, the same FRB will arrive at LOFAR frequencies tens of seconds later. By triggering the LOFAR Transient Buffer Boards at the -- now known -- correct direction, arrival time and dispersion measure, these FRBs can be even better localised. We thus take two of the best radio telescopes in the world -- and combine them to produce a burst-finding machine that is far more powerful than the sum of its parts.

Apertif; the next stage

Chapter 15.3 From Multi-frequency to Widefield; the System

Wim van Cappellen, Gert Kruithof*

The ability to survey the radio sky to high sensitivity and at high resolution provides a powerful probe of a number of key questions in modern astronomy. In this fiftieth year of the WSRT, ASTRON and partners are finalising the major upgrade of 12 dishes of the Westerbork Array, termed 'Apertif', to become one of only two arrays equipped with powerful phased array receiver systems for that purpose. In the first part of this chapter, Tom Oosterloo sets out the exciting science case for developing such a powerful GHz-range wide field survey instrument. In the second chapter part, Joeri van Leeuwen details the instrumental expansion with ARTS to be able to observe the time-varying universe in combination with Apertif. In this third contribution, the scope and design of the combined Apertif-ARTS system are presented which will ensure that the WSRT performs as a world-leading instrument for many years to come.

The APERTIF-ARTS system

The WSRT upgrade from multi-frequency front end (MFFEs) receivers to one utilising Phased Array Feeds delivers a telescope capable of multi-beam observing such that a whole new scope of astronomical research can be realised. In this upgrade, the WSRT dishes are reused with only minor modifications, whereas the remainder of the WSRT systems are replaced with innovative technologies.

The Apertif-ARTS system is a unique telescope array in the northern hemisphere. Together with ASKAP (the Australian SKA Pathfinder) in Australia, it provides the possibility of surveying the whole sky. As an imaging telescope, the system operates with a multi-pixel aperture synthesis array on 12 dishes in dual polarization, at frequencies 1130-1750 MHz with a maximum baseline length of about 2.5km. The ARTS aspect of this system is dedicated to transient object searches and surveys, pulsar timing and VLBI. In either mode, the system observes the sky over a remarkably large field of view (8 square degrees, about 30x larger than with the MFFE receivers). This system also has the ability to process 300MHz instantaneous bandwidth – another factor of two compared to the MFFE system.

* ASTRON, The Netherlands

The Apertif-ARTS system has four main parts: phased array feeds in the focus of each dish, a cabin below each dish where the signals are conditioned, digitized and beam formed, a correlator in the central building to combine the signals of all dishes in parallel, and a tied-array backend. An overview of the system is shown in Figure 1.

The system components from the feeds to the correlator/beam former are common to both the APERTIF (imaging) and ARTS (time domain) aspects. It is only post-correlator/beam former that the two systems differ.

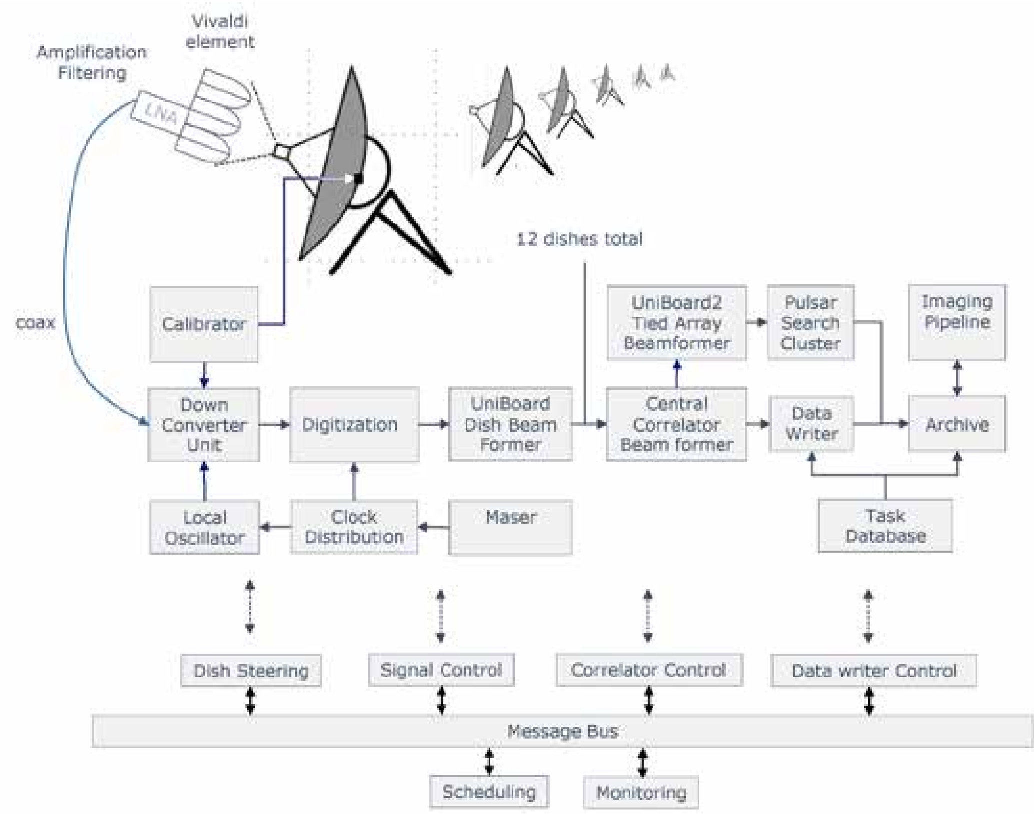


Figure 1 Overview of the APERTIF ARTS system

During observations radio signals from the sky are detected by the phased array feeds in the focus of the dishes. These uncooled arrays are each made up of 121 Vivaldi antenna elements, including the Low Noise Amplifiers, arranged in two orthogonal polarisations (Figure 2). A summary of the Apertif-ARTS system parameters is shown in Table 1.

Figure 2 The phased array feed of the Apertif system as mounted in the prime focus box of each WSRT dish.

Table 1: Overall System parameters

Parameter	Value
Field of View	8 square degrees
Number of beams	40
Angular resolution at 1.4 GHz	13x 13/sin(δ) arcsec2 (EW by NS)
System temperature	70 Kelvin
Aperture efficiency	0.75
Frequency range	1130- 1750 MHz
Instantaneous bandwidth	300 MHz
Number of channels (=#subbands x #channels/sub.)	384 * 64 = 24576
Noise spectral line (12 hr)	0.5 mJy/beam over 16 km/s
Noise continuum (12 hr)	10 μJy/beam over 300 MHz
Noise uniformity over Field-of-View	10-25%
Primary beam size of one beam	33 arcmin
Survey speed increase compared to WSRT-MFFE system	15x

After filtering and amplification, the radio frequency signals are transported over coaxial cables to the telescope cabins. Here the signals are conditioned, digitized and beam formed. After conversion to an intermediate frequency, the signals are digitised by 8-bit analogue to digital converters at a sampling clock rate of 800 MHz. The raw data rate per phased array feed for two polarizations is 800 Gbps , i.e. then effectively 300 MHz is digitized into 781 kHz wide sub bands. Each of these bands is processed independently.

Figure 3 shows one Apertif dish beam former capable of processing a single polarization of one phased array feed. It shows a backplane board with eight digitizer boards plugged into the left side and two of the four UniBoards used (see below and also Chapter 10) mounted at the right side. The dish beam former combines the responses of all elements into 40 compound beams, reducing the data rate by a factor of almost 3. Each dish uses an online calibration system to stabilise the compound beam patterns. A switched noise source in the apex of each dish is used to monitor and compensate temporal gain and phase variations of the receiver chains. Each dish beam former sends its output over optical fibre to the central signal processing unit which then either correlates the signal for imaging observations (APERTIF) or beam forms the signal for time domain observations (ARTS).

The combined data rate into the central correlator/beam former for all 12 dishes is about 3.5Tbps: this makes it one of the most powerful signal processing systems used in Radio Astronomy today. During imaging observations, we can

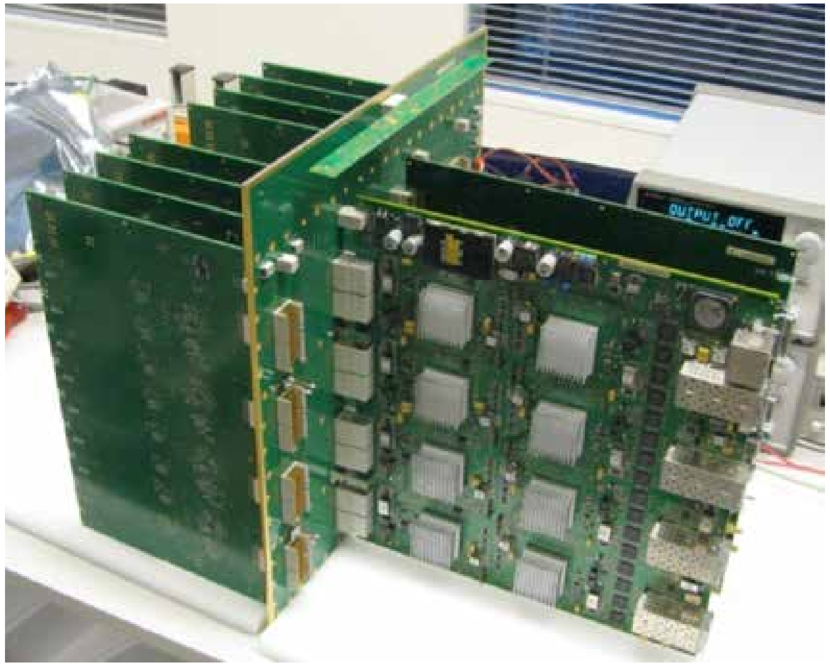


Figure 3 The Analog to Digital conversion on the backplane of the Dish Beam Former Boards (housing removed)

also do commensal observations of radio transients via the dedicated tied array beam forming unit, thus maximising the scientific output of each observation. ARTS can create up to 12 tied array beams to fill a single compound beam.

The system uses both first and second-generation versions of the powerful “UniBoard” digital signal processing systems. These systems have been developed by ASTRON and partners in the EC-FP7 Radionet3 program. These boards have been specially designed to handle the extreme data streams in real time. The dish beam formers and the central correlator/beam former use the first generation UniBoard. Each dish has 8 UniBoards (4 per polarisation), and the central signal processing unit has 16 UniBoards. Each UniBoard has 8 FPGA’s (Field Programmable Gate Arrays), storage memory and about 10.000 connections in 14 Printed Circuit Board layers between the components. Interestingly, this single board has about the same number of connections between the components as shown on the backplane of the DLB (see Chapter 10). In correlator mode, the complex sub bands of each telescope beam are Fourier transformed into 64 channels of about 12 kHz width, cross multiplied and integrated.

The tied-array backend for transient surveys, pulsar timing and VLBI uses UniBoard2. This second generation UniBoard is the first of its type to use the Arria10 20 nm chip and also the first such system that can achieve a processing rate exceeding 1 Tbps.

A Monitoring and Control framework is used to schedule each observation, steer all the components in the signal chain and monitor the entire system during observations. The framework is

An overview of the Apertif Phased Array Feed principles

Gert Kruithof, Carole Jackson

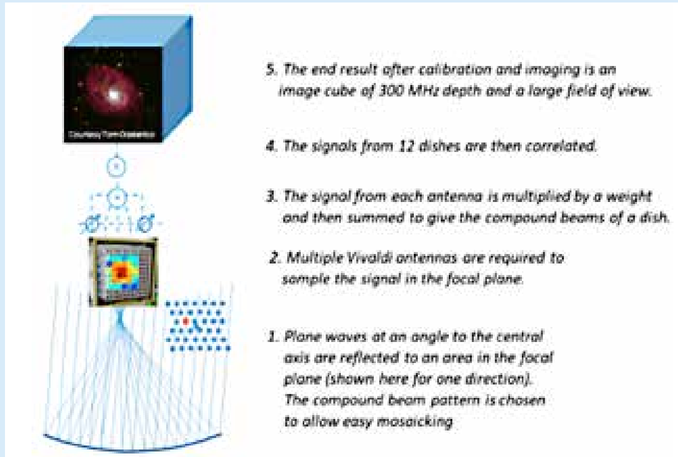
The key topics of an international workshop in Sydney, Australia (2017: www.pafworkshop.org/) emphasised the technologies, science and applications of so-called Phased Array Feeds (PAFs) . Whilst the focus was on Radio Astronomy as the originating discipline, the use of PAFs in other applications were noted e.g. in the next generation 5G telecom infrastructures. This, and other similar reviews demonstrate the potential of the PAF technology. Having been steadily developed over the last two decades, we are at the time when PAFs are mature and installed as ‘live’ systems.

Recognising the potential of aperture arrays in general for either or both of SKA and LOFAR, ASTRON commenced research in the underlying concepts in the mid-nineties. This provided the foundation for ASTRON to drive the concept to maturity with the Apertif system for the Westerbork Synthesis Radio Telescope.

Whilst other parts of this contribution discuss the details of the innovations demanded by the PAFs, we take this opportunity to summarise how these systems work in principle:

We should first consider the case of a single dish telescope: A single pixel horn feed mounted at prime focus of a parabolic dish is sensitive to the incoming radiation (a plane wave) from an object aligned with the central axis of the dish. In fact *only* the incoming waves on the central axis are focused in the feed area of the focal plane. Incoming waves at other angles are not detected.

To detect off axis signals requires a larger area receiver in the focal plane region. The challenge has been to design a receiver of many adjacent antennas, spaced less than half one wavelength apart.



In this type of receiver, each antenna collects a part of the signal at the focal plane. By applying weights to the signals from each antenna before summation, we can reconstruct the wave across a wide area of the focal plane (and thus, the wave that arrives at angles off the main axis). In fact, this type of receiver allows for effective “reconstruction” of the signals received resulting in a high efficiency array feed with small smooth frequency response. The phased array feed in the ASTRON Apertif system is one manifestation of a focal plane feed with an array of 121 Vivaldi antennas in each receiver. This receiver collects signals from a circular area of 8 square degrees on the sky. This area is distributed across 40 beams arranged in a hexagonal pattern. Each beam is formed (in our terminology we call this ‘beamforming’) by adding the signals of a subset of antennas, with each signal assigned a very specific weight. Obviously, this demands intense, high-data-rate signal processing techniques to make it all work - this challenge has been solved as part of the Apertif system.

Secondly, what does it mean for Apertif as a survey (and more!) instrument? Sometimes termed a radio ‘camera’, the array feed is termed as ‘dense’ – it is able to form tens of optimised (‘shaped’) and overlapping compound beams on the sky electronically. As this type of phased array feed is uncooled, it operates at ambient temperature. The noise temperature of each beam is higher than the equivalent single pixel (e.g. horn) cryogenically cooled feed. However, Apertif has 40 instantaneous beams that more than compensate for this. Combined with the increased efficiency (i.e. less loss of signal) a net survey speed increase of the WSRT of 15 times results (see Table1).

based on a Service Oriented Architecture allowing a flexible, loose coupling between all the components. Each hardware component uses drivers that connect as a service to the message bus. A workflow orchestrates the components in the signal chain. Each component provides information on the message bus on its status. These messages are collected in the successor of the TMS database (see Chapter 10), called Artamis to monitor the system health, and quality of the observations.

During imaging observations, the data flow from the correlator to the data writer, creating a measurement set in the Apertif Long Term Archive (ALTA): ALTA comprises 1.5 petabyte of disk storage used to store the data for further processing. The measurement sets can be processed off-line with the “Apercal” pipeline to produce higher-level data products such as data cubes and catalogues. In beam forming mode, the data flows to the ARTS GPU cluster. This cluster uses machine learning for automatic detection of transient candidates. These are analysed further in pipelines. The same backend is also used for pulsar search and timing.

All resultant data is published to the ALTA long-term archive which is designed to scale up to 20 petabyte of storage. This data is publicly available, forming a legacy dataset ready for use across a wide range of astronomical research.

Chapter 16 Radio Astronomy and Innovation

Arnold van Ardenne, Carole Jackson*

It can be asked, "What is it good for and why invest in radio astronomy?" Is it sufficient that it is the singular pursuit of knowledge? Or does it have more value, and if so, how do we assess its impact on our lives and the wider society?

There are some simplistic and perhaps satisfactory answers to the first part of the question: radio astronomy is a curiosity-led science and salves our collective *want to know more about our Universe*. However, the question is more usually asked from a different perspective and this simplistic answer does not always suffice: We need to be far more precise. For example, we know that the enabling factor for the good use of public funds is underpinned by governmental enquiries. These enquiries are driven in such a way as to yield valuable answers. At the same time, the political context can change, such that we need to be fully prepared to promote this investment to the general public, who after all are the ultimate funders as taxpayers.

Investing for new knowledge

A hundred years ago, mankind was unaware of the scale of the Universe, its constituent billions of galaxies and only had a general belief that the cosmos was 'very old'. Today we have a confident measure of its age and its likely evolutionary path. We observe the physical manifestations of its constituent objects (stars, galaxies, clusters, etc) across the entire electromagnetic (EM) spectrum, from radio to hard x-rays, as well as use non-EM instruments to detect particles, cosmic rays and gravitational wave ripples of ongoing and cataclysmic events. It is no exaggeration to say that our understanding of the cosmos has made huge strides through the last two decades. Massive surveys have been compiled using new detector technologies, advancing our knowledge of the gross structure and evolution of the Universe. Alongside this, non-EM detectors have allowed the detection of gravitational waves confirming Einstein's fundamental predictions of 100 years prior (2016), earth-like planetary systems have been located and dark energy is both inferred and generally accepted. As a result, we live in an era where astronomy continues to mature at a rapid pace, probing ever more extreme tests of fundamental physics. Radio astronomy is a relatively young aspect of astronomy, having developed rapidly over the last 80 years or so. It is both remarkable, and a note to the unique discovery space of the radio

* ASTRON, The Netherlands

regime, that 80% of the Nobel prizes awarded to astronomical subjects are in the radio regime of astronomy. This is partly supported because of its huge, five orders of frequency spectral coverage observable by using ground-based instrumentation.

To arrive and remain at the front line of observational discoveries, this ground-based instrumentation must be leading edge and, by implication, innovative. For example, the WSRT was precisely on time because for 10 years, it was the most sensitive synthesis radio telescope in the world enabling spectacular discoveries to be made. It continued to push frontiers induced by a climate of close collaboration between scientist and engineers, many of whom also taught at universities and educational institutes and had close connections to industry.

I once challenged Ger de Bruyn with the "why invest" question. His reply was more or less a solid "because pure science deserves to be funded as it appeals on mankind's universal curiosity and mankind wants to understand nature". True as that may be and as important as it is, more is required to allow this statement to bear fruits. For example, not only is there a significant financial commitment necessary to enable excellent radio astronomy in the Netherlands, it relies on the educational excellence at the Dutch universities. These work as a

Expanding field of view with aperture arrays

Dion Kant, Parbhu Patel
(both formerly at ASTRON)

At ASTRON, in the early nineties, the first idea was born for a large international radio telescope with a total collecting area of one square kilometre, known as SKAI. It would be a global successor for classic telescopes such as the WSRT. The original idea was to use phased array antenna technology to implement collecting area supporting electronically steerable, multiple, independent beams with a potential field of view which is limited only by available (digital) processing power. ASTRON started a development programme exploring and maturing phased array antenna technology guided and pushed forward by Arnold van Ardenne. The SKAI project rapidly became the key international project for the future of radio astronomy. Around the late nineties, the 'I' in SKAI was dropped after discussions within the international radio astronomy community. Originally the name used at ASTRON for the future telescope was Square Kilometre Array Interferometer but the resulting name SKA is used since then for the project which today, more than 25 years after its conception, is still alive and kicking.

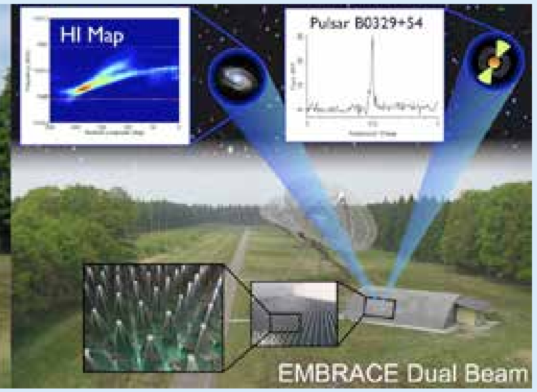
As part of a long range plan for maturing the technology and risk mitigation, the ASTRON technology programme delivered a series of phased array systems: The Adaptive Array Demonstrator (AAD in 1998), the One Square Metre Array (OSMA in 1999), the THousand Element Array (THEA in 2004) and within the European Framework Programme 6 (FP6) project SKADS (www.skads-eu.org). The Proof-Of-Principal Array (POPA) was developed and built under the name Electronic Multi-Beam Radio Astronomy ConcEpt (EMBRACE in 2008). Furthermore, APERTIF and LOFAR are additional spin-offs resulting from the aperture array endeavour.

