European Commission

European Radio Astronomy Facilities and Very Long Baseline Interferometry

by Richard Schilizzi, RadioNET Co-ordinator

Editor: Anna Maria Johannson (European Commission)

Improving the human research potential and the socio-economic knowledge base

Directorate-General for Research

A great deal of additional information on the European Union is available on the Internet.
It can be accessed through the Europa server (http://europa.eu.int).

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FOREWORD

Many fields of European research are underpinned by access to world-class research infrastructures. However, the majority of such facilities are owned by National Government agencies and are open mainly to their national user community. In view of this, successive editions of the 'Framework Programme' (FP) for Community R&D have supported transnational access to a selected group of outstanding research infrastructures.

This has been widened to include the funding of a series of Networks which have brought together the operators and representatives of the user community in a particular class of facilities around a common research theme, in this case radio astronomy. These Networks have been much more effective than 'usual' interactions between scientists because they have guaranteed the participation of the full range of institutional facilities and the representatives of the users, avoiding obvious problems of narrow or partisan actions. Their mission has focused on finding and implementing the solutions to problems of common interest and seeding new transnational collaborations.

One such Network, the Infrastructure Cooperation Network in Radio Astronomy (RadioNET) brings together thirteen of Europe's radio astronomy institutes. This brochure has been prepared by Prof. Richard Schilizzi, the co-ordinator of RadioNET. It aims at providing useful information both to researchers active in radioastronomy and to those responsible for developing new research infrastructures in this field.

I am very pleased to present this excellent example of multi-national research co-operation. The EC wishes to continue to encourage and support such cooperation in Europe. To this end, it will make available during the period 2002-2006 a range of funding mechanisms to support top-class research infrastructure through the activity 'Research Infrastructures' of FP6.

Marco Malacarne
Head of Unit
Access to Research Infrastructures
(Improving the Human Research Potential and the Socio-economic Knowledge Base)

The radio telescopes of the European VLBI Network:

1. Westerbork Synthesis Radio Telescope – fourteen 25-m telescopes (ASTRON – Dwingeloo, The Netherlands)
2. Medicina 32-m telescope (Institute of Radio Astronomy – Bologna, Italy)
3. Noto 32-m telescope (Institute of Radio Astronomy – Bologna, Italy)
4. Cagliari 64-m telescope (construction about to start) (Institute of Radio Astronomy – Bologna, Italy)
5. Joint Institute for VLBI in Europe (JIVE, central institute for EVN – Dwingeloo, The Netherlands)
6. Lovell 76-m telescope and MkII 25-m telescope (Jodrell Bank Observatory – Macclesfield, UK)
7. Cambridge 32-m telescope (Jodrell Bank Observatory – Macclesfield, UK)
8. Effelsberg 100-m telescope (Max-Planck-Institute for Radioastronomy – Bonn, Germany)
9. Metsähovi 14-m telescope (Metsähovi Radio Observatory – Kylmala, Finland)
10. Yebes 14-m telescope and 40-m telescope (under construction) (National Astronomical Observatory – Madrid, Spain)
11. Onsala 26-m and 20-m telescopes, (Onsala Space Observatory – Onsala, Sweden)
12. Toruń 32-m telescope (Toruń Centre for Astronomy – Toruń, Poland)
13. Wettzell 20-m telescope (Federal Office for Cartography and Geodesy, Germany)

EXECUTIVE SUMMARY

Radio astronomy has a long and illustrious history in Europe, starting with the first interferometric experiments after the second World War, a development that eventually led to the Nobel Prize for Physics being awarded in 1974 to Sir Martin Ryle of Cambridge University for his development of this technique. Instrumental innovation and front-line research continue to this day.

Radio astronomers in Europe have long been attracted by the idea of harnessing their individual national telescopes together to create a single distributed European-scale radio interferometer capable of examining distant astrophysical phenomena with unprecedented angular resolution and sensitivity. The first intra-European experiments took place 25 years ago and involved telescopes in Germany, the Netherlands and Sweden. Since then the number of infrastructures regularly taking part in the European Very long baseline interferometry Network (EVN) has grown to 13 including facilities in South Africa and China, with individual telescopes often spending up to 100 days a year on VLBI observations. An international management structure has been developed that is both effective and responsive to the needs of the individual facilities. This is a truly trans-national cooperative activity of which European science can be proud.

