PROCEEDINGS OF SCIENCE

The first 10 years of Discovery

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PoS(westerbork)004

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50 Years Westerbork Radio Observatory, A Continuing Journey to Discoveries and Innovations
Richard Strom, Arnold van Ardenne, Steve Torchinsky (eds)

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The first 10 years of Discovery

Chapter 3.1 From Design to Observations

Wim Brouw*

1. International

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

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

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

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

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

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

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

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

2. From analogue to digital

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

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

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

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

Staatsbezoek?

Richard Strom

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

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

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

A Thousand words on early Phase Control

Johan Hamaker

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

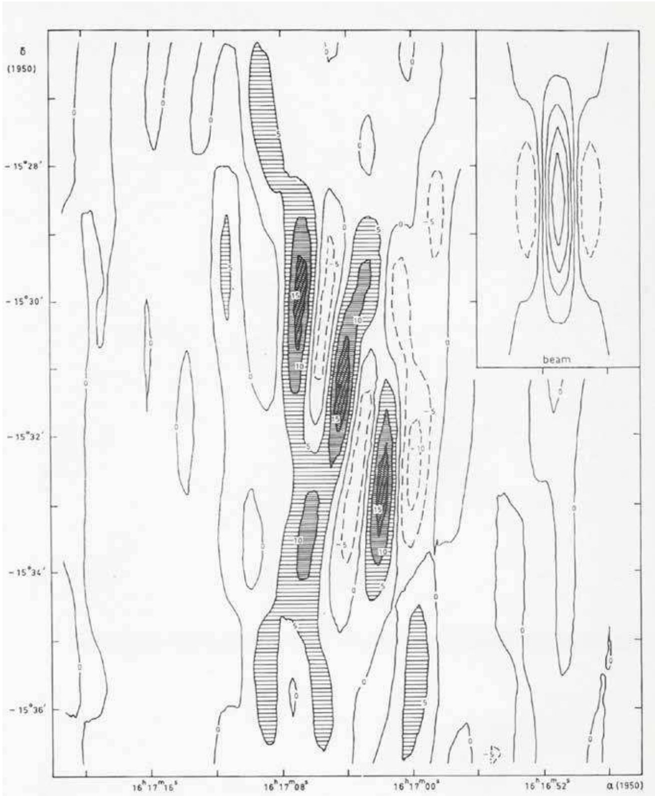


Figure 2: One of the first results of the new telescope was the observation of the X-ray source SCO-X1. It was resolved into 3 separate sources (a central variable source and 2 outlying sources). (J.H. Oort, Jaarboek ZWO 1970)

