Space VLBI

Richard Schilizzi
University of Manchester

Arnold van Ardenne Symposium, 29 May 2013

The history books now tell you that Space VLBI is all about the two missions, VSOP and RadioAstron, but there’s much more to it than that…..

But let’s start with how VLBI got going in Europe and in the Netherlands.

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The early days of VLBI in Europe

1975 June MPIfR cafetaria in Bonn
(Miley, Booth, Pauliny-Toth, Preuss)

Sept first meeting of interested astronomers, Bonn
(including Casse, Baud, Brouw, Habing)

1976 Second and third meetings in Bonn (+AvA)
and Onsala (+RTS)

and in NL, it all began with an ode…

“ODE to October 1976”

- ODE: the first purely European VLBI observations

  Onsala-Dwingeloo-Effelsberg
- 18 cm
- Primary targets: 3C236, NML Cygnus
- Main players:

  Arnold, George Miley, Baudewijn Baud, RTS, all under the benevolent eye of Jean Casse

ODE: the observations

ODE EXPERIMENT

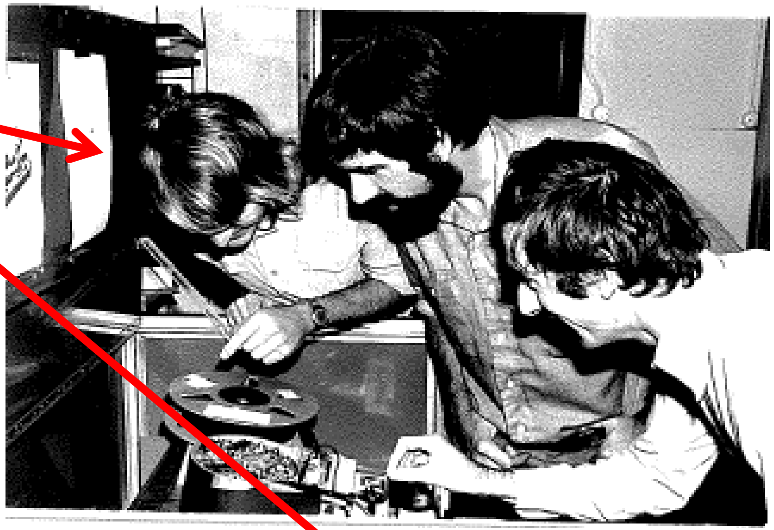
OCTOBER 1,2

[A] CONTINUUM. F = 1610. MHz. BW = 2. MHz. STATION B = EFFELSBERG, C=

SOURCE	SCAN #	START			STOP	TAPES			SCAN TIMES		
		B	C	A		B	C	A	B-C	A-C	A-B
3C273	275-1530	15 02 32	14 59 55	15 00 00	15 30	MPI-151	MPI-76	050-1	27½	30	27½
3C315	-1600	15 36 45	15 35 55	15 33 10	16 00	"	"	"	23½	24	23½
4C39.25	276-0230	02 02 00	02 00 00	02 01 00	02 30	MPI-041	MPI-018	050-7	28	29	28
A00235	-0300	02 35 00	02 38 06	02 35 18	03 00	"	"	"	22	22	25
3C22	-0330	03 04 30	03 04 40	03 03 07	03 30	"	"	"	25½	25½	25½
3C84	-0400	03 35 00	03 35 15	03 33 15	04 00	"	"	"	25	25	25
3C263	-0430	04 07 06	04 08 05	04 06 20	04 30	MPI-042	MPI-019	050-8	22	22	23
4C39.25	-0500	04 40 15	04 34 33	04 32 15	05 00	"	"	"	20	25½	20
3C236	-0600	05 02 30	05 04 11	05 01 14	06 00	"	"	"	56	56	57½
"	-0700	06 06 10	06 07 46	06 05 42	07 00	MPI-043	MPI-025	050-9	52½	52½	54
"	-0800	07 02 10	07 02 33	07 00 27	08 00	"	"	"	57½	57½	58
"	-0900	08 05 00	08 08 25	08 05 18	09 00	MPI-053	MPI-012	050-10	51½	51½	55
"	-1000	09 00 00	09 02 39	09 00 25	10 00	"	"	"	57½	57½	59½
"	-1100	10 06 30	10 09 33	10 05 00	11 00	MPI-055	MPI-013	050-11	50½	50½	53½
"	-1200	11 00 00	11 03 44	11 00 48	12 00	"	"	"	56½	56½	59½
"	-1300	12 05 30	12 07 00	12 06 07	13 00	MPI-056	MPI-014	050-12	53	53	54

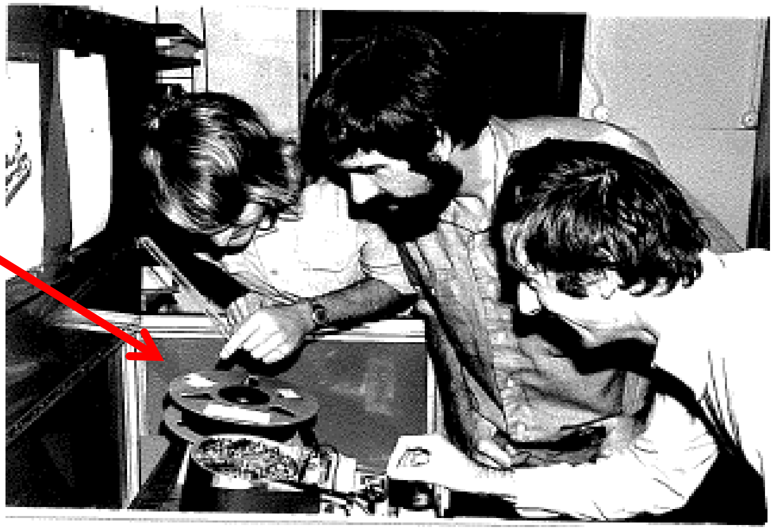
ODE: the observations

Who is this person?
Arnold or Baudewijn



ODE: the observations

Ampex 2-inch tape recorder from Onsala



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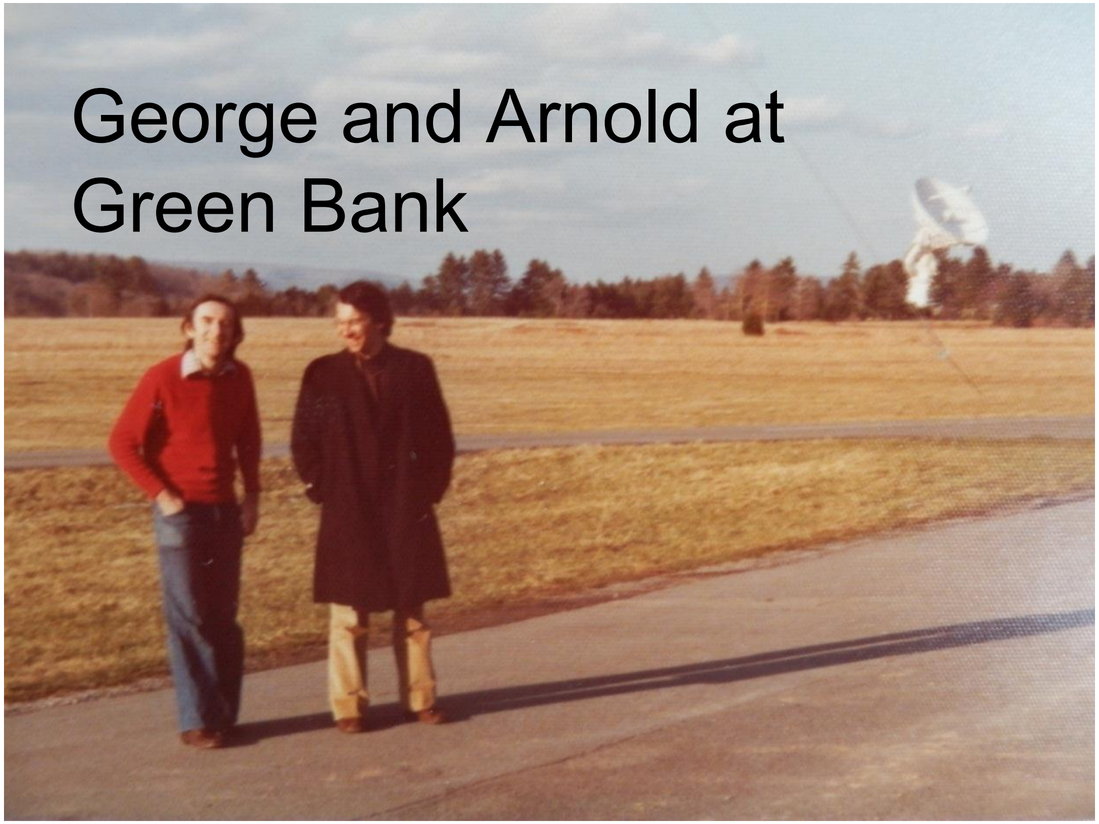
ODE: the correlation



George and Arnold at Green Bank

Some people took it easy

while others did the work in Charlottesville….

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ODE: the results

Astron. Astrophys. 77, 1–6 (1979)

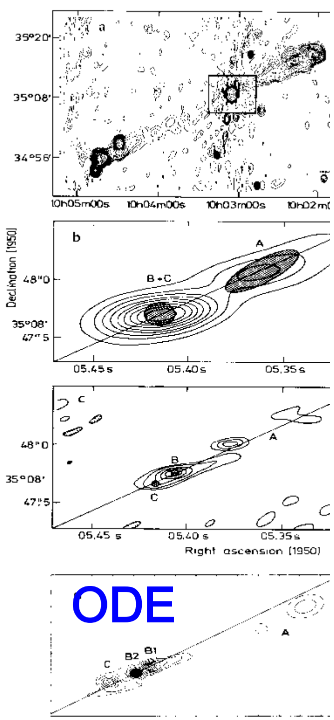
ASTRONOMY
AND
ASTROPHYSICS

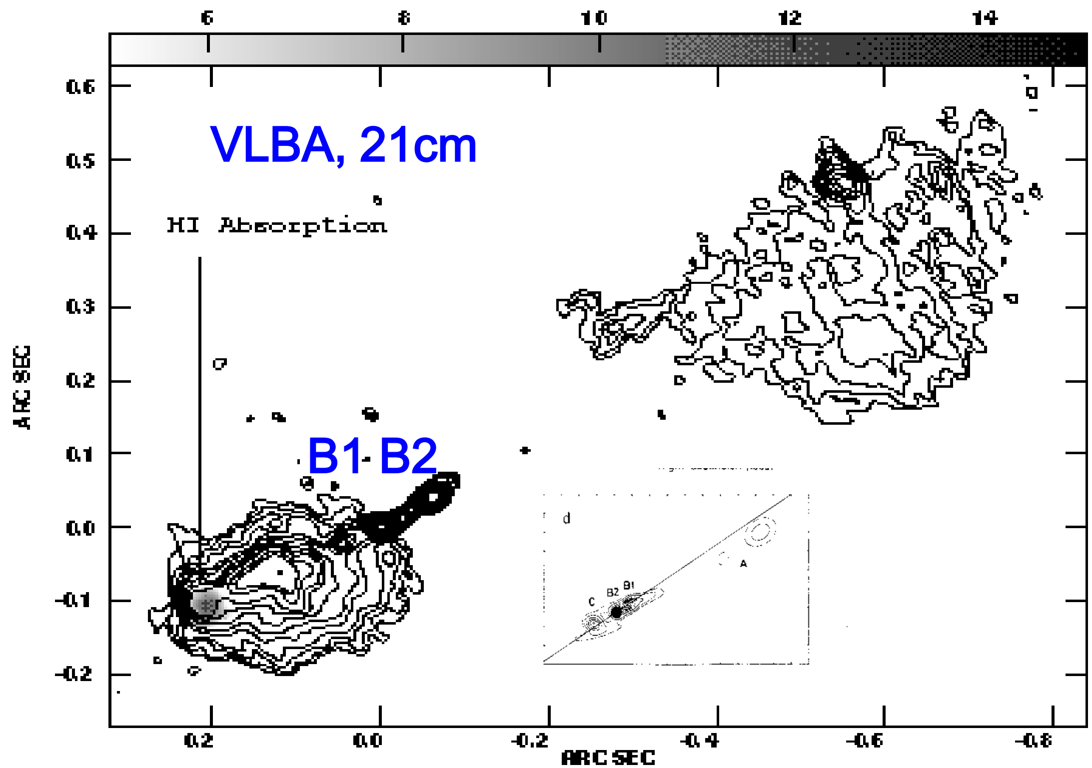
High Resolution Observations of the Compact Central Component in the Giant Radio Source 3 C 236

R. T. Schilizzi[1], G. K. Miley[2], A. van Ardenne[1], B. Baud[2,*], L. Bååth[3], B. O. Rönnäng[3], and I. I. K. Pauliny-Toth[4]

[1] Netherlands Foundation fo
[2] Sterrewacht, Huygens Labc
[3] Onsala Space Observatory,
[4] Max Planck Institut für Ra

Received October 16, 1978



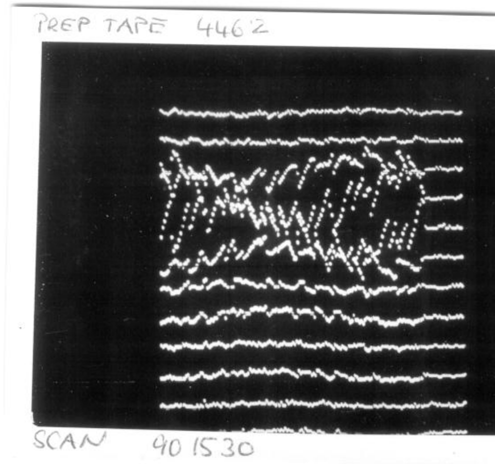


VLBI in Europe: the early days

1977 Fourth meeting in Jodrell Bank:
European VLBI Network discussed

Study of satellite linked VLBI using L-SAT (Olympus) initiated

1978 Mk2 correlator in Bonn started operation



Second observation session J-O-D-E (resulted in 2 baselines!)