EMBRACE was completed around 2008 and it consists of two aperture array stations. One station is situated at Paris Observatory radio facility in Nançay, France, and the other one is at the WSRT. The SKADS project was a successful example of cooperation between a large number of international partners. Within the team which developed EMBRACE there were Italian, French, German and Dutch contributions and SKADS, with even more international partners, became an example project for the EC.

The station in the Netherlands, shown in Fig. 1, is situated between telescope 4 and 5 of the WSRT. It has an aperture of about 160 m^2, an effective noise system temperature less than 100 K and it provides two independent analogue beams. Each beam has a field of view (FoV) of more than 200 square degrees and this is a result of the size of the tiles used as the basic building block of the antenna array. It operates in the frequency range of 500 to 1500 MHz using tapered slot antenna elements known as Vivaldi elements.

A novel radome concept was used where polystyrene plates were pushed into a curved global cover over the antenna system to protect it from the weather conditions. However, during the first winter, heavy snowfall damaged the radome. After fixing the damaged radome, it has survived all subsequent winters to-date. The radome for the station in Nançay was built slightly after the one built at the WSRT. The quality of the polystyrene material used for the radome in Nançay was much better and after about ten years the station in Nançay is still in optimal shape. The EMBRACE station in Nançay continued until very recently with various astronomical observations (see Torchinsky et al, 2016, A&A, 589, A77) as the largest operating AA-station in the world!

Turning the soil at the location between WSRT Telescopes 4 and 5 for the first EMBRACE station, while Jan Pieter de Reijer and Dion Kant are supervising the process.



An impression of the EMBRACE station configuration showing the radome and the cabin with the processing system on the right. Two beams are depicted showing the capability of one beam being used for HI imaging while the other beam is being used for observing pulsars.

positive feedback system. In this manner, top-level astronomy research and education systems produce top students who develop to become top researchers and so on. Furthermore, the international outlook helps in acquiring European funds to do further research, here or elsewhere with a wide range of collaborators. Dutch radio astronomy has long supported the route to move overseas after a PhD, to connect and learn, and possibly to return later.

Collaboration and society

We can provide a heuristic definition of Radio Astronomy as the manipulation of increasingly larger datasets from observations of the Universe in the radio regime of the electromagnetic spectrum to provide meaningful and scientifically justifiable data, interpretations and discoveries. For example, working at the edge of the capabilities of new observing instruments such as LOFAR and in future the SKA, these processes involve intense data mapping onto the highest performance computing platforms.

Therefore, whilst radio astronomy is a curiosity driven science, it fundamentally demands technologies and directed advances in radio instrumentation, signal-processing and high performance computing and imaging techniques to achieve its discoveries. Exploring this idea a bit further, a wide range of technological challenges, entrepreneurship and shared talents are the basis for collaborations besides funding, providing fertile ground from which impactful discoveries eventuate. This defines the rich innovative domain with wider applications illustrated below.

Radio and therefore, radio techniques are the primary sensors underlying radio astronomical discoveries. Both are elements of our present-day telecommunication infrastructure, but at the birth of radio astronomy in the 1940's they were not well developed. As a result, many aspects of our telecom systems almost immediately profited from radio astronomical instrumental developments: These range from fully steerable antennas, low noise receivers and antennas. It goes beyond this chapter to follow these lines in any detail so a most recent example may illustrate this.

In this book, the chapter on Apertif describes a new observing system for the WSRT. Apertif adopts a multi-pixel radio "camera" receiver as an upgrade to the single pixel (horn) receivers traditionally used in this part of radio frequency domain. Early technical R&D towards this multi-pixel system started at ASTRON as part of first phase SKA R&D in the late 1990's and has now matured to the point of being implemented as a new radio astronomical instrument. It is exactly this same principle of the focal plane arrays that now has found a suggested application in the next generation ("5G") network infrastructure through work at the technical University Eindhoven.

Thanks to its ultra-wide viewing angle on the sky, a similar technique without the use of a reflector antenna is termed an aperture array. This has been implemented as LOFAR and other more recent low frequency telescopes worldwide. This technique is now proposed for simultaneous multi satellite observations in ground station applications and was first demonstrated at ASTRON around 2001.

Besides the use in the "physical layer" of the telecom infrastructure as illustrated above, other applications originate from the use of optimized algorithms and imaging techniques now also used in MRI apparatus. Research starting in ASTRON in the early eighties by John O'Sullivan, now in Australia, ultimately contributed to the innovation of wireless computing (WiFi) many years later. Moving further toward the computing infrastructure and intense data processing, collaborations with IBM into the next, exa-scale computing platform and some enabling technologies (see: http://www.dome-exascale.nl/) naturally connect future radio astronomy needs with generic computing requirements e.g. required for broader, demanding applications beneficial to society.

For the last two decades ASTRON has maintained a structured effort to strengthen the relations both to engineering societies and institutes for technology and education as well as to the users i.e. companies and industrial domains. First, by establishing a technology transfer platform and later a private company (AstroTech) through which now LOFAR stations are sold. The latter is a great success and most is acquired from industry; a true "export product". Nationally, by virtue of the breadth of science enabled by ASTRON facilities and the technological innovation required to develop them, ASTRON is deeply embedded in the National Science Agenda (NWA) as well as to the Universities. Also, ASTRON collaborates with the astroparticle physics community, via NWO institute as mother organization, NIKHEF and others, to further research on gravitational waves and cosmic rays, and with KNMI and NLR for research on Space Weather.

Finally, ASTRON collaborates with the four NL Technical Universities and the NL eScience Centre on science areas relevant to innovation towards the future generation of radio facilities including radio science, antennas, photonics, signal processing technologies, distributed algorithms and high-performance computing all with relevant associated application domains and often in collaboration with industry.

Application domains for Innovation

Capturing the specific and broader, societal impacts of radio astronomy is not trivial. An attempt is shown in the picture below which is inspired by an insightful presentation some years ago by Simon Garrington now Associate Director for Jodrell Bank Observatory in the UK.

Radio Astronomy	Technological Spinoff	Application
Radio Interferometry Low Frequency Interferometry (LOFAR)	Wireless LAN technology Location of wireless sensor nodes Sun-Earth Interaction, Ionosphere	WiFi Internet networking e.g. Location of mobile emergency calls Critical infrastructures, Safety&Security
Very Long Baseline Interferometry Precision astrometry	Most accurate (hydrogen maser) clocks International celestial reference frame. GPS reference frames Precision State Vector/position	Space communication, satellite navigation Earth orientation parameters, geodesy, time keeping Interplanetary spacecraft navigation, Planetary science
Aperture synthesis and image reconstruction	(Fourier) imaging techniques Massive Data, Algorithms & Database Thinned aperture imaging radiometry	Medical imaging tomography Image de-blurring (Green) Computing, Wireless Computing Earth sciences, Oceanography (HI-freq. band)
(Homologous) antenna design	Precision antennas Widefield Antennas Focal Plane Arrays	Communications and radar Earth Obs., GNSS (Safety&Rescue) 5G(?)
Low Noise Amplifiers	Highly sensitive commercial cryogenically cooled receiving systems	Telecommunications 
Endeavour	Societal, Public	Education , Inspiration UNAWE, Astrotechnology

This again, indicates the broad interest in making explicit connections between science and society and illustrates interconnectedness between astronomical research and technology development.

Our discussion and evaluation of our 'value' becomes ever more relevant as the funding horizon for technology tends to move in closer with less free space to allow the potential for serendipitous R&D (as the 5G example and the wireless application example showed with lead times of 15-20 years). Effectivity therefore is hard to measure on a short term timescale, contrasting perhaps results and efficiency.

Whilst an assessment of the scientific (pure and technological) endeavour of radio astronomy's long-term impact is best done in retrospect as is illustrated in the earlier picture, it is clear that for innovation to work, a mix and match of research and technology is essential.

Observations outside Radio Astronomy

Chapter 17.1 The NuMoon experiment at the WSRT

Olaf Scholten[1], Jose Bacelar[2], Stijn Buitink[3] and Heino Falcke[4,5]

It was at a party at ASTRON in 2005 that Ger de Bruyn suggested to some of us that it should be possible to use the WSRT to measure ultra-high energy (UHE) neutrinos.

Neutrinos are particles that interact only through the weak interactions and thus they travel basically un-attenuated over cosmological distances along straight-line trajectories. They are expected to be produced when high energy cosmic rays interact with matter. However while cosmic rays travel finite distances and furthermore travel along curved trajectories due to magnetic fields, the neutrinos always point back to their source. To detect neutrinos requires large detectors to compensate for their small interaction cross section. High energy neutrinos, with energies up to 10^{16} eV, have been observed with IceCube [Aartsen+ (2015)] a detector of cubic kilometer size. Since the flux is expected to drop steeply with energy we need much larger detectors to detect ultra-high energy ($E > 10^{20}$ eV) neutrinos. They are of much interest since they are the messengers of the most energetic processes in the universe, such as Blazars [IceCube (2018)], supermassive black-hole mergers, or may result from the decay of massive particles that are relics from the Big Bang.

The basic idea of the UHE neutrino observations, first proposed by Dagesamanskii & Zheleznyk (1989), is that we have a really big detector in our back-yard, the moon. UHE neutrinos hitting the moon will form a cascade of secondary particles (called a shower) in the regolith all moving with almost the light velocity. This shower will have a net charge because of the electrons that are knocked out from the atoms of the regolith and thus emit radio-waves. Since the lunar regolith is very transparent to radio waves they may penetrate through the lunar surface and reach Earth where they may be detected with powerful radio telescopes. The first experiments using this approach were carried out with the Parkes telescope [Hankins+ (1996)], at Goldstone (GLUE) [Gorham+ (2004)], and with the Kalyazin Radio Telescope [Beresnyak+ (2005)]. In more recent years there has also a similar measurement been performed at a

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pathfinder of SKA, ATCA (the Australia Telescope Compact Array) with a 600 MHz bandwidth at 1.2-1.8 GHz [Bray+ (2015)].

The idea of Ger was to use the WSRT for this detection. It should be noted that the proposed WSRT observations differs from the usual astronomical observations. We are interested in detecting short, nanosecond scale, pulses emanating from the moon. This cannot be done with the standard equipment available at WSRT at the time however Ben Stappers had just developed his pulsar machine which was perfectly suited for storing the raw time-traces with zero integration time for later off-line processing.

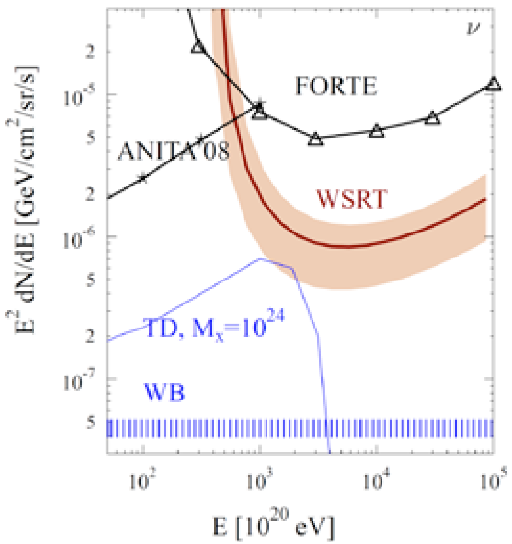
When back at the KVI we thought more about the crazy idea of using the moon to detect neutrinos. The major differences with the previous GLUE experiment was the detection frequency (200 MHz instead of 2 GHz) and that we could use the WSRT as a phased array. Both turned out to give a major advantage over previous experiments.

Because of subtleties related to aspects such as the width of the Cherenkov radiation cone that is emitted by the particle shower in the regolith, internal reflection at the lunar surface, and the dependence of radio absorption in the regolith, the detection efficiency increases strongly with wavelength. In [Scholten+ (2006)] we could show that the detection efficiency for detecting UHE neutrinos via the moon scales with wavelength to the third power. This implies that one gains about a factor 1000 when shifting from 2GeV at GLUE to the 100 — 200 MHz window at WSRT. This finding came as a great surprise to the UHE neutrino community.

By phasing the WSRT telescopes two rectangular beams can be formed where each covers one half of the moon. Since the main challenge in performing the observation is to distinguish true neutrino initiated pulses from noise much of this can be eliminated by requiring that a neutrino pulse should be seen in only one of the two beams. This condition eliminated much of the noise and increased our sensitivity. Another important suppression of noise is achieved by realizing that neutrino pulses from the moon have traversed the ionosphere and thus should be dispersed with the appropriate slanted total electron content (STEC) while noise pulses directly from sources on Earth should have no dispersion, or double this value when they reach WSRT through a Moon bounce.

In the off-line analysis these conditions can easily be implemented as well as additional ones such as the fact that lunar neutrino pulses should be bandwidth limited with an intrinsic duration of a few nanoseconds.

By the non-detection of a pulse of a certain magnitude (120 times the galactic background) over the duration of the observations (47.6 hours) we could set an upper limit on the flux of UHE neutrinos taking into account the attenuation of the neutrino pulse in the regolith as well as the geometrical acceptance. The resulting 90% confidence flux limit [Scholten+ (2009), Buitink+ (2010)] is shown in figure 1 by the curve labeled WSRT. The band around the curve shows the possible error of the determined flux limit, mostly due to uncertainties in the attenuation of radio waves in the regolith.



The WSRT limits are compared with those of other competitive observations in figure 1. All these have used different techniques to cover a large area. The FORTE satellite [Lehtinen+ (2004)], observes the Greenland ice cap for radio flashes coming from neutrino interactions in the ice cap. ANITA is a balloon mission where the Antarctic ice cap is searched for radio flashes [Gorham+ (2009)]. Since for these observations the receiving antenna is much closer to the source than with our lunar observations one is sensitive to neutrinos of lower energy. However with the moon we have a target volume that is much larger than in either of these two experiments which means that at higher energies, since the flux is expected to drop with at least E^{-3}, our experiment sets the most competitive limits. In the Figure also two model predictions are given. Waxman and Bahcall (1998) derived an estimate of the flux of neutrinos based on the observed flux of UHE cosmic rays assuming a generic model for neutrino production at the production sites of the cosmic rays. In Top-Down (TD) models UHE neutrinos are created from the decay of super massive relics ($M_x = 10^{24}$ eV is used in the figure) formed at the time of the Big Bang. The data from our WSRT observations allows for setting limit on the flux of UHE neutrinos which is just touching the predicted flux of this TD model.

Figure 1 The brown line gives the neutrino flux limit established with 46.7 hours of WSRT data where the band shows the systematic error. For a neutrino flux exceeding the indicated limits one should have detected at least a single event with 90% confidence. Shown are also the limits set by ANITA [Gorham+ (2009)] and FORTE [Lehtinen+ (2004)]. The predicted Waxman-Bahcall flux [Waxman & Bahcall (1998)] and that of a Top-Down model [Protheroe & Stanev (1996)]

The Future of NuMoon

Over the past years, we began preparations to search for pulses of the impacts of cosmic particles in the Moon with LOFAR. Like the WSRT, the LOFAR High-Band Antennas provide an optimal frequency window for this technique. However, LOFAR has an increased sensitivity and the shape of the array allows for much more control over the beam shape, leading to better localization of pulses on the Moon.

Another improvement is the development of an online trigger. For the WSRT observations, the time-series data of all dishes was temporarily stored on a local computer at the observatory. Here, we had to run our data reduction software as fast as possible to make space for the next observations – typically within 24 hours or so. This was sometimes stressful, since the analysis needed up-to-date ionospheric electron density values as input, information that only became available the day after the observation.

The data rate of LOFAR makes it completely impossible to store hours of raw time-series data, so the whole detection pipeline has to work in real-time. This includes inversion of polyphase filters, forming 50 beams simultaneously to cover the lunar surface, correct for ionospheric dispersion, search for pulses, and make a trigger decision based on differences in the 50 beams. All of this has to be finished within 5 seconds – the length of transient buffer boards installed at each antenna.

The challenge is surprisingly similar to pulsar searches. The formation of multiple beams, the pulse searches, and the de-dispersion steps are the same, albeit on very different time-scales. It was therefore a logical step to seek collaboration with Jason Hessels who had just installed a GPU-based pulsar-search machine called DRAGNET. Using this cluster, we will be able to reach a sensitivity well below the previous WSRT limits.

The most interesting particles in this search may turn out to be cosmic rays instead of neutrinos. In contrast to neutrinos, cosmic rays convert all their power into the particle cascade that emits the radio pulse, lowering the energy threshold. This threshold comes very close to the cut-off energy observed by the largest cosmic ray detector arrays in the world: the Pierre Auger observatory and the Telescope Array.

The techniques that we are developing for LOFAR will in the future be applicable to the Square Kilometer Array. A first detection may be on the horizon and would be mind-boggling: detecting a single elementary particle impact at a distance of 380 thousand kilometers is surely the stuff only crazy astronomers dare to dream of.

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Observations outside Radio Astronomy

Chapter 17.2 Geodesy and Gravity at the WSRT

Hans van der Marel and Roland Klees*

Astrometry and geodesy are two complementary scientific disciplines that are closely related. In the past, optical observations both served geodesy and astronomy to determine the positions on the Earth, the positions of stars and the orientation of the Earth in space.

After 1957, with the launch of the first artificial satellites, geodesy became gradually less dependent on the stars. In the early 1960s, the photogrammetric determination of the direction towards satellites equipped with flashlights, albeit still measured with respect to the stars as background, resulted in the formation of world-wide geodetic networks, as well as methods for the practical calculation of these networks, the computation of satellite orbits and the Earth gravity field. An enormous boost to the accuracy of the world-wide geodetic networks arrived with the development of highly accurate satellite laser-ranging systems to measure distances to specially designed geodetic satellites covered with retro-reflectors. These satellites, basically a heavy sphere to minimize drag and other perturbing forces, and covered with laser reflectors, played a crucial role in the determination of the Earth's gravity field. Satellite geodesy, as it was called, truly revolutionized geodesy.

In 1973, after the first successful experiments near Delft, the Delft University of Technology built the Kootwijk Observatory for Satellite Geodesy (KOSG) near Apeldoorn [2] . The observatory housed two satellite cameras for the photogrammetric satellite observation, satellite laser ranging (SLR) equipment, and the necessary workshops. The satellite laser ranging equipment was developed together with the Technische Physische Dienst in Delft (TPD). Large steps were made in the processing of the measurements towards the dynamical determination of all parameters involved: The Earth gravity field, accurate satellite orbits and station positions on the Earth. Sensing the Earth gravity field implicitly meant the determination of the center of mass of the Earth and motion of the Earth rotation pole in the same reference frame as the station positions. As the accuracy of the satellite ranging measurements improved, the next big

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challenge became the measurement of Earth deformation due to plate tectonics, Earth tides and various loading processes. Therefore, two transportable laser-ranging systems were developed (MTLRS-1/2), one for the German colleagues, and one for ourselves, which were deployed in the Mediterranean for observing the complicated plate tectonics in that area.

In the 1980's geodesy started to use differential phase measurements to Global Positioning System (GPS) satellites using specially developed geodetic receivers. First observations were done in dedicated campaigns, but the first continuously operating GPS receiver in the Netherlands was installed in 1991 at Kootwijk, which soon became one of the core stations of the International GNSS service (IGS) which was founded in 1994. With the development of transportable satellite laser-ranging systems and the upcoming geodetic applications of GPS (which eventually replaced the transportable satellite ranging systems), and because of diminishing funding, the department of geodesy had to stop the activities in Kootwijk and move the staff back to Delft.

After consultation with ASTRON, it was decided to continue the satellite geodetic observations in a newly established Astrometric Geodetic Observatory at Westerbork (AGOW) [3]. The decision to move the observations to Westerbork was made easy by the fact that TUD and ASTRON already cooperated in geodetic Very Long Baseline Interferometry (VLBI) campaigns. The co-location of several important geodetic observation techniques at a single site was seen as a great opportunity.

