Finishing the Westerbork Upgrade

Willem A. Baan (ASTRON) - Director of the WSRT

It has been said that there is “no radio telescope in the world that is operating at its original design frequency and design specifications”. That will become very true for the Westerbork Synthesis Radio Telescope (WSRT) after the end-to-end Upgrade will be completed in the Fall of 2002. The Westerbork telescope was the brainchild of Professor Jan Oort, who realized that after the “large” Dwingeloo Telescope was completed in 1956, an interferometer operating at 21-cm would represent a great step forward for radio astronomy. The WSRT was constructed in the period 1967-1968 and has made many contributions to galactic and extra-galactic research. For an historical account of the Dwingeloo and Westerbork telescopes I refer to Raimond & Genee (eds.) - "The Westerbork Observatory, Continuing Adventure in Radio Astronomy", Kluwer (1996).

The Upgrade that happened during these last ten years has resulted in a substantial increase of the capabilities of the WSRT in terms of frequency range, sensitivity, and operational flexibility. As all the new hardware and the functionality has been installed at Westerbork, it has been decided to mark the official end of this important phase of the WSRT upgrade on the 18th of October, 2002. After this event the work on the telescope system will continue in order to further increase the functionality of the system and to build in more bells and whistles into the Telescope Management System (TMS) in order to make it more attractive to the users. Also the work on the final version of the Tied Array Distribution Unit (TADU) will continue. The WSRT Upgrade consists of a long series of project related activities. The main parts of the Upgrade consist of 1) the mechanical refurbishing of the telescopes, 2) the production of sixteen Multi-Frequency Front Ends, 3) the 8 x 20 MHz Intermediate Frequency Conversion (IVC) system, and 4) the half million lags DZB correlator. These projects have already been described in detail in a previous ASTRON Newsletter (January 2000). The Upgrade process started in 1990 with the first feasibility studies for the MFFE systems in the time that Hans Kahlmann was the director of WSRT.

The mechanical refurbishing of the telescopes consisted of a cleaning and re-fitting procedure that took place in the hangar on the site. Jan-Pieter de Reijer and his WSRT team have led this project efficiently. The project started in 1995 with RT5 and was finished on schedule in 1998. It took about three months to do the work on each telescope. In the course of this program the telescope counterweights and the telescope control microcomputers were also renewed.

The new WSRT front-end system for the fourteen telescopes has been designed to provide flexible operation in nine major frequency bands ranging from 250 MHz to 8.6 GHz. After the prototype of the Multi-frequency Front Ends had been tested in 1995, the sixteen production modules arrived at regular intervals in the period September 1996 to March 1999. Gie-Han Tan from the ASTRON Technical Development Laboratory (TL) led the design and production teams for the MFFE.
A number of improvement projects are currently underway, that will further broaden the capabilities of the WSRT. A prototype system is being built that would give the WSRT an Ultra-Low UHF capability in the 110–170 MHz range. Since this band will be part of the upper band of the new-generation LOFAR telescope, there is a strong interest for exploring the spectrum where the re-ionisation signature of hydrogen (at redshifts of about 7) is expected to be. If the prototype performs satisfactorily, it is our intention to implement these systems on all fourteen telescopes. Another prototype receiver system is under construction operating at 6 GHz, which will serve as a stand-alone system on RT7 mainly for Methanol observations within the European VLBI Network. The design of this system would also allow the mounting of the phased array prototype at L-band that is currently being developed by an international development program. (EU-program: FARADAY)

A major project that is currently underway in the Development Laboratory and the Westerbork Observatory is the final version of the Tied Array Distribution Unit (TADU). This unit provides the combined signal of the WSRT in single-dish mode (equivalent to 94 m telescope) that is used for VLBI and for pulsar observations. The first version of this system, called TADUmin, is already operational. Funding has also been received from NWO for the implementation of RFI mitigation algorithms using 28 FPGA digital processors at the fourteen telescopes. These units will be placed between the IVC and the DZB correlator and are designed to suppress strong RFI before the correlation takes place. The development work on a number of RFI mitigation algorithms and the practical testing of these methods has been underway for several years and the results have already been published.

Looking into the Future

Before turning to the science in the following sections, I would like to mention that improvements will continue to be made at the WSRT. Considering that only the new-generation telescopes covering the same frequency range will surpass the sensitivity of the current systems, the WSRT will need to serve the astronomical community until the Square Kilometre Array comes on-line.

Bert Woestenburg and his TL team have designed the eight-band IVC system starting in 1996. The system was finished in the Development Laboratory in August 2000 but some fixes were made to the modules and the final installation in the basement of the WSRT control building happened in January 2001. All eight bands were in production in April 2002.

On the other hand, the first part of the hardware for Albert Bos’ (TL) “last correlator”, the DZB, had already arrived at the WSRT site in 1997. In January 2001 also the second part of all the DZB hardware arrived at the site. Until April 2001 only one-eighth of the correlator was used in the 1 x 10 MHz Minimal System. After that time the Nominal 1 x 20 MHz System was operated, which actually used one quarter of the correlator. However, the full system functionality could only be implemented as the embedded software and control software for both the IVC and DZB was completed. On 1 April 2002, the 8 x 20 MHz system was first made operational, which used the complete correlator and the complete IVC. Final commissioning of the IVC and the DZB systems happened during the summer months of 2002.

Besides the major technical changes in the Westerbork system, the telescope management system has experienced a total rebirth. The design of the system has been done by Marco de Vos (TL) and he led this software project until the delivery of release 3 in November 1999. After that point Mark Bentum and his WSRT team completed TMS-4 for the Nominal 20 MHz system in April 2001, and TMS-5 for the production 160 MHz IVC-DZB systems in April 2002. The effort for Release 6 of TMS, which is planned for December 2002, is currently led by Arno Schoenmakers. TMS-6 will include the control of TADUmin (see below), and a number of new important observing modes such as mosaicking, drifts cans, and multi-pointing and multi-frequency observing modes. It will also include 90° and 180° phase-switching modes in the correlator as well as 180° in the frontend. After that there will be TMS-7 with more functionality.

Pulsar observations at the WSRT are being done using the workhorse PuMa system, which has been developed by the Universities of Amsterdam and Utrecht. While PuMa I is a state-of-the-art system, development work is well underway to take advantage of the developments in digital hardware to build a new PuMa II system. The PuMa system on the WSRT has already produced breathtaking new insights in the physics of pulsar emission regions.

In addition to all these Upgrade activities, also the whole computer system was renewed and the network structure was adapted for the massive data volumes that are being produced by the system. These is also a new hydrogen maser and all the major digital hardware has been placed in de Faraday cage to prevent these systems from interfering with the data taking process itself. Also the staffing levels as well as the organisational structure in the Observatory were modified to allow a better response to the demands of operating this brand-new telescope.

All these major efforts have brought the WSRT again into the forefront of radio astronomy with its end-to-end renewal from the receivers to the data export system. The WSRT is the first interferometer for which an upgrade has been finished and upgrades for other systems have also been planned in coming years. At present the WSRT is the most sensitive system in the world at least at L-band (1150 – 1800 MHz) and P-band (300 - 400 MHz) and provides a wide suite of receiver bands that permit a wide variety of astronomical research programs. For instance, HI and OH studies are possible from the here and now up to redshifts of respectively 4.7 and 5.7. For targeted spectral line observations the WSRT will remain state-of-the-art for many years to come. Its continuum sensitivity will be surpassed by other upgraded interferometers only by employing bandwidths that are significantly larger than the 160 MHz bandwidth of Westerbork.

The new system has already produced some spectacular results. Rather than describing these results, I refer the reader to the following sections in order to see the beauty of the new data.
Finally I would like to mention the users of the WSRT. They are very important for the Observatory and their active participation is much appreciated. At the recent Users’ Meeting the issues of user support were discussed extensively. While the level of support appeared adequate at present, a number of attention areas has been identified that will be followed up at Westerbork in the coming year. The high-speed fibre connection that will be installed in the coming months between Westerbork and Dwingeloo and the connection that already exists between Dwingeloo and the SurfNet POP in Amsterdam will play an important role in our efforts to increase user support. One of these attention areas is data archiving and pipeline processing. For this purpose, we had already purchased the hardware for on-line archiving of ALL WSRT data at two locations. Efforts are also underway to implement pipeline calibration and processing for all WSRT data as well as for implementation of cluster computing and establishing a real WSRT presence as a World Wide Telescope within the Astrophysical Virtual Observatory.

A Big Thank You

It is important to note that many people have achieved the success of this Upgrade at the expense of hard work, personal time, and personal life. I want to thank all of these people in the Technical Laboratory that worked on the hardware, the software groups in the Technical Development Laboratory and the Observatory, the Facilities department that did the mechanical work, and the wonderful team at the Observatory that worked very hard to put it all together. We also thank our colleagues at the Universities that have supported all these activities. Finally, a special thank you is due for the taxpayers of The Netherlands that financed these projects. We trust that they will be thrilled with the beautiful results that will be produced by the Westerbork Telescope, a glimpse of which can already be seen in the following pages.