First VLBI fringes with Westerbork in phased array mode using Arnold's analogue adding box

and in NL from 1978 to 1982

- 1-inch IVS tape recorder (Mk2A, 2 MHz)
- Hydrogen maser (original Oscilloquartz physics package)
- MkIII tape recorder (56 MHz)
- Arnold starts designing the tied-array box for WSRT Digital Continuum Backend (designed by John O'Sullivan)

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and in NL from 1978 to 1982

- 1-inch IVS tape recorder (Mk2A, 2 MHz)
- Hydrogen maser (original Oscilloquartz physics package)
- MkIII tape recorder (56 MHz)
- Arnold starts designing the tied-array system for WSRT Digital Continuum Backend (being built by John O'Sullivan)
- **The EVN gets going in 1980….**
  - Arnold was chair of the Technical Working Group from 1984
- **And the first thoughts of a big correlator in Dwingeloo emerge, also in 1980**

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EVN Board in Noto (Sicily) in 1988

Noto

and now to Space VLBI

Stage 0: First thoughts

Radiophysics 1965

On Radiointerferometry with long baseline

L. I. Matveyenko, N. S. Kardashev, G. B. Sholomitskii

Stage 1: The very early days of space VLBI: 1977 - 1982

JET PROPULSION LABORATORY

ENGINEERING MEMORANDUM

315-16

11 February 1977

TO:

FROM: R. A. Preston

SUBJECT: VLBI with an Earth-Orbiting Antenna

ABSTRACT:

Satellite-borne VLBI terminals could be used to provide maps of compact celestial radio sources with finer resolution, less ambiguity, and more efficiency than earth-bound VLBI techniques. These maps and their time variability would help unravel the physical processes that govern some of the most enigmatic classes of celestial objects. Hence, VLBI should be one of the principle justifications for placing a large parabolic antenna in earth orbit. This memorandum explores the advantages, technical problems, and scientific goals associated with earth-orbiting VLBI.

RAP:tg

Stage 1:The very early days of space VLBI: 1977 - 1982

INVESTIGATION AND TECHNICAL PLAN

Volume 1

Of a Proposal to the

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

for a

VERY LONG BASELINE INTERFEROMETER STATION ON 1981-1983 SPACELAB MISSION

This joint proposal is submitted by the

CENTER FOR SPACE RESEARCH OF THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
and

GODDARD SPACE FLIGHT CENTER

and the
JET PROPULSION LABORATORY OF THE
CALIFORNIA INSTITUTE OF TECHNOLOGY

DR BERNARD F. BURKE

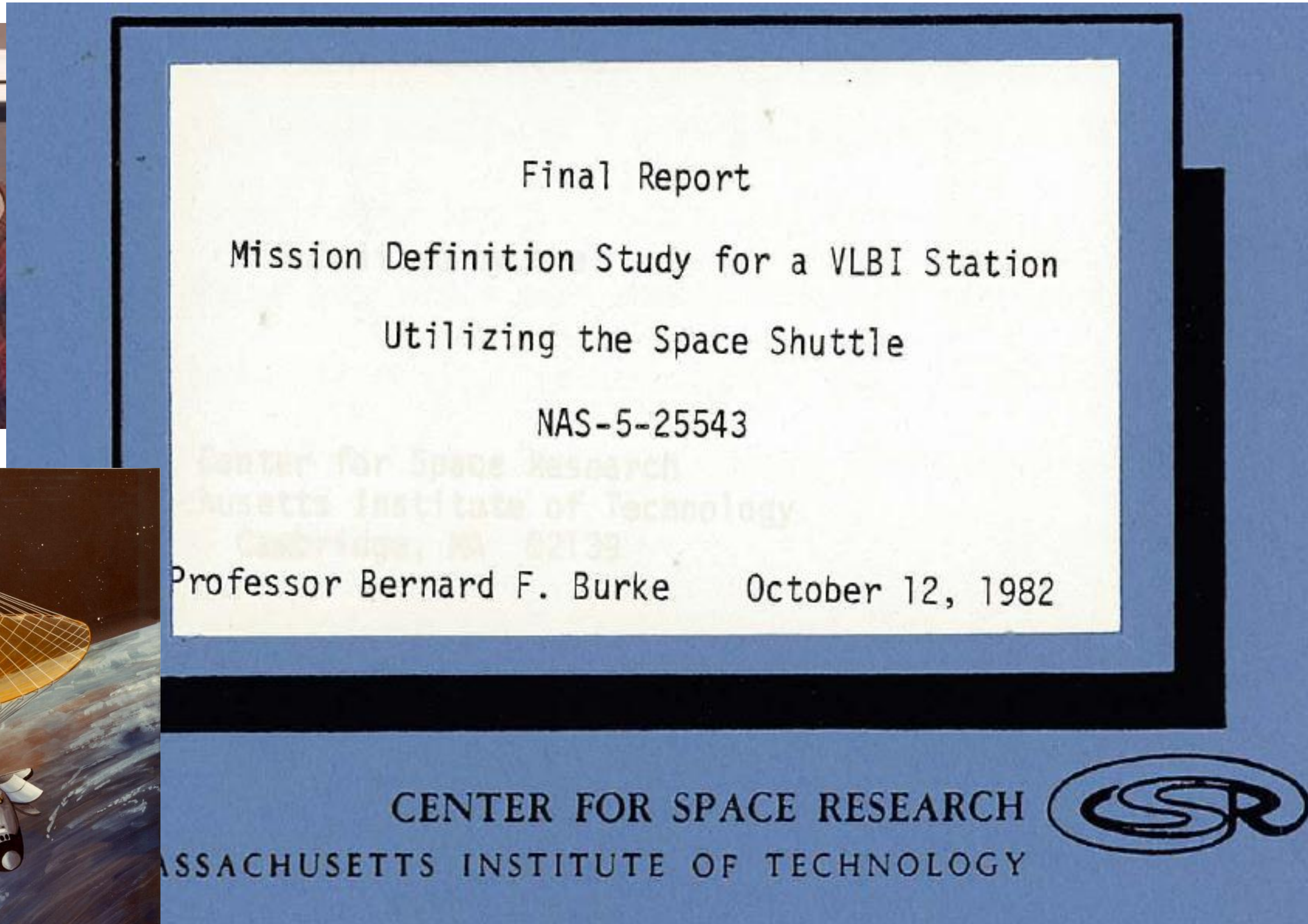
15 NOVEMBER 1978

MIT, 26-335
Cambridge, Mass. 02139
617-253-2572

AO-OSS-2-78

15 November 1978

Stage 1:The very early days of space VLBI: 1977 - 1982



Final Report

Mission Definition Study for a VLBI Station

Utilizing the Space Shuttle

NAS-5-25543

Professor Bernard F. Burke October 12, 1982

CENTER FOR SPACE RESEARCH

ASSACHUSETTS INSTITUTE OF TECHNOLOGY

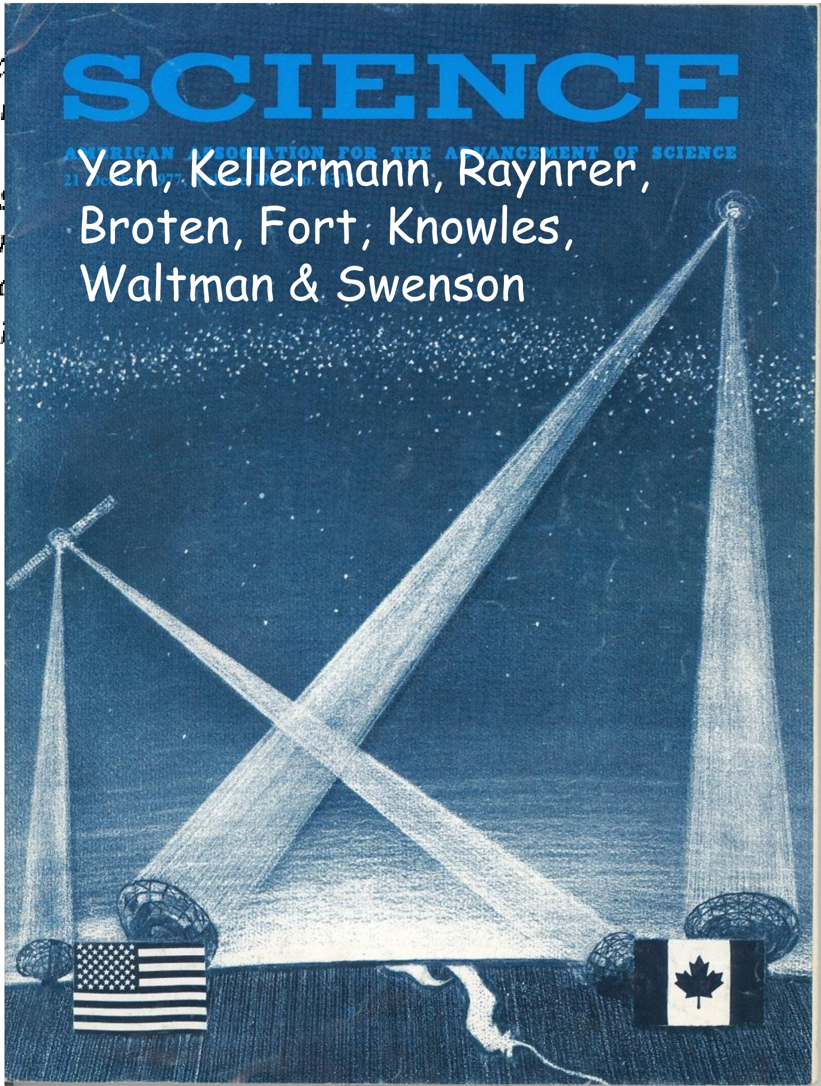
617-253-2572

15 November 1978

Europe got involved via a different route - satellite-linked VLBI

1977 **Real-Time, Very-Long-Baseline Interferometry Based on the Use of a Communications Satellite**

Abstract. *The Hermes satellite, a joint Canadi*
used to provide a communication channel between
and Ontario, for very-long-baseline interferometry
sible instantaneous correlation of the data as well a
than that of earlier VLBI systems, by virtue of a b
With the use of a geostationary communications s
the tape recorders and the most troublesome part o
cessing. A further possibility is the development of a



Yen, Kellermann, Rayhrer, Broten, Fort, Knowles, Waltman & Swenson

1978: ESA Feasibility Study of satellite-linked VLBI (Schilizzi et al)

1981: ESA Phase A study of satellite-linked VLBI using L-SAT (Schilizzi et al)

1982: Phase comparison via ESA's Orbital Test Satellite by van Ardenne et al

1982: QUASAT Space VLBI proposal to ESA

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esa

european space agency

SCI (80) 1

PARIS, February 198(

VERY LONG BASELINE RADIO INTERFEROMETRY USING A GEOSTATIONARY SATELLITE

PHASE A STUDY

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Phase Comparison

A High-Precision Phase-Comparison Experiment Using a Geostationary Satellite

ARNOLD VAN ARDENNE, JOHN D. O'SULLIVAN, AND ALAIN DE DIANOUS

Abstract—**A phase-comparison experiment using a two-way communication link at 14.2/11.5 GHz via a geostationary satellite and a single groundstation is described. Links of this kind can be used in applications where a high degree of phase synchronization is required between signals at frequencies of the order of gigahertz, which are derived from remotely located high-stability clocks, or where a high degree of fractional-frequency stability between remote clocks needs to be maintained.**

The link precision was found to be better than 10 ps over intervals in the range 10–1000 s. At these and longer timescales, the link is more stable than a rubidium standard. Present fractional-frequency stability capabilities are better than 10^{-14} in 1000 s and indicate better than 10^{-15} in 24 h. Improvements may lead to 10^{-15} in 1000 s and a few parts in 10^{-16} in 24 h. In the latter case, the link performance would exceed the capabilities of present H-maser in the region between a few times 10^3 and 10^4 s.