The geodetic part of the AGOW observatory was built in 1996 and consisted of:

- Continuously operating GPS (GNSS) receivers as part of the International GNSS Service (IGS) and national Active GPS Reference System (AGRS)
- A very stable 24 m high steel mast, on a concrete foundation, for the GPS observations.
- Underground concrete block of 3x3x3 m^3 in a climate controlled bunker for absolute and relative gravity measurements.
- Universal 9x9 m^2 concrete platform for transportable VLBI and SLR systems.
- An underground NAP (Normaal Amsterdams Peil) marker, connected by primary levelling measurements to other underground markers.

In 1997 the Netherlands Commission for Geodesy (NCG) formed a task group to investigate the added value of the synthesis of different measurement techniques at Westerbork [3]. Central in its report [3] is the role of the AGOW as a global anchor point for the Netherlands, especially in relation to the anticipated sea-level rise and challenges faced in the global determination of the height component. According to the task group, the focus should be on long continuous time series of parallel geodetic measurements, in particular for the height component, in combination with international efforts on the establishment of geodetic reference systems. The task group also recommended the feasibility of the participation of one of the telescopes in regular geodetic VLBI campaigns.

The AGOW was officially opened on 29 September 1999 with a symposium in Dwingeloo and visit to the observatory at Westerbork. The presentations of this symposium were published [1].

A rigid and stable GPS antenna mast is necessary in order to have a clear unobstructed view of the GPS satellites because of the tree growth at Westerbork. See Figure 1.

Figure 1. GPS Antenna mast at Westerbork in 1997.

The mast has a special invar-wire construction to keep the influence of temperature changes on the vertical position of the antenna to an absolute minimum, while it will not move by more than 2 mm in a gale force storm. The position of the antenna is checked once per year using a local survey and levelling to the nearby underground NAP marker, thereby connecting the GPS heights directly to NAP.

The two GPS receivers are placed in the cellar of the main building. Both receivers are connected to the hydrogen maser at Westerbork, providing a very stable reference frequency for the GPS. Over the years the receiver hardware has changed and receivers have been upgraded to full GNSS (Global Navigation Satellite Systems) capable receivers supporting not only GPS, but also the Russian built Glonass system, the European Galileo and Chinese Beidou systems. However, the same GPS antenna has been in use since 1997, making this station a very unique and stable reference point for the International GNSS service (IGS) and International Terrestrial Reference Frame (ITRF). For the maintenance of the ITRF and anchor points in the Netherlands it is important to keep GPS antenna changes to an absolute minimum, as installing a new antenna will inevitably results in a small discontinuity in the time series, especially in the height. Westerbork is therefore unique and important point in the ITRF reference frame because of the long term stability and long uninterrupted time series, see Figure 2, in particular in combination with Kootwijk for which there is a long overlap and history goes back to 1991.

Figure 2. IGS residual position time series of WSRT after removal of the secular velocity component (16.5 mm/y North, 17.7 mm/y East and 0.5 mm/y down) and effects of equipment changes. Source https://webigs.ign.fr/tfcc/en/station/WSRT/residuals

GPS observations from Westerbork are used for the determination of accurate satellite orbits for almost all geodetic and Earth observation satellites, which are in turn used for computing atmospheric parameters such as the integrated water vapour content and total electron content, and many other applications.

Measurements of absolute gravity at Westerbork have been done since the bunker became available at the end of the twentieth century. They are part of a long-term plan to monitor the vertical stability of the Dutch NAP height network. The observed changes in absolute gravity are transformed into vertical displacement rates. Linking the Westerbork station to the NAP network using spirit levelling, measured relative vertical movements of NAP height markers can be transformed into absolute movements. The information about absolute vertical movements of NAP height markers is used determine absolute vertical land motion at the tide gauge stations along the Dutch coast. In this way, variations in sea level caused by changes in the volume of water in the oceans can be extracted from the tide gauge records, a prerequisite for a proper interpretation of observed relative sea level variations.

Before 2006, the measurements were done by the University of Luxembourg, because no absolute gravimeter was available in the Netherlands. This changed in 2006, and since then, TU Delft measures absolute gravity once a year in Westerbork and other stations in the Netherlands (currently, these stations are located in Epen, Kootwijk, Zundert, Oudemirdum, and Oudeschild). Figure 3 shows the observational record of absolute gravity variations after corrections for instrumental errors and geophysical signals, including tides and ground water table variations.

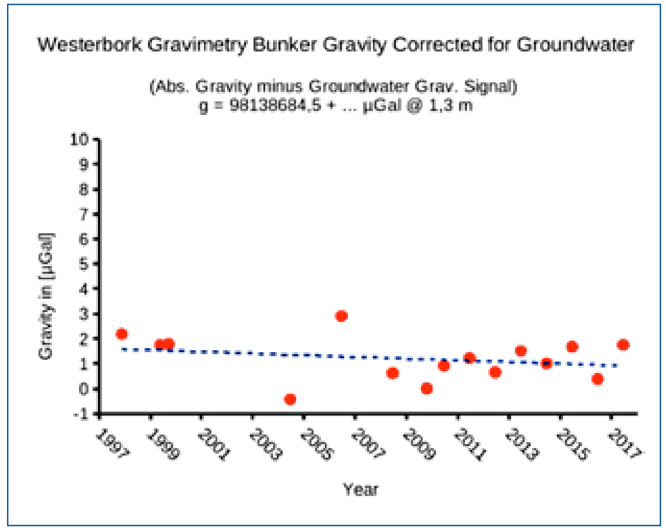

Figure 3 Time series of absolute gravity measurements at station Westerbork. The estimated trend is -0.034 ± 0.041 microGal/year (1 microGal = 10^{-8} m/s²).

The linear trend in gravity is estimated as -0.034 ± 0.041 microGal/yr (1 microGal = 10^{-8} m/s²). This corresponds to a vertical motion rate of 0.17 ± 0.21 mm/yr over the last 20 years.

Not all of the original ambitions of 1997 have been fulfilled. For instance geodetic VLBI, although done periodically, and satellite laser ranging (SLR), have been completely replaced by GNSS observations. However, the Astrometric Geodetic Observatory at Westerbork (AGOW) has become one of the core geodetic reference stations in the world and is crucial for geodesy in the Netherlands. Its observations are used by countless groups in the world for reference frame maintenance, computation of satellite orbits, monitoring of subsidence and sea level change, and atmospheric research. WSRT is an acronym that is immediately recognised by geodesists around the world, although not all geodesists will immediately associate WSRT with radio telescopes.

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Observations outside Radio Astronomy

Chapter 17.3 Ionosphere, the WSRT, LOFAR and Space Weather

Arnold van Ardenne, Maaijke Mevius*

Around 1980 Titus Spoelstra was responsible for the Westerbork data reduction. Because of this responsibility, his scientific interest and continuing quest for improving the precision of the data, Titus wished to understand better the effects of the ionosphere on the data set. His ultimate goal was, of course, to seek ways to correct the data using this knowledge.

As ASTRON was not tasked to conduct ionospheric research, of which effects and insights were considered merely byproducts, Titus contacted in the early eighties Hennie Kelder from the Department of Geophysics at KNMI the Royal Netherlands Meteorological Institute. This contact resulted in a joint paper in the subject "Effects of the Ionosphere on Radio Astronomy" which appeared in June 1984 (*Radio Science, Volume 19, Number 3, Pages 779-788)* spelling out the refraction effects of the ionosphere on the WSRT fringes as observables.

Titus approach was that a better understanding was necessary to apply radio astronomical data corrections for both local WSRT interferometric work as well as for VLBI. While tracking the radio source 3C286 at 608,5MHz (the nominal 50 cm wavelength) Titus and Hennie measured the solar-driven, notably diurnal, phase effect (amplitude and polarization angle, the latter from KNMI data) in the ionosphere. This effect of the sun on the ionosphere is clearly visible in the top picture on the left (copied from the article) from which it was noted that the phase effects are most notable during sunrise and sunset. But there are also many irregularities caused by "medium" scale Travelling Ionospheric Disturbances ("TID"'s). Further investigations in 1982, with the WSRT, used satellite passages in the eastern and western skies as artificial radio sources. The measured phase behaviour of a satellite signal is shown in the lower figure (from the same article). These studies improved the knowledge of TID's (scale size, direction of propagation, time scales) and their effects on radio interferometry. As a general main conclusion the article therefore mentions that "*Radio interferometers turn out to be excellent instruments to measure ionospheric parameters (i.e. irregularities)*". And also, reflecting the state of understanding at the time:

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Figure 1: The two pictures are taken from the 1984 article by Hennie Kelder and Titus Spoelstra showing the effect of the sun on the measured Westerbork phase data and of Travelling Ionospheric Disturbances ("TID"'s) using satellites as artificial radio sources (see the text).

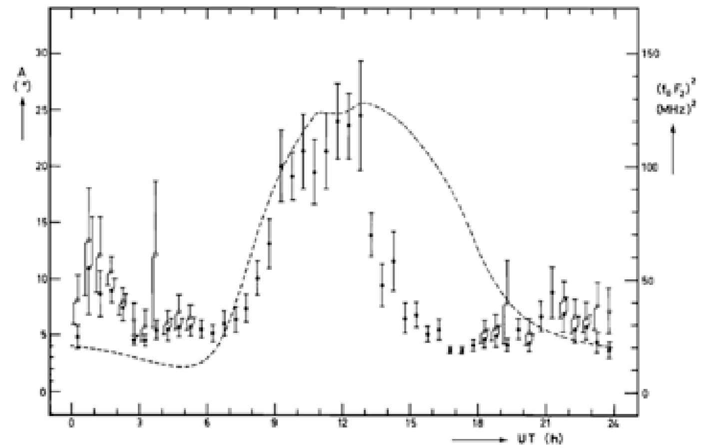

Fig. 2. Variation in the amplitude of WSRT phase variations at 2.7 km baseline due to ionospheric irregularities as a function of time. Solid circles indicate that data with apparent periods less than 4 min have not been used. Open circles show values determined from all data. The dashed line represents the average $(f_oF_2)^2$ variation with time. Local noon is at 1133.24 UT. Sunrise is around 0600, and sunset around 1800 UT.

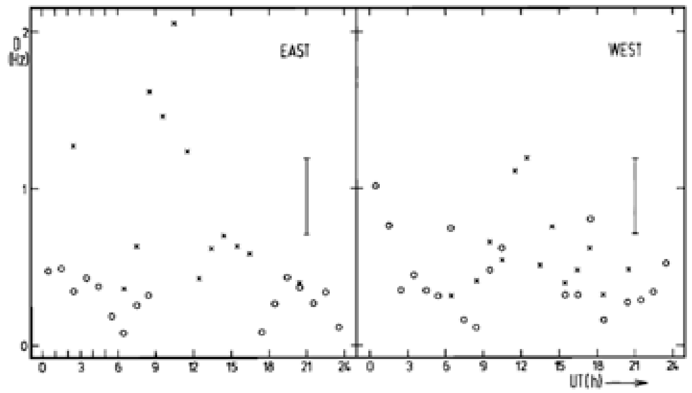

Fig. 4. Hourly averages of the amplitudes of the irregularities for satellite passages in the eastern as well as in the western sky. The different behavior for waves with apparent periods of 4.6 s or less (circles) and medium-scale TID's (crosses) is indicated. The error bar indicates the spread per averaged data point.

"*The absence of medium-scale TID's during the night suggests that the sun may be the main "engine"*".

Critically proofread by Richard Strom, it proved the beginning of more thorough work in particular on TID's. This is reflected in the article by Hennie Kelder and Titus Spoelstra with the title *Medium scale TlDs observed by radio interferometry and differential Doppler techniques (Journal of Atmospheric Terrestrial Physics, Vol. 49, No. I, pp. 7-17, 1987)*. It again demonstrated the importance of (lower) frequency radio interferometry techniques to understand the ionosphere and in this case postulating a hypothesis about the cause of TID's.

In a relatively unknown but nice overview in 1997 *"The Ionosphere and Radio Interferometry (Annali di Geofisica, Vol.XL, nr4, pp 865-914, August 1997)"* the previous work was summarized and expanded. In the Netherlands through the PhD thesis work of Peter van Veldhoven (now senior researcher at KNMI), additional work at the lower WSRT frequency of 327 MHz and through comparisons of results from other telescopes and GPS data. Important additional insights dealt with the effect of ionospheric scintillation and instrumental effects. After these studies there is no doubt that interferometric radio astronomy and ionospheric research go hand in hand.

Titus retired in 2008 (see also the AJDI archive and then look for the one of 07-11-2008) and his ailing health led to his premature death on 30 April 2010. The connection between radio interferometry and the ionosphere, that was scientifically explored by Titus, received less attention after his demise but is becoming again a very relevant subject.

The postulated conclusion of 1984 that the sun is the main engine for effects in the ionosphere by now is taken for granted. In fact, the magnetic activity of the sun affects the magnetosphere and ionosphere of the Earth and can have pronounced effects on modern technology (commonly called the effects of space weather). A good understanding of the heliosphere and the ionosphere are paramount to now cast or forecast these effects. As it happened, the LOFAR telescope is evolving into a formidable instrument for this purpose.

With the LOFAR telescope we gain insight on the ionosphere in various ways. Since ionospheric diffractive delays are a main source of calibration errors, calibration parameters give a direct measure of the differential integrated electron content over the array. Amplitude scintillation can be measured with single station data while moving scintillation patterns are observed if the data of more stations is combined. Also, dual polarization elements allow the measurement of rotation of the polarization angle of a linear polarized signal due to the interaction with the ionospheric plasma and the Earth magnetic field, known as Faraday rotation. Interestingly, even an unpolarized signal can become artificially polarized if the Faraday rotation effect above the two arms of an interferometer differ.

We have used the LOFAR station beam data to find ionospheric scintillation patterns of a bright astronomical source, such as Cas A. Comparing the scintillation amplitudes of several stations, one gets a direct view of the patterns in the ionosphere at the station positions projected along the line of sight. Imaging these patterns in time this gives a movie of the ultra-fine structures in the ionosphere, moving around above the LOFAR core. Although at mid-latitudes, at these frequencies amplitude scintillation is observed almost continuously, contrary to what has been observed with GNSS measurements at higher frequencies (*R. A. Fallows et al, 2016 ApJL 828 L7*).

In interferometric mode, the data of all stations are correlated and averaged to typical 1 second time resolution. Since, in this mode the system is only sensitive to the phase difference of a signal arriving at two stations, the measured ionospheric effects are also mainly differential. A linear gradient in the ionospheric total column electron content (TEC) over the array will cause a (frequency dependent) shift of the measured position of a source. Higher order terms will cause source deformations in the image plane. Typically, the ionospheric variation in a single direction can be described by a linear gradient for the LOFAR core, where higher order terms show up at longer baselines. When imaging the position shifts of a large number of sources inside the LOFAR beam as a vector field, larger scale disturbances, like TIDs or duct like structures, become visible over an area corresponding to the LOFAR beam. Although a single pointing of the LOFAR HBA beam only corresponds to about 10 degrees, and therefore to about 50 square km at an altitude of 300 km, it is possible to use LOFAR in simultaneous multi beaming mode, sacrificing bandwidth for more pointings.

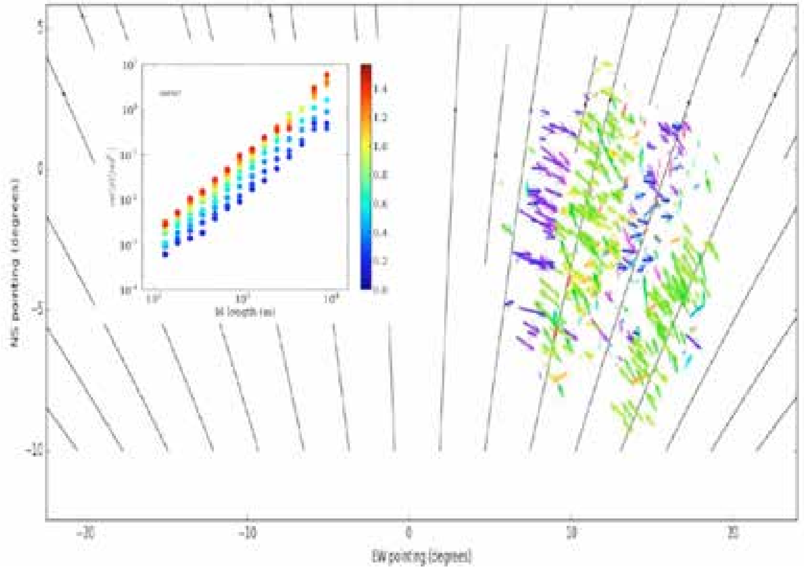

Figure 2: 2 minutes snapshot of position shifts of ~800 sources of combined data of 7 LOFAR beams. The black lines show the projected magnetic field lines. The insert shows the structure function of the same observation, binned for angle wrst magnetic field (colorbar). The elongated structures along the magnetic field lines are clearly visible in both.

By comparing a model of the sources in the sky to the actual data during calibration, station based phase errors are estimated. By making use of the wide bandwidth and the typical frequency behavior of ionospheric delay, the ionospheric effects are separated from other (instrumental) phase effects. To first order the ionospheric phase errors scale with the inverse of frequency (1/f), although at the lowest LOFAR frequencies (<40 MHz) third order frequency effects (scaling as $1/f^3$) become visible. As LOFAR can measure phase errors with very high accuracy, differential integrated total electron content ("TEC") can be measured with an accuracy smaller than 1 milli-TECU (10^{13} electrons/m^2), using a typical HBA calibrator observation and 10 sec integration. These are "local" if the phase solutions are used in the direction of a single calibrator

when the differential TEC on an area in the ionosphere equal to the footprint of LOFAR is measured (*Mevius et. al., 2016, Radio Sci. 51, 927–941*)

Faraday rotation as the second order phase delay effect, scales with ($1/f^2$), causing a phase delay of circular polarized signals like those from GNSS. With LOFAR it becomes visible as a rotation of the linear polarization angle. Given an Earth magnetic field model, the measured time varying rotation angle of a polarized source can give a direct measure of the absolute TEC (*Sotomayor-Beltran C. et al 2013 A&A 552 A58*). Even for an unpolarized source the effect is visible if the ionospheric Faraday rotation angle above the stations of a baseline differ, either because of differential TEC, or because of a slightly different parallel magnetic field vector. See: *de Gasperin et al* (*2018, A&A, https://doi.org/10.1051/0004-6361/201833012*) showing all three orders of ionospheric phase effects in LBA calibrator data.

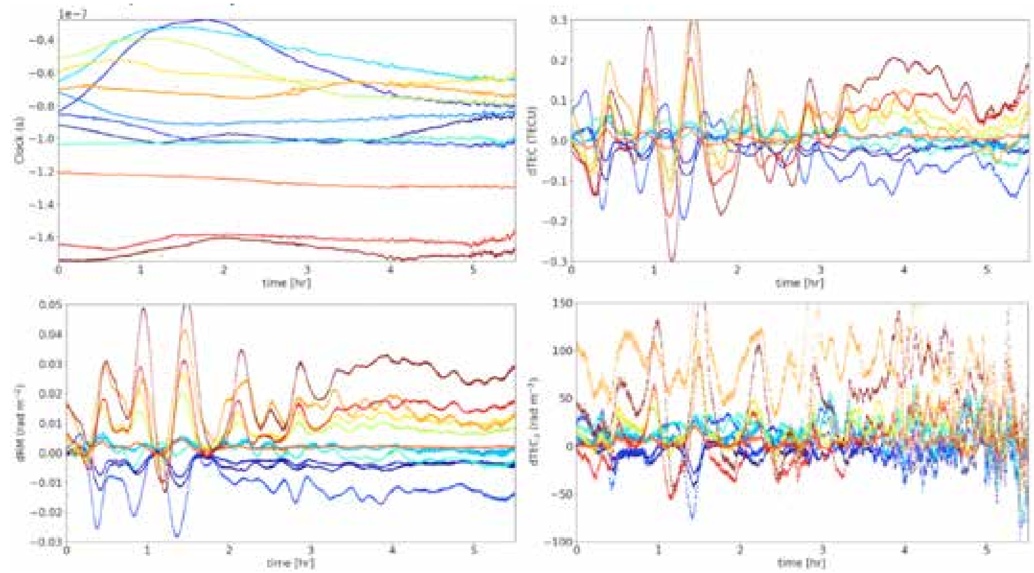

Figure 3: from de Gasperin et al.: *From top-left to bottom-right: instrumental clock delay (in s). Total electron content variation along the observation (TECU). Faraday rotation (in rad m−2). Ionospheric third-order effect (in rad m−3). All values are differential between CS 001 (assumed constant at 0) and all remote stations (from blue to red in alphabetical order).*

This work and other observing capabilities of LOFAR made it possible to now get an approved role (e.g. through an ESA contract) in exploring its use for Space Weather for both civil and defense purposes but in any case for societal benefit. It is interesting to note that the foundations were laid by people like Titus Spoelstra an Hennie Kelder more than thirty years ago.