Gas and Dark Matter in the Outskirts of M31

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The outer regions of spiral galaxies are important tools for understanding the basic processes of galaxy formation and the influence of the environment on their evolution. The lack of star formation due to the low gas column densities implies a quiescent gas which more closely reflects the primordial gas distribution. Moreover, outer disks enable direct measurement of the properties of the dark halo through the HI kinematics. Far from the optical edge, the dark matter halo becomes the only dynamically important component and many ambiguities present in the inner regions become less severe (e.g. the M/L ratio). Knowledge of the halo density profile in the outermost regions is essential for solving crucial issues at the heart of galaxy formation theories including the extent and the nature of the dark matter itself. Numerical simulations of structure formation in a Cold Dark Matter scenario predict, for example, a well-defined radial density profile for the collisionless particles from the center of the galaxy out to its virial radius (e.g. Navarro et al., 1997, ApJ 490, 493). On the other hand, a strong link between the radial distribution of the gas and of the dark matter could unveil a possible baryonic nature of the latter.

The nearby spirals M31 and M33 form especially unique targets, due to their obvious relevance for understanding the formation and evolution of the Local Group, but also because (1) their distances are well known, independent of H0; (2) the high angular resolution that can be obtained; and (3) the extensive information that exists at other wavelengths on the gas and stellar distributions. An example of the information that can be obtained from a careful analysis of the HI disk of M33 is given by Corbelli & Salucci (2000, MNRAS 311, 441) where, in the framework of CDM theories, the measured extended rotation curve implies a halo virial radius of about 100 kpc. If the dark matter halo of M33 extends this far, it is quite plausible that the M31 and M33 halos overlap. However, no such comparable study can be done for M31 without a new HI survey. A second important result obtained for the nearby galaxy M33 is the demonstration that the outer HI disk cuts off abruptly over only 1 kpc due to ionization by the extra-galactic radiation field (Corbelli & Salpeter 1993, ApJ 419, 104).

M31 is the largest and plausibly dominant member of the Local Group. We have obtained new WSRT HI observations of the M31 HI disk at high spatial and velocity resolution, with uniform sensitivity, to address the following issues.

1. The extended HI rotation curve and warp, and implications for the dark matter halo of M31.

Our survey is the first to combine high spatial and velocity resolution (50 pc and 2 km/s) across the entire 80 kpc extent of the HI disk, allowing for a detailed determination of the core and extended structure of the dark halo. For a proper determination of the rotation curve, it is essential to have a detailed understanding of the HI warp in the outer disk. Previous modeling of the HI warp (e.g. Henderson 1979, A&A 75, 311, Brinks & Burton 1984, A&A 141, 195) has been based on a combination of high resolution inner disk HI data and much lower resolution and sensitivity outer disk HI data. The models have all assumed a flat rotation curve, but no independent fit of rotation curve and warping of the disk has been attempted. In the case of M31, HI was previously detected out to 150’ (31 kpc at 740 kpc), while the optical radius is Rp=95’, or 20 kpc. The column density limit of the earlier surveys was only 5x10^{18} cm^{-2}, while our new WSRT total power data reach down to about 1x10^{18} cm^{-2} for emission filling the 30 arcmin beam. Our synthesis survey region was chosen accordingly.
2. The radial decrease of the outer HI disk: measuring the extragalactic UV radiation field.

As the column density decreases, HI gas no longer remains optically thick to the external UV ionizing radiation and a sharp HI-HII transition occurs. This can be inferred from sensitive, high resolution HI maps of the HI decline in outer disks. Complementing these maps with dynamical information on the dark matter distribution in those regions makes it possible to estimate the intensity of the UV background radiation field in the local universe, which is otherwise unmeasurable. Very few galaxies have been mapped at 21-cm with sensitivity as high as $5 \times 10^{18}$ cm$^{-2}$ and even fewer have been observed with sufficient resolution to infer the sharpness of the HI-HII transition. Only in the nearby galaxies M33 (Corbelli & Salpeter 1993, ApJ 419, 104) and NGC3198 (Maloney et al. 1992, ApJ 398, 89) have previous 21-cm observations resolved the sharp truncation (about 1 kpc) of the HI disk. Our M31 survey will give a new determination of the local UV field, thereby testing the M33 result and the derived constraints on the dark matter halos of both galaxies, because the derived background ionizing radiation fields should be the same in both cases. The SW side of M31 is the ideal place for this, as the velocities are well offset from Galactic HI and our deep total power observations have demonstrated that the edge will be well-sampled with our survey coverage.
3. HI morphology and velocity structure in M31: the two-phase medium in the inner and outer disk.

The VLA HI survey by Braun (1990, ApJS 72, 761) has delineated the two-phase HI medium in M31 through detection of a high brightness, highly filamentary cool HI medium over the inner HI disk with an increasing temperature with radial distance from the center (Braun 1997, ApJ 484, 637). The new data will allow us to study the radial distribution of the two phase medium i.e. how far out in the disk large HI cloud complexes exist as part of the high density phase of the ISM inside a warmer and diffuse gas. The presence and the size of the clouds depend on the gas thermal pressure (especially outside star forming regions such as in outer disks) and on metal abundances (e.g. Wolfire et al. 1995, ApJ 443, 152). Therefore, information on the cloud distribution can be used to trace the metal enrichment process and the heating mechanism in the absence of stars. Related to this subject is the overall question of HI morphology and small-scale velocity structure in- and outside the star-forming disk; is the outer HI disk as structured as that at smaller radii, and if so, what shapes and stirs it?

4. A search for HI clouds and streams: continuing gas accretion in the outer disk?

A search at the 7.5 kpc spatial resolution of our WSRT autocorrelation data for faint cloud complexes has recovered a previously discovered extended HI cloud near M31 (the `Davies cloud" 1975, MNRAS 170, 45p) and a new extended HI tail on the other side of the disk. How are these features related to M31? A stellar counterpart to our HI tail has been found by Ibata et al. (2001, Nature 412, 491). Continuing accretion of gas in galactic disks has become one of the standard assumptions in understanding the chemical evolution of spiral disks (e.g. Chiappini et al. 1997, ApJ 477, 765, Cuillandre et al 2001, ApJ 554, 190), yet concrete observational evidence for this process is absent. Smoothing the proposed survey data to 0.5 kpc spatial resolution will give us information on the extent of the gas at column densities approaching 10^{18} cm^{-2}, comparable with high redshift Lyman Limit Systems, and therefore will give us information on whether LLS are more likely progenitors of isolated clouds and of low luminosity dwarf galaxies, or if they were extended faint outer disks connected with the bright luminous part of galaxies.

In short, our observations provide the most detailed view yet of the HI disk of any galaxy ever observed (50 pc beam over a 80 kpc source) and may shed significant new light on these important questions.

The synthesis data were acquired in the WSRT maxi-short configuration during the period Aug. 2001 to Jan. 2002. A Nyquist sampled (15 arcmin spacing) pointing grid was defined in the M31 (major, minor) axis coordinate system. A total of 163 pointing positions were chosen from this grid to provide good coverage of the region of HI emission indicated by our previous WSRT total power survey of a 6x6 degree field, as well as sufficient (empty) background. A total of 27 tracks of 12 hour duration were acquired, each sampling 6 different pointing positions. Each 12 hour track consisted of cycling through the 6 relevant pointing positions with a series of 10 minute snap-shots. Calibration and flagging of the data were done in Classic AIPS. After external band-pass and gain calibration, each pointing was self-calibrated using the continuum emission which happened to be present. The continuum model of each field was subtracted from the visibilities and residual continuum was removed with UVLIN. A joint deconvolution of all 163 pointings was done with Miriad’s MOSSDI, after forming a weighted sum of the combined dirty synthesis image with a relevant total power image. The large physical memory (2 GByte) required to carry out joint processing of even a single spectral channel was found in a Dec Alpha machine operated by the PuMa II group in Amsterdam purchased with NOVA funding. Individual channels required about 5 CPU hours processing. The 300 independent spectral channels (each of 2 km/s width) containing M31’s HI emission therefore required some 1500 CPU hours. This was carried out in parallel using the 4 CPU’s (and 8 GByte total memory) of the PuMa II machine over a period of several weeks.

A first glimpse of the resulting HI database is given in Figure 1, where an image of peak brightness temperature is presented at the full spatial and velocity resolution (of about 50 pc and 2 km/s). Displayed brightnesses range from about 2 to 145 Kelvin and are presented with a square-root transfer function to accommodate the large dynamic range. Intricate detail is apparent in the inner disk, while warping and streamers are seen at larger radii. The diffuse feature located about 2 deg. to the NW of the M31 nucleus is Davies’ compact high velocity cloud. Recent WSRT imaging of this source (De Heij et al. 2002, A&A 391, 67) suggests that this object may currently be undergoing a tidal interaction with M31. HI streamers extend more than 3 deg. to the South of the M31 nucleus. Some of these are coextensive with the optical streams seen by Ferguson et al. (2002, AJ, astro-ph/0205530). These streamers presumably represent ongoing gas accretion onto the M31 disk from disrupted or stripped satellites. Extensive analysis of the M31 database is now underway.
Serendipitous HI Emission in Deep Radio Continuum Surveys

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The superb sensitivity and wide-field capabilities of the upgraded WSRT, make it a very attractive instrument to conduct deep radio continuum surveys. The introduction of the new 160 MHz IVC/DZB backend now permits a 1-sigma noise level of ~10 microJy/beam to be obtained in a single 12 hour observation at L-band. Previous deep field studies using the old system (e.g. the HDF-N, Garrett et al. 2000, A&A 361, L41) could only attain these sensitivity levels by employing long integration times (several days), targeting relatively small regions of the sky. The impressive observing “speed” of the upgraded WSRT permits significantly larger areas of sky to be surveyed. This is an important advantage in carrying out detailed studies of the clustering properties of radio sources and the nature of the faint radio source population more generally. Even before the 160 MHz system was in place, the trend towards observing much larger areas of the sky had begun. In particular, de Vries et al. (2002, AJ 123, 1784) recently published a catalogue of over 3000 faint radio sources in an ambitious survey covering ~7 square degrees of the NOAO Deep Wide-Field Survey in Bootes. These observations reached a 1-sigma noise level of 28 microJy/beam - the new system permits areas of this size to be surveyed to much deeper sensitivity levels.