Preliminary estimates of the link performance for a multistation setup indicate that ionospheric variations may determine the overall fractional-frequency stability.

INTRODUCTION

WITH THE ADVENT of the geosynchronous satellite, the ability to transfer time between remotely located clocks has been dramatically improved [1]–[4]. Saburi *et al.* [4] demonstrated the possibility of comparing high-stability atomic clocks to within an accuracy of 10 ns by means of a two-way satellite communication link. Other techniques are potentially capable of even higher accuracies [5], [6]; the needs and merits of existing and planned methods are summarized by Leschiutta [7]. There are a number of other applications where, as a measure of link performance, a precision of 10 ps or better, on time scales from 10 s to 24 h, is necessary or desired. Among these is the radio-astronomy technique of Very Long Baseline Interferometry (VLBI), also used for geodetic purposes, for which the method of comparison described in this paper was proposed [8], [9].

The high fractional-frequency stability requirement of 10^{-12} to 10^{-16}, corresponding to a link precision of 10 ps over these timescales, is not limited to VLBI applications and could be applied where frequency synchronization or comparison to a high level of precision is of prime importance. Such stabilities are apparently not obtainable with other methods.

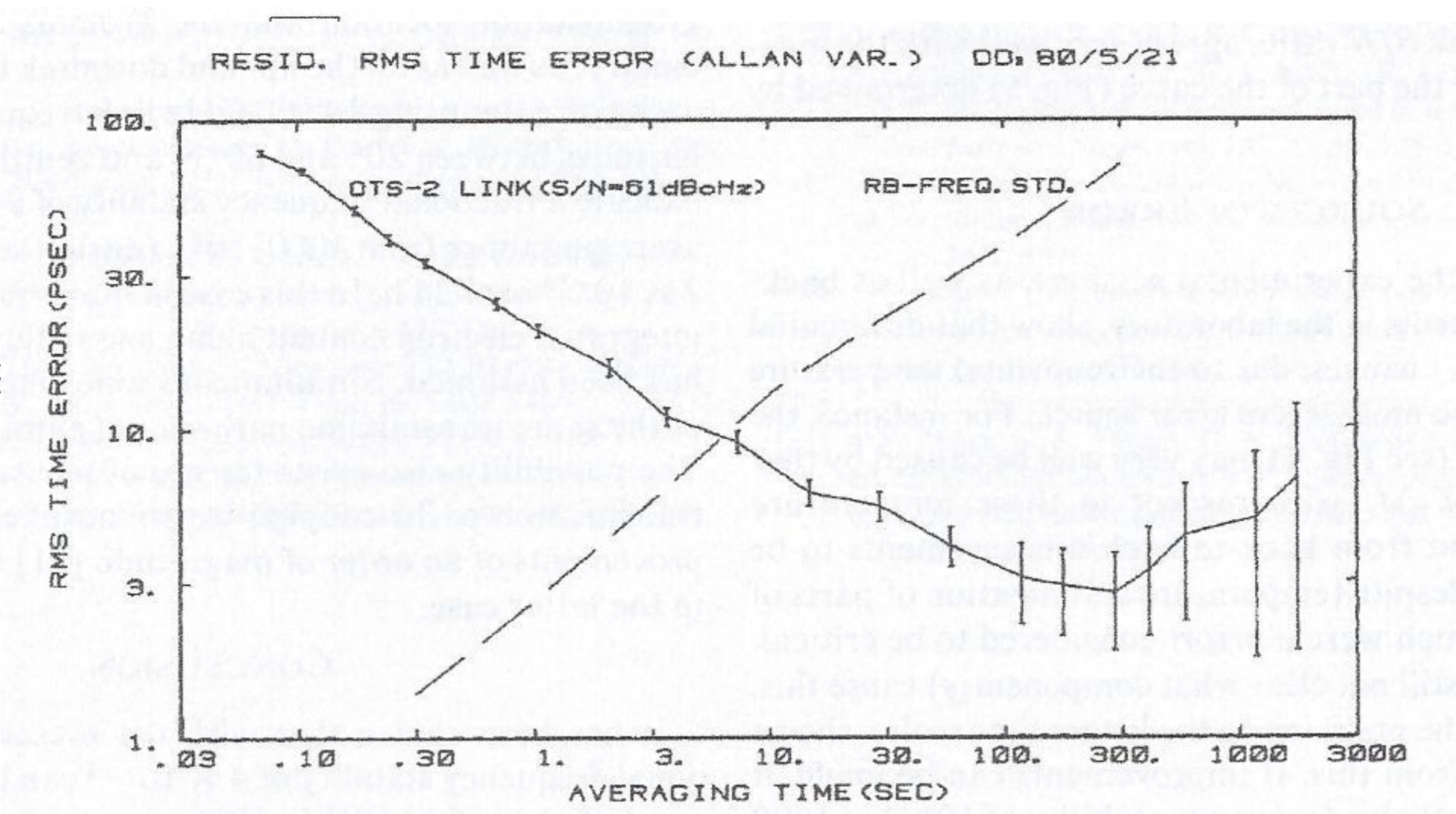
These precisions exceed the capabilities of a present-day rubidium standard after some tens of seconds and of hydrogen masers after a few $\times 10^3$ to 10^4 s [10], [11]. Attainment of such stabilities dictates near optimal use of the available transmission channel and places severe requirements on the choice of the signal-modulation scheme.

The present experiment made use of the OTS-2 satellite operating at 14.2/11.5 GHz in geosynchronous orbit and launched in 1978 under the auspices of the European Space

Manuscript received June 8, 1981; revised November 30, 1982.
A. van Ardenne and J. D. O'Sullivan are with The Netherlands Foundation for Radio Astronomy (NFRA), 7990 AA Dwingeloo, The Netherlands.
A. de Dianous is with the European Space Technological Centre (ESTEC), 2200 AG Noordwikj, The Netherlands.

0018-9456/83/0600-0370$01.00

Phase comparison via OTS



Stage 1:The very early days of space VLBI: 1977 - 1982

KRT-10 deployed
on Salyut-6 in 1979

kolay Kardashev

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Stage 1:The very early days of space VLBI: 1977 - 1982

SPACE VLBI

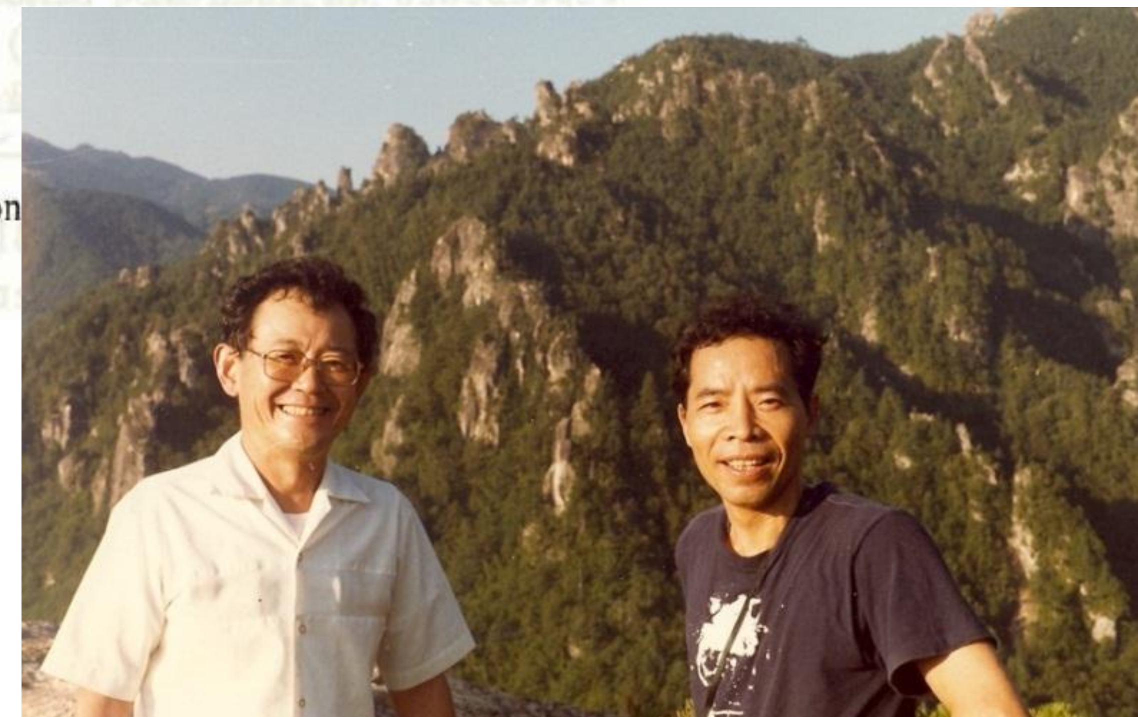
H. HIRABAYASHI, Y. CHIKADA, M. INOUE, M. MORIMOTO

Nobeyama Radio Observatory* Tokyo Astronomical Observatory,
University of Tokyo, Nobeyama, Minamisaku−gun
Nagano −Ken 384−13, Japan

(Submitted to Space Station

Oct. 1982

Large diameter antenna on US Space Station



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Stage 2 was ushered in by QUASAT

‚QuaSat' brengt kleine radiobronnen in heelal in beeld

Naarmate de sterrenkunde
technisch in staat is, meer
te achterhalen van wat zich
diep in het heelal afspeelt,
ontdekt ze steeds meer
dsels. Uit zuiver wetenschappelijk
gpunt is het van belang, natuurkun-
e processen te bestuderen die zich
der extreme omstandigheden afspe-
op tienduizenden of miljoenen ma-
de afstand die het licht in een jaar
egt. Maar het kan van praktisch nut
n die processen te begrijpen, die zich
er weg in de ijle ruimte voltrekken.
ocessen waarbij zo onvoorstelbaar
te hoeveelheden energie in het spel
n, dat men ze in aardse laboratoria
fs niet kan simuleren. Zo weten-
appelijk kan zulk onderzoek niet
n, of het levert bovendien wel een
ntal praktische bijdragen aan de
hnologie.