The search for NASA's Mars Polar Lander

Mark Bentum

Early December 1999, at more than 300 million kilometres from Earth, a spacecraft from NASA landed on the planet Mars: the Mars Polar Lander (MPL). The main goal of the MPL was to find traces of water in the bottom of Mars. Unfortunately, nothing has been heard from the Lander since the start of the decent towards the red planet. What happened? Did it crash, was the communication broken, or something else? Questions that might be answered by observing possible radio signals from the MPL, using the Westerbork Synthesis Radio Telecope. On Wednesday, January 26, 2000, it all started for us: we received an email from NASA asking if we would like to contribute to an experiment to determine whether the Mars Polar Lander was still 'alive'. A very interesting journey started...

The Mars Polar Lander

On January 3, 1999, the American space organization NASA launched the Mars Polar Lander. On December 3, 1999 the decent started to the surface of the red planet. The communication between the MPL and the Earth took place via an X-band system. But this system did not work! A second option was an UHF link. On the MPL a UHF transceiver was mounted, with which a connection could be made with a satellite that orbits around Mars. This satellite, the Mars Global Surveyor (MGS) takes pictures of the planet at an altitude of 380 km. The MGS can serve as a relay station between the MPL and the Earth. But this function was also not working.

The final option was trying to pick up the UHF signal directly from the MPL! This signal is very weak: a transmitter of about 10 Watt at a distance of 300 million kilometres from Earth! Due to the weakness of this signal, a radio telescope must be used to even have a chance to detect the signal. The radio telescope in Stanford (California, USA) reports that it might have seen the signal in a measurement of January 4. The detection is doubtful, but nonetheless encouraging to look further.

Figure 1: Artist impression of the Mars Polar Lander on Mars (© JPL/NASA)

There are only three radio telescopes in the world that are sensitive enough to detect the signal at the frequency emitted by the MPL: the Stanford telescope in California (USA), the radio telescope in Jodrell Bank (England) and the Westerbork Synthesis Radio Telescope in the Netherlands, of which the WSRT is by far the most sensitive one.

What are we looking for?

The UHF communication between the MPL and the MGS takes place via an FSK modulated signal at 401.5 MHz. This means that at a distance of +/- 128 kHz around the central frequency of 401.5 MHz a signal should be found. But this frequency is somewhat influenced by the fact that Mars moves with respect to the Earth. Mars moved away from Earth during the measurements at a speed of almost 10 km/s, taking into account the rotational speed of both Mars and the Earth. As a result, the original frequencies are reduced by about 10 kHz.

The experiment

It was agreed with NASA that they would program the MPL in such a way that the UHF transceiver on the MPL would be turned on at exactly 15:30 (UT). This will last for half an hour. Then the electronics must cool down for two hours, after which the whole thing would be repeated once more. The distance between Mars and the Earth was about 300 million kilometres, which means that the signal takes 16 minutes and 55 seconds to reach Earth.

The real challenge

The real challenge was the fact that the signal was very very weak. We use a special mode at the WSRT, in which we add up all the 14 telescope signals to capture the signal. The difference between the signal from the MPL and the strongest signal in the band, the TV-smilde Nederland-2 signal, is almost 200 dB (that is a factor of about 100.000.000.000.000.000.000). Using the PuMa (Pulsar Machine), it might be possible to detect the MPL signal. The PuMa is an instrument built by the University of Utrecht in a collaborative project between ASTRON and the universities of Utrecht and Amsterdam. To make this possible, we had to eliminate all possible interference around the MPL frequency (401.5 MHz). So, we completely closed the park in Westerbork (nobody was allowed to come in), we shut down all the electronics not needed in the observations (computers, telephone equipment, alarm). Local HAM radio amateurs were asked not to transmit during the observations. And even the KNMI was asked to arrange that weather balloons in

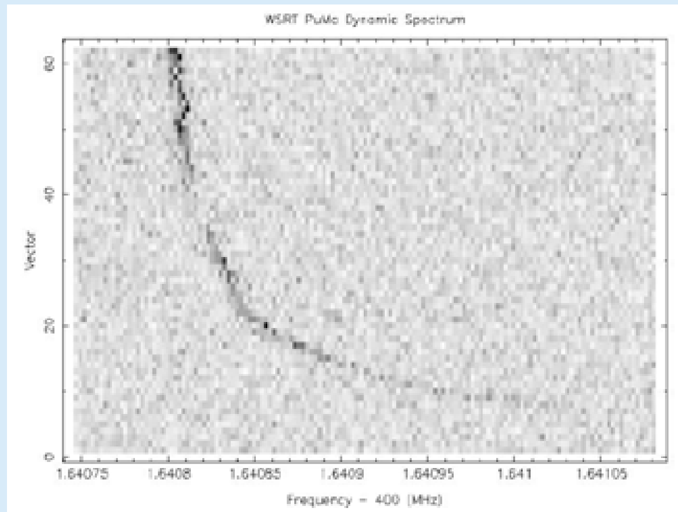

Figure 2: The first possible signal from the MPL.

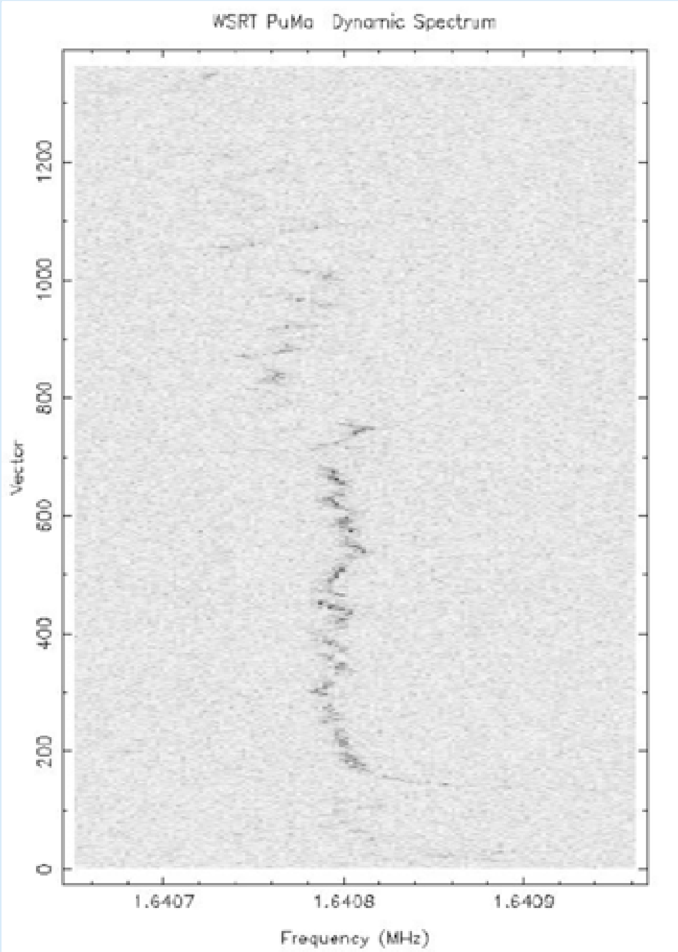

Figure 3: The complete time series of the possible MPL signal. (note that the frequency scale is not correct).

Belgium, the Netherlands, Germany and the UK were not launched during the observations. This resulted in compete RFI free observations (perhaps the only time in the existence of the WSRT).

The big day.

Friday, February 4 (2000) was the big day. After the system had been perfectly tuned and all RFI had been removed as well, it was time to make the first MPL detection at exactly 15:46:55 UT. Except for a very tense atmosphere at the observatory, nothing happened. First the recorded data had to be processed. After the first few minutes were observed, the data was processed. After an hour of processing the first picture appeared on the screen. And to our big surprise, there was actually a signal on the screen (see Figure 2). Did we really detect the MPL?

Did we believe the results? Of course not, so we redid the calculations. Same results again. Unbelievable. The signal started exactly on the right time (within a second). The signature of the signal was exactly what we expected: a drift in the first seconds and stable afterwards. And the frequency was exactly what was expected as well.

Logically, the mood was euphoric at that moment. Everyone was really convinced: we detected the MPL signal! But .... of course, we remain scientists and therefore: check and check again. After all, there were more characteristics of a possible MPL signal: a second carrier of the FSK signal must be there as well, and if we performed an on-off sequence the signal must disappear. So, we really had to check these facts before we could open the champagne bottle.

After a night of number crunching, finally in the morning the complete picture showed up as can be seen in Figure 3.

After seeing this image, we were quite disappointed. The second signal for the FSK modulation wasn't there, but more important, the signal didn't disappear in our on-off source (Mars) actions. Therefore, it couldn't be from Mars. Unfortunately. Also nothing was found in the rest of the data. And in a second experiment on February 9, no signal from Mars was found. We never found the cause of that first promising signal. It will always remain a big mystery.

Nothing found - Experiment successful

Therefore, our conclusion was that the MPL no longer broadcast signals in the UHF band. A couple of months later, NASA indicated that there were a number of problems with the MPL and that it was very likely that it actually had crashed on the Martian surface. This was confirmed by NASA a few years later. Nevertheless, the entire experiment for the WSRT was very successful and absolutely fun to do.

Figure 4: the schedule of the observation mounted on the DCB.

Figure 5: Ben Stappers, Peter Fridman and Marco Kouwenhoven working on the PuMa data in the evening of 4 Februari 2000. Not sure!?

Observations outside Radio Astronomy

Chapter 17.4 A Westerbork Radio Telescope for Galileo Monitoring

Arnold van Ardenne, Hans van der Marel, Koos Kegel, Andre Bos*

Introduction

In the first decade of this millennium, Europe started to build its own Global Navigation Satellite Service ("GNSS") system called Galileo. Aimed to be ready in a few years form now, it will consist of 28 satellites of which 22 have been successfully launched so far.

Leading up to this, preparations started in 2007 to suitably modify one telescope out of the 14 of the Westerbork Synthesis Radio Telescope ("WSRT") array in order to support the early assessment of the Galileo system in the first, In Orbit Validation phase. While preparations continued, a contract was awarded through the European Space Agency in the end of 2008 to develop a Signal In Space monitoring system for observations on the early Galileo test satellites Giove A and B (see: http://www.esa.int/esapub/br/br251/br251.pdf) and the first 4 flight models of the Galileo satellites.

This Signal Monitoring Facility ("SMF") system was initially using telescope 6 with a suitably modified multifrequency frontend receiver to allow for the required calibration and circular polarization observations for GNSS usage. The MFFE build under the leadership of Gie Han Tan, now at ESO, has been described elsewhere in this book.

As very stringent requirements called on the accurate calibration of group-delay and absolute power levels, the telescope apex was equipped with a suitable comb generator. Furthermore, a new "software" receiver allowed for the SIS performance analysis. This resulted in the successful qualification by Thales Alenia Space(It.) under auspices of the European Space Agency (ESA) and its

* This contribution is modified from the published paper "A Westerbork Telescope for GNSS Signal In Space Monitoring" for the AT-RASC URSI conference in Gran Canaria, 2018.
Andre Bos, from Science & Technology B.V., Delft, Neth., has been collaborating since the early GNSS activities in ASTRON.

Technical Centre (ESTEC) in early 2014 at the onset of further Galileo satellites in the next phase.

The picture shows the team in front of the then GNSS telescope RT6. ASTRON collaborators from the Technical University Delft and from TNO were not present but contributed as well. The authors are (from left to right) Arnold van Ardenne (third form left), Koos Kegel and Andre Bos (second from left) and Hans van der Marel.

Through this success, further developments lead to a new prototype wideband receiver and an awarded contract with the European GNSS Agency ("GSA"). This facilitated the move of the facility to another telescope ("0") of the WSRT used for limited VLBI programs and limited other radio astronomy purposes.

System Layout

The principle system layout is given in Figure 1 below depicting the relation between the SIS monitoring and analysis receiver which functionality is largely software PC-based.

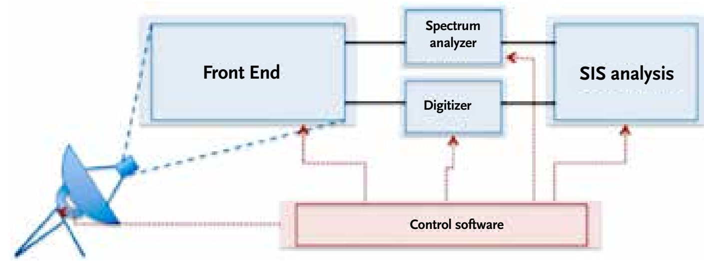

Figure 1. Principle system block diagrams. The default High Gain Antenna is Telescope 0, with Telescope 1 as fall back. A duplicate cooled receiver also a modified MFFE frontend, allows for redundancy.

Table 1 summarizes pertinent data of the telescope used for the GNSS observations using a modified cryogenically cooled receiver i.e a modified MFFE. The telescope includes a comb generator in the apex for accurate group-delay calibration an approach derived from geodetic VLBI.

Table 1. Pertinent data describing the High Gain Antenna.

Antenna type	25m High gain antenna, equatorial mount, prime focus
Antenna gain	48 dBi @ 1.2GHz
Polarization	RHCP/LHCP or X/Y
Frequency range	1.12-1.65 GHz
Instantaneous bandwidth	160 MHz
Half-beam width	0.5 deg.
Pointing accuracy	0.005 deg.
Slew rate	18 deg./min
System temperature	25 K
Calibration	Apex comb generator

Figure 2 presents the full SMF system in more detail depicting the left-/right-hand circular outputs from the HGA. Other instruments are for RF monitoring and data analysis, storage and -user distribution.

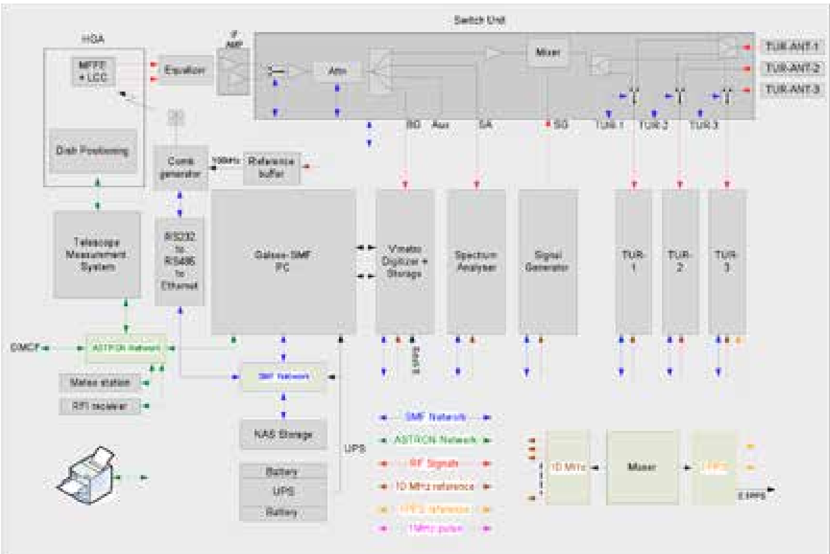

Figure 2. Detailed block diagram of the full SMF system. The full post-processing analysis is done in the SIS PC-based receiver after 8-bit digitization at 400 Ms/sec. over max. 160 MHz bandwidth. Some elements i.e Test Unit Receivers 1-3, were removed from the system after completion of the IOV phase.

In the present system, the maximum observable bandwidth of 160 MHz allows to simultaneously observe and analyse the Galileo specific E5+E6 (1145-1300 MHz) bands and the E1 (1554-1596 MHz) band separately.

While the very low system noise is not strictly necessary, its proven advantage is the very high dynamic range observation of the Galileo spectra to allow analysing the signal spectral purity to a high degree.
With some sensitivity compromise, a new uncooled and dedicated wideband receiver is now being developed, allowing for the coherent observation of all Galileo bands besides those of other, GNSS satellites, in one go. This dedicated wideband receiver makes use of a special frequency mixing scheme to gain experience in coherent spectra reception and data analysis without affecting the digital back-end. A next receiver architecture will be designed such that the complete 500 MHz frequency band can be analyzed.

Gain calibration

The receiver antenna pattern is calibrated using holographic measurements on radio astronomical sources. From these measurements, the antenna pattern is characterized in detail from which the efficiency and pointing errors are determined.

The absolute gain of the receiver chain is calibrated using strong astronomical radio sources of which the spectral power flux density at the Earth is accurately known. Measurements have shown that the stability of the gain of the receiver chain is better than 0.06 dB over a period of 8 hours.

Phase calibration

As the WSRT is usually used as an interferometer, it has been demonstrated that the phase stability (obtained from astronomical measurements) is better than ± 4 degrees over a period of 12 hours. However, due to the fact that all telescopes in the interferometer have the same properties, it is not possible to use these measurements to calibrate the frequency-dependent group delay or phase properties of the receiver chain.

The method used for the frequency dependent broadband phase calibration is described in detail in "*J. van der Marel and A. Bos, "Broadband Phase Calibration of a High Gain Antenna", Proc. of the 32nd ESA Workshop on Antennas for Space Applications, October 2010"*. A summary from this is given here.
The impulse response of a filter or a receiver chain is the Fourier transform of the transfer function of the filter or receiver chain. The spectrum of a pulse is wide and its phase is well defined. Therefore, pulses are very well suited for the calibration of a receiver chain with a large instantaneous bandwidth. Frequency conversions in the receiver chain do not have an impact on the analysis. A repetitive pulse generator, or comb generator, can be used for accurate pass-band calibration, both in amplitude and phase. The signal is transmitted from near to the apex of the telescope and synchronized to the H-maser and subsequently received by the modified frontend in the focus.

The picture shows the telescope with the mounted Galileo receiver. The insert shows the wideband spiral antenna close to the apex from which the pulse train is transmitted for reception in the receiver.

In the ideal case the periodic signal consists of a repetition of Dirac delta pulses but in practise have a finite bandwidth, thus producing an impulse with a finite length. It is shown in [5] that the inverse of the transfer function can be computed from which a deconvolution filter can be determined. From this a highly accurate time delay response function can be derived. Together with the installed noise calibration system and using radio source calibration, the accuracy with which the phase of the band pass can be determined is ±0.3° and for the amplitude an accuracy of better than ±0.05 dB can be obtained. These numbers have been obtained during repeating measurements over a period of 8 hours, which shows that both the impulse generator and the receiver chain are very stable.

Measurement analyses

As described in the introduction of this paper, the analyses is performed by a software receiver schematically shown in Figure 4. The received data is being sampled by a high-speed data sample, and the stored data is being processed to perform a number of analyses, including –but not restricted to-- the estimation of the Power Spectral Density (PSD) of the signal, the estimation of the Doppler-shift, signal demodulation, power estimation, and the constellation diagram.

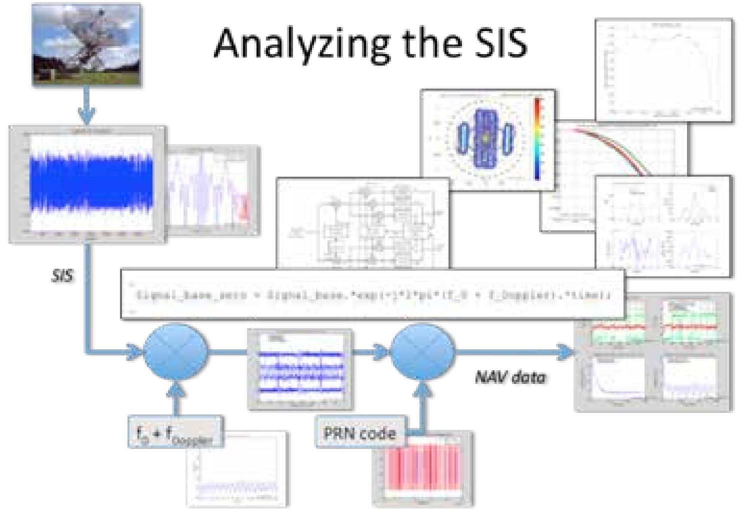

Figure 4. Schematic structure of the signal analyses method.

An example the PSD of the E1 signal of Galileo is given in the following figure 5. Some additional analyses are being made as well, such as the comparison with the theoretical PSD, and the estimation of imbalances in the PSD by comparing the amplitude of the main lobes of the PSD.