Figure 1 WSRT 1.4GHz continuum image (contours) superimposed upon the NOAO optical image. The lowest contour is 40 microJy/beam.

The new system covers the full 160 MHz observing band (including all the polarisation products) with eight 20 MHz bands. Each of these bands can be independently tuned - the optimal continuum band thus avoids known areas of RFI (e.g. 1380 MHz at L-band) as well as galactic emission. Even in continuum mode, each band consists of 64 (or 128) channels - this is useful for RFI rejection but an interesting by-product is the possibility of detecting HI. We have conducted a deep survey at the edge of the Bootes field. The WSRT observations were made in support of a deep, sub-mJy wide-field VLBI survey of a small area of the field, that includes a possible in-beam VLBI “calibrator”. Figure 1 presents a continuum WSRT contour map superimposed upon the NOAO optical image of the same field. The measured r.m.s. (1-sigma) noise level is ~13 microJy per beam - close to the limit that is expected from the thermal noise characteristics of the array and various problems that arose during the observations (in particular solar radio emission in the last few hours of the observations).

Serendipitous HI Emission

For these observations we used the default continuum set-up that is now being adopted with the new 160 MHz system. Six of the eight 20 MHz bands are then located at frequencies below 1421 MHz, thus covering a range of frequencies where emission from neutral hydrogen redshifted up to z~0.1 (i.e. ~28000 km/s) may be observed. The 64 channels used for each 20 MHz band ensure a velocity resolution of about 60 km/s. This velocity resolution is good enough to distinguish between single or multiple galaxies, and, for the more massive ones, even measure the rotation velocity. The noise that is reached for every channel in a 12 hour observation (using natural weighting and Hanning smoothing of the data) is about 0.1 mJy/beam. A standard continuum observation is therefore well suited to a serendipitous search for HI emission in the observed field.

The presence of HI emission can be detected by generating a data cube from the full visibility data set, after subtracting all the associated continuum CLEAN components. We have performed this for our observations of the Bootes field, and at least four HI detections have indeed been found in a radius within ~15 arcmin of the field center. In Figure 2 we present an example of a position

Figure 2 An example of position (r.a.) vs velocity plot obtained for a constant declination in the continuum-subtracted cube. One of the HI detections is shown in the plot.
(r.a.) vs velocity plot obtained for a constant declination in the continuum-subtracted cube. One of the detections is shown in the plot, and the rotation of the galaxy is clearly visible.

The HI distribution, superimposed on the optical image of the four detections, is shown in Figure 3. Only for one nearby object, NGC 5656, was the presence of HI already known (Figure 3a). This galaxy is situated at a velocity of 3150 km/s and includes about $5 \times 10^9 M_\odot$ of neutral hydrogen. Extended radio continuum is also detected in this galaxy. A second detection was found coincident with the faint galaxy MCG+06-32-054 at ~4080 km/s (Figure 3b). Here the radio continuum is much weaker with a peak flux density of only ~60 microJy. At 4500 km/s neutral hydrogen was detected corresponding to an anonymous galaxy (Figure 3c). No radio continuum (to a ~3-sigma level of 40 microJy) has been detected in this case. Finally, neutral hydrogen was also detected at a velocity of 9500 km/s (Figure 3d). The peak of this HI emission is only about 0.8 mJy. A rough estimate of the HI mass gives $-4 \times 10^8 M_\odot$ (for $H_0=65$ km/s/Mpc). The bright galaxy visible in the optical image next to this HI detection is NGC 5646. HI emission from NGC 5646 is not detected - with a velocity of 8576 km/s it falls within a gap between two of the 20 MHz bands, a known region of RFI.

An estimate using the HI mass function (Zwaan 2000, PhD thesis), suggests that every field observed with a similar depth, should contain a handful of objects with detectable HI emission. The majority of the expected objects will be M* galaxies, i.e. galaxies with an amount of neutral hydrogen between $10^9$ to $10^{10} M_\odot$. The bias toward the detection of massive systems is partly due to the coarse velocity resolution that is obtained using the “default” continuum set-up, which normally would be done with full polarization (note that the velocity resolution can be improved by a factor of two by sacrificing two polarisations).

**More Possibilities with the New System**

The new IVC/DZB backend at the WSRT provides a number of new possibilities for deep surveys. The default continuum configuration using the 160 MHz band, permits very sensitive observations to be made, reaching ~10 microJy in 12 hours (L-band). The impressive observing “speed” of the new instrument allows vast areas of the sky to be surveyed in relatively modest integration times. As described above, the default spectral line mode used for all standard continuum observations, permits, without adversely affecting the continuum observations in any way, to search for HI emission in the field. In the example described here, the optimal set-up (in terms of frequency coverage and the RFI environment) has been employed, but nothing really prevents the user from centering the bands at even lower frequencies. For very deep continuum observations (many times 12h), a search for much more distant HI emission can then be conducted.

In addition, the 160 MHz-wide band combined with the spectral line capability permits both spectral index and rapid changes in the rotation measure to be determined for continuum sources in the field. Like the HI capability, such measurements also come “for free”, and are useful by-products that can now be extracted from every continuum observation.

Finally, we note that as the WSRT archive becomes populated with new data from the IVC/DZB system, there will be an important opportunity to automatically extract a wide-range of information from standard continuum data sets. Such developments are timely, and are particularly interesting in the context of Virtual Observatory tools and applications. In any case, it will be wise to “mine” such archives with the understanding that various products can be derived, not only the total intensity or polarization images.
Rapid Radio Variability in AGN: The Case of J1819+3845

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The radio sources in the nuclei of active galaxies are known to be extremely compact. This means we have only two methods available to study them: VLBI and variability. Variations in the radio emission of quasars and radio galaxy cores have been known since the mid sixties. Until recently the WSRT only played a very minor role in this field. However, with the arrival of the Multi-Frequency-Frontends in the spring of 1999 the study of variability phenomena, in extragalactic as well as Galactic sources, received an enormous boost. The frequency agility of the WSRT finally made it possible to switch between frequencies, on minute or daily timescales, whatever the need. The greatly improved sensitivity also helped a lot. Exciting results did not take long in coming, in more than one way...

In the ‘infamous’ long weekend of May 13/14, 1999 the frequency switching capabilities of the WSRT MFFE’s were first put through a rigorous test (resulting in broken cables, helium leakage and frontends heating up one after the other over the course of one week ...). The observations were useful as an (unplanned) test; the problem was solved quickly and has not recurred since!

Despite these minor technical problems the data did not prevent science to be done because it was then that we discovered the incredibly fast variations in the radio flux-density of the distant quasar J1819+3845 with up to 10% fluxdensity changes in one minute! (see Dennet-Thorpe and de Bruyn, ApJ Letters, 529, L65, 2000).

This weekend marked the start of two very exciting years of astronomical discovery during which we slowly began to solve the mystery of J1819+3845, and its implication for the study of Intra Day Variable sources. Over the summer we completed 3 years of WSRT monitoring of J1819+3845 providing us with a unique dataset. In the last two years many observations were done with the array split in three sub-arrays, each sub-array working at a different frequency.

What Have We Learned?

Our marvellous database on J1819+3845 has taught us a lot about interstellar scintillation and is also starting to tell us new things about the nature of the smallest and hottest AGN. Here is a brief summary:

1) The extremely rapid variations in J1819+3845 are due to interstellar scintillation of a very compact radio source. Variations of more up to 20% in 2 minutes have been seen (see Figure 1). We discovered that the screen is
unusually nearby, probably somewhere in the range from 10-30 parsecs from the Sun. Because of the proximity of the screen the source angular size can still be of the order of several tens of microarcseconds. (If the screen would have been at a few hundred parsec, as expected, the source would have to be only a few microarcseconds in size in order to exhibit such strong scintillation).

2) In a delightful experiment (see Figure 2) we have proven, beyond a shadow of a doubt, that the variations in J1819+3845 are due to interstellar scintillation. We did this through the measurement of a timedelay of order 100 seconds, in the signal received at two telescopes far apart. This timedelay is the hallmark of scintillation, in the presence of a moving screen or observer. IF the variations were intrinsic the same intensity should be observed at all telescopes on Earth with at most a timedelay of a few milliseconds (see Dennett-Thorpe and de Bruyn, 2002, Nature, 415, 57).

3) The scintillations are most pronounced at 6 cm, which marks the transition from weak to strong scintillations (see Figure 3). The modulation index, the rms normalized variation, at 6cm is about 40%. This is not as high as in pulsars but far higher than any other extragalactic radio source. The modulation index has remained remarkably constant over the last 3 years.