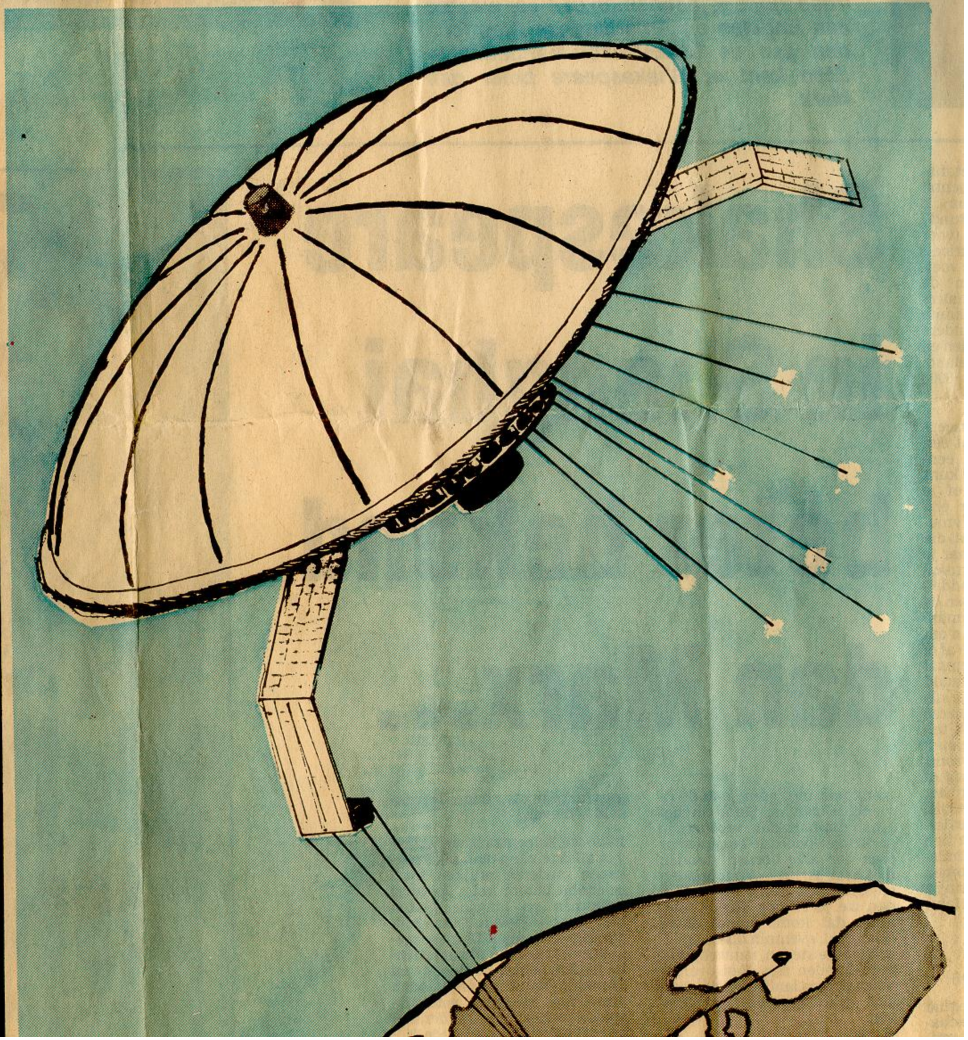
n voorbeeld van dergelijk onder-
ek is het Very Long Baseline Interfe-
metry-programma (VLBI), waaraan
stichting Radiostraling Zon- en
lkwegstelsel in Dwingeloo - samen
t elf andere observatoria tussen Ita-
en Californië - werkt.

‚Big Bang'

'n twintig miljard jaar geleden moet
t heelal ontstaan zijn uit een im-
ense ontploffing, ‚the Big Bang'. De
ergie van die explosie werd omgezet
materie die we nu waarnemen als
aneten, sterren, melkwegstelsels,
s- en stofwolken en quasars - objek-
n, die sterke radiostraling uitzenden
aar die tot nu toe optisch niet zicht-
ar gemaakt konden worden.

e sterren ontstonden door de ver-
chting van onvoorstelbaar grote
lken van moleculen. Onder de druk
n hun eigen zwaartekracht ont-
andden ze tot wat we nu als een ster
arnemen. Deze ster blijft zichzelf sa-
endrukken en haar nucleaire brand-
of verbruiken door processen van

Sterren geven licht. Daardoor kan je ze zien. Tussen alle sterren die aan de hemel zichtbaar zijn, staan er nog miljoenen die zelfs met de sterkste optische telescoop niet meer te bereiken zijn. Ze zijn te zwak of ze worden gemaskeerd door enorme wolken van gas en stof.
Maar sterren, daar kan je ook naar luisteren. Uit de peilloze diepten van het heelal bereiken ook signalen van allerlei (meestal) kernfysische processen onze aarde. Het zijn ethergolven, die alle tesamen op een gerichte ontvanger een cacofonie van constante ruis vormen. Die ruis is een uitdaging aan sterrenkundigen om de aard van vele onbekende - maar vermoede - processen te ontraadselen.
Daarmee houdt in Nederland de stichting Radiostraling Zon en Melkweg zich bezig. De stichting heeft observatoria in Westerbork (sinds 1970) en Dwingeloo (sinds 1955).
In Dwingeloo wordt een plan uitgewerkt om - in internationale samenwerking - de aard van een aantal „zeer kleine" stralingsbronnen meer effectief te onderzoeken dan tot nu toe mogelijk was. De eerste fase van het projekt was het koppelen van een aantal radiotelescopen tot één grote radiotelescoop met een effectieve diameter van 10.000 kilometer. De tweede stap is „QuaSat", een radiotelescoop, te plaatsen in een elliptische baan van 5.700 tot 12.500 km de aarde.
Als de European Space Agency (ESA) in 1988 het plan voor de satellietantenne aanvaardt zal, vooruitlopend op de lancering, in Dwingeloo een centrale voor opslag en verwerking van de gegevens gebouwd moeten worden. Want door de internationale samenwerking zou anders de capaciteit voor dataverwerking binnen enkele jaren uitgeput zijn.



Stage 2: 1983-1988

esa
european space agency

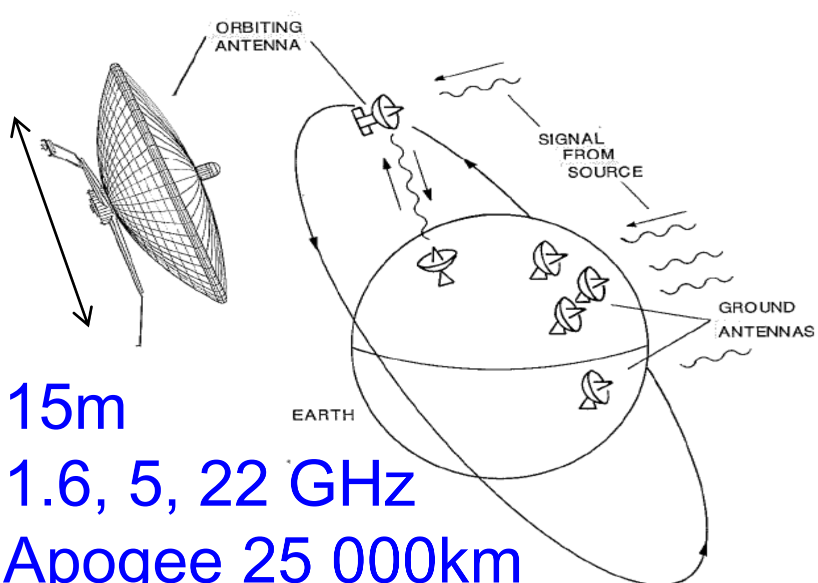
SCI(85)5
NOVEMBER 1985

QUASAT

A SPACE VLBI SATELLITE

1983-1985

ASSESSMENT STUDY



15m
1.6, 5, 22 GHz
Apogee 25 000km

esa SP-213

1984

Quasat –
a VLBI observatory
in space

Proceedings of a Workshop
held at Gross Enzersdorf, Austria,
on 18 – 22 June 1984

Study team
included Arnold
and Peter W

esa
european space agency

1984: QUASAT Workshop

CONTENTS

High-level coordination began to take place in 1984

- COSPAR Ad-hoc Committee on Space VLBI

  -served as a body to coordinate the three different efforts until the mission-specific International Scientific Committees were formed

- Inter-(Space) Agency Consultative Group

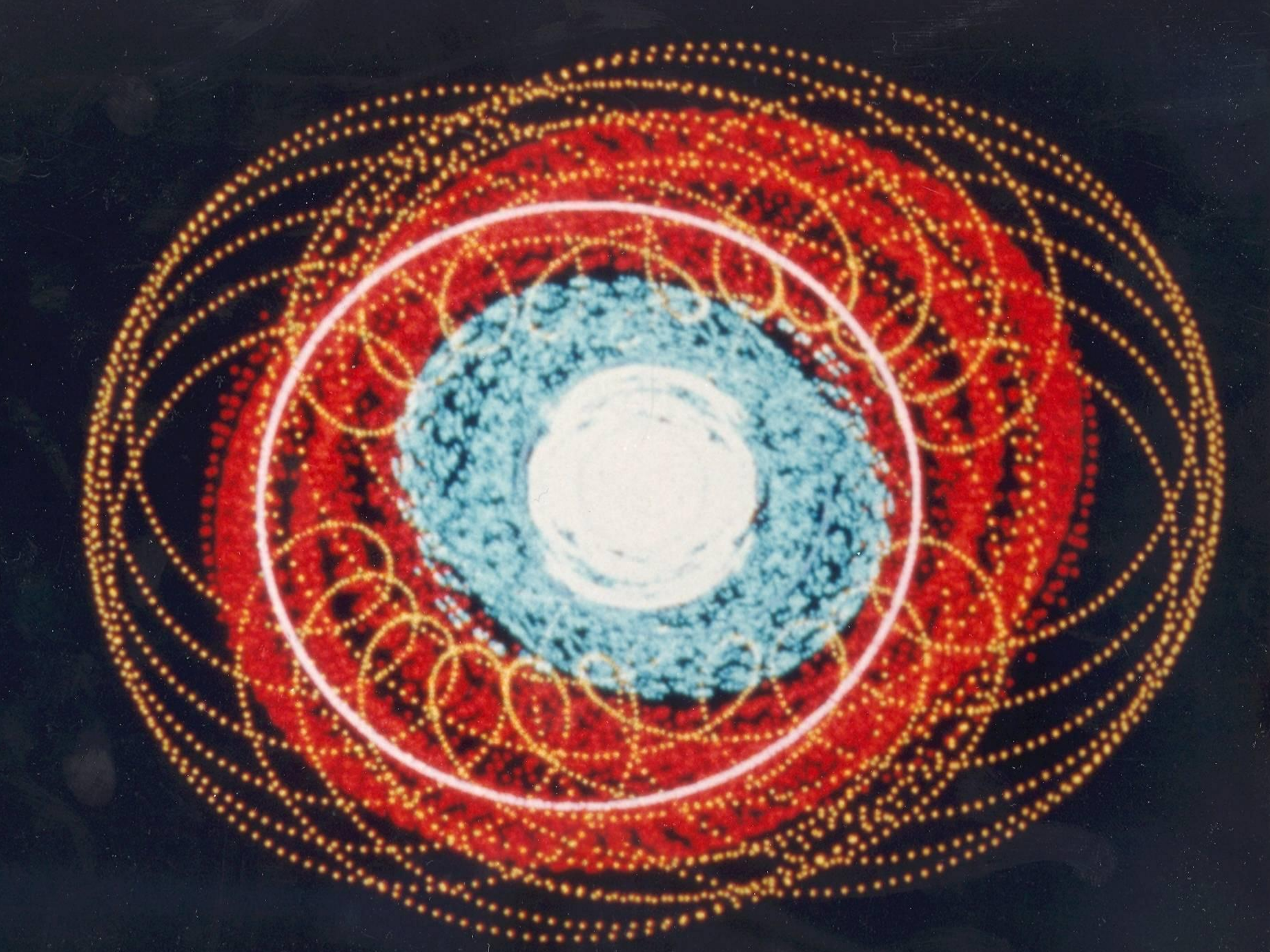
  -Panel 1 on Space VLBI

Dual-satellite space VLBI

In 1984, the QUASAT team realised that it was impossible to combine superb uv-coverage with a substantial jump in angular resolution compared to ground-based VLBI.

So why not combine forces and simultaneously fly two satellites in complementary orbits, and achieve "perfect" uv coverage out to 60 000 km?