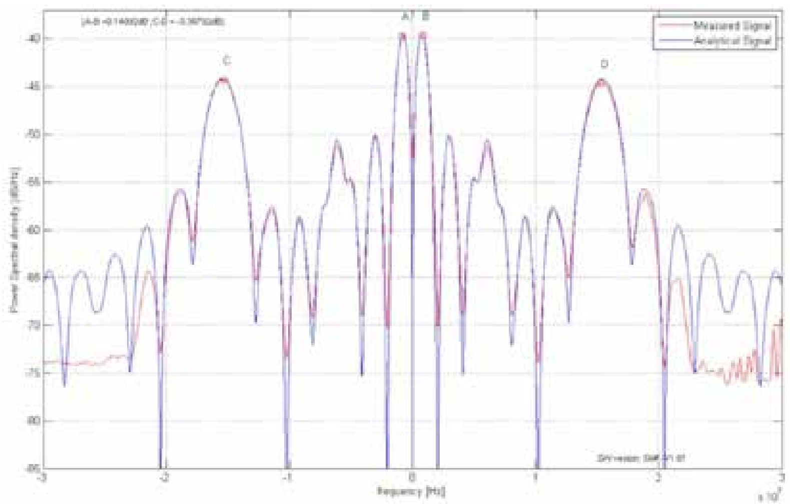

Figure 5. PSD as measured by the WSRT system, including comparison of the measured signal with the theoretical PSD.

Summary

We demonstrated that with adequate modifications including dedicated phase and amplitude calibration and the development of the Signal in Space receiver, a radio telescope of the Westerbork array could successfully be employed for high performance GNSS monitoring. With some sensitivity compromise, the development of a wider band uncooled digital receiver instead of the relatively complicated Multi Frequency Front End, holds promise for a highly flexible next step.

Discovery of Heaven in Westerbork

Mark Bentum

In September 2000 the WSRT was the scene of the movie “Discovery of Heaven” based on the Harry Mulish novel “De ontdekking van de hemel”, and produced by Jeroen Krabbé, Edwin de Vries and Ate de Jong. Hosting a complete film crew is something we underestimated a bit. They literally took over the entire site! But it gave us a lot joy and to be fair, we had to close down the WSRT for a couple of weeks anyway because of major infrastructure work.

Figure 1: Scene from the movie. Quinten is biking along the telescopes.

It all started in spring 2000. Jeroen Krabbé and Edwin de Vries visited the WSRT, looking for possible places to shoot the movie. They loved the place! Of course, Jan Pieter gave them “the full tour”, so they concluded that a major part of the movie must be recorded in Westerbork. I do not know if this tour was the reason for changing the script, but the original Dwingeloo parts in the book by Harry Mulish were recorded in Westerbork as well.

wThe production team arrived in September 2000 to shoot the first scenes. In the construction hall “little Hollywood” arose, including campers for the lead movie actors, Stephen Fry, Greg Wise, Flora Montgomery and Neil Newbon, and full catering service, etc.

Making a movie requires a lot of so-called ‘takes’ and scenes sometimes had to be redone over ten times. One of the scenes included a car accident during which a tree would fall down on the road and hit the car. To make multiple takes possible, the tree was equipped with a hinge – a klap-boom in Dutch. They shot this scene in the middle of the night and they needed some ASTRON people to assist them. Rob Millenaar, Harm-Jan Stiepel and myself were there the whole time!

A somewhat expensive mistake was made when two time periods were mixed up. The producers wanted an overview shot in which a car arrives at the telescopes. Drones were not yet available in 2000 so one of the biggest cranes available was rented. It was a beautiful shot, but when Jeroen Krabbé saw it, he was unhappy. They had used the wrong car! The 1970s car was used for the 1980s shot. The next day, the crane was rented again and the shot redone, but this time with the correct car.

One of the most difficult “takes”, was the arrival at the telescope during rainfall. Lots of rain was needed in the script. However, it was not raining at all! It was a

Figure 2: Rob Millenaar and Mark Bentum enjoying the full catering service of the film crew.

beautiful night at the WSRT so the technical crew created rain. Since we do not have a huge amount of water available at the telescopes, the crew rented two big trucks of water. At night time, the illuminated telescopes sprayed with water created a beautiful scene! (see Figure 3 thanks to Harm Jan Stiepel.)

In one of the scenes, Max Delius (the astronomer) had a discussion with one of his colleagues in the observing room. There was a black board in the room and Jeroen Krabbé asked us to put some “intelligent stuff” on it. This was our chance to immortalize ourselves (of course not telling Jeroen). We used “intelligent” equations, but with our own initials, and with our kids initials, and making 42 the answer which readers of the “Hitchhikers guide to the Galaxy” know to be the answer to the question of Life, the Universe, and Everything!

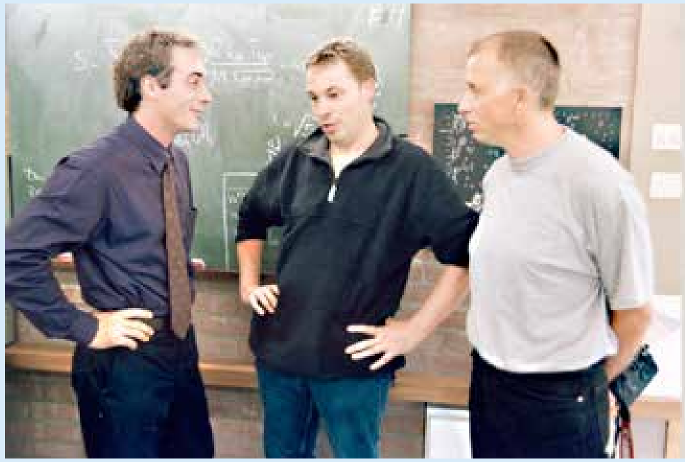

Figure 3: Telescope 6 illuminated for the night and when rain was needed!

ASTRON and JIVE personnel got to see the movie before it was released in a special showing just for us in the movie theatre in Hoogeveen in October 2001. We were about 200 people really enjoying it. The movie is, of course, still available. Look for all scenes with the WSRT in it!

Figure 4 : The actor Greg Wise (Max Delius) with Mark Bentum and Rob Millenaar before the black board with “intelligent equations”.

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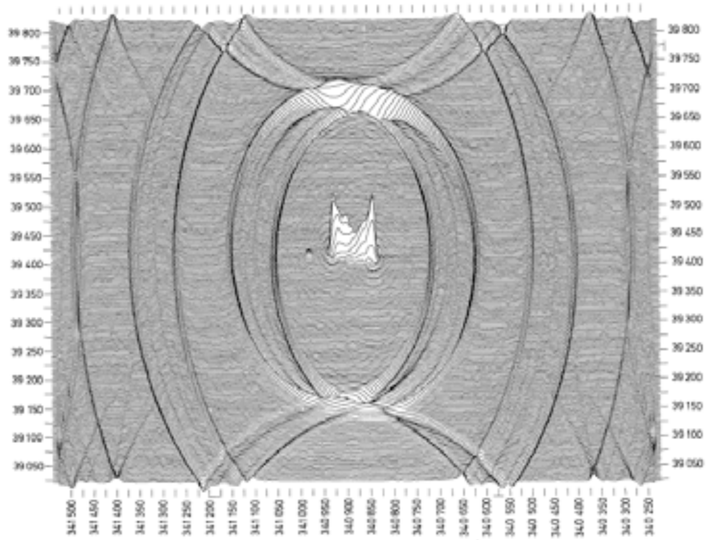
Chapter 18 Fifty WSRT highlights

Richard Strom[1], Thijs van der Hulst[2], Arnold van Ardenne[3]

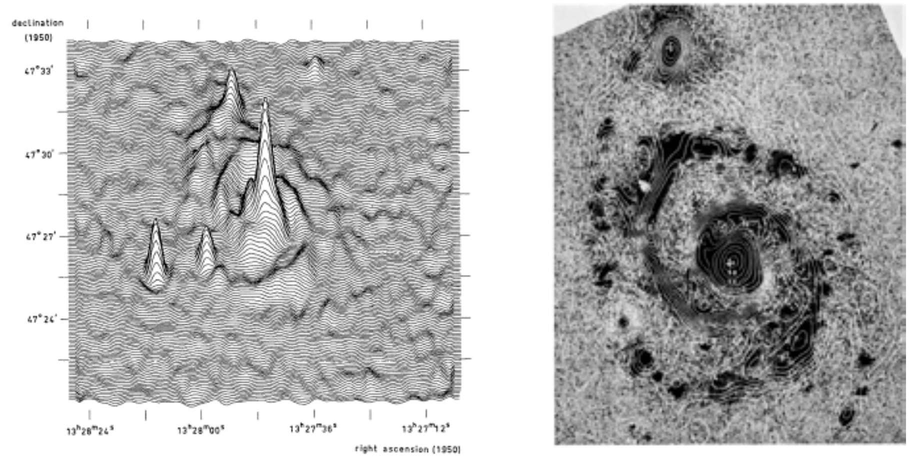
Ger de Bruyn felt that a leading telescope should produce about one outstanding result each year. He maintained a list of exciting science coming out of the WSRT, and when last updated it numbered 50 noteworthy results, about one per year with the 50th anniversary of the telescope soon upon us. Largely based on that with a few additions and modifications, the following pages represent WSRT milestones most of which are represented by an image as published by those who did the research. Most of the highlights concern astronomical results, though 10% fall in the categories of hard-/software development. Each highlight is presented with a minimum of descriptive text: the pictures should speak for themselves. Enjoy the almost abstract shapes, shades and colors which rolled out of the WSRT (a search of the Astrophysics Data System (ADS) will help satisfy the curious) – relish these WSRT highlights!

1 ASTRON, University of Amsterdam, The Netherlands
2 University of Groningen, The Netherlands
3 ASTRON, The Netherlands

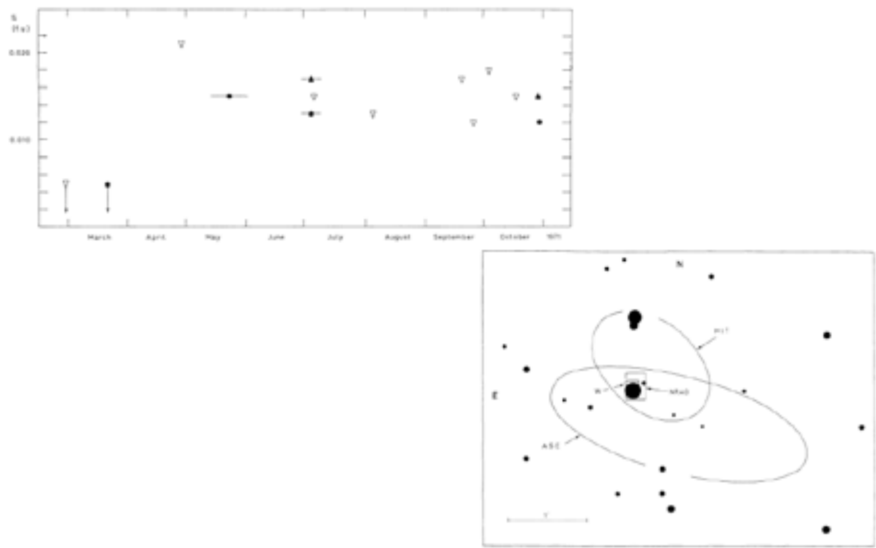
Software (mapping, display), 1970



M51 radio spiral arms, 1972

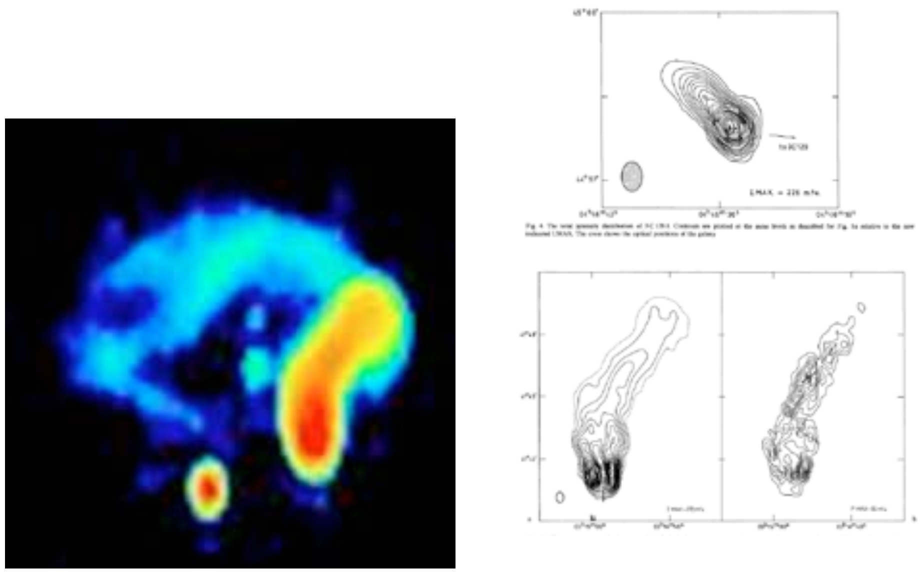


Cyg X-1 radio flares & identification, 1971

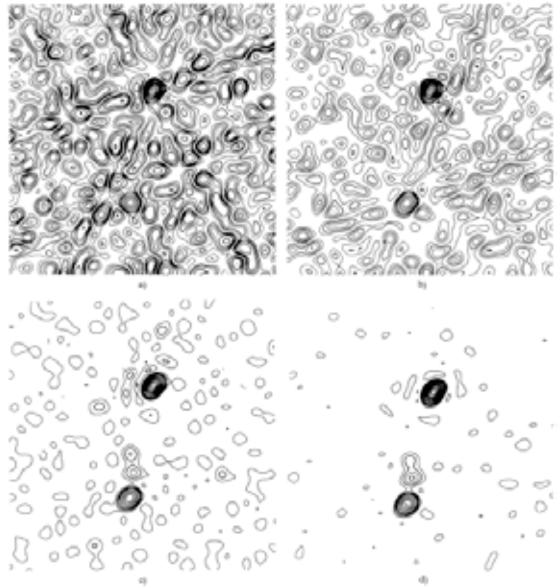


NGC 4258 radio spiral arms, 1972

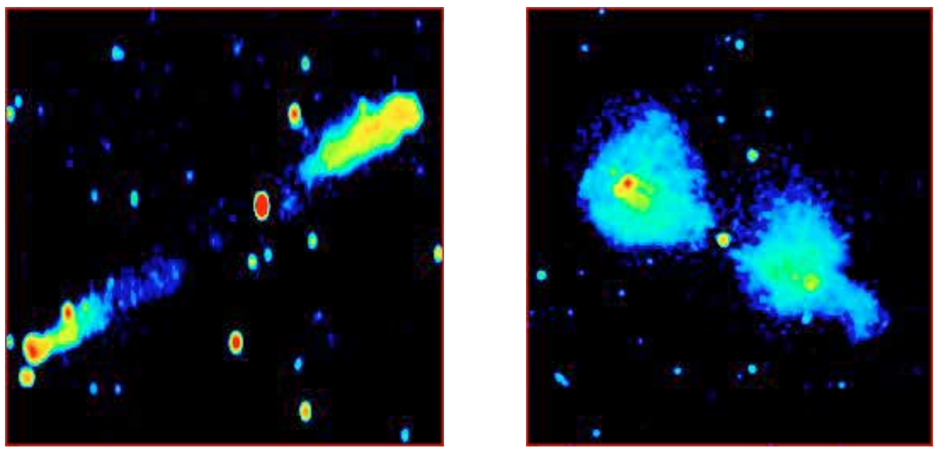
Head-tail radio galaxies, 1973



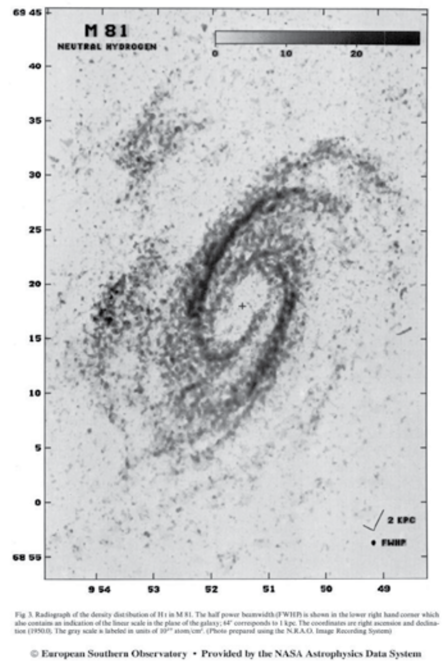
Högbom CLEAN, 1974



Giant radio galaxies, 1974



Hydrogen (HI) in galaxy M81, 1975



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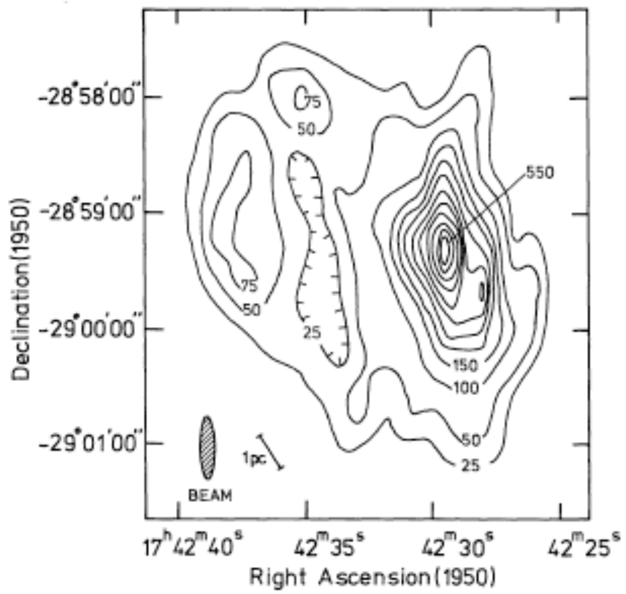
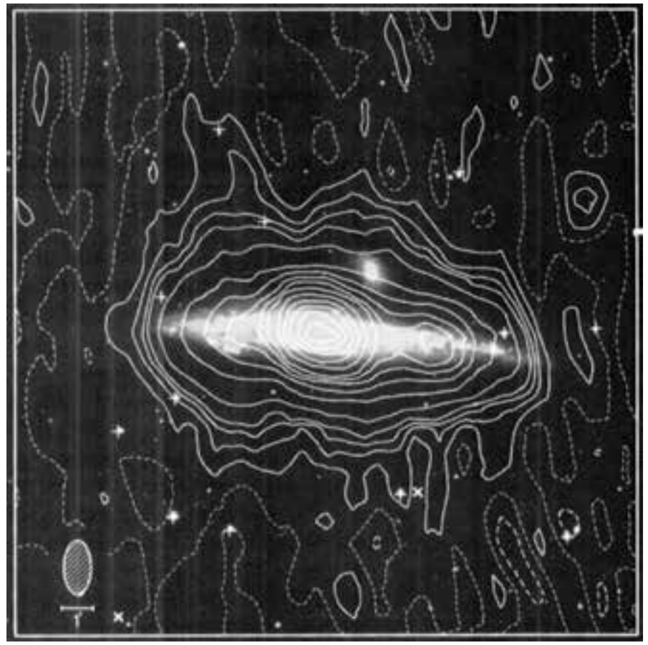
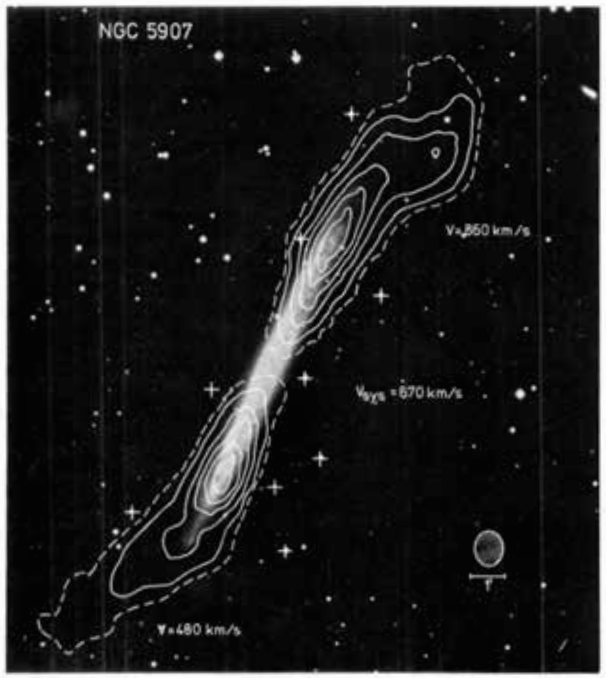
Nucleus of the Milky Way, 1975