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

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

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

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

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

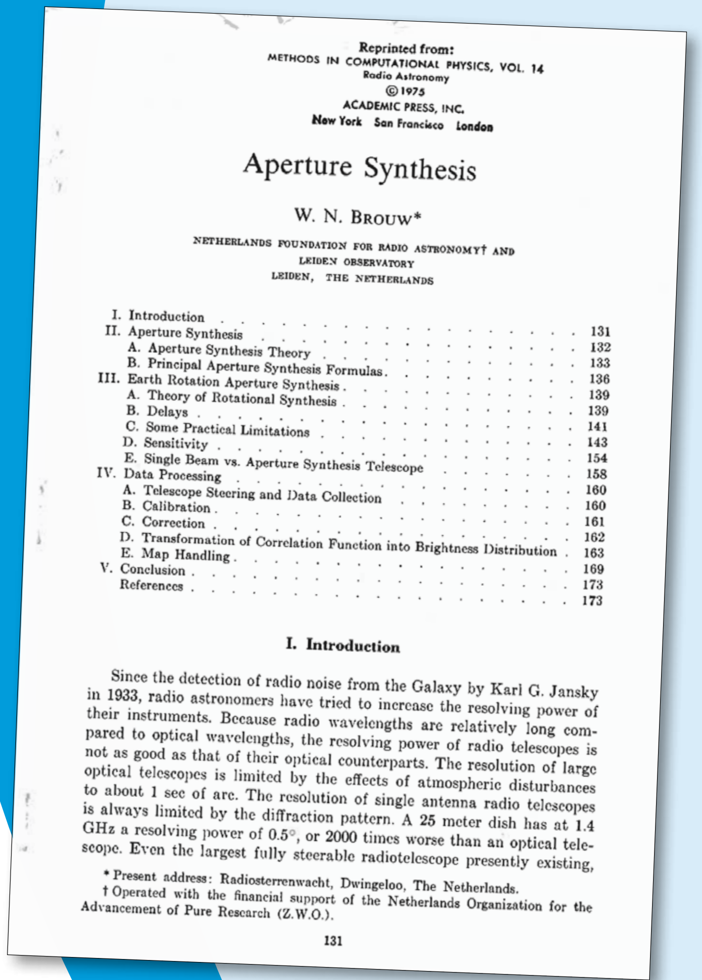
The Last Word on Aperture Synthesis

Jan Noordam, Arnold van Ardenne

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

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

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



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Aperture Synthesis

W. N. Brouw*

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LEIDEN, THE NETHERLANDS

I. Introduction

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

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

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

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

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

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

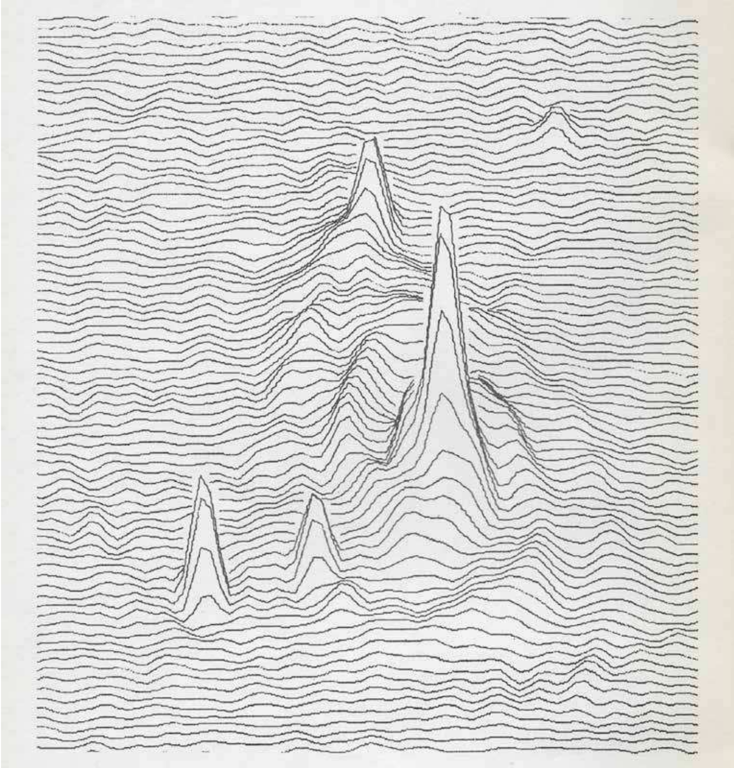
One of the results of the intimate knowledge of the internals of the Leiden Computer, was the first city wide network of terminals connected to a central computer. Institutes could use these special terminals to calculate with an interactive language, and with A Programming Language (APL). Later, Groningen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

3. The broader field

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

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

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



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

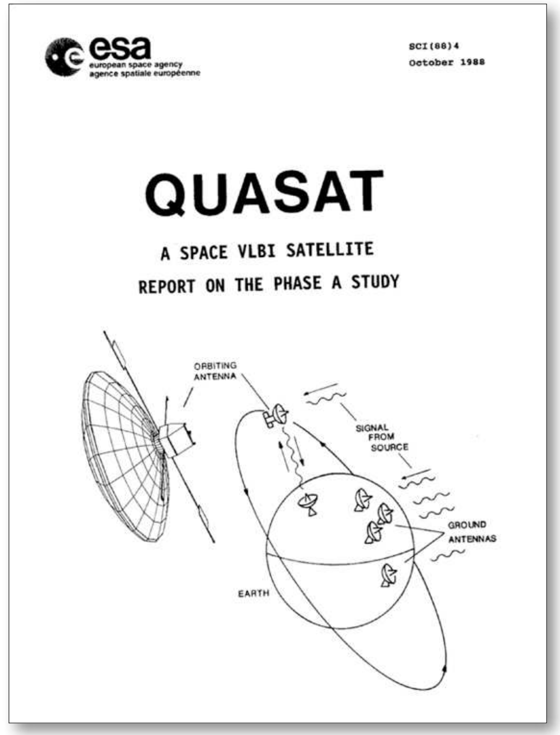
Other disciplines also need methods to convert measured data by Fourier Transforms. In the early days of the WSRT a more or less bi-annual set of symposia was organised. It started with an imaging conference by the Dutch Space Organisation (*Image Processing Techniques in Astronomy, Astrophysics and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