QUASAT + RadioAstron or
QUASAT + Japanese satellite



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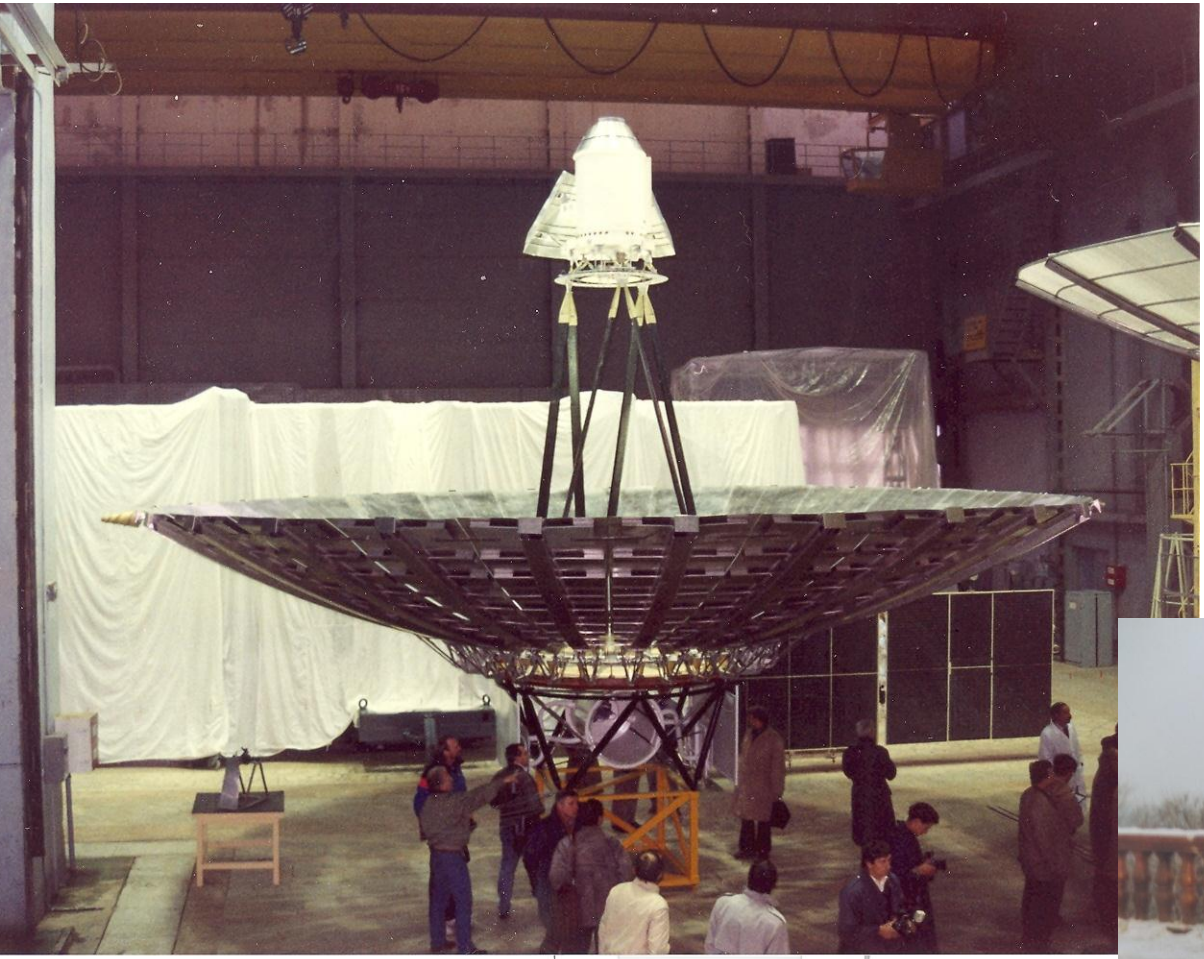
RadioAstron was approved in 1985



Moscow in -25^0 C weather

10m diameter, 0.3, 1.6, 5, 22 GHz, apogee 100 000km, later changed to 350 000 km

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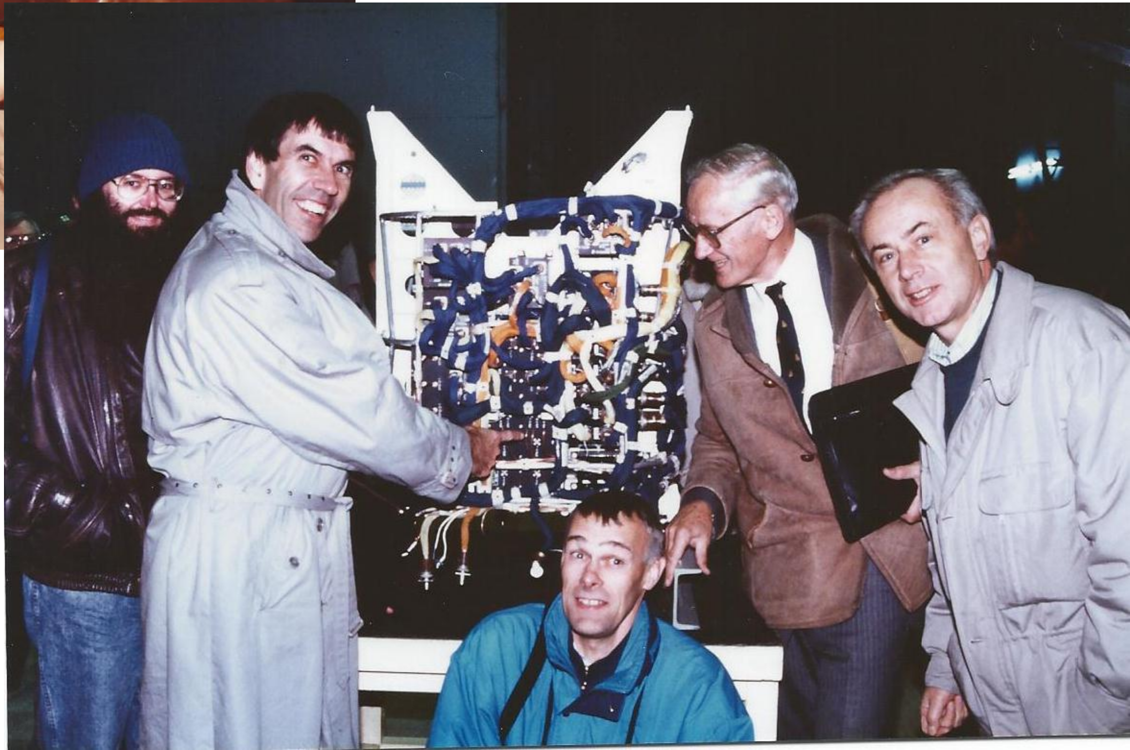
YERAC XII in1979

EVN 6cm receiver for Radioastron

Kardashev and Setti signing the agreement in 1986



Although it was built in Dwingeloo and Bonn, tested at ESTEC, and delivered to Moscow, it did not fly on RADIOASTRON.

But that's another story…..

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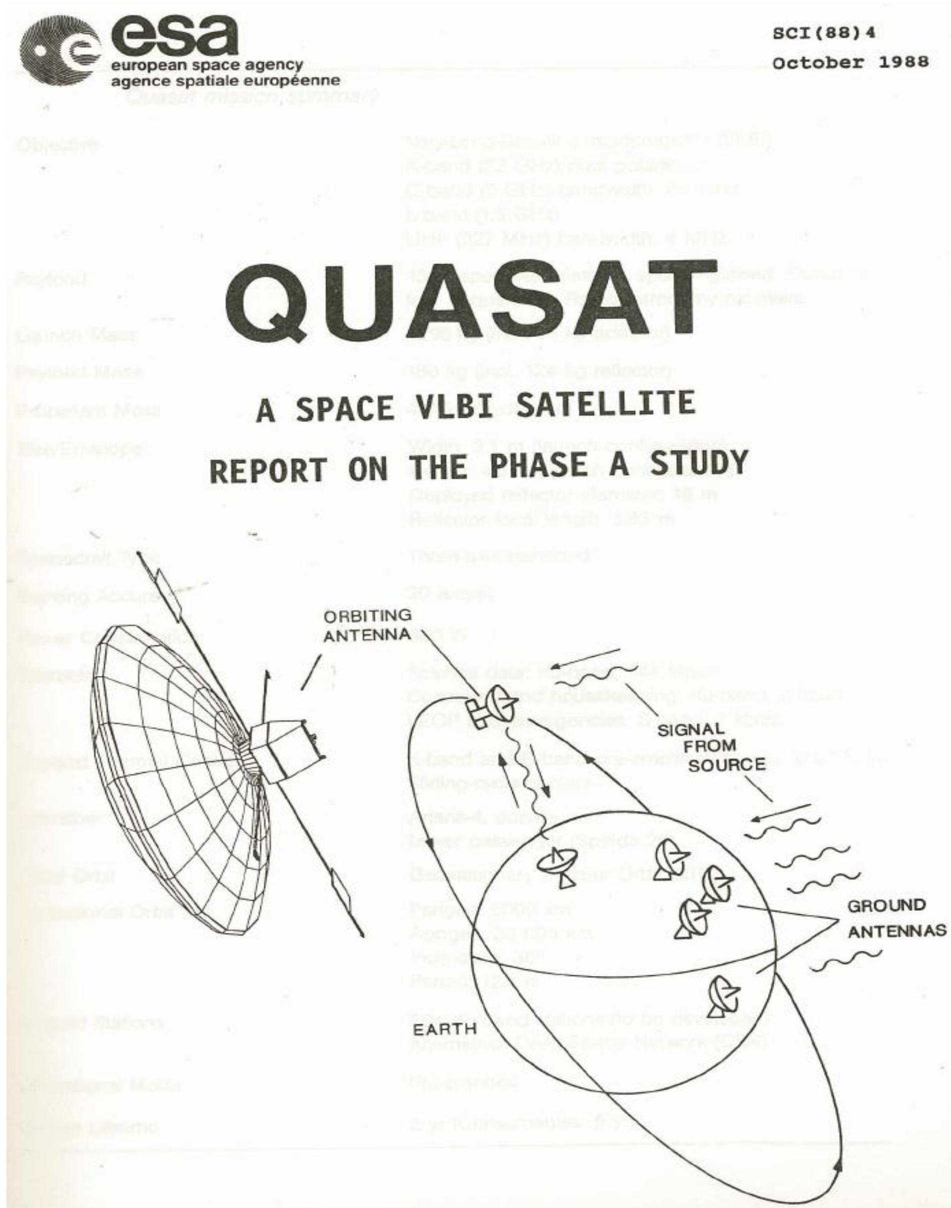
Phase A Study