4) The source does not appear to be expanding, even though its intrinsic flux density is rising slowly and the source is radiating at a brightness temperature of about 5x10^{12} K, well above the 'inverse Compton limit'. Yet, expansion speed limits are well below that of the speed of light (Dennett-Thorpe and de Bruyn, A&A, in press).

5) The order-of-magnitude change in the scintillation timescale over the course of a year is the accidental result of the peculiar transverse plasma screen velocity (see Figure 4). In the fall season the projected velocity of the Earth is then almost cancelled, i.e. we are ‘moving along with the scintels’, and the timescale becomes very long. On the other hand, in the spring season, the effective projected velocity gets to be as large as 50 km/sec and the scintillations are fast. These results once again prove that Copernicus’ view of the solar system is the correct one.

6) There is a finestructure in the source with a significant gradient in both the spectral index and the linear polarization. This is the topic we are currently busy investigating.

What Next in J1819+3845?

Is there more to be learned from J1819+3845? Yes, we think so. In the late spring of 2002 we began observing J1819+3845 with the new wideband spectrometer providing enhanced sensitivity. With 10 microJy noise in WSRT’s most-sensitive L-band we can now start to address the polarization variability of J1819+3845 and possible diffractive scintillation aspects. With J1819+3845 typically showing less than 1% polarization we definitely need this sensitivity (it also helps that the source has slowly gotten brighter over the years) and the first results are just coming in. Significant timedelays between total intensity and linear polarization have been observed suggesting that we start to resolve the source and may be able to map out its polarization structure with 5-10 microarcsecond angular resolution.
Pulsar Timing: A High Velocity Millisecond Pulsar

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We have been carrying out a high precision pulsar timing program at the WSRT since June 1999 and it is beginning to produce some excellent results. One of the most exciting results is the first ever measurement of the proper motion of the millisecond pulsar PSR J0218+4232.

The pulsar timing program has profited from a combination of the excellent sensitivity of WSRT, the rapidity with which we can change observing frequency using the Multi Frequency Front Ends and the unique capabilities of the Dutch pulsar machine PuMa. PSR J0218+4232 has a very steep spectrum and therefore our most sensitive measurements at the WSRT are made using the 92 cm receiver. To further improve our sensitivity we use two 10 MHz bands. The large dispersion measure (DM = 61.25 pc cm$^{-3}$) of PSR J0218+4232 results in a large degree of smearing of the pulsations at these frequencies and such large bandwidths could not normally be observed. However the high frequency resolution capabilities of PuMa, we typically divide the 10 MHz band into 512 channels, mean we can regularly make observations of PSR J0218+4232 with very high time and frequency resolution and thereby improve our timing accuracy by more than a factor of three over previous measurements.

PSR J0218+4232 was first discovered as a steep-spectrum, very highly polarised radio source in WSRT synthesis imaging measurements. Pulsations at a period of 2.3 ms were discovered at Jodrell Bank and pulsar timing soon revealed that this pulsar is in a 2-day binary orbit with a companion of white-dwarf mass. The high dispersion measure and a rotation measure similar to nearby extragalactic sources indicates that this system is at a distance $d > 5.8$ kpc.

Our WSRT/PuMa timing measurements are shown in Figure 1. In the top panel we show the residuals from our best fit timing model for the spin history of the pulsar excluding the proper motion term. The sinusoidal shape of the residuals with a period of one year and with a quadratically increasing amplitude is characteristic of proper motion. In the bottom panel we show the fit after including a proper motion term and a clear improvement in the root-mean-square residual is seen. The proper motion we measure is $27\pm5$ mas/yr. If the pulsar is at a distance of 5.8 kpc this proper motion corresponds to a velocity of $800\pm170$ km/s making PSR J0218+4232 the highest velocity millisecond pulsar known. While distances derived from dispersion measures in this direction are not well constrained it is unlikely that it is in error by more than a factor two. Even in this case the velocity of the PSR J0218+4232 is much higher than expected from the current best models of how millisecond pulsar binaries form.

Subpulse Drifting in Radio Pulsars


In the thirty years since their discovery, drifting subpulses have featured in many discussions about the nature of pulsars and the pulsar’s emission mechanism. The subpulse-drifting phenomenon in itself is simple: when comparing adjacent individual pulses, the subpulses that comprise them are seen to shift regularly through the average pulse window. The left panel of the figure, for example, shows a recent WSRT/PuMa observation of radio pulsar B0809+74 in which these subpulses form their driftbands.

The drifting subpulse phenomenon can be explained with radio emission being formed in discrete locations (‘sparks’) on a circle around the pulsar’s magnetic pole. We observe each spark as a single subpulse and their carousel-like rotation around the pulsar magnetic pole causes the subpulse drifting.

Occasionally however, the pulsar ceases to emit. In the figure, it does so from pulse 30 to 40 – but the mechanisms behind these so-called nulls are still not clear at all. It is interesting to note that the position of the subpulses is identical before and after the null. Furthermore we see
that the drift rate is less after a null. We have used this drifting-nulling interaction to probe the mechanisms of pulsar emission and nulling.

**Recent discoveries with WSRT/PuMa**

Over the last two years, we have built a set of high quality 0809+74 observations, all taken with WSRT/PuMa. We find that the drift pattern of the 0809+74 subpulses comes in two modes: the first one is the normal one we see in the figure (although it is disturbed by the null there). The second one is much more rare, and stable only on a timescale of about two minutes; in it, the subpulses drift less fast, but they are also wider and more closely spaced. To cause these changes in the subpulse behaviour, clearly something must have changed on or near the pulsar.

Yet to infer the actual emission region changes from this new drifting pattern we need to solve the so-called alias order problem: when all subpulses are identical, the shift of an individual subpulse cannot be determined. Looking at the figure, we see that if we compare the subpulses in pulse 1 with those in pulse 2, they may have moved either a little to the left, or a lot to the right.

For 0809+74 we devised a new method that exploits the aforementioned drifting-nulling interaction to solve for the alias order. We find – contrary to the expectations of many – that the subpulse drifting in 0809+74 is not aliased. That means the ‘sparks’ rotate only very slowly around the pulsar magnetic pole, taking approximately 200 seconds to finish one revolution.

With this, 0809+74 is only the second pulsar for which the carousel rotation time is known. It is interesting to note that the rotation time is about two orders of magnitude larger than was predicted by theories on pulsar emission, indicating these theories are not yet correct. With a rotation time now actually observed, we expect to improve emission theories.

We can now use the absence of aliasing to determine the underlying changes in the subbeam-carousel geometry, and show that after nulls, the subbeam carousel is reduced in size, suggesting that it originates lower in the pulsar magnetosphere. The many striking similarities with emission at higher frequencies, thought to also be emitted lower, indicate that after nulls we look deeper in the pulsar magnetosphere than we do normally.

That means we have also come one step closer to understanding the nulling mechanism: this change in emission height indicates an increase of the particle velocity and/or a decrease in plasma density after nulls.

**Further reading**


HI Absorption in Compact Radio Galaxies

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Compact steep spectrum sources (CSS), Gigahertz peaked spectrum sources (GPS), and compact symmetric objects (CSO) are characterised by radio emission confined to galactic (<10 kpc) or sub-galactic (<1 kpc) scales. The currently most favoured explanation is that they are young sources expanding into and interacting with a medium with some power law radial density profile which provides ram-pressure confinement. Studying such sources is therefore important both to understand the birth, fuelling, environment, and initial evolution of radio-loud AGN, and because they are laboratories for jet propagation models.

...depths, from $\tau=0.44$ to $\tau=0.001$, and a substantial variety of line profiles, from Gaussians of less than ten km s$^{-1}$ to more typically a few hundred km s$^{-1}$, as well as irregular and multi-peaked absorption, sometimes spanning many hundreds of km s$^{-1}$. This might indicate that some absorbing regions could be substantially non-uniform with much sub-structure. Most CSS and GPS sources are too compact to ascertain the detailed HI absorption distribution with respect to the background continuum using the WSRT. VLBI observations of some sources at the unusual UHF frequencies are now being analysed.

Meanwhile, the WSRT HI column depths were used together with some literature values on lower redshift GPS/CSSs for a statistical study. This was part of the PhD Thesis by Pihlström (2001, Chalmers University of Technology, Göteborg); see also Pihlström et al. (2002, PASA submitted; 2002, A&A in preparation). All column depths, shown in Figure 2, were computed assuming $T_{\text{spin}}=100$ K. The overall HI absorption detection rate in the sample is 53% in sources smaller than 1 kpc, and 36% in the larger sources. This probably already shows that the more compact sources have a larger fraction of their radio continuum emission behind the densest nuclear gas, but not all sources have been surveyed to the same depth, given their substantial flux density differences. Using survival analysis to take into account the upper limits, Kendall Tau and Spearman Rho tests show probabilities >99% and >95%, respectively, that there exists an anti-correlation between the column density ($N_{\text{HI}}$ in cm$^{-2}$) and the (projected) linear size (LS, in kpc).

These HI column densities were based on equivalent widths computed assuming gaussian profiles, i.e. from...
the product of the peak optical depth ($\tau$) and the line width (FWHM). We find that $\tau$ anti-correlates with LS with >95% probability, while there is no significant correlation between the FWHM and LS. Along with the complexity of some profiles, this may again suggest that the larger sources do not necessarily sample a larger part of a cohesive rotation curve in HI, and, conversely, that a significant fraction of the absorbers might be located only in front of relatively small parts of the radio sources.