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

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

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

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



esa
european space agency
agence spatiale européenne

SCI(88)4
October 1988

QUASAT

A SPACE VLBI SATELLITE

REPORT ON THE PHASE A STUDY

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

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

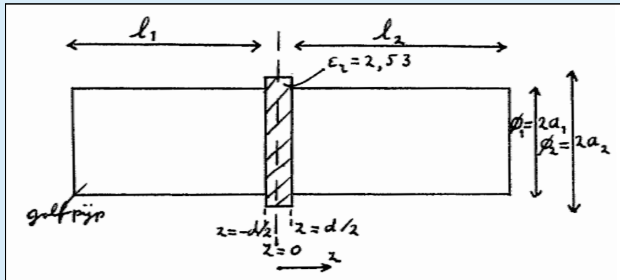
Early data reduction and computing in the Dwingeloo lab computers

Arnold van Ardenne

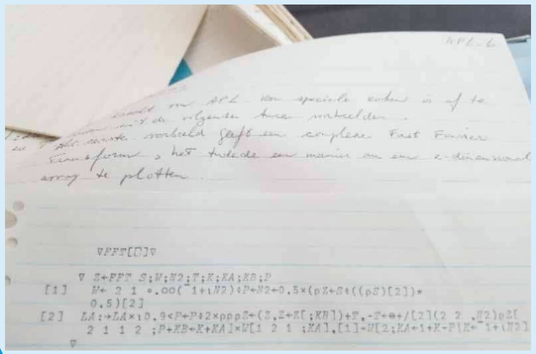
Before the advent of the PC, the Dwingeloo lab engineers programmed either in Fortran on the central IBM computer in Leiden, or on a small dedicated PDP11 computer in the lab.

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

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



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



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

Chapter 3.2 Early WSRT receiver work in the Leiden Laboratory

Jean Casse*

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

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

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

* ASTRON, The Netherlands

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

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

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

The WSRT on its own

Hans van Someren Greve

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

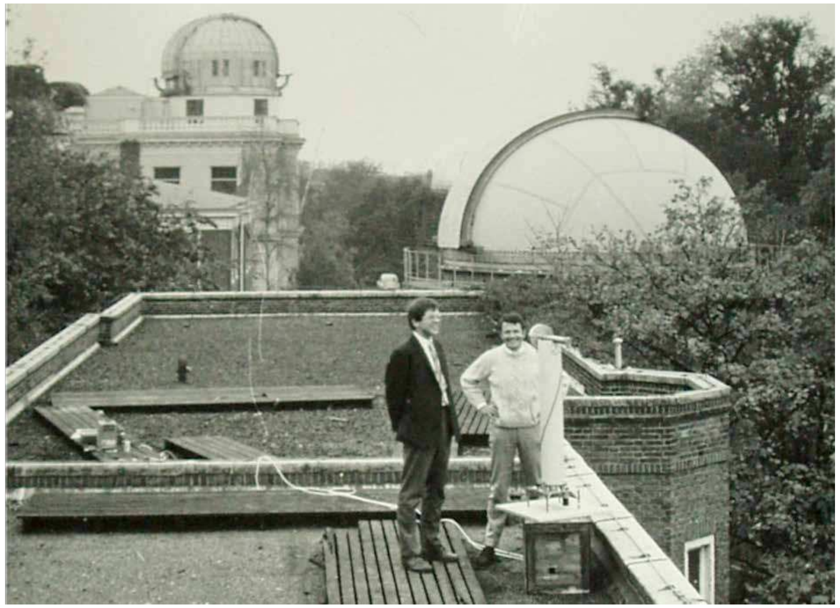
With the prototype receiver we were in a position to perform site tests at 1414 MHz on the electronics, including the cable system. Testing the WSRT receiver took place at the Pesthuis Polder, a site near the train station of Leiden. It consisted of 2 equatorial mounted dishes of 4 m diameter and separated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