1986-1988


esa
european space agency
agence spatiale européenne

SCI(88)4
October 1988

QUASAT

A SPACE VLBI SATELLITE

REPORT ON THE PHASE A STUDY

First space VLBI fringes with TDRSS in1986

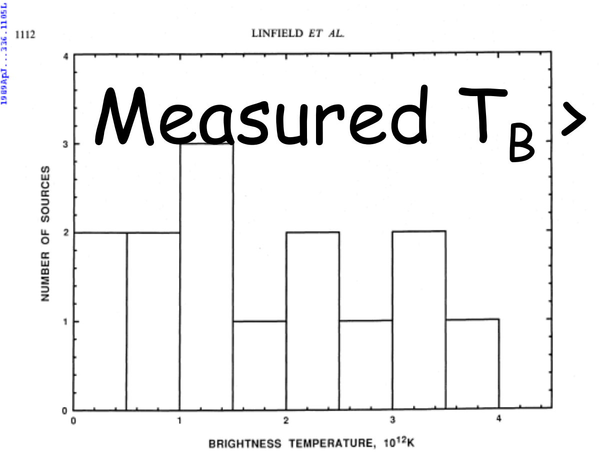
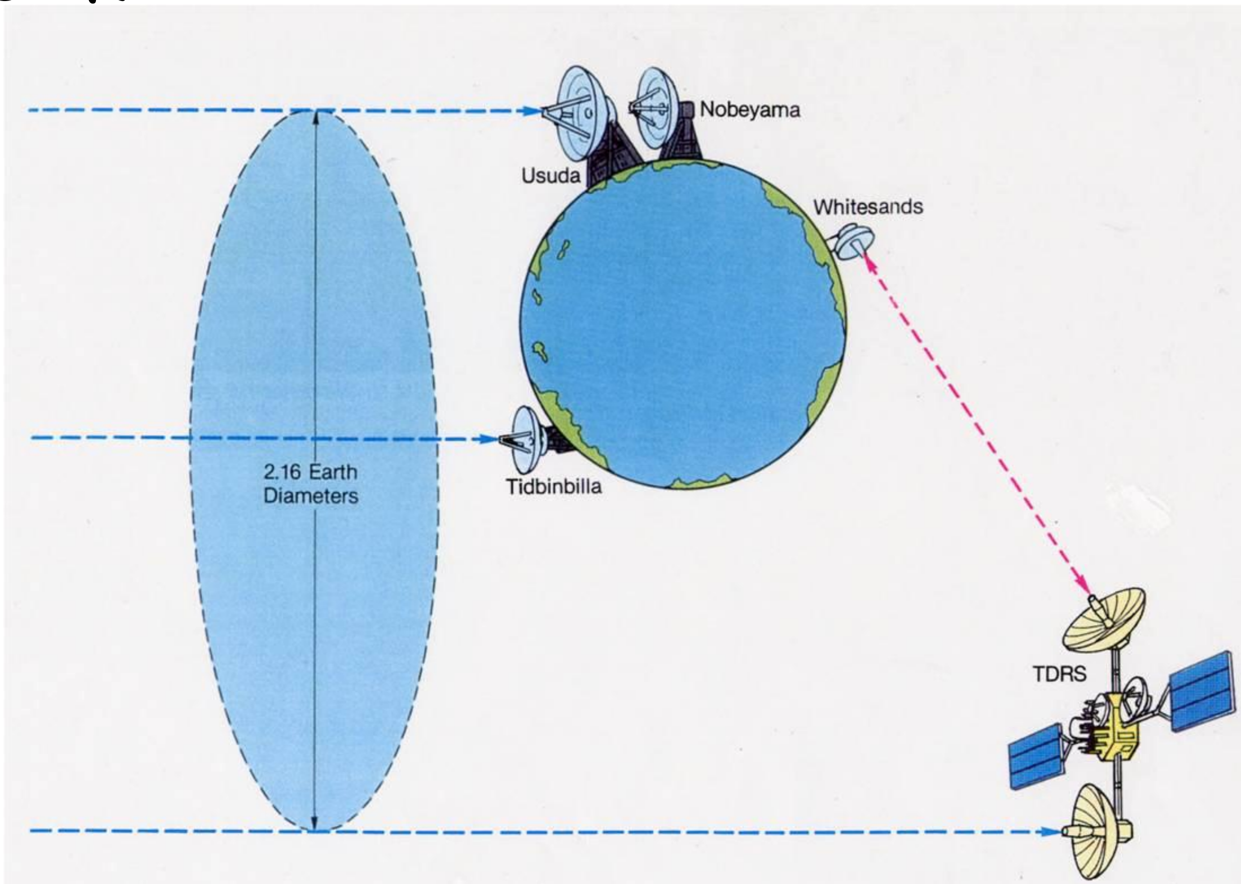


FIG. 4.—Histogram of the measured brightness temperatures for the 14 sources listed in Table 4



1730-130 (NRAO530), 1510-089 and 1741-038, detected at 2.3 GHz

So what happened in the end?

QUASAT was shot down by ESA in October 1988 and finally died in 1989 (lost out to Cassini-Huygens)

VSOP was approved by ISAS in December 1988

- 8m diameter 1.6, 5, 22 GHz; apogee 21 600 km

Working closely with the Soviet Union on RadioAstron still didn't have the seal of approval from you know who…

So the primary focus for the QUASAT team was on VSOP

while continuing to work on RadioAstron, participating in advisory committee meetings and building receivers