The Effervescent HI Disk of NGC 6946

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In our Galaxy, most of the interstellar matter is found in the disk. However, a significant amount of gas is present in the halo. This halo gas is found in a broad range of physical states, ranging from ionised gas at very high temperatures to large complexes of neutral gas. For most of this gas, its presence in the halo is thought to be related to the star formation in the disk. This star formation drives, through supernova explosions and stellar winds, large-scale flows of gas from the disk into the halo. In the halo, this gas cools and falls back to the disk. Such a large-scale gas circulation is commonly referred to as a galactic fountain. The intermediate-velocity HI clouds, and some of the high-velocity HI clouds, are related to such a galactic fountain occurring in the Galaxy. Apart from such fountain-related clouds, some of the HI clouds in the halo are thought to be of external origin and are small gas-rich objects that are being accreted by the Galaxy.

Although many of the basic processes involved in galactic fountains are understood, many fundamental questions remain. Moreover, not much is known about the characteristics of such gas flows in other normal spiral galaxies. The main obstacle is that very sensitive observations are required to detect such gas in normal spiral galaxies, given the faintness of the HI in the haloes of normal spiral galaxies. Recent deep HI observations of a small number of nearby normal spiral galaxies have started to reveal some of the properties of the neutral gas in the haloes of normal spiral galaxies and have demonstrated that very deep HI observations are very useful in understanding the physics of gaseous haloes in spiral galaxies.

To obtain a full observational view of the halo gas, observations are needed of a number of galaxies of various inclinations since projection effects allow to detect only certain components of the distribution and kinematics in a single galaxy. Edge-on galaxies provide information about the vertical structure and about the tangential motion. Observations of galaxies of intermediate inclination supply valuable additional information about the kinematics and the spatial distribution of the halo gas. However, to study the vertical motions of the HI and the
correlation with other features in the disk of the galaxy, such as sites of star formation, observations of face-on galaxies are required. An excellent candidate for such a study is the galaxy NGC 6946. Previous WSRT observations (Kamphuis & Sancisi, 1993, A&A, 273, 31) had shown the presence of HI with large vertical motions. However, the limited sensitivity did not allow a detailed study of this gas. In the spring of 2002, NGC 6946 was observed for 16 x 12 hours with the WSRT, using the full capacity of the new IVC+DZB system. This resulted in one of the deepest HI datasets ever obtained of a nearby galaxy (and about a factor 5 deeper than the previous observations of NGC 6946).

The total HI image derived from the observations is given in Figure 1, together with the optical image at the same scale. This image shows the intricate structure of the HI in great detail. It shows a beautiful spiral pattern that extends to well beyond the boundaries of the bright optical disk. It also shows the presence of many holes in the HI disk. Most of these holes are caused by star formation blowing the gas out from the disk into the halo. In many cases, clouds of HI are found near such holes. This is illustrated in Figure 2 where the position-velocity diagram across one of the HI holes in the disk of NGC 6946 is given. Apart from HI in the regularly rotating disk, a hole in the disk is present as well as a cloud at an anomalous velocity. The velocities of such clouds are observed, as in Figure 2, to deviate up to 100 km/s from the gas in the disk, indicating vertical outflows of that magnitude. In most cases, the HI clouds are found at velocities towards the systemic velocity, although in several places gas is detected away from the systemic velocity. The large number of holes and associated flows will allow to study the statistical properties of these features. A particularly interesting object is the large hole, of about 3 kpc in diameter, detected about 10 kpc W of the centre. The position-velocity diagram taken through this hole (Figure 3) shows several small clouds of HI that probably originate in the hole. Not only in HI, but also in other wavebands, such as the radio continuum and optical bands, this hole is empty.

Not all features in the HI appear to be associated with star formation. An interesting example is a small hole near the southern edge of the HI disk. It is located well outside the optical disk and there are no optical features visible at the location and it is unlikely to be related to star formation. Near this hole, a small HI cloud with a velocity deviating 40 km/s from the disk gas is observed. Perhaps this feature is caused by the accretion of a small object. At a few other locations there is evidence for accretion of small HI clouds.

Apart from the clouds that are associated with individual holes, a more diffuse halo component is also detected. This component can be inferred from Figure 2 by the asymmetric shape of the line profiles of the HI in the disk. This component is probably similar to the diffuse halo gas (a.k.a. the “beard”) detected in NGC 891 (Swaters, Sancisi & van der Hulst 1997, ApJ, 491, 140) and NGC 2403 (Fraternali et al. 2001, ApJ, 562, L47). As in these two galaxies, this diffuse halo gas shows lower rotation velocities than the gas in the disk. Given the large number of holes with associated outflows detected, the observations of NGC 6946 will enable us to study, for the first time, the relationship between the outflows with the more diffuse HI halo and will allow us to build a more complete picture of the fountain flows in an external galaxy.

The observations of NGC 6946 show that very deep HI observations can reveal the HI in the haloes of nearby galaxies and that the properties of such halo HI can be studied in great detail. They also show that the much improved sensitivity and correlator capacity, combined with its traditionally excellent imaging characteristics, make the WSRT a very competitive instrument for doing very deep HI observations of nearby spiral galaxies.
The Role of the Westerbork Astrometric-Geodetic Observatory

Roland Klees and Danny van Loon (Delft University of Technology)

In July 1997 the Astrometric-Geodetic Observatory at Westerbork (WAGO) became operational. Therefore, it is time to discuss the role of the observatory in the future. First, we give a short history of its predecessor, the Observatory for Space Geodesy at Kootwijk (KOSG), and the reasons for establishing a new observatory at Westerbork. Then, we describe the facilities at the WAGO, and finally, we give a concise review of the role of the WAGO for geodetic and geodynamic research.

The Rationale

The Westerbork Astrometric-Geodetic Observatory (WAGO) is the successor of the Observatory for Space Geodesy at Kootwijk (KOSG). The KOSG was built in 1972 after approval by the Ministry of Education and became operational in 1973. For more than 25 years, the KOSG participated in many international campaigns for precise point positioning, orbit determination, crustal dynamics, plate tectonics, earth rotation monitoring, and earthquake research. As part of a global network of reference stations the KOSG contributed to the establishment and maintenance of global and regional terrestrial reference frames. Various space-geodetic techniques have been exploited at KOSG in that period corresponding to the technological evolution in space geodesy, e.g., optical cameras for satellite triangulation (1973-1976), satellite laser ranging (1976-present day), and GPS tracking (1990-present day). As a base station for satellite geodesy the KOSG was often visited by geodetic radio-tracking systems, initially with Doppler receivers, later on with GPS receivers. In this way, the KOSG participated in all major regional geodetic radio-tracking campaigns up to the present day. Moreover, the KOSG is a station of the national primary triangulation and gravimetric network, the secondary leveling network, and one of in total five absolute gravity stations in the Netherlands. Finally, the KOSG hosts one station of the the Dutch Active GPS Reference System (AGRS.NL). For financial reasons and in order to guarantee and assure the continuation of these very important and succesful activities on the long term, the responsible Faculty of Geodetic Engineering and the board of the Delft University of Technology decided to move the Kootwijk observatory to the location of ASTRON at Westerbork. Within two years a new observatory was built with facilities for satellite laser ranging, GPS tracking, VLBI, and high accurate relative and absolute gravity measurements, corresponding to international standards.

The Facilities

In order to be able to deploy the instruments of the space geodetic techniques specific platforms have been constructed to guarantee the highest stability. Moreover, the location of the platforms is chosen in a rather limited area to obtain the highest accuracy in the mutual geodetic ties between the concerning geodetic instrumentation. Another requirement is maintaining the RFI-free environment of the original Westerbork Synthesis Radio Telescope observatory. Especially the main building has to be free of any electromagnetic disturbance.

For Satellite Laser Ranging (SLR) a universal platform, originally designed by NASA however slightly modified in accordance with the local circumstances, has been built. It has the ability to host as well mobile SLR as mobile VLBI systems. The platform consists of five markers installed on concrete pillars independently founded directly on the sand layers, surrounded by a concrete block with dimensions of 9x9 m². The instrument can then be installed on the block itself while its reference point should be connected to one of the markers, representing the site reference point. Around this platform trucks and containers can be easily manoeuvred on concrete plates.

The GPS antenna assembly for permanent tracking of GPS satellites, operating in the framework of the International GPS Service (IGS) and the Dutch Active GPS Reference System (AGRS-NL), is attached on top of a mast of about 24m height in order to avoid obstructions from telescopes and trees. The lattice mast is made of high quality steel, designed and constructed by the Dutch PTT whereby a maximum horizontal deviation of 1.7mm with a wind speed of about 20 m/s is secured. Furthermore the mast has been modified so that the position of the GPS antennas phase center is not changing in vertical
Temperature variations are causing an elongation or a shortening of the steel-framed mast. This effect has been compensated by utilizing a height stabilization system, consisting of a 24 m wire of invar alloy with 5 mm diameter, a floating GPS antenna support with spring tensioning and an additional counteracting 4 m aluminium tube. The IGS and AGRS Turborogue GPS receivers are installed in a climate controlled housing in the cellar of the main building near the Hydrogen Maser time and frequency standard, in order to get directly delivered its 5 MHz frequency signal. To prevent electromagnetic interference in the main building the substitution of the 80 m standard antenna cable by a glass fiber one is in consideration.