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

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

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

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



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

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

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

First Discoveries

Chapter 3.3.1 Polarization and depolarization

Richard Strom*

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

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

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

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

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

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

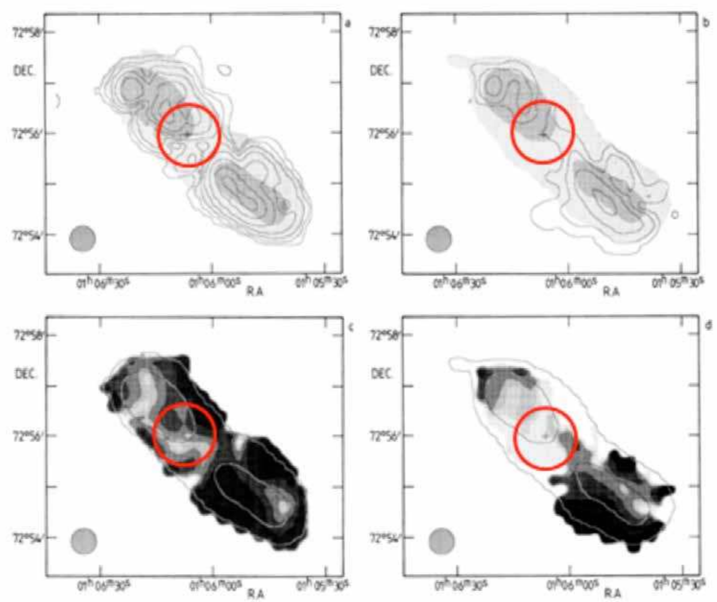

Figure 1. The radio galaxy 3C 33.1 observed by the WSRT at 21 cm (left-side images, a and c) and 49 cm (right, b and d). Contours show the strength of polarized emission (a and b). Strong polarized emission (c and d) is shaded dark. A region about 200 kpc diameter is shown by a red circle centered on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

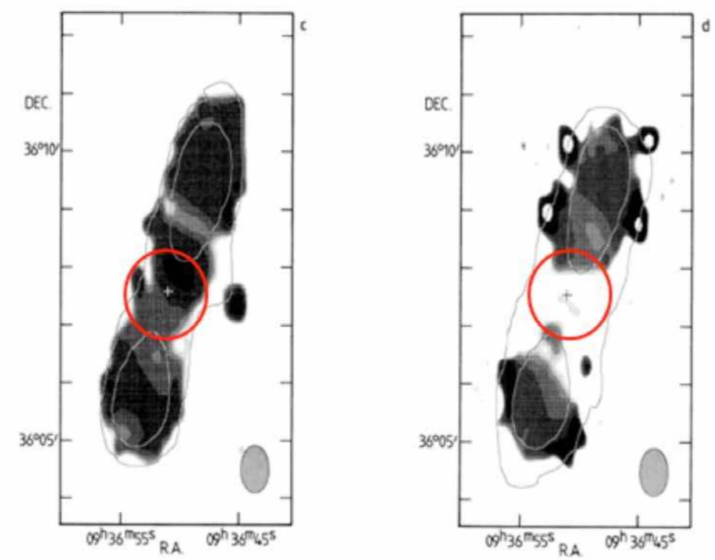

Figure 2. Polarization of the radio galaxy 3C 223 observed with the WSRT at 21 cm (left image) and 49 cm (right). Strong polarized emission is dark in both maps. A region about 200 kpc in diameter is indicated by a red circle, centered on the optical galaxy (cross). Note the absence of polarization around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

To boldly go...