Stage 3: 1988 – 2012

VSOP and RadioAstron

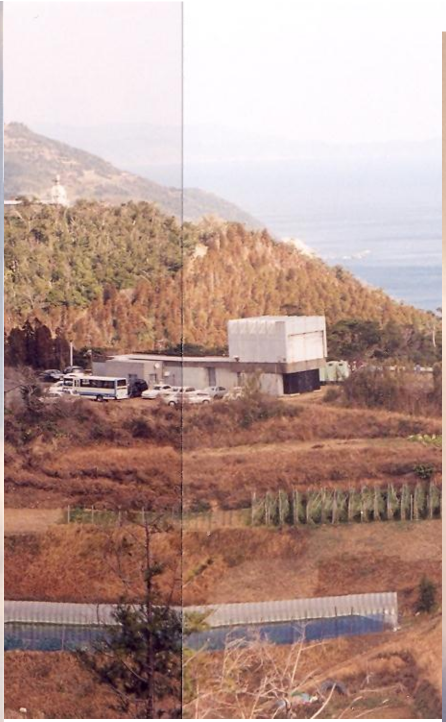
The Ground Segment

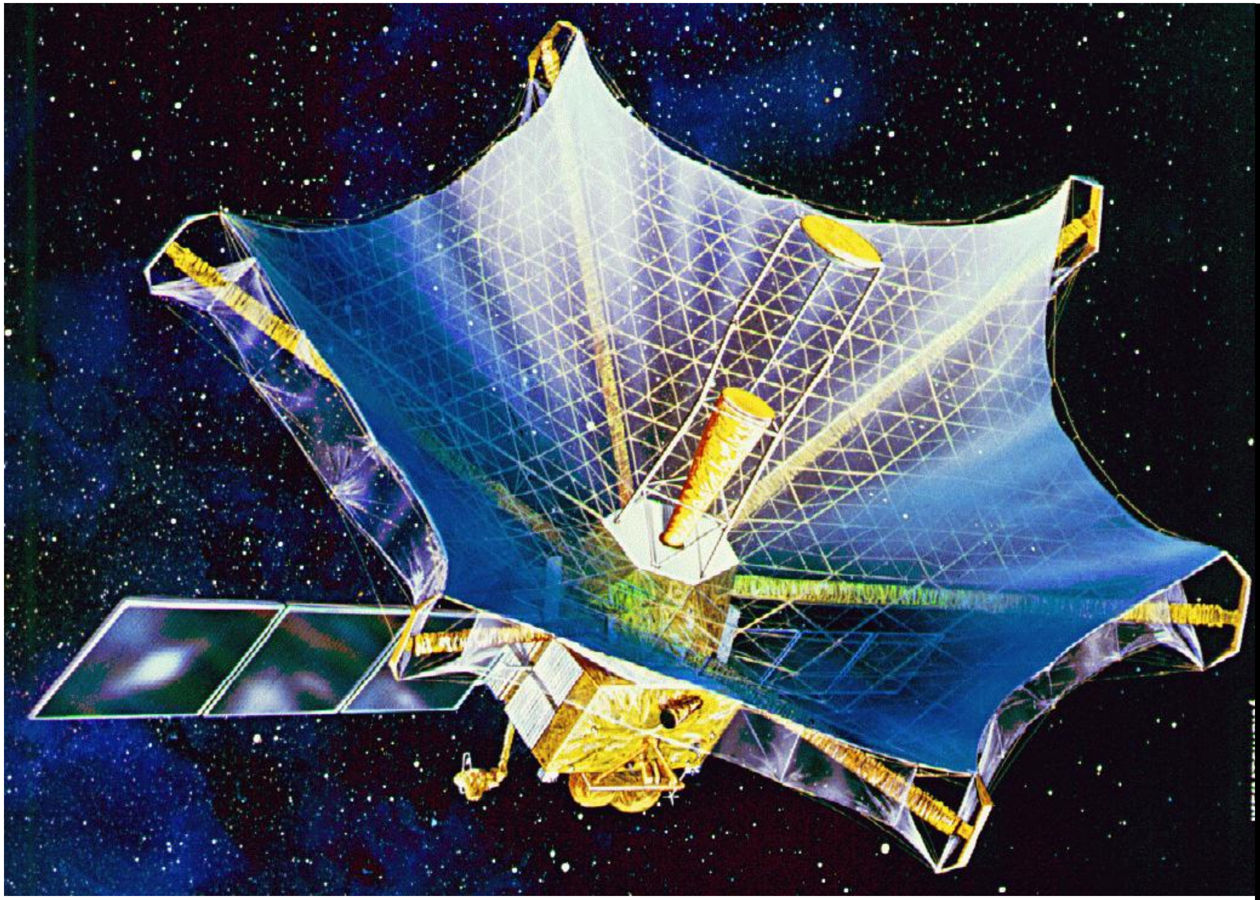
Global VLBI Working Group

Onsala, May1993

VSOP needed a bit of help from friends with connections…

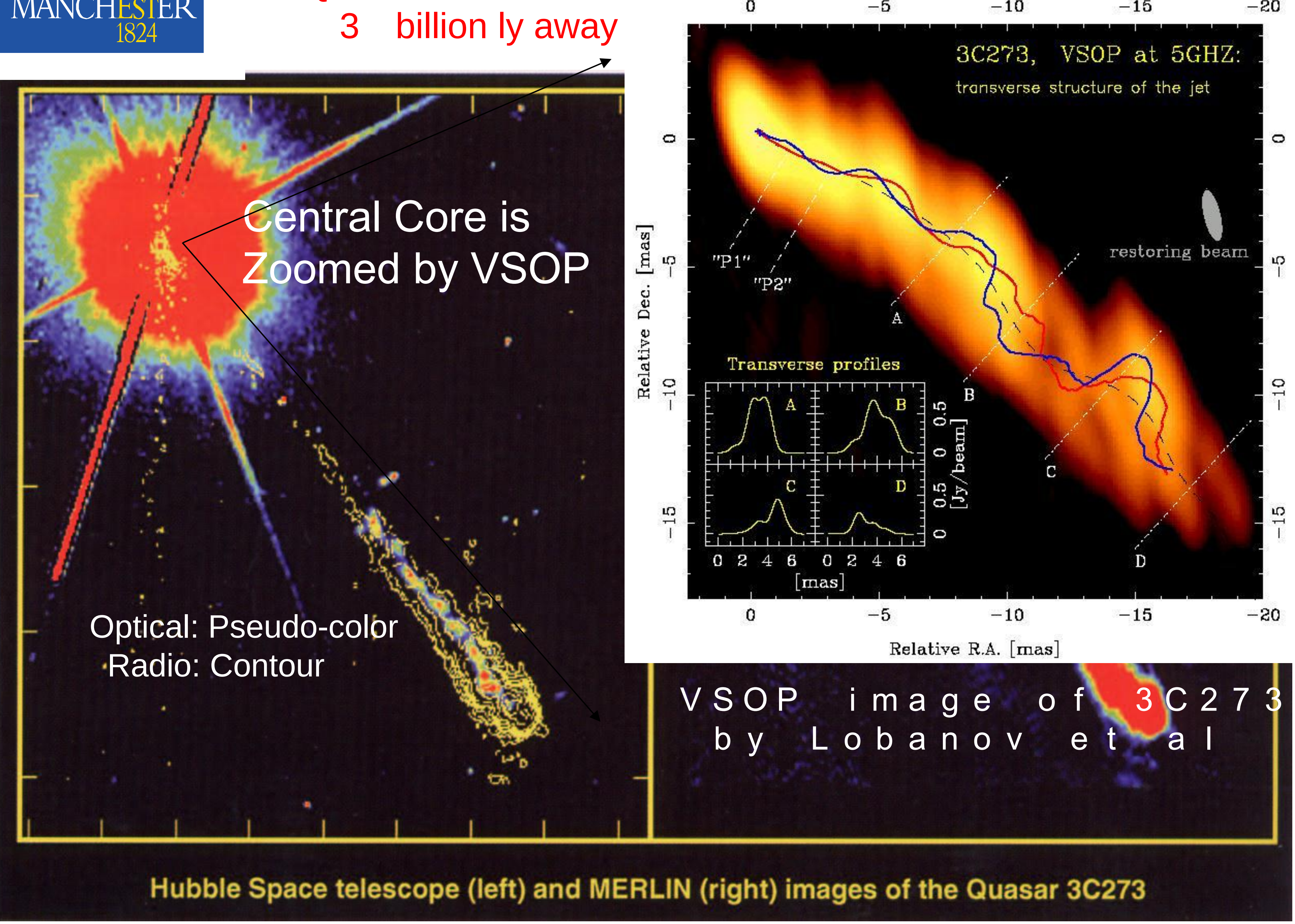
Launch in February 1997

VSOP - HALCA operational until Nov 2005

Quasar 3 C273
3 billion ly away



In the meantime, Nikolay and his team carried on…

getting all the help he could…

Prime Minister Putin

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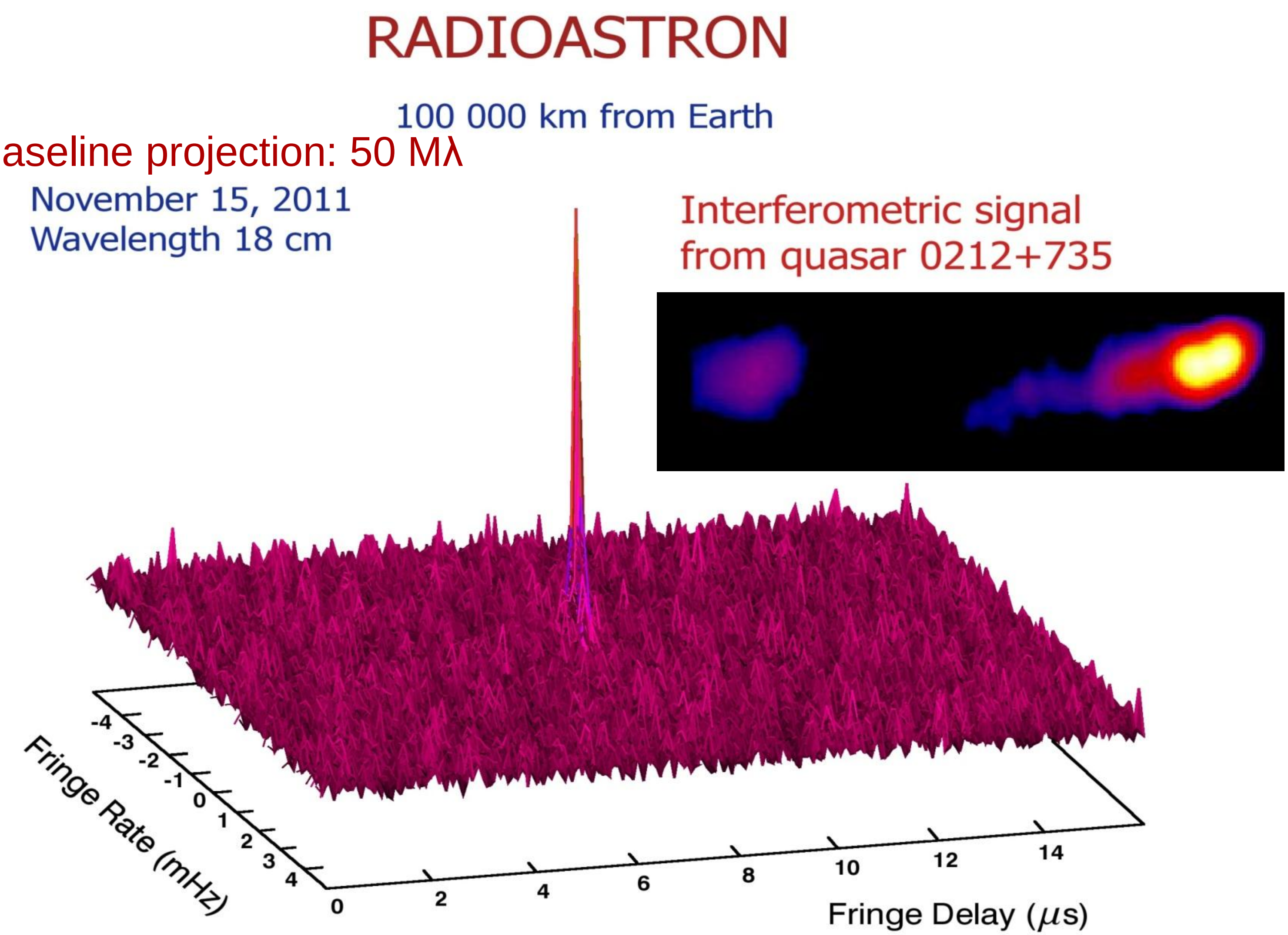
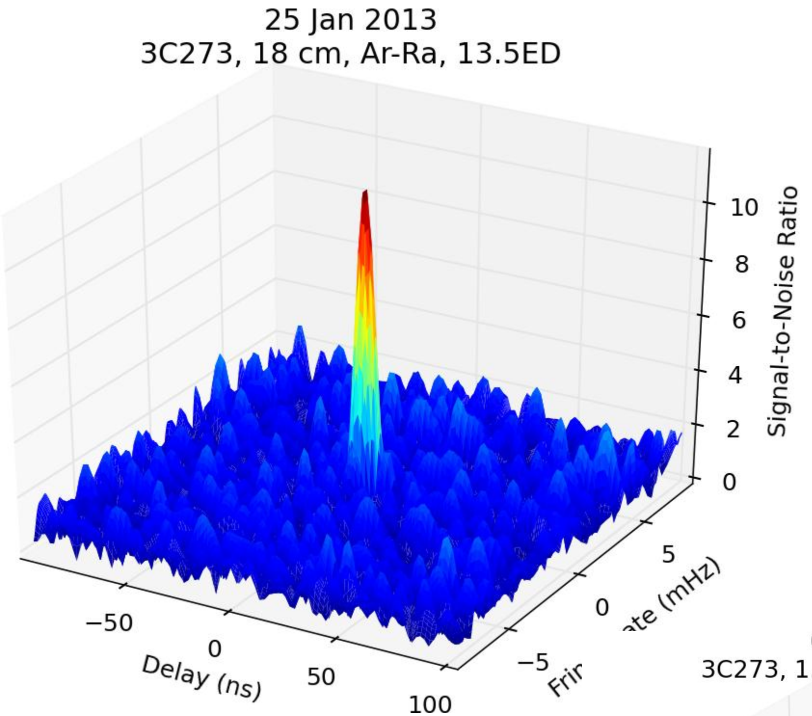
Ready to go to Baikonur

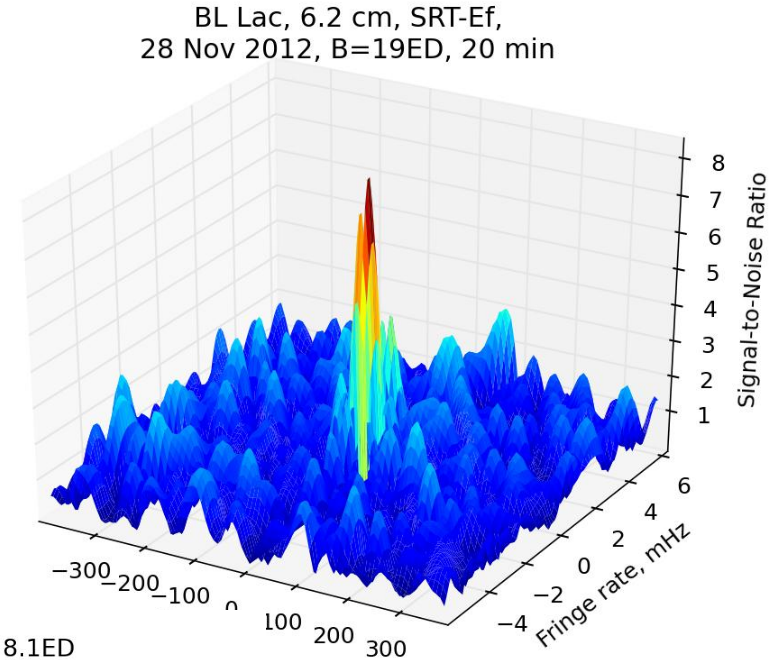
And finally the launch in July 2011

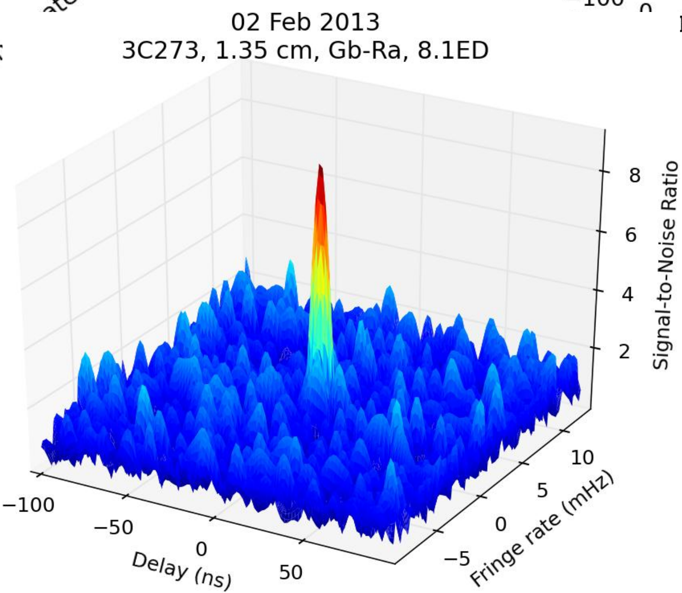
First fringes!