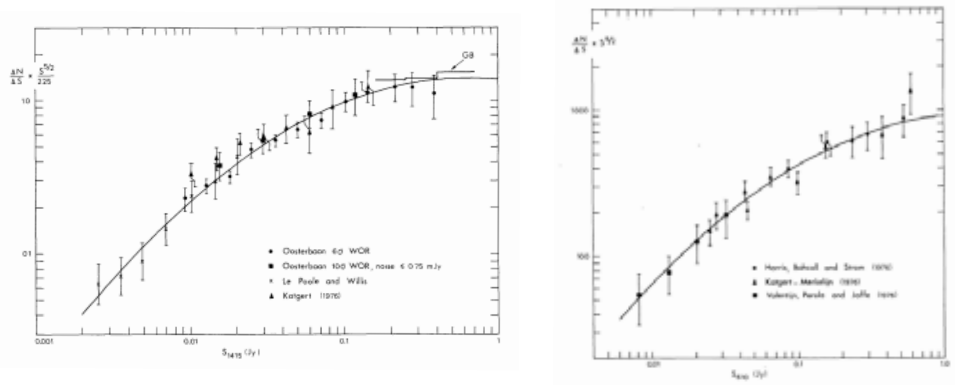
NGC 4631 – radio halo, 1976



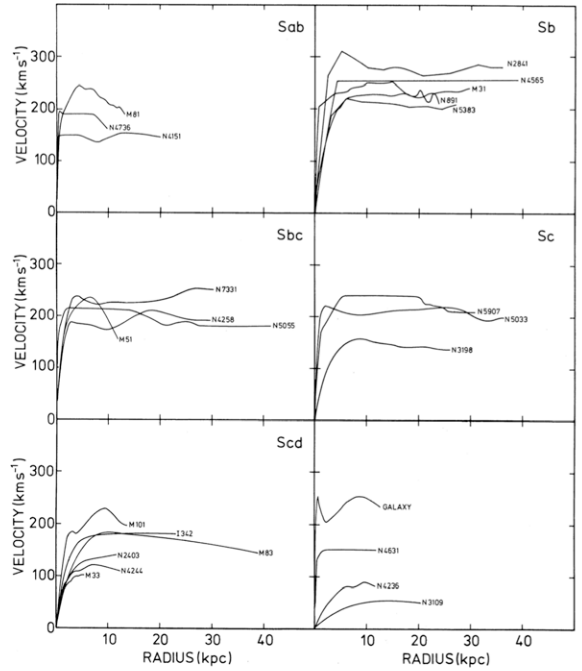
"Warps" in spiral galaxies, 1976



Deep source counts, 1977



Dark matter in spirals, 1978



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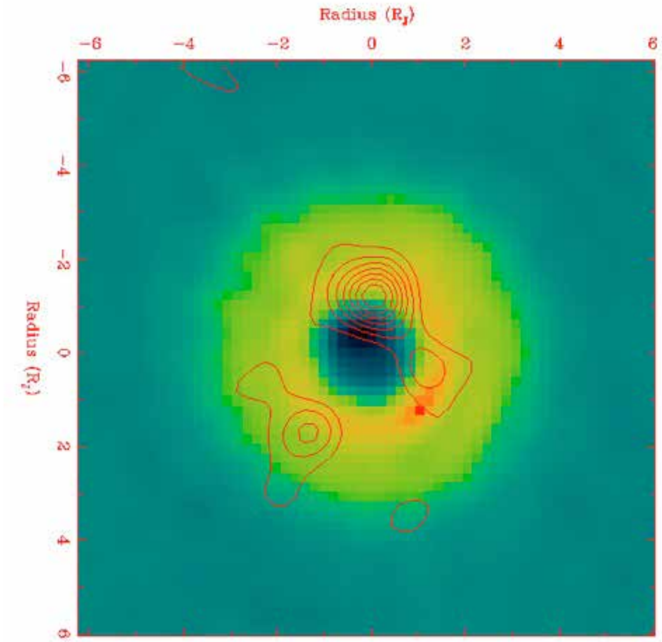

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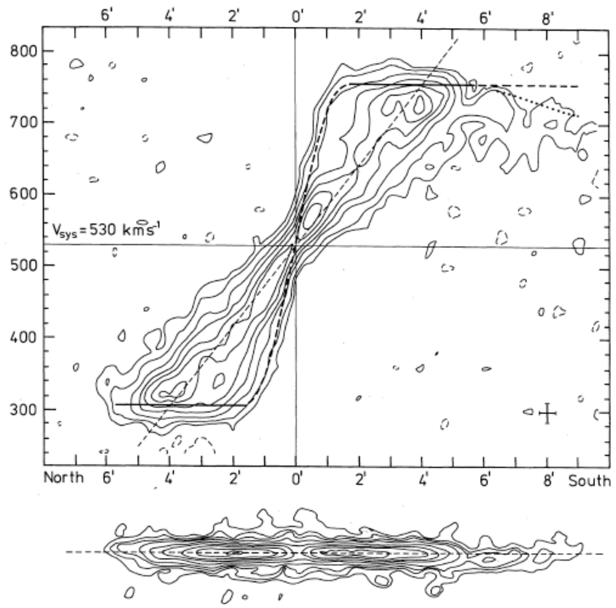

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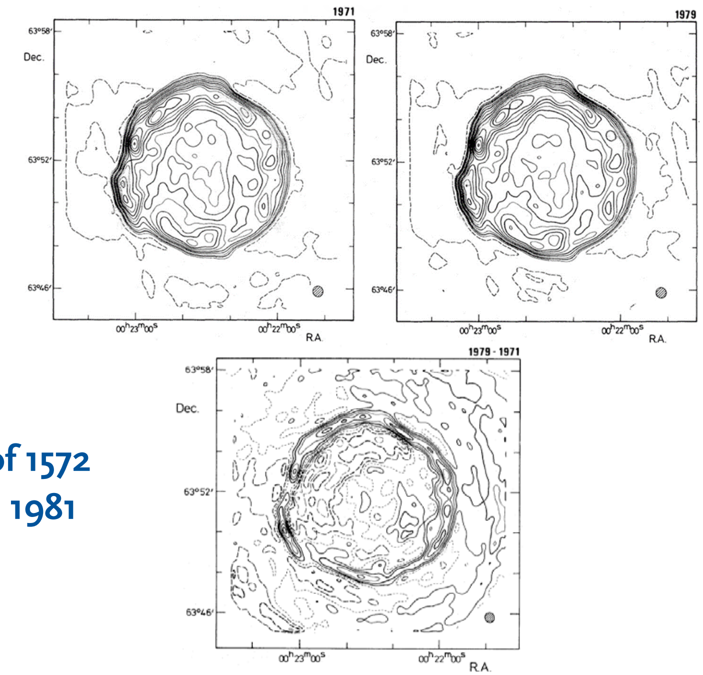

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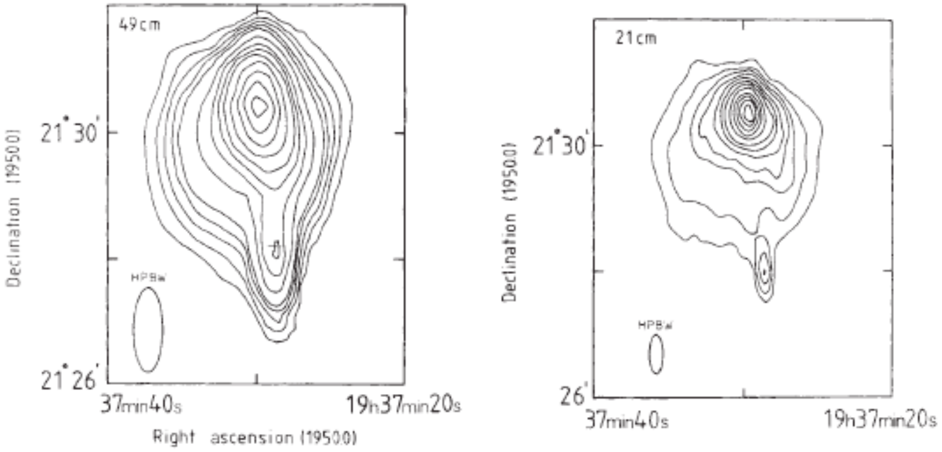

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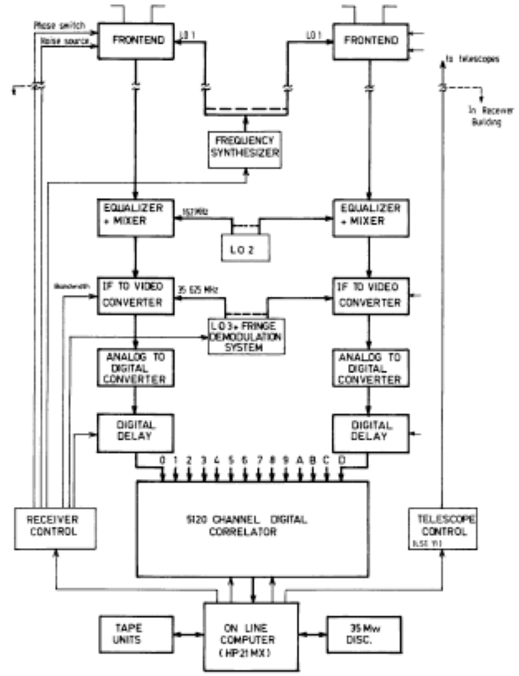

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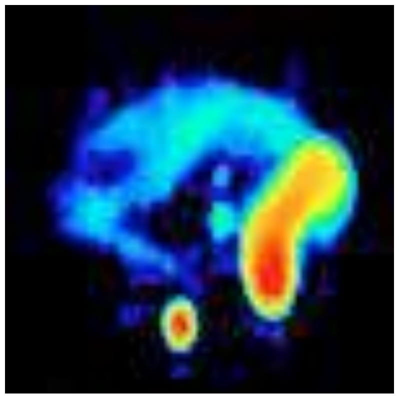

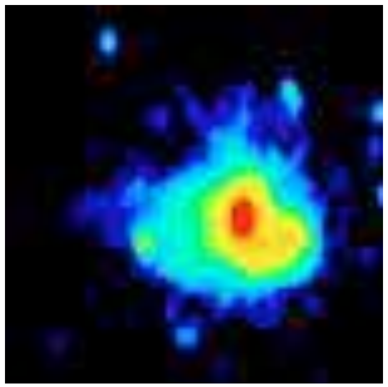

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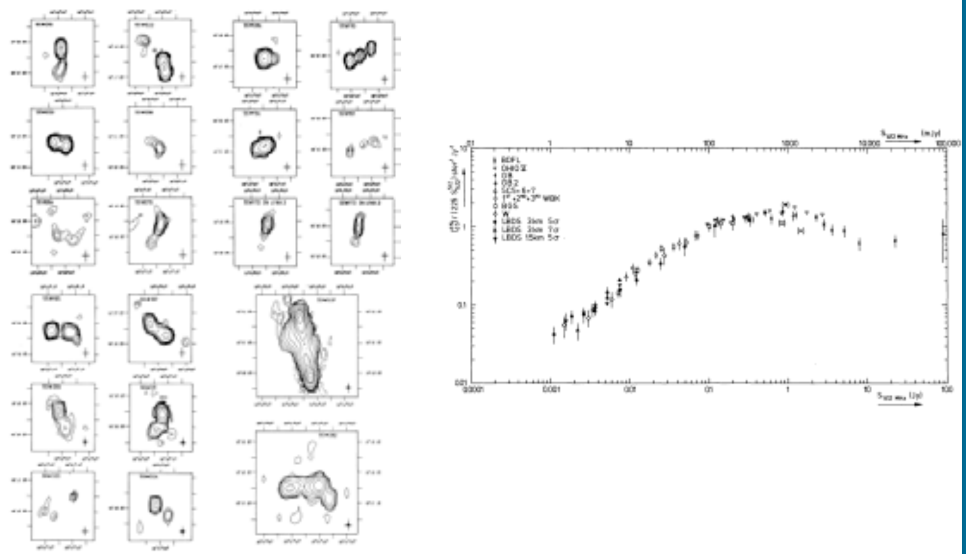

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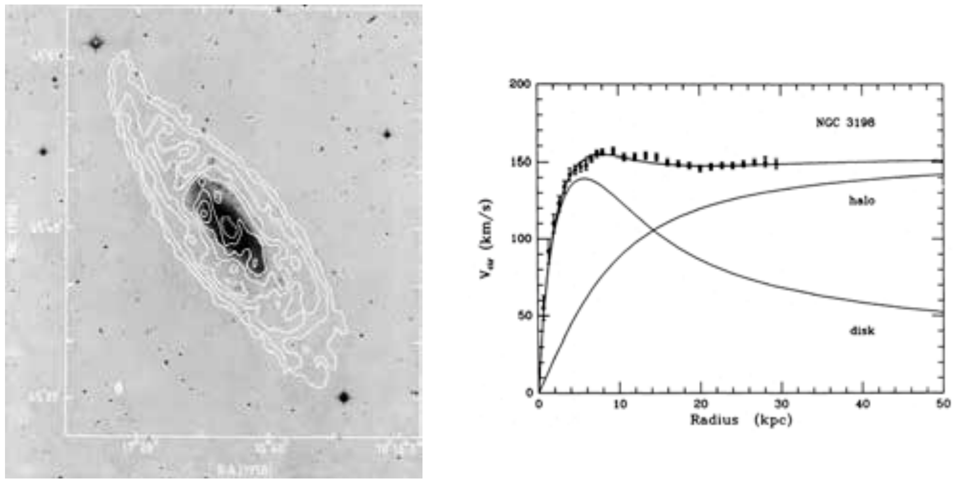

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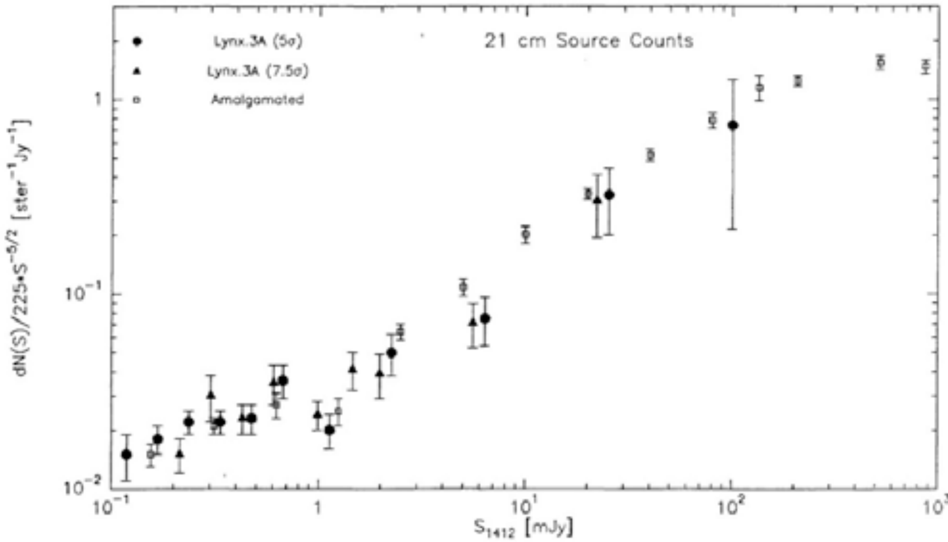

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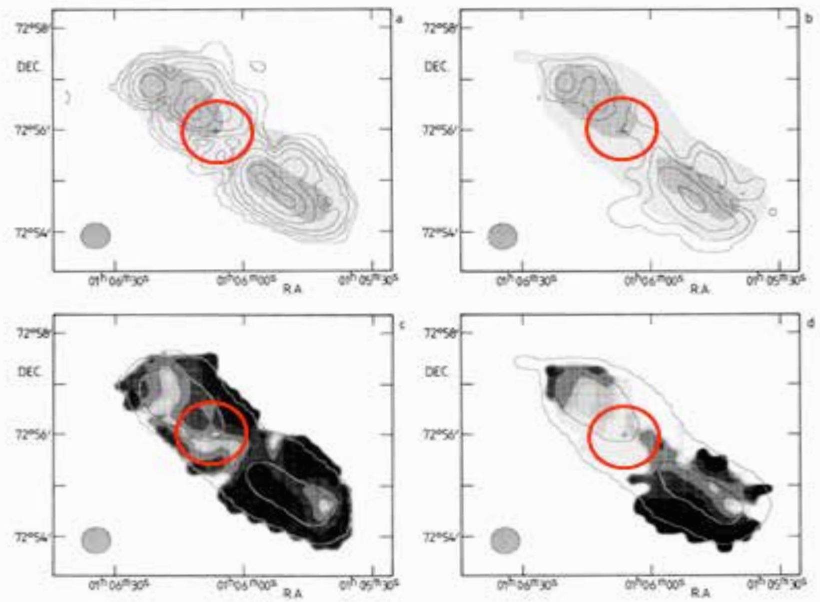

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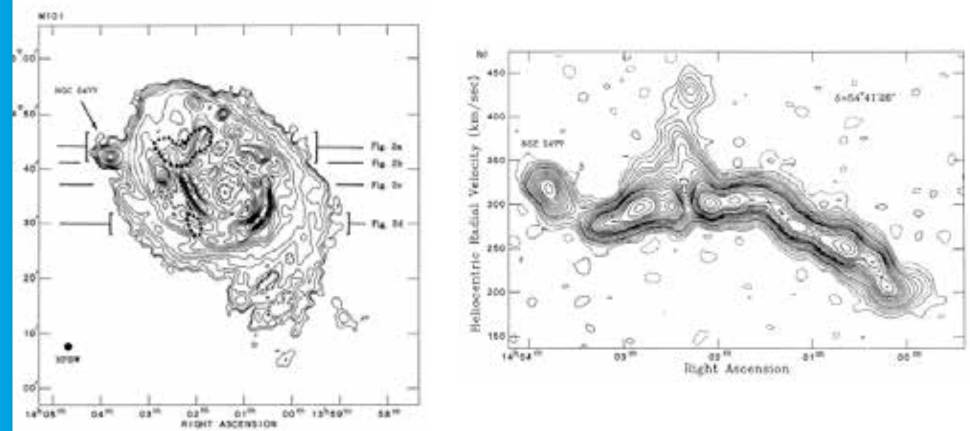

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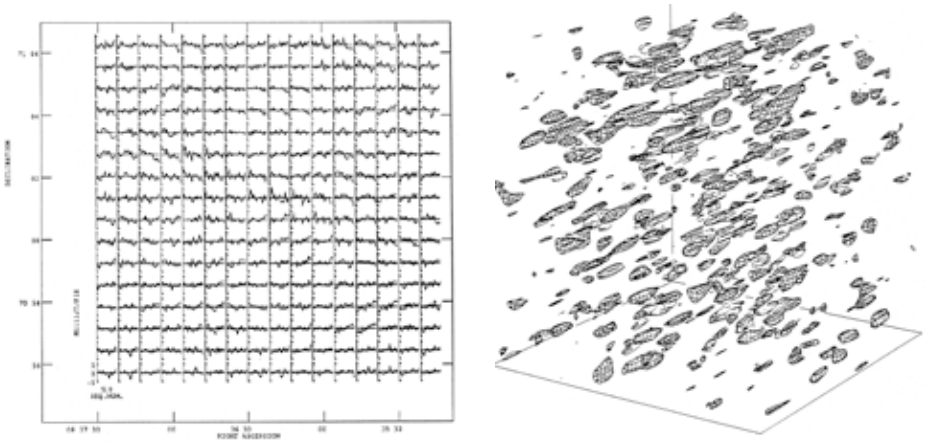

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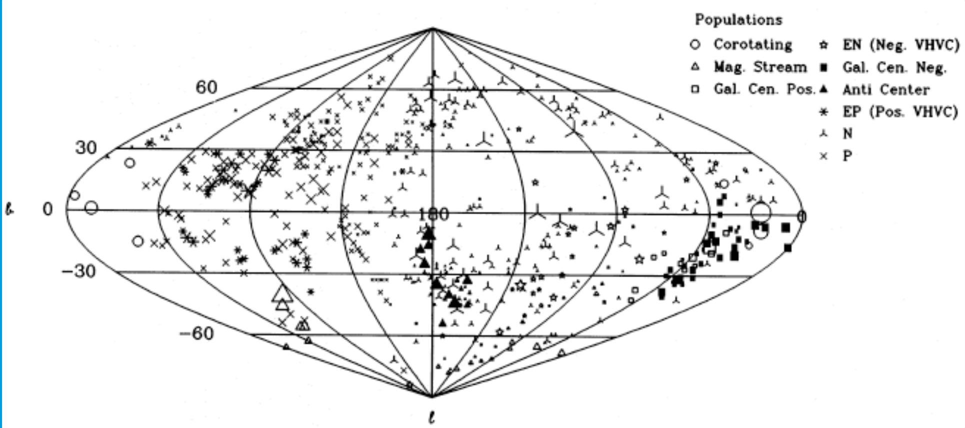