Michael Garrett, Jon Lomberg

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

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

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

Reference

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

First Discoveries

Chapter 3.3.2 1974: the discovery of giant radio galaxies

Richard Strom*

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

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

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

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The second source had been previously catalogued in radio surveys as 4C 56.16 (at a frequency of 178 MHz) and DA 240 (at 1420 MHz), but this only refers

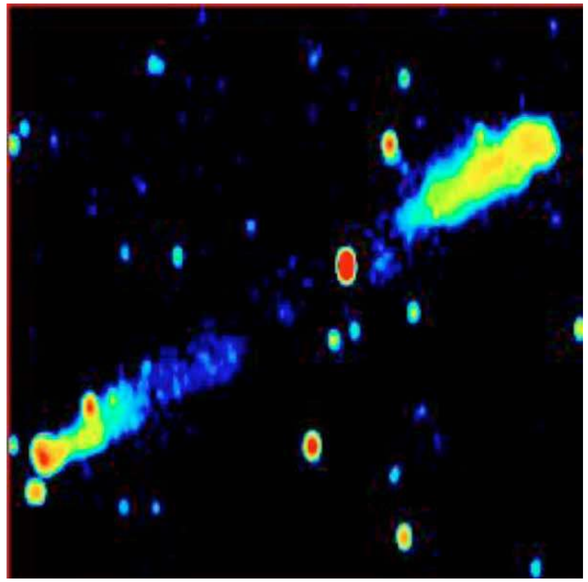

Figure 1: The radio source 3C 236 observed at a wavelength of 92 cm with the WSRT. The red ellipse near the middle of the map is the bright nucleus (the original 3C 236). It has a length of 2 kpc oriented (to within 10°) in the same direction as the outer components. (The other elliptical spots in this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

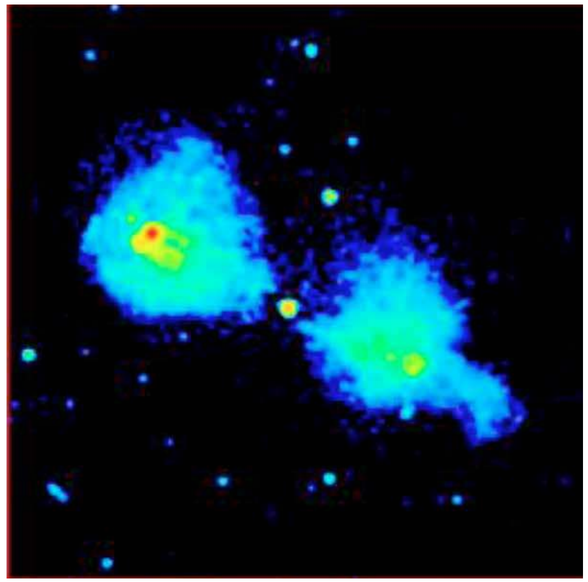

Figure 2: A WSRT map of DA 240 observed at 49 cm wavelength. The nuclear component which coincides with VV 91357 is in the center of this image. The other galaxy (VV 91366) lies just left of the brightest peak (red, upper left). In addition to these two galaxies, there are some 20 others which form a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

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

First Discoveries

Chapter 3.3.3 1981: the expansion of a supernova remnant

Richard Strom*

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

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

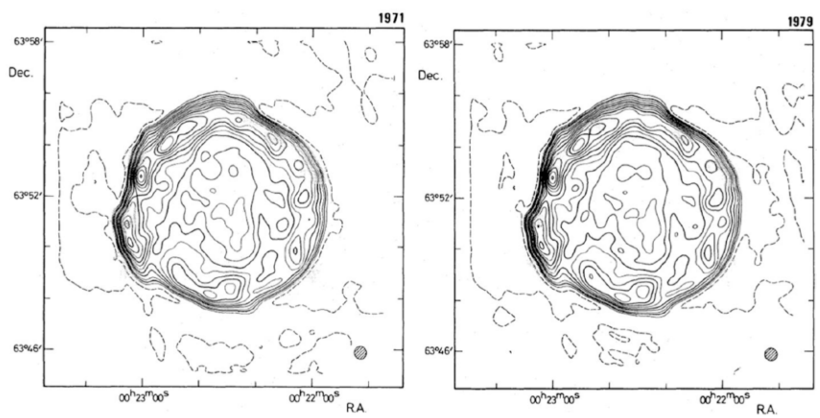

Figure 1a (left, Tycho SNR in 1971), and Figure 1b (right, Tycho SNR in 1979)