One of the main reasons why Westerbork has been selected is the availability of telescopes of which one can be easily utilized for geodetic VLBI. The decision has been made to use telescope no.7 for these activities, since it is located in the direct neighbourhood of the other space geodetic techniques. Recently the telescopes are equipped with receivers of 3.6 and 13 cm bandwidth, typically required for geodetic purposes. The telescopes are twenty-four hours per day in operation and produce a continuous motion of the local surface. Since gravimetric instruments are sensitive to any slight motion a well-protected platform had to be constructed. The gravimetry platform itself is constructed in the shape of a concrete cube with dimensions of 3x3x3 m$^3$, in order to obtain the highest stability. It rests on a stable subsurface sand layer at about 4 m depth. Moreover it is protected against the nuisance of the moving telescopes by the construction of surrounding barrages. Over the platform a climate-controlled blockhouse is built wherein absolute and relative gravimeters, eventually seismometers can operate. In front of this house the Survey Department of the Ministry of Transport, Public Works and Water Management installed an underground vertical reference point.

Space geodetic techniques require time systems for accurate time keeping relative to international atomic time and for stable frequency control. At the Westerbork observatory an H-Maser and a Rubidium frequency standard are available to meet these requirements.

For evaluation of the meteorological effects on the space geodetic observations the weather station at Westerbork controls pressure, humidity, temperature, speed and direction of wind. For the data communication a local network, based on glass fiber, is installed and connected to internet. The requirement to maintain the main building EMI-free is still guaranteed. Besides there is always the possibility to transfer data, utilizing the ISDN telephone network.

**The Role**

Astrometric-geodetic observatories are mainly designed to (1) represent the Earth and its motion in space, (2) realize a terrestrial reference frame, and (3) maintain the terrestrial reference frame by observing variations in the Earth rotational vector and relative movements of the lithospheric plates. This allows to (1) address several global issues such as sea-level change, postglacial rebound, and ice-sheet mass balance, (2) monitor tectonic motion and deformations, (3) monitor Earth rotation, (4) constrain rheological parameters of the Earth, (5) validate models of ocean dynamics, (6) determining Earth satellite orbits, (7) provide spacecraft tracking support for missions in low Earth orbit, and (8) provide support for local and regional geodetic and geophysical studies.

In order to meet the global objectives, a global network of stations equipped with facilities for space geodetic and gravimetric measurements is needed. The Westerbork Astrometric-Geodetic Observatory (WAGO) will be a part of the international space geodetic and gravimetric networks. Although the primary scientific objective of the global networks is mainly directed to the improvement of our understanding of geodynamic phenomena that operate on global scales, the WAGO allows the proper interpretation of many signals that take place on ~em local and ~em regional scales by providing a regional terrestrial reference and tying local and regional nets to the global network. Moreover, it allows precise regional and local geodetic surveys and as such has a significant impact on almost all aspects of geodesy and land surveying.

Typical applications of the available facilities at the Westerbork observatory in the future are (1) realization and maintenance of the celestial and terrestrial reference frame, (2) monitoring of variations in the Earth rotational vector, (3) supporting geophysical studies of the internal structure and dynamics of the Earth, (4) precise orbit de-
sources within a global network of antennas determine VLBI measurements to a number of extragalactic radio observing sites. Finally, SLR improves the knowledge for the measurement of global mean sea level changes for precise calibration of radar altimeters, a prerequisite temporal resolution on global scales. SLR is also unique anthropogenic activities with high spatial and reasonable deformations due to volcanic activities, earthquakes, and carries a synthetic aperture radar map the continental of the key elements in global change studies. Satellites observing satellites. For instance, radar altimeter satel- lows to precisely determine the orbits of various Earth precision of absolute positioning w.r.t. the geocenter al the oceans, and the atmosphere. The subcentimeter precision of absolute positioning w.r.t. the geocenter with subcen- timeter precision and satellite orbits with a precision of a few centimeters or better. It also provides information about the Earth rotational vector w.r.t. the adopted terrestrial reference frame. This makes SLR one of the prime techniques for the establishment and maintenance of the terrestrial reference frame. Repeated measurements provide tectonic plate motion rates, crustal deformations, variations in the Earth rotational vector, and information about the static and time-varying gravitational field of the Earth. This makes SLR a unique tool for long-term climate change studies by providing an absolute reference for measurements of post-glacial rebound, sea level variations, and ice volume change, and by determining the temporal mass redistribution within the solid Earth, the oceans, and the atmosphere. The subcentimeter precision of absolute positioning w.r.t. the geocenter allows to precisely determine the orbits of various Earth observing satellites. For instance, radar altimeter satel- lite maps the ocean and continental ice surfaces as two of the key elements in global change studies. Satellites carrying a synthetic aperture radar map the continental surface and allow to determine among others crustal deformations due to volcanic activities, earthquakes, and anthropogenic activities with high spatial and reasonable temporal resolution on global scales. SLR is also unique for precise calibration of radar altimeters, a prerequisite for the measurement of global mean sea level changes of a few mm/yr. Finally, SLR improves the knowledge of mm/yr-level secular changes in the height of coastal observing sites.

VLBI measurements to a number of extragalactic radio sources within a global network of antennas determine the inertial reference frame defined by the radio sources, the coordinate differences between the antennas (to a few millimeters), and the orientation of the Earth in inertial space (to a few milliarcseconds). From a time series of measurements, relative changes in the antenna positions can be derived, which indicate tectonic plate motion, and regional or local deformations. VLBI allows to address many Earth science research areas across a broad spectrum of disciplines and therefore will make a significant contribution to Earth system science. VLBI is unique in realizing and maintaining an inertial reference frame and in measuring the Earth’s rotational vector in this frame. The maintenance of the inertial reference frame is indispensable for the long-term stability of Earth orientation data and of the terrestrial reference frame. From the continuous time series of Earth rotation data geoscientists can study continuous momentum exchange between various subsystems, periodic signals such as tides, non-periodic signals such as atmospheric angular momentum, and episodic signals such as earthquakes. Moreover, since the response of the Earth to the gravitational attraction of Sun and Moon depends on the structure of the Earth, models of the Earth deep interior can be improved.

Regular observations of the Westerbork observatory by SLR will provide an accurate tie of regional monitoring networks to the global SLR reference frame, which is a space geodetic frame for the European triangulation network (EUREF) and for the European leveling network (UELN). In the same way, regular VLBI observations at the WAGO will provide a link to the celestial reference frame. This will provide a reference for studies of the kinematics of the Eurasian plate and for regional studies of sea level variations and post-glacial rebound.

Tracking of the GPS allows to determine coordinate differences between ground stations with subcentimeter precision at local scales (tens of km) and at the centimeter level on regional (hundreds of km) and global (thousands of km) scales. The easy and economical access to GPS hard- and software, the high portability, and the dramatic technological improvements open numerous applications in many disciplines. Geophysical applications are, e.g., monitoring of surface topographic change, plate boundary structure, intra-plate deformation, plate tectonics, sea-level change, post-glacial rebound, variations in the orientation of the Earth rotational vector, medium resolution gravity field, and oceanic and atmospheric loading.

The collocation of VLBI, SLR, and GPS at the WAGO allow to determine high quality high resolution time series of Earth rotation data. In this respect, GPS is used to interpolate between the VLBI and SLR data in order to determine high frequency variations in Earth rotation. Full exploitation of this application requires a global network of tracking stations linked to the terrestrial reference frame. As part of the global network, the WAGO will participate in international campaigns for the determination of high frequency variations in Earth rotation.

The Precise Range and Range-rate equipment (PRARE) is used to determine station coordinates, satellite orbits, and Earth rotation parameters, for gravity field modelling, ionospheric modelling, and time transfer and clock synchronisation.
The contribution of the WAGO to the precise orbit determination of Earth observing satellites mainly serves regional projects for sea level monitoring, e.g., over the North Sea region. The available techniques are SLR, GPS, and PRARE.

The major contribution of the WAGO lies in the participation in regional space geodetic networks for the monitoring of sea level change and crustal motions and in providing a reference for tying regional and national datums. Monitoring sea level variations requires (1) the connection of the individual tide gauges to regional clusters, (2) the connection of the regional clusters to the global space geodetic and gravimetric network, and (3) the detection and monitoring of vertical crustal movements. The Westerbork observatory will be one station within the European sea level monitoring network, which can be seen as a densification of the global sea level monitoring network. The various connections will mainly be done by means of GPS. The monitoring of vertical movements of tide gauge stations will allow to extract the sea level variation signal from the tide gauge signal.