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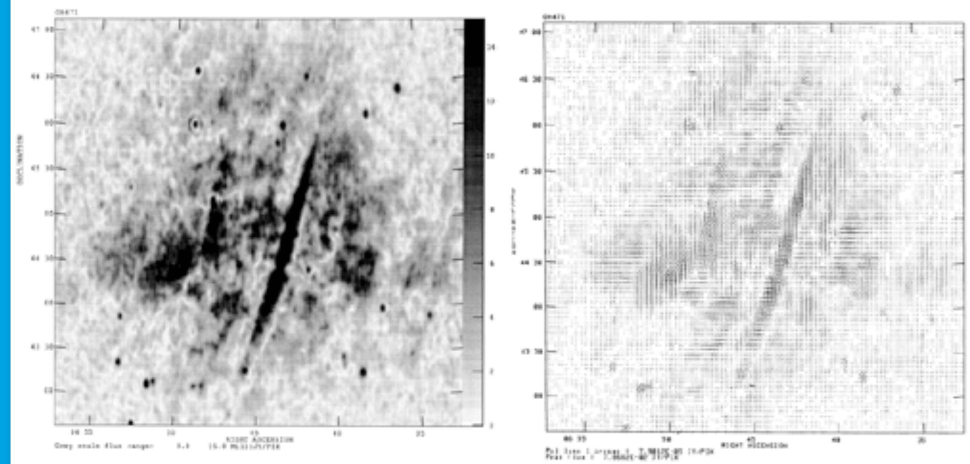

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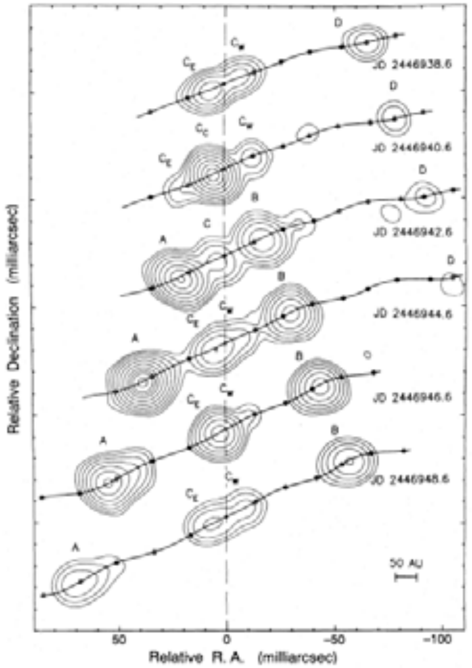

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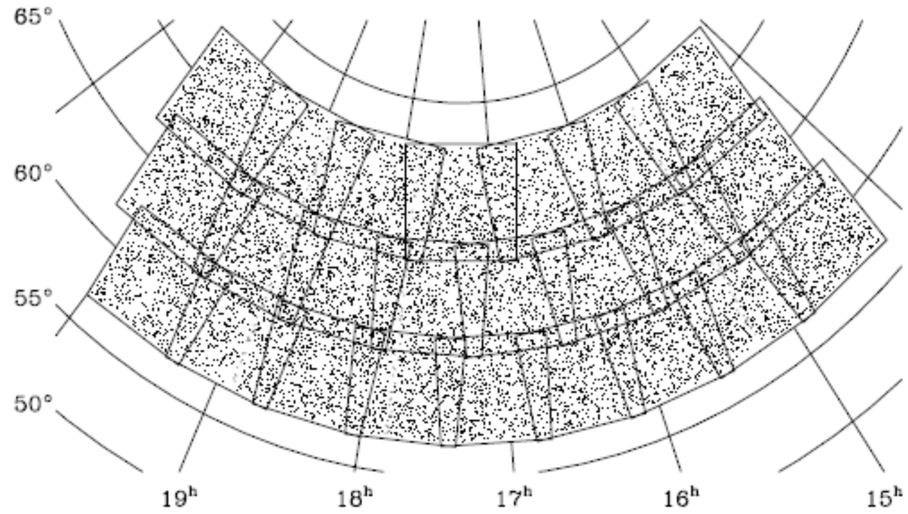

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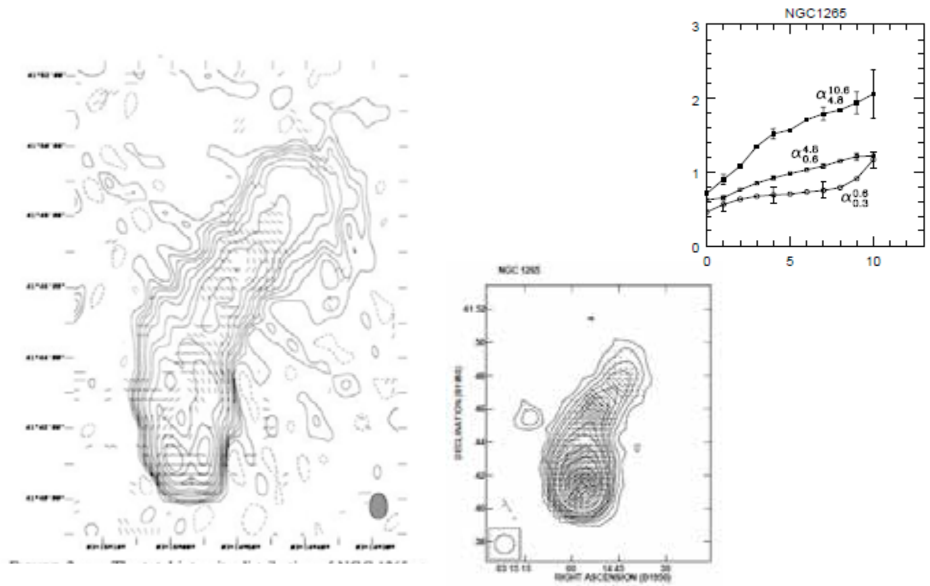

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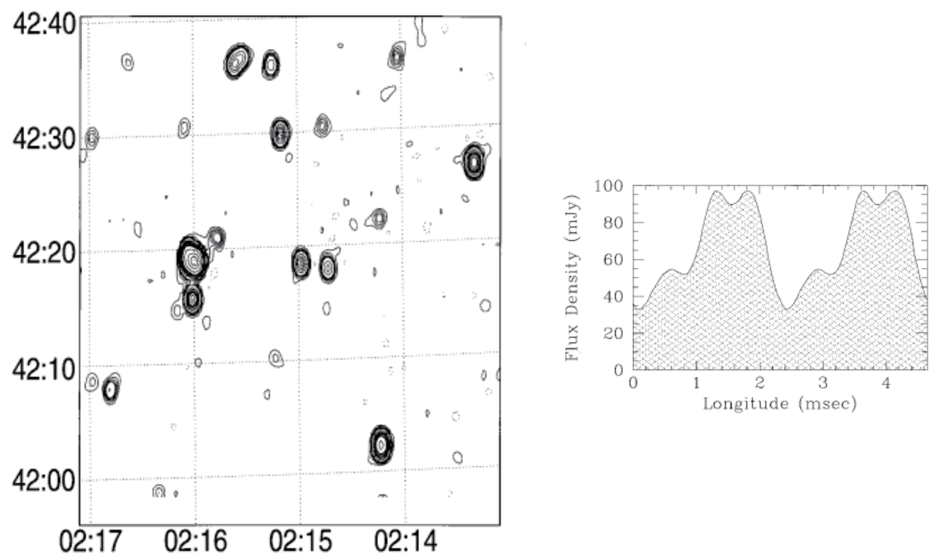

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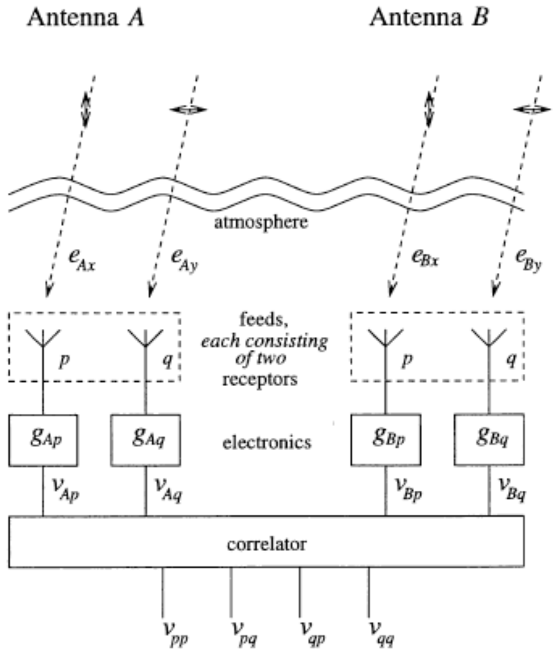

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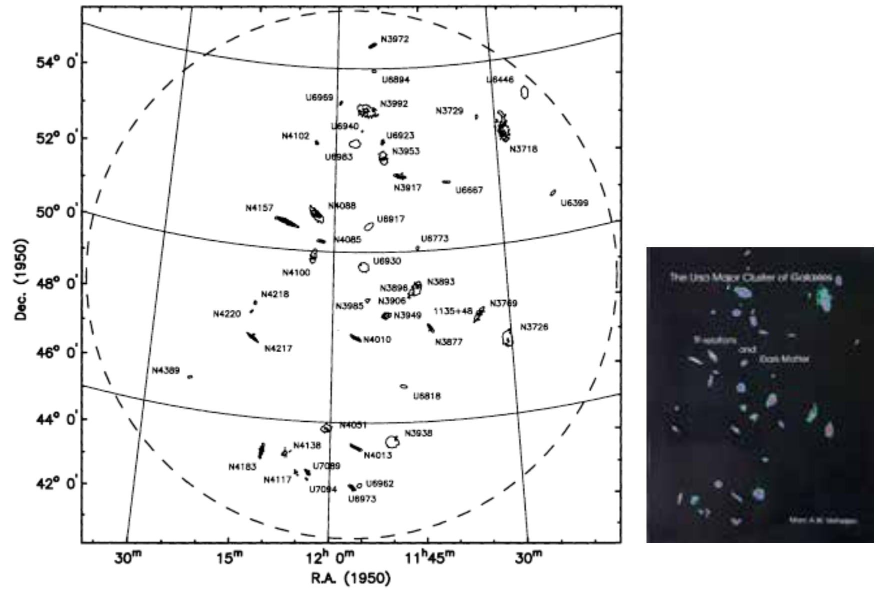

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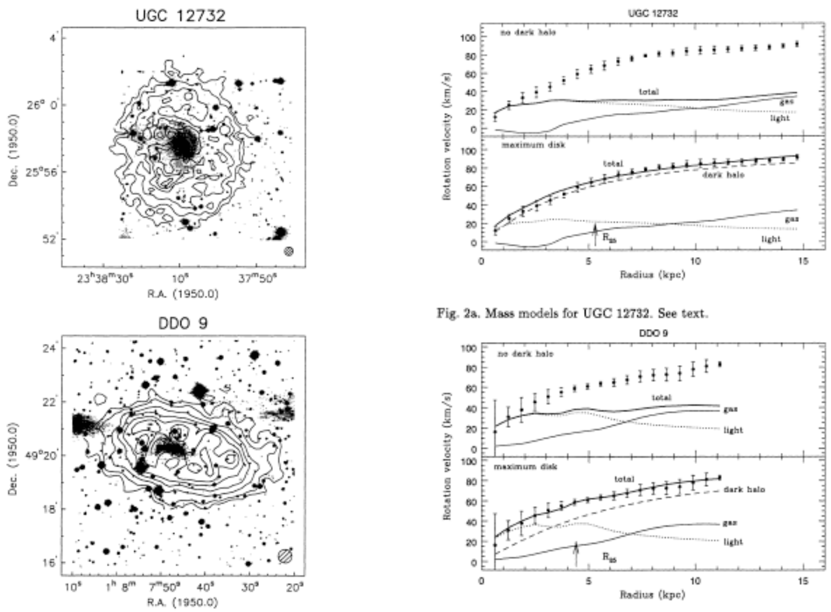

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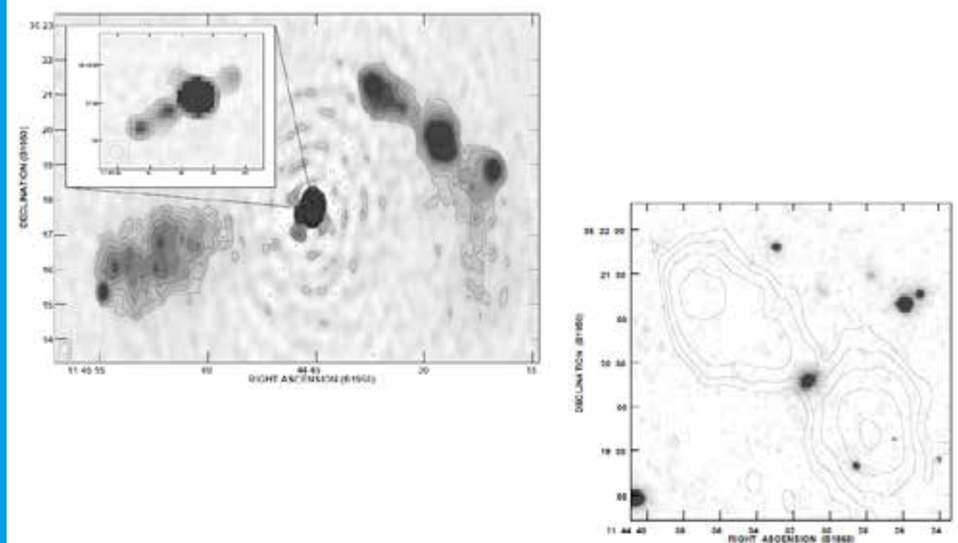

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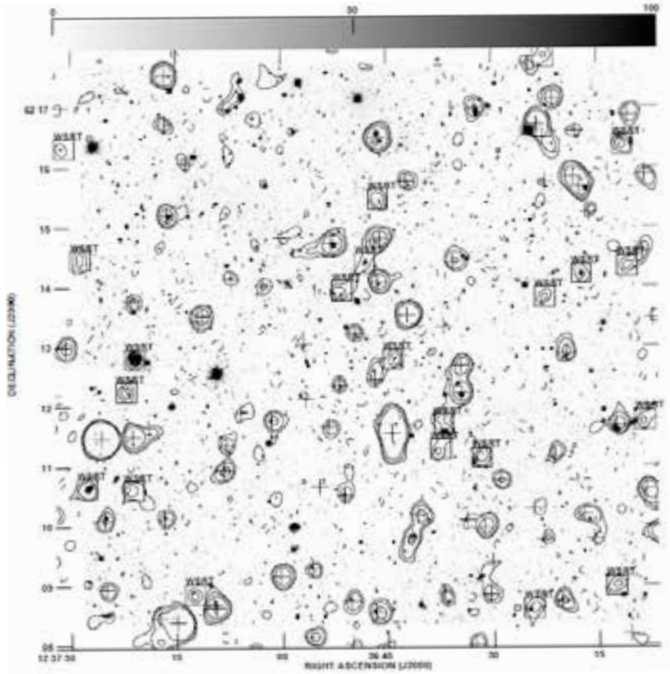

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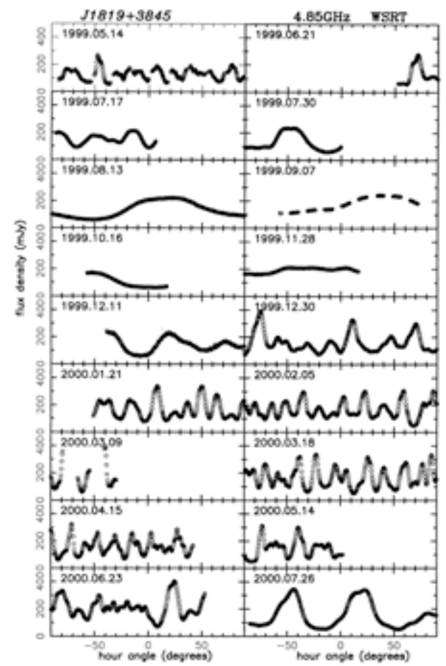

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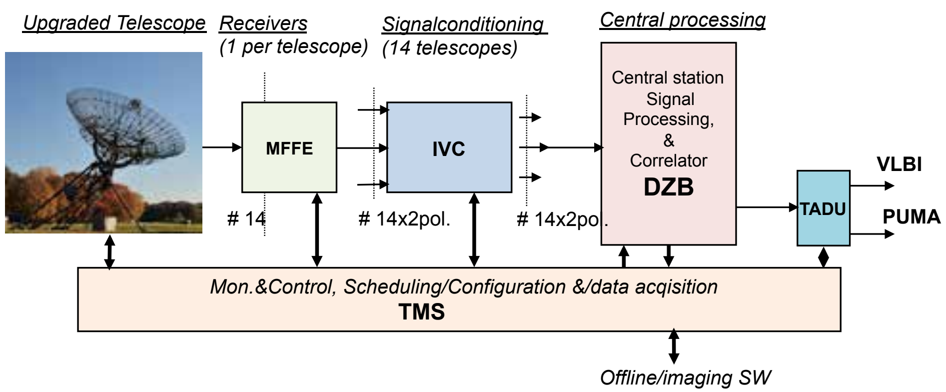

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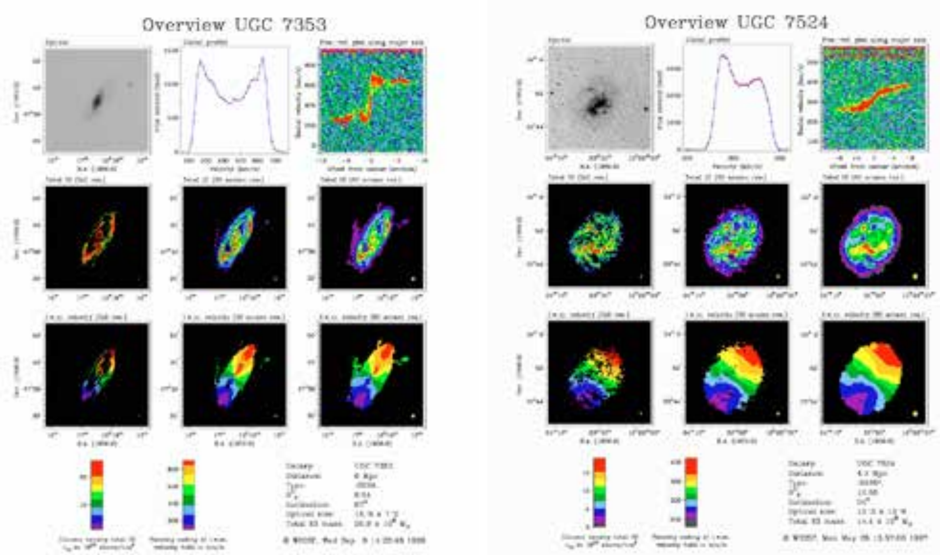

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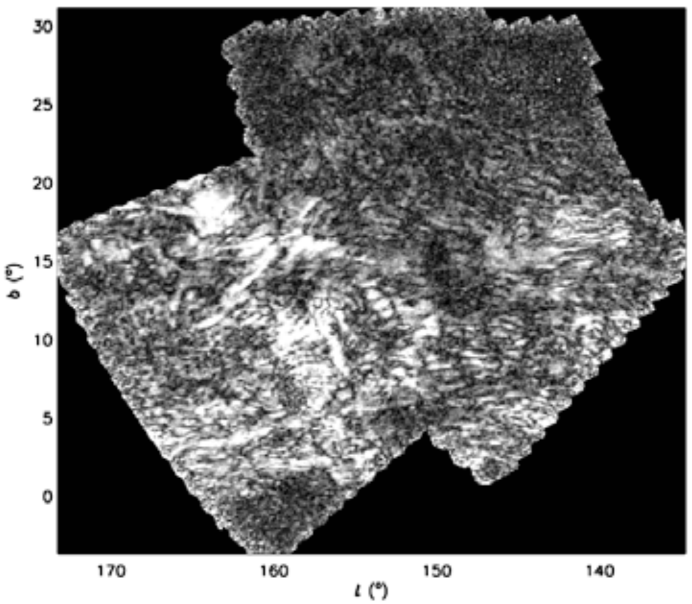