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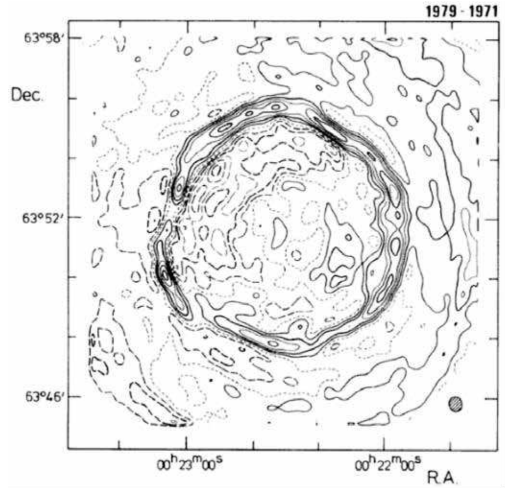


Figure 2, the thin shell which remains after subtracting the image of 1971 from that observed in 1979

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

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

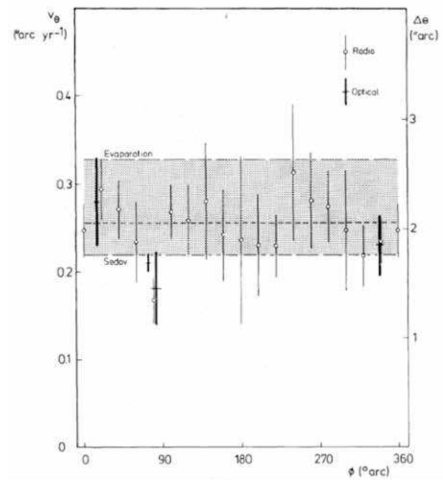


Figure 3, the expansion of Tycho measured from north (0, 360) to south (180) and west (270)

First Discoveries

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

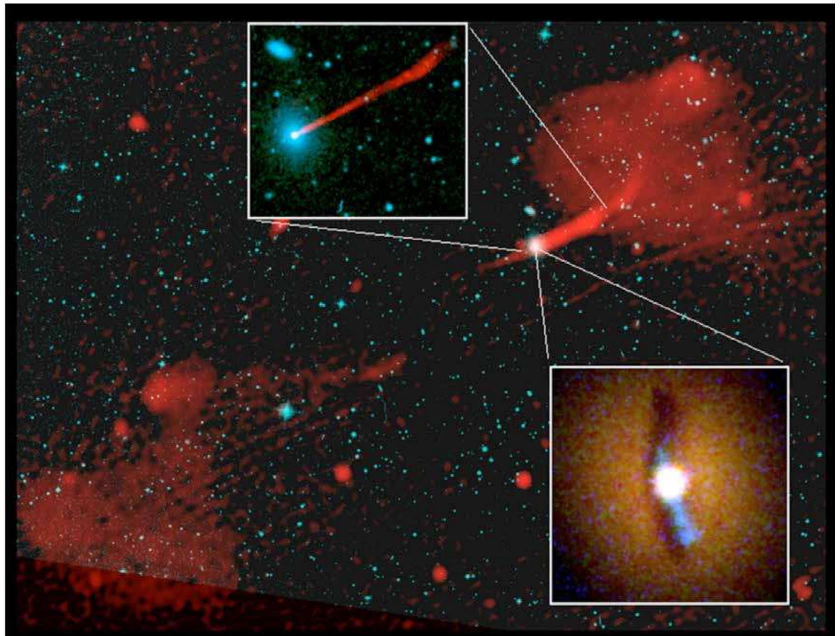
Tony Willis*

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

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

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

* National Research Council of Canada



Radio Galaxy NGC 6251 Radio/Optical Superposition
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den Heuvel of the University of Amsterdam has made significant contributions to the theory of how binary star systems can evolve to such a configuration.

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

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

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

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

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

First Discoveries

Chapter 3.4.2 Identifying WSRT Radio Sources in the 1970s

Tony Willis*

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

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

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

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