The absolute gravity measurements at the Westerbork observatory contribute to the establishment and maintenance of global gravity networks. The main purpose, however, is to establish and maintain a precise vertical reference frame for the Netherlands, which is indispensable for long-term monitoring of mean sea level changes induced by global warming. Regular links to the other base points of the Dutch gravity network allows to measure relative gravity changes throughout the Netherlands. The absolute gravity measurements at the WAGO also provide an independent control of the vertical crustal movements due to tectonics and other geophysical and geological processes as measured by GPS, SLR, and VLBI. In the future, the absolute gravity measurements will probably be supplemented by permanent relative gravity measurements by means of a superconducting gravimeter. It allow to correct the absolute measurements for the influence of many local disturbances such as earth and ocean tides, loading and atmospheric tides, ground water level changes, and local crustal deformations, thus significantly increasing the quality of the absolute gravity measurements. It also supports the interpretation of geometrical changes in time as observed by the mentioned space geodetic techniques. Besides, observations of surface gravity changes with superconducting gravimeters will allow to validate and constrain geophysical models of the internal structure and the global dynamics of the Earth. Examples are the retrieval of elastic normal modes, the detection of gravity-inertial core modes, the study of the Earth’s (an-)elastic transfer function, the retrieval of loading contributions due to the dynamic ocean response and non-linear tides, the validation of ocean tide models, and the retrieval of several parameters directly related to properties of the core-mantle boundary.

The ability to collocate the space geodetic techniques VLBI, SLR, GPS, and PRARE at the WAGO is a key item. In general, it allows to address a number of specific issues, e.g., to distinguish between postglacial rebound and the instantaneous elastic response from contemporaneous ice-sheet mass balance, to assess the impact of tectonic motions in tide gauge measurements, to establish rheological properties of fault zones, and assess the stability and the coupling of surface locations to deeper structures. Collocation of VLBI, SLR, and GPS at the Westerbork observatory will in particular allow to better understand the error budget of these space geodetic techniques, to reduce their observations to the same reference frame, and to aid in the separation of errors of geo-

![Figure 4 Time series of resp. the north-, east- and up-component of the baseline between the IGS-stations KOSG at Kootwijk and WSRT at Westerbork. The period shown is from July 1997 until January 2001.](image-url)
Observing Multiple Hydrogen Recombination Lines in M82

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Radio recombination lines are a well-known tool to study regions of star formation, especially in the optically obscured central regions of galaxies. These studies are usually done at high frequencies (> 5 GHz), where the lines are strong and free-free opacity effects, by the same gas responsible for the lines, are significantly reduced. At low frequencies recombination lines tend to be faint, with typical line-to-continuum ratios much less than 1%. Low frequencies recombination lines probe mostly lower density gas (see e.g. Anantharamaiah et al., ApJ 419, 585, 1993). In our Galaxy recombination lines, especially from neutral carbon in the diffuse warm ionized medium, have been observed at 327 MHz with the Ooty and with the Ukraine UTR-2 telescopes down to frequencies as low as 25 MHz.

The faintness of the low-frequency lines dictates either long integrations or the ability to observe many transitions at the same time. The separation of the transitions around 1.424 GHz (the location of H166α at rest) is about 24 MHz decreasing to only 3.5 MHz at 325 MHz (where we observe H272α at rest). The new WSRT broadband backend offers the combination of wide bandwidth, tunability and a sufficient number of spectral channels to obtain good spectral resolution on up to 8 transitions simultaneously in L-band and up to 25 transitions in the 300-400 MHz band (see Figure 1). High spectral dynamic range is also an important requirement, an area where the WSRT has an excellent reputation.

Observations of M82

As part of the astronomical and technical commissioning of the new wideband IF/backend we therefore set out to test this multiple recombination line capability. An excellent target is presented by the nearby starburst galaxy M82 which was observed 17 years ago with the WSRT by Peter Roelfsema and Miller Goss (see Roelfsema, PhD thesis, 1987) and has been the subject of many subsequent studies, mostly at much higher frequencies.

For the M82 observations a bandwidth of 5 MHz for each of the 8 transitions was chosen, sufficient to cover a 1000 km/sec wide band with 8-9 km/sec channel spacing. The frequencies observed were those corresponding to transitions H166α (1424 MHz) up to H172α (1281 MHz). In addition we observed the 21cm HI transition at 1420 MHz. The data were Hamming tapered to 16-18 km/sec. [Note that the constant correlator spectral resolution (in kHz) converts to slightly different velocity resolution for the wide range of transitions].

To effectively utilize up to 8 recombination line transitions (in WSRT’s very sensitive 21cm band) it is essential that the spectral dynamic range is high enough to go down to the thermal noise. In the new broadband 8x20 MHz system the spectral dynamic range appears to be better for smaller bandwidth. This is a subject of vigorous study by ASTRON staff. The total flux density of M82 at 1.4 GHz is 7.5 Jy but the source is heavily resolved. At 13” angular resolution M82, however, still has a formidable 2.2 Jy peak flux density, requiring a spectral dynamic range well in excess of a few thousand to 1.

No Doppler tracking was done. The central frequency for each transition was chosen for a topo-centric redshift of +240 km/sec placing the transition in the middle of each band. The 22 Jy sources 3C147 and 3C295 were observed as bandpass calibrators for a period of 1 hour before and after the 12h track on M82. Note that the

References

calibration procedure assumes they have featureless continua at a level of 10,000:1! (this appears to be borne out by the results).

**Results**

The data reduction was straightforward and will be presented elsewhere. We suffered from some intermittent RFI in the lower two frequency bands (at 1302 and 1281 MHz) and decided not to include them in this preliminary report. The individual datacubes were calibrated and processed in NEWSTAR and then ported to AIPS where a small linear residual continuum baseline was removed using the outermost pairs of 10 channels each. Figure 2 shows a montage of 49 images (channels), at 16 km/sec spectral resolution and 13" angular resolution, of the average emission of the H166-170 transitions. Image number 28 corresponds to a heliocentric velocity of +250 km/sec and velocity increases with image number.

The peak flux density of the recombination line is about 4.5 mJy. The rms noise is about 0.15 mJy/beam/channel, a factor SQRT(5) down from the 0.35 mJy in the individual image cubes. The spectral dynamic range appears to be of the order of a stunning 10,000:1, better than we hoped for. The negative emission in image 47-49 (corresponding to channels 102-107 from the original 128 channel spectrum) is probably not real and signals that limitations in the spectral baseline fidelity are always present in extragalactic systems with their wide range of velocities.

From this first attempt at multi-recombination line observations it is clear that there may be interesting possibilities ahead in the future. Using recirculation in the DZB, planned for 2003, we expect to further increase the number of spectral channels, especially at low frequencies where this is necessary to get sufficient velocity resolution.

I dedicate this article to the memory of Anantha(ramaiah) who passed away last year. He would have enjoyed to go deeper in the study of (stimulated) low-frequency far-extragalactic recombination lines and we were both looking forward to tackle this possibility.

Comparing Figure 2 with Roelfsema and Goss' 1424 MHz image we appear to go almost a factor 7 deeper, in half the observing time. We also note that the H-recombination line emission covers the same velocity range as the HI-21cm absorption (not shown), sharing its kinematic properties and therefore presumably its spatial disposition as well.

An intriguing fact to note from the image-cube shown in Fig. 2 is the fact that there is low level emission (in images 12-17, at levels of 0.3-0.6 mJy/beam) that appears to extend the emission to higher frequencies (i.e. more negative velocities). Rather than hydrogen recombination line emission this might in fact be emission from the corresponding helium transitions which are located at 122 km/sec more negative velocities (about 7 channels/images). If this interpretation is correct the helium line would be present at about 10% of the hydrogen line, perhaps not unexpected. This confusion of hydrogen and helium transitions is always present in extragalactic systems with their wide range of velocities.

Figure 2 Image mosaic from a preliminary reduction of WSRT observation of M82 in 8 line transitions (see text for further details). Every sub-panel measures 112'x112' and is centered at the radio continuum centroid.
The LINER elliptical galaxy NGC 1052 has an unusually prominent central radio source (1 to 2 Jy). It is variable on timescales of months to years and has a fairly flat spectrum between 1 and 30 GHz, which has sometimes been classified as Gigahertz peaked. The overall radio structure is core-dominated, and has two lobes spanning only about 3 kpc, so that NGC 1052 meets the traditional size limit for Compact Steep-spectrum Sources (CSSs), but not for Compact Symmetric Objects (CSOs). We have used the powerful multi-channel, wideband IVC/DZB on the WSRT as well as VLBI observations which reach sub-pc scales (1 mas ~ 0.1 pc with \( c = 1474 \) km s\(^{-1}\) for \( H_0 = 65 \) km s\(^{-1}\) Mpc\(^{-1}\)) for a detailed study of the active nucleus and its inner environment. A more extensive analysis of the results presented below is in Vermeulen et al. (2002a A&A submitted, 2002b PASA in press astro-ph/0210012).

Ten epochs of 15 GHz VLBA data show a two-sided source, with oppositely directed, slightly curved jets and a prominent gap 0.1 to 0.2 pc west of the brightest feature in most images. Features on the two sides move in opposite directions with roughly equal apparent velocities of 0.26±0.04c. Using these error margins, the jets must be oriented at most 33º from the plane of the sky.

![Figure 1](1) Left: HI optical depths at various locations along the VLBI jets of NGC 1052; dotted lines show the zero levels. Right: WSRT optical depth measurements (negative is emission) for all four 18 cm OH lines. The offset zero lines are indicated; also note the different scale for our integrated VLBI HI spectrum, shown convolved to the same resolution for comparison.