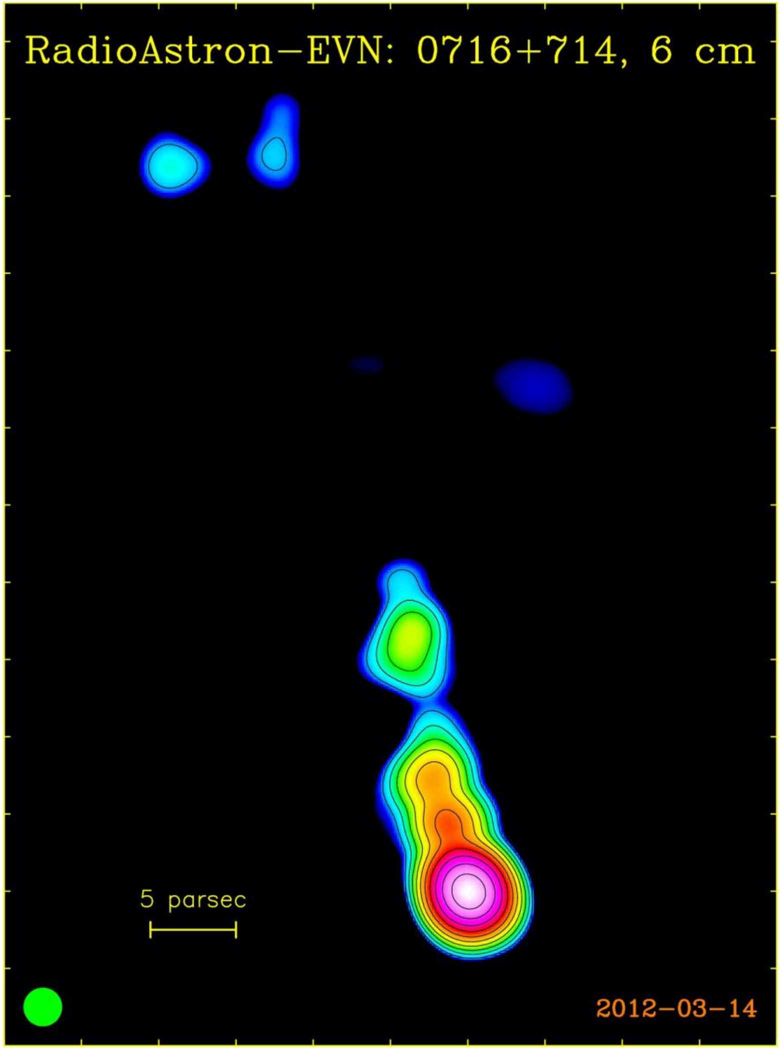
Baseline projection: 50 Mλ




25 Jan 2013
3C273, 18 cm, Ar-Ra, 13.5ED
Signal-to-Noise Ratio
Delay (ns)
Fringe rate (mHz)

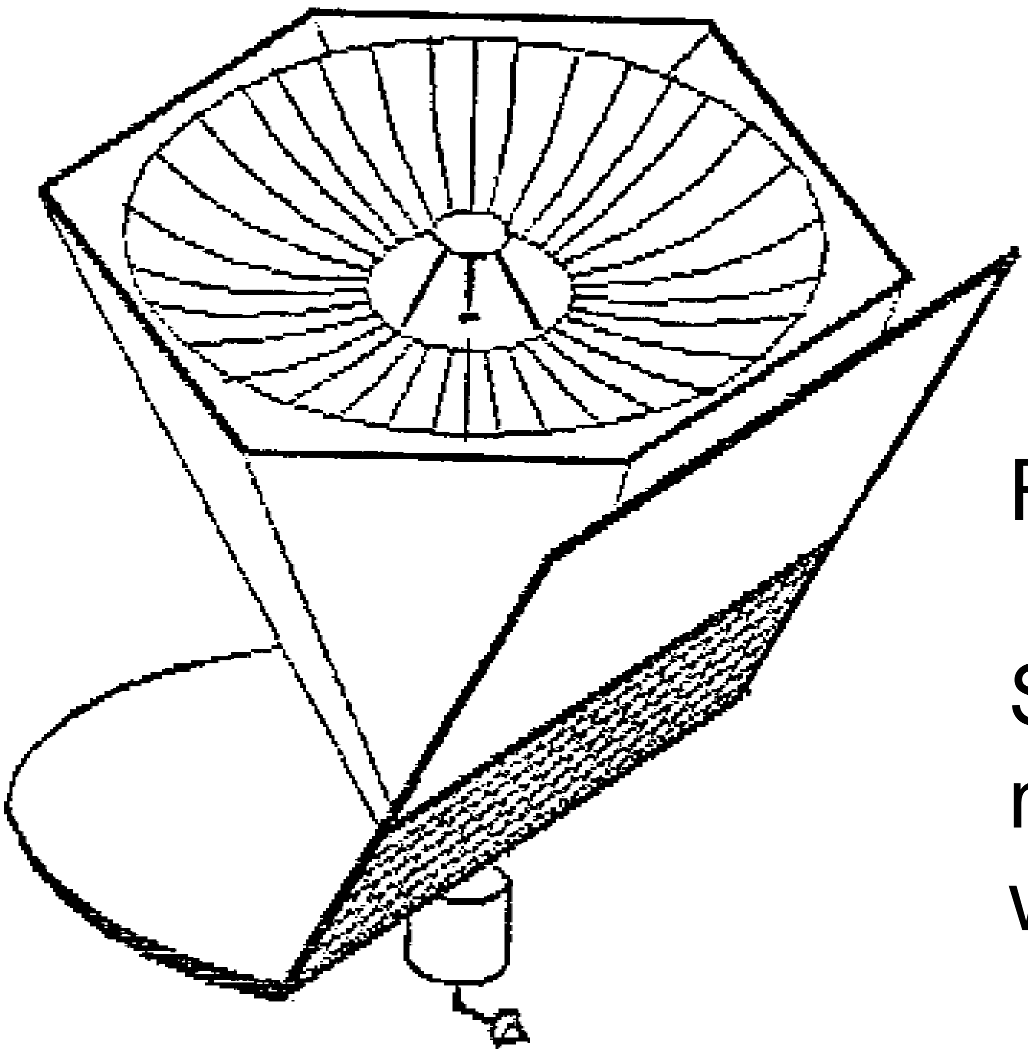

BL Lac, 6.2 cm, SRT-Ef,
28 Nov 2012, B=19ED, 20 min
Signal-to-Noise Ratio
Fringe rate, mHz


02 Feb 2013
3C273, 1.35 cm, Gb-Ra, 8.1ED
Signal-to-Noise Ratio
Delay (ns)
Fringe rate (mHz)



24 hours
0.5 mas
DR>1000:1

The future: Millimetron?

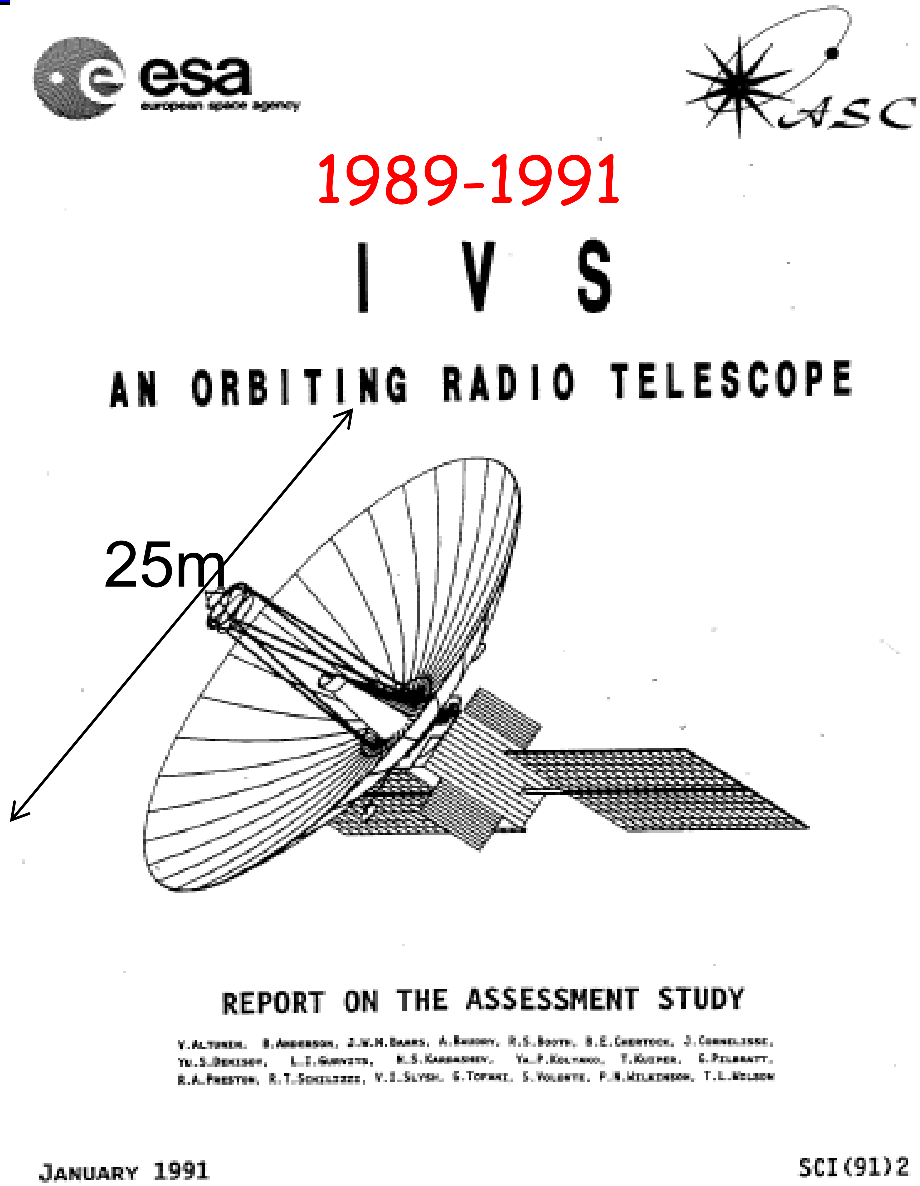


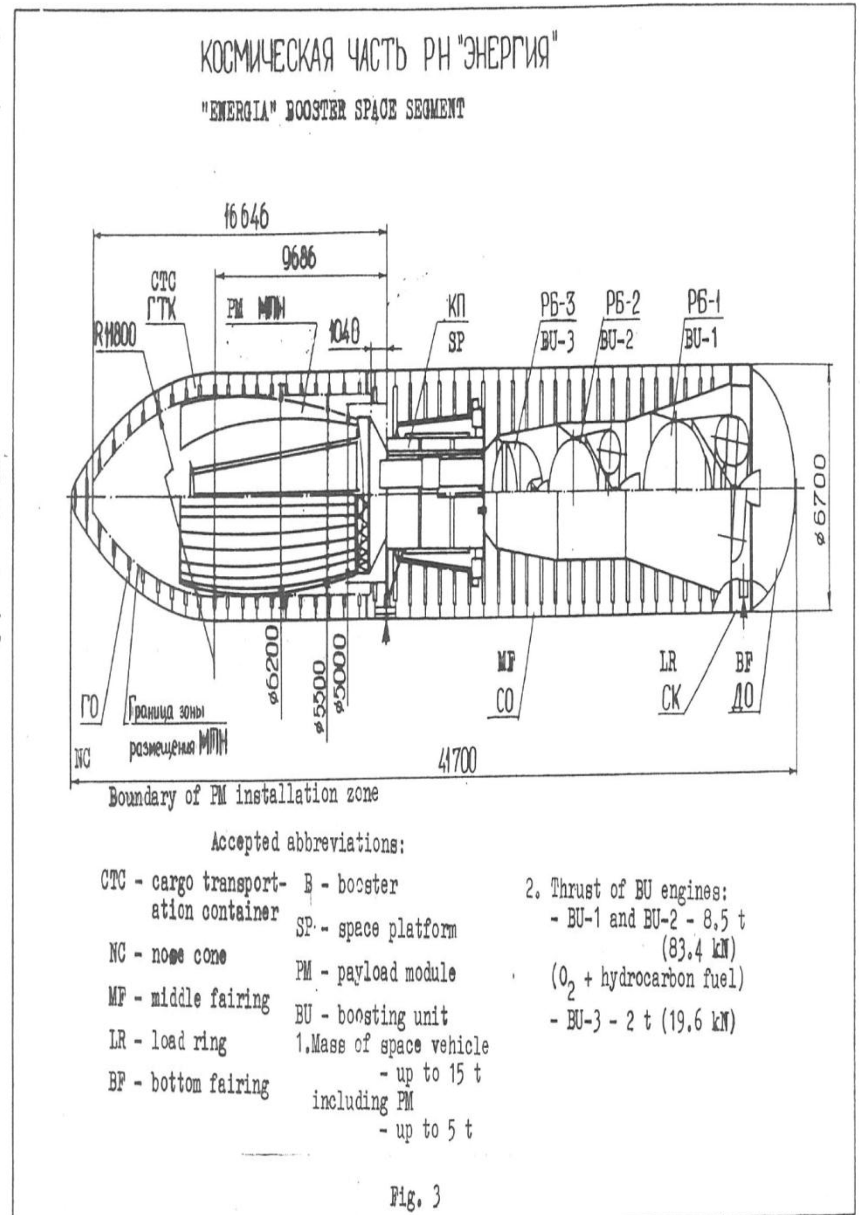
Russia

Space VLBI at millimetre wavelengths

Or ?

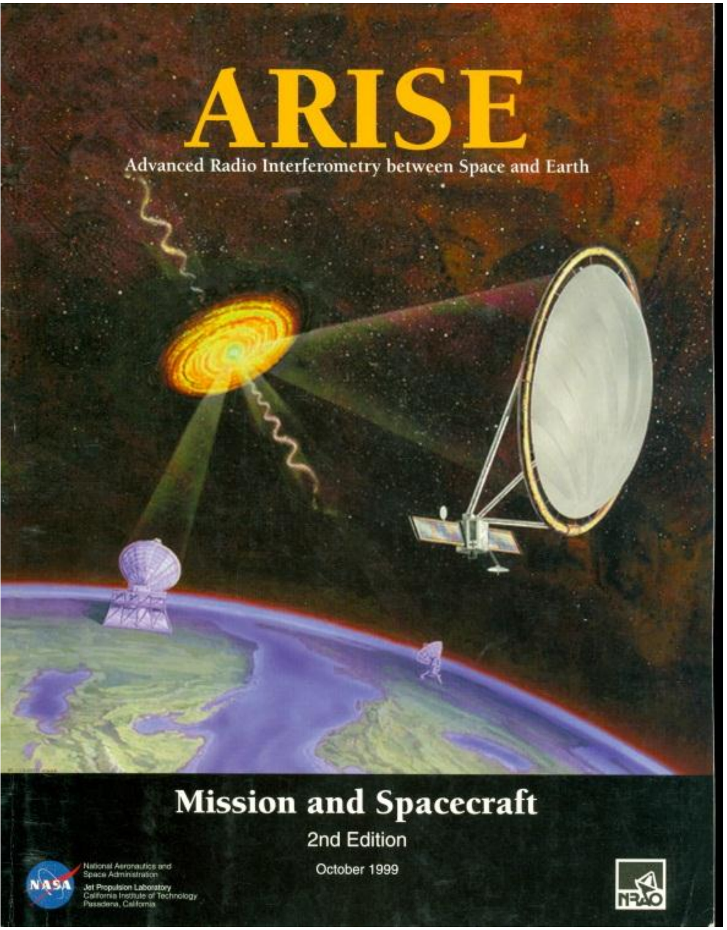
Last gasps from ESA and NASA





SKA SQUARE KILOMETRE ARRAY

Last gasps from ESA and NASA



1999

ALFA (~2002)

Antenna :	100 km array of 16 spacecraft
Frequency Bands (MHz):	0.03 - 30 (tunable)
Resolution (arcseconds):	10,000 - 10
Sensitivity:	several Jy