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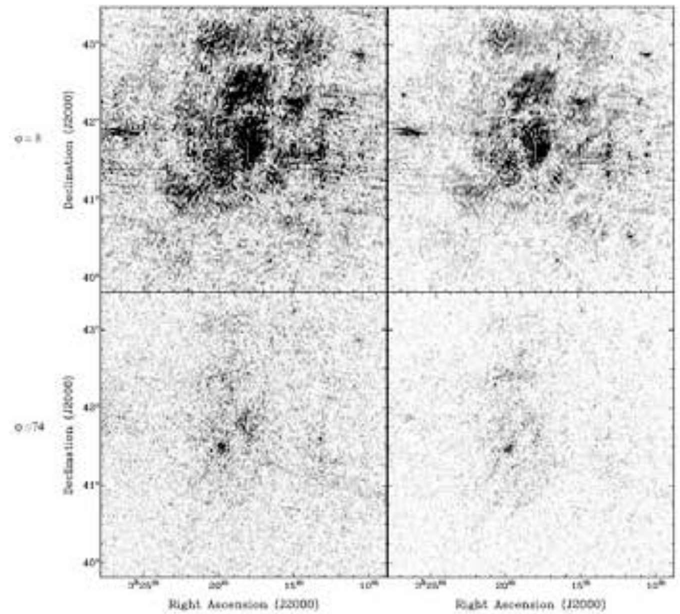

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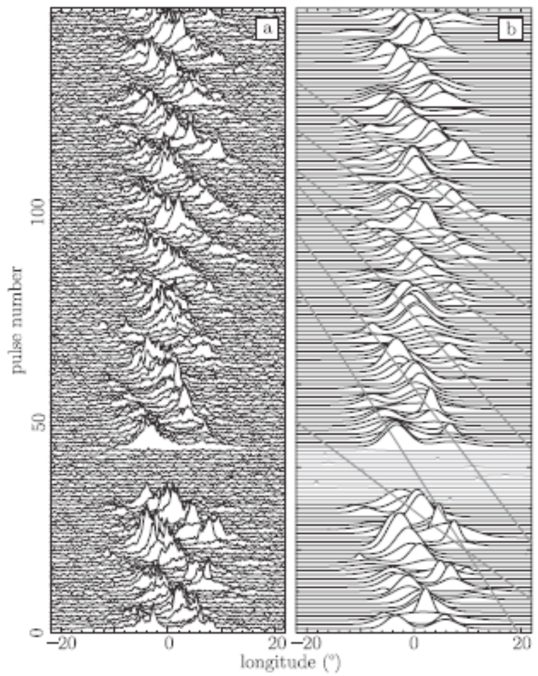

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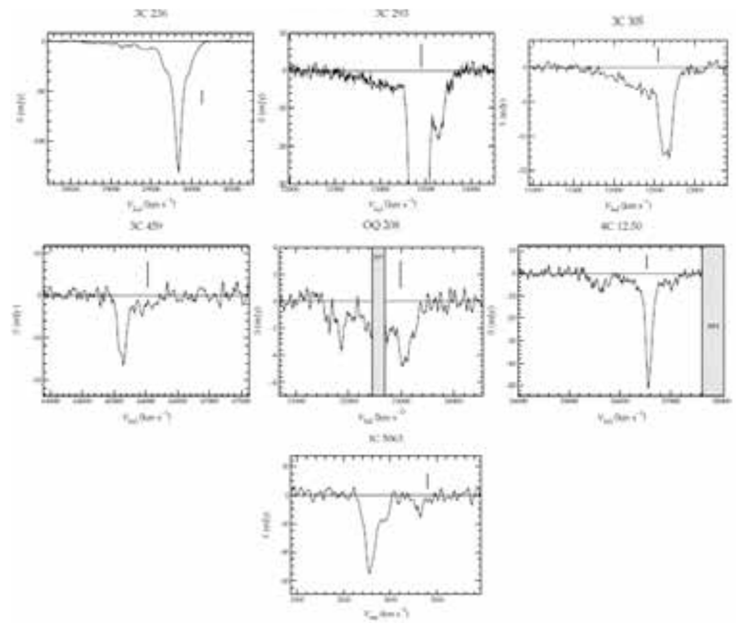

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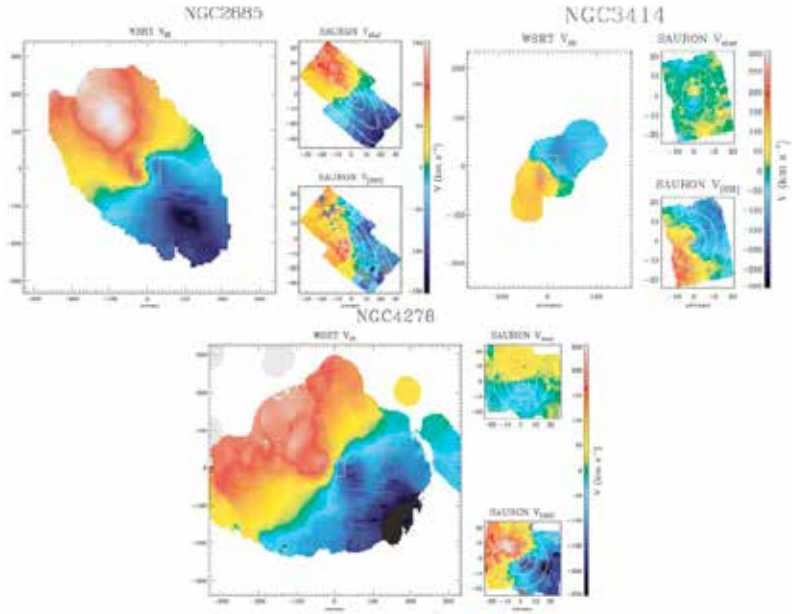

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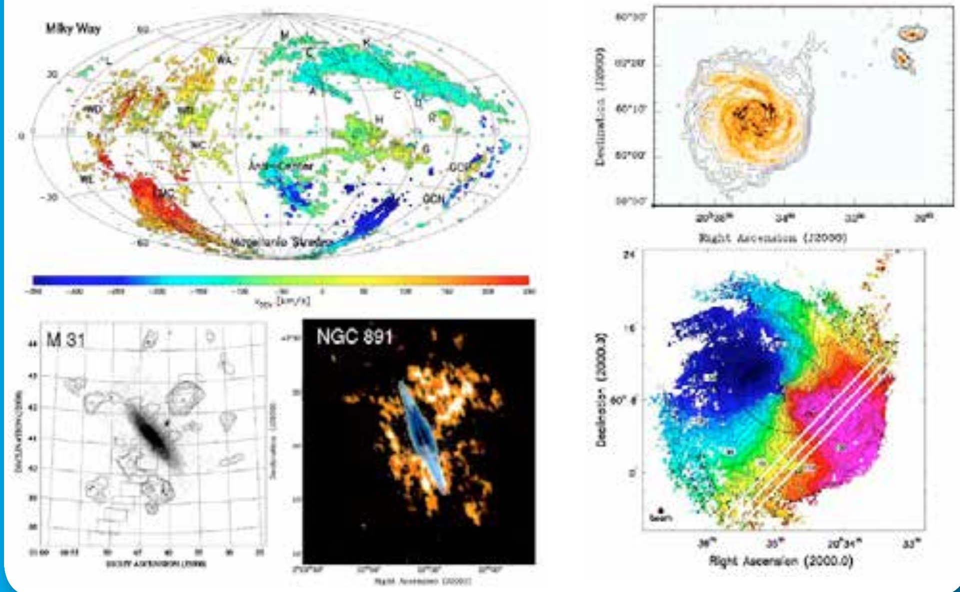

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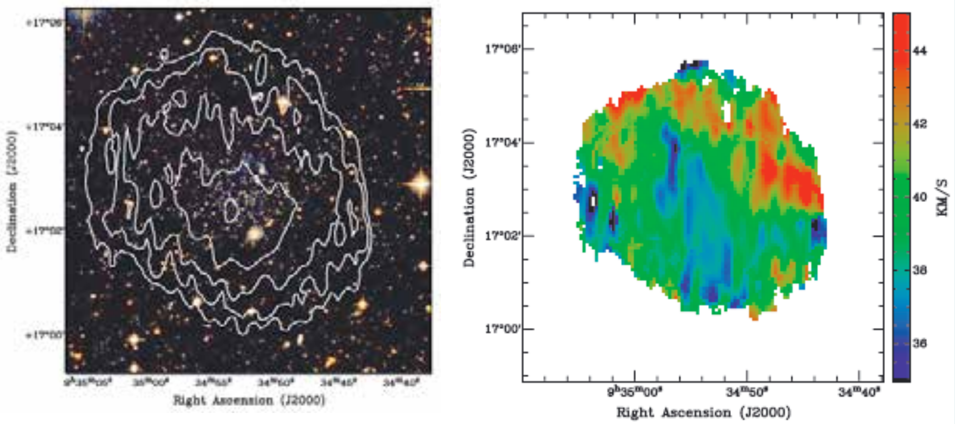

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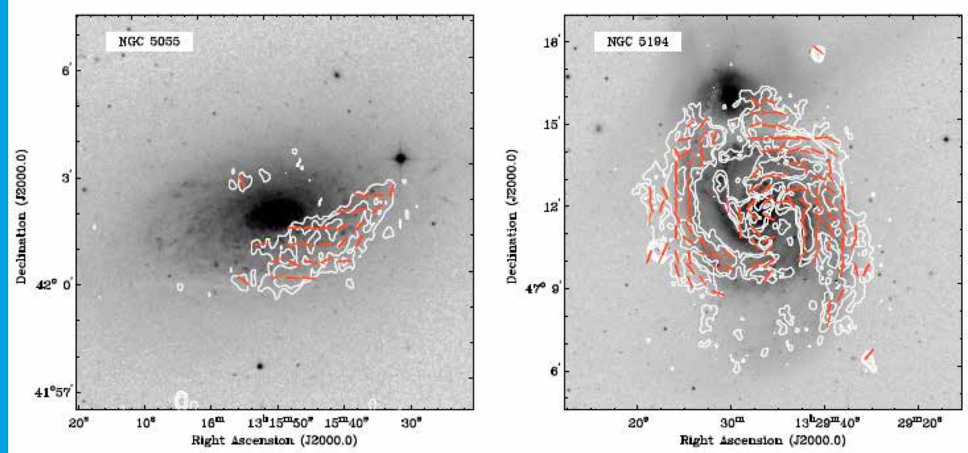

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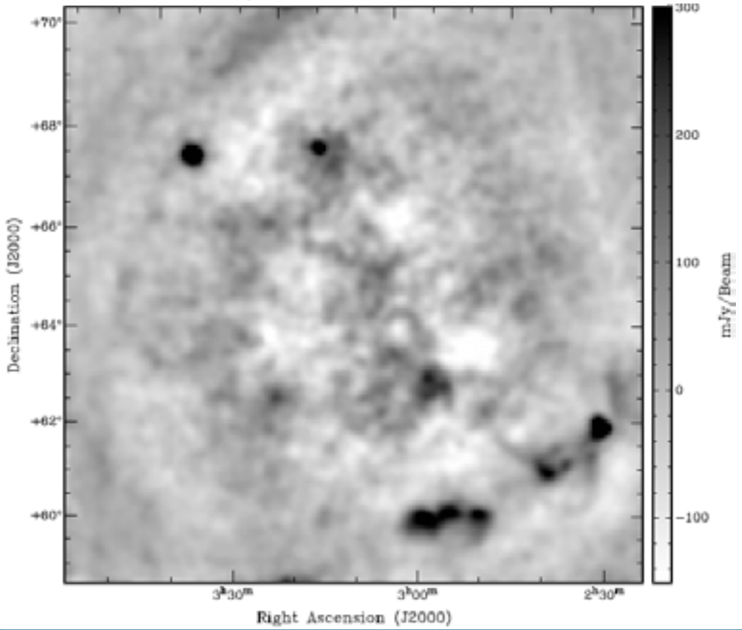

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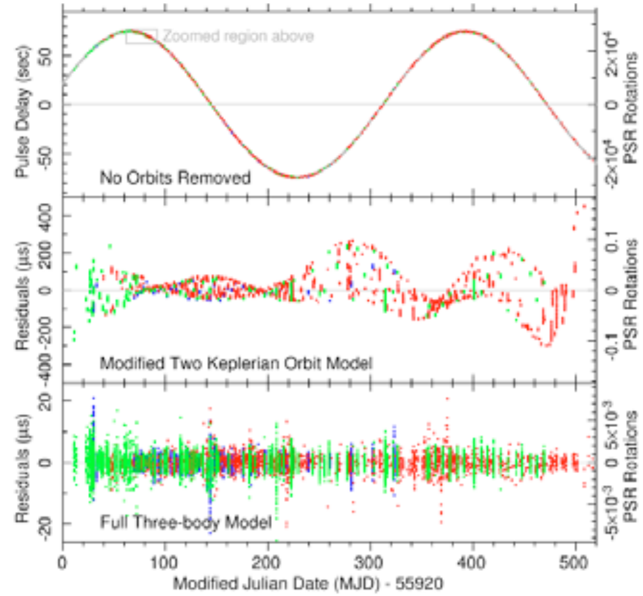

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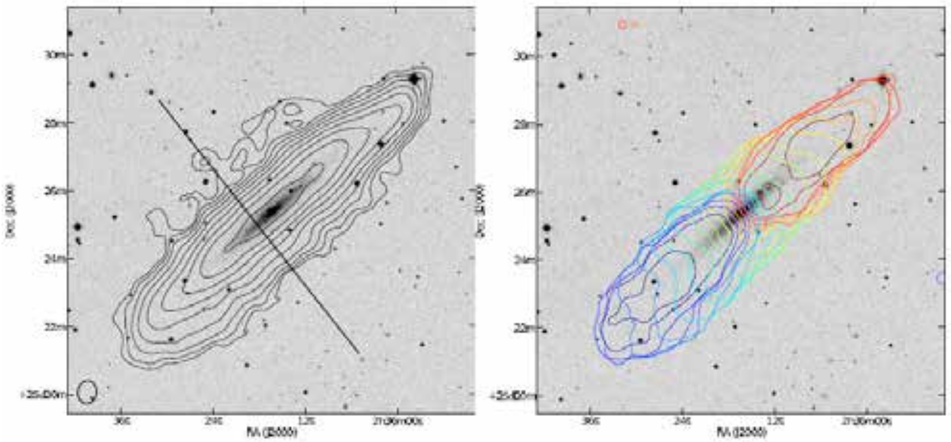

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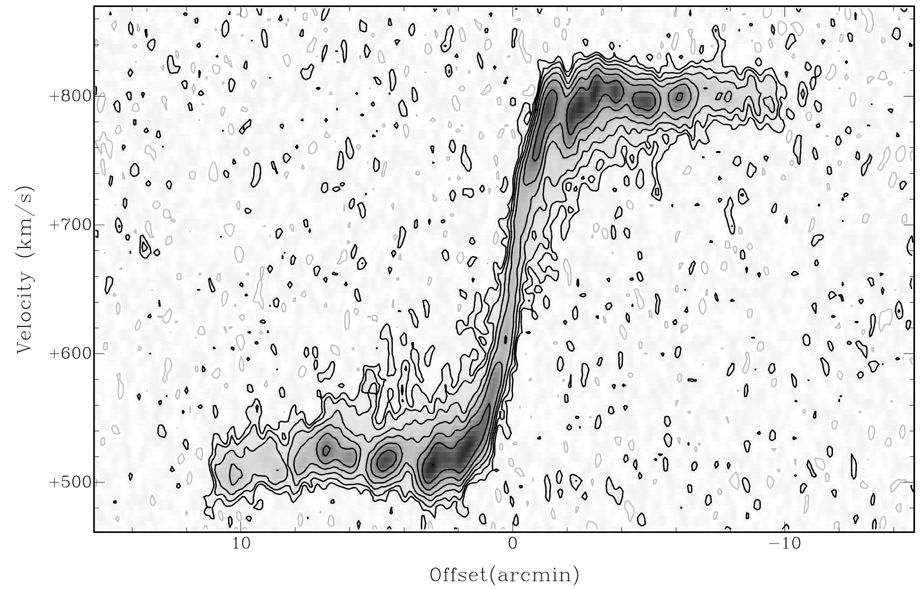

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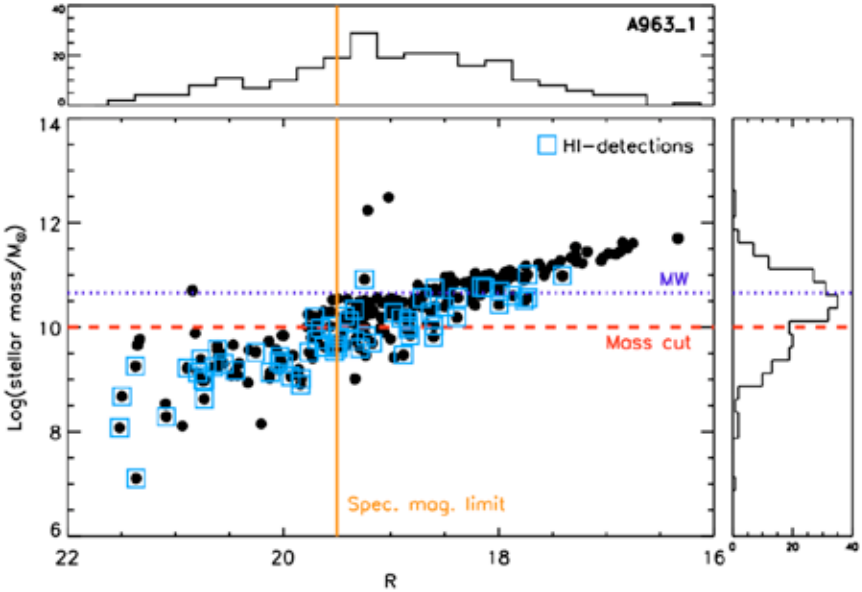

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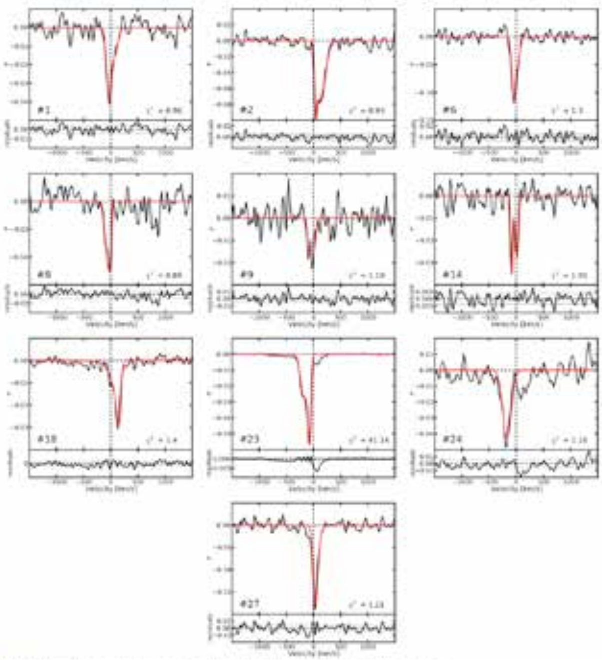

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The Westerbork synthesis radio telescope (WSRT) was constructed 50 years ago. The WSRT's original 12, and subsequently 14, 25 metre diameter dishes are the realisation of Jan Oort's dream to observe the sky at resolutions of more than one hundred times that of the single dish Dwingeloo radio telescope.

The WSRT's 50 year history reflects not only the significant technological progress in electronics, systems and computing but also the particularly close and fruitful cooperation of talented engineers and scientists brought together at ASTRON. In this book, many of these scientists and engineers describe the WSRT's role in astronomical discoveries of the past decades, and its wider impact. Its success has enabled ASTRON and the Dutch community to design, build and subsequently exploit a major new metre wavelength telescope (LOFAR), and to lead the design and development of new multi-pixel wide-field radio "camera" systems. This "camera" system is at the core of a major system upgrade on the WSRT, setting the scene for significant new survey science starting in 2019.

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