In the inner parsec, VLBA observations at seven frequencies between 43 and 1.4 GHz show spectral shapes which proceed in both jets from steep, through convex, to highly inverted towards the middle, and are connected with low brightness temperatures and the distinctive central hole. This can only be reasonably explained by free-free absorption, probably due to a geometrically thick disk- or torus-like ionised region which is likely to be more or less perpendicular to the jets, with the eastern jet approaching and the western jet receding, because the latter shows more absorption. The deepest absorption seen, \( \tau \sim 1 \) at 43 GHz over the central region, would imply a volume density of \( n_e \sim 10^5 \) cm\(^{-3}\) if free-free absorbing gas at \( T = 10^4 \) K were distributed uniformly along a path-length of 0.5 pc.

We think there are three different HI absorption systems towards NGC 1052, at least two of which are probably due to atomic gas on parsec or sub-parsec scales, local to the AGN environment, rather than distributed on galactic scales. The most remarkable one is redshifted by 125 to 200 km s\(^{-1}\) with respect to the stellar systemic velocity. Our VLBI spectral imaging shows ``high velocity'' atomic gas only at 1 to 2 pc along both jets (\( \tau = 5-20\% \), Figure 1 left panel). This could well be in an annulus around the...
ionised, free-free absorbing gas, as one might expect given that the innermost region and/or the surface of an accretion disk or torus receive the most intense ionising radiation. An HI optical depth of 20% with a FWHM of 20 km s\(^{-1}\) implies a column depth of \(N_\text{HI} = 10^{21} \ T_{\text{sp},100} \ cm^{-2}\), but conditions close to an AGN may well raise \(T_{\text{sp}}\) by one or two orders of magnitude.

We used the multi-channel wideband IVC/DZB backend on the WSRT to establish that the 1667 MHz and 1665 MHz OH absorption recently discovered over a limited velocity span by Omar et al. (2002, A&A, 381, L29) extends over at least as wide a range as HI (see Figure 1 right panel). The peak 1667 MHz depth, 0.4% in the high velocity system, suggests a column depth of order \(10^{14} \ cm^{-2}\). The 1667/1665 ratio ranges from near 1 at low velocities to approximately 2 in the high velocity system. The “high velocity” profile is remarkably similar to that of total HI, and we suggest co-location of these atomic and molecular gas components. Interpretation of a tentative velocity gradient in HI across the nucleus as evidence for a rotating structure is contradicted by the fact that the centroid is redshifted by 150 km/s or more from the systemic velocity. But if this is instead infalling gas, the nature of the central hole in HI is unclear. The OH and HI gas probably does not coincide with the H\(_2\)O masers at 0.1 to 0.2 pc along the receding jet (Claussen et al. 1998, ApJ, 500, L129), even though these are at the same velocity.

We have also discovered with the WSRT that the satellite OH lines are present: 1612 MHz in absorption and 1720 MHz in emission. Their conjugate profiles probably result from excitation in a far infra-red radiation field when the OH column density is sufficiently large; competing pumping mechanisms determine which line is in emission and which one in absorption in specific density and temperature regimes; we will model this with planned global VLBI OH observations in hand.
First Detection of the HI Emission Line at z=0.2

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The upgraded WSRT is an excellent instrument for studying for the first time the neutral gas content of galaxies at intermediate redshifts. So far, measurements of the HI emission line have been limited to the very local universe because radio synthesis telescopes were not equipped to operate at frequencies corresponding to the redshifted HI line, or lacked the sensitivity.

Our deep WSRT observations have resulted in the first detection of HI emission line at cosmologically significant distance. The HI originates in a spiral galaxy 2.0$h_{65}^{-1}$ Mpc west of the core of the rich galaxy cluster Abell 2218 at a redshift $z=0.18$. This cluster was observed as part of our program to study the content and distribution of the HI in cluster galaxies at intermediate redshifts.

It is well established that galaxies in clusters have experienced significant evolution in the past few Gyr. Optical surveys have shown that the fraction of blue galaxies in clusters was higher in the past (the Butcher-Oemler effect) and that spiral galaxies were more prevalent. It has been suggested that these effects are caused by enhanced accretion of gas rich star forming galaxies from the surrounding field. Modeling of the infall of field galaxies suggests that the HI disks of galaxies can be stripped by the hot X-ray gas that surrounds rich galaxy clusters. Because the neutral gas provided the fuel for star formation, the star formation rate drops precipitously after the cold gas has been removed. The observed low HI content of galaxies in the cores of the nearby Coma and Virgo clusters supports these models.

At higher redshift, where the galaxy accretion rate is thought to be higher and spiral galaxies increasingly populate the central regions of rich clusters, the models have not been tested by direct observations of the neutral gas reservoir of infalling galaxies. We observed Abell 2218 at $z=0.18$ with the WSRT. Abell 2218 is one of the best studied clusters at intermediate redshift. The cluster is extremely rich and massive, has a luminous and extended X-ray halo, and has become widely known for the HST imaging that revealed a rich structure of strong gravitational arcs.

Observations were performed in the period from July to September 1999. Data were taken in two adjacent bands of 10 MHz each, thus producing 2x128 channels of each 78.1 kHz corresponding to a velocity spacing of 19.5 km/s at the redshift of the cluster and a resolution of 38.9 km/s after Hanning smoothing. Each frequency band was observed for 18x12 hours, with varying positions of the four movable telescopes. The results reported here are based on the analysis of the usable 60 per cent of the data. The data were taken around 1200 MHz, which is well outside the protected frequency bands for radio astronomy. As a result, a large fraction of the data was affected by RFI and careful inspection and editing of the data was essential. The r.m.s. noise level after Hanning smoothing is 0.11 mJy/beam in the lower frequency band and 0.10 mJy/beam in the higher frequency band.

The most prominent signal in our data set adds up to 8σ, with optimal smoothing in both the spatial and the frequency domain (Figure 1). No other significant (>6σ) signals were found. The integrated flux in the detection, corrected for primary beam attenuation, is 33 mJy km/s. This is equivalent to an HI mass of $(5.4\pm0.7) \times 10^9 h_{65}^{-2} M_{\odot}$, which is slightly less than the typical HI mass of a field galaxy. The velocity width of the detected emission line is very small, $60\pm20$ km/s at 50 per cent of the peak flux. The narrowness of the signal explains why this modest HI mass stands out from the noise so clearly. The redshift of the HI line is $z=0.1766$, coincident with the peak in the redshift distribution of the confirmed cluster members.

Figure 1 Spectra of the first HI selected galaxy at $z=0.18$. The top panel shows the global HI profile. It is Hanning smoothed which results in a spectral resolution of 38.9 km/s. The optical redshifts of the spiral galaxy and its companion are also indicated, with 1σ uncertainties. The lower panel shows the optical spectra of the spiral galaxy A2218-H1 and its companion.
We used the Keck telescope to obtain optical imaging and spectroscopic observations of the source responsible for the HI emission. Figure 2 shows a colour representation of the galaxy based on B and R images, with HI contours overlaid. This image shows that the HI emission coincides with a spiral galaxy with two well developed blue spiral arms emanating from a redder and elongated bar-like structure. The western spiral arm runs along and extends beyond a redder companion galaxy ~18 h\textsubscript{65}\textsuperscript{-1} kpc to the south-west. From the imaging observations we infer R=18.9±0.1 mag for the spiral galaxy, which means that its intrinsic luminosity is approximately half that of the Milky Way galaxy. Our spectroscopic observations (Figure 1) show that the optical redshift of the galaxy is z=0.1766±0.0001 and that of the companion is z=0.1768±0.0002, thus giving a velocity separation of 50±60 km/s. Both redshifts are within 1σ of the redshift of the HI detection. This confirms the identification and suggests that the spiral and its companion are interacting.

Surprisingly, the optical spectra indicate that both A2218-H1 and its companion galaxy have evolved stellar populations, and a low star formation rate although the spiral arms of A2218-H1 are too faint to contribute much to its optical spectrum. The galaxies are not detected in our deep 1200 MHz continuum map (rms noise 29µJy), which provides a 3σ upper limit to the star formation rate of 1.4M\textsubscript{\odot} yr\textsuperscript{-1}. For comparison, the current star formation rate of the Milky Way Galaxy is approximately 4M\textsubscript{\odot} yr\textsuperscript{-1}. Apparently star formation is inhibited, even though all the conditions for a strong star burst seem to be met: sufficient fuel and an interaction to trigger the burst.

The lack of a significant population of HI rich galaxies in the outskirts of Abell 2218 implies that there is a low accretion rate of gas rich field galaxies at the observed epoch. Using the fact that the survey is sensitive to galaxies with HI masses larger than M\textsubscript{HI} through the primary beam, and the assumption that HI disks of in-falling galaxies remain undepleted at distances from the cluster core larger than that of the detected galaxy, we can derive a 95% confidence upper limit to the accretion rate of 3 Gyr\textsuperscript{-1}. We conclude that there is no large reservoir of gas rich galaxies that might form a future ‘Butcher-Oemler’ population. This result is consistent with the low Butcher-Oemler effect observed at z~0.

The galaxy detected in Abell 2218 is at present the highest redshift galaxy in which HI has been detected in the 21cm line in emission. The previous record holder was Malin 1 at a redshift of z=0.083, of which the spectrum was recorded with the Arecibo Telescope. The detection of this galaxy at intermediate redshift using the upgraded WSRT demonstrates the capabilities of this system to measure the HI content of galaxies at redshifts >0.

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