The IHP Programme for Transnational Access has played an important role in opening up the EVN to non-experts, in particular young astronomers from other fields of astronomy. They have received assistance in preparing their observations as well as calibrating and analysing their data at the data processing centre at the Joint Institute for VLBI in Europe. This is a popular programme that we hope will be continued in the future. Research & Techical Development (RTD) programmes also play an important role in supporting developments in technology and techniques designed to improve the quality and quantity of data from the EVN and the individual facilities.

The opportunity to create an Infrastructure Cooperation Network in Radio Astronomy (RadioNET) in the Fifth Framework Programme was taken up with enthusiasm in the radio astronomy community because it provided a framework within which to expand the scope of the collaboration to include activities on future global-scale projects. These are ALMA (Atacama Large Millimetre Array) and SKA (Square Kilometre Array), both of which have major European roles. RadioNET now lies at the heart of the radio astronomy programme in Europe, and it has the potential on the longer term to evolve into a Council for Radio Astronomy in Europe, and possibly into a European Radio Astronomy Observatory.

This brochure provides a glimpse of the participating infrastructures and the highlights of the research carried out with the European VLBI Network. It also includes a statement of our vision of the future of radio astronomy in Europe, looking to the exciting new facilities being constructed or planned, including fibre-optic links for the EVN. Finally the activities coordinated by RadioNET are described.

It is a pleasure to present this publication on behalf of RadioNET. I hope you enjoy this overview of a very exciting branch of European science.

Richard Schilizzi
RadioNET Coordinator

RADIO ASTRONOMY

Seventy years ago, radio emission from the centre of our own Galaxy, the Milky Way, was discovered by chance by Karl Jansky during investigations of the origin of background noise in trans-Atlantic microwave communication. This signaled the birth of radio astronomy as a new science. The full significance for astronomy was not apparent until the 1950's and 1960's when a number of momentous discoveries, including the 21 cm hydrogen line, radio galaxies, quasars, pulsars, and the cosmic microwave background, were made which changed our perception of the universe and transformed radio astronomy into the fully-fledged branch of astronomy it is today. Some of these discoveries were awarded the Nobel Prize in Physics.

We can define radio astronomy generally as the study of the universe by observing electromagnetic radiation after it has been coherently amplified in such a way that the wave-like character of the radiation, the phase information, is preserved. The radio astronomy part of the electromagnetic spectrum is generally taken to extend from about 10 MHz to 1 THz, equivalent to wavelengths of 30 m to 0.3 mm. The lower limit is set by absorption by free electrons in the Earth's ionosphere, and the upper limit by absorption by molecules in the Earth's atmosphere.

Radio emission arises from thermal processes in stars and the interstellar medium of our Galaxy, including the 21 cm line of hydrogen and a wide variety of molecular lines. It also arises from a completely different non-thermal process called synchrotron radiation, generated by electrons with very high energies moving at relativistic speeds in the magnetic fields in the interstellar medium. This accounts for the intense radio radiation from active galactic nuclei and quasars, and gives radio astronomy a unique role in the investigation of some of the most energetic phenomena in the universe.

The RadioNET collaboration is centred around the use of multiple radio telescopes in an interferometer configuration. This allows us to make measurements of the fine angular detail in the radio emission in the sky. It also allows the most precise measurements of the positions of the stars and other cosmic objects to be made and how they change. Such measurements are an essential step in the establishment of the distance scale of the universe. As part of the measurement process, the orientation of the interferometer relative to the celestial reference frame can be found. This has the unexpected benefit of allowing a number of geophysical effects like polar motion and changes in the rate of rotation of the Earth to be measured with exquisite accuracy. Part of the process includes determining the vector distance between the radio telescopes with accuracies of a few millimetres over distances of thousands of kilometres and using this information for studies of tectonic motion in active areas of the Earth's crust.

RADIO ASTRONOMICAL INTERFEROMETRY WITH VERY LONG BASELINES (VLBI): THE QUEST FOR RESOLVING POWER

Radio telescopes come in many shapes and sizes. Large steerable reflectors like the Effelsberg 100-m diameter Radio Telescope in Germany and the 76-m Lovell Telescope in the UK are very efficient at collecting the weak radio waves that come to us from the cosmos, but they are rather poor at discerning fine detail in radio sources. In fact, the human eye is more acute than these giant telescopes!

The ability to discern fine detail or resolving power of a telescope (θ) depends on the width of its collecting aperture (D) compared to the wavelength at which it operates (λ). Radio astronomers are at a disadvantage compared with their optical colleagues, because radio waves are many thousands of times longer than light waves. To achieve the same resolution, a radio telescope needs to be correspondingly bigger than an optical telescope. With adaptive optics and under favourable atmospheric conditions the largest optical telescopes on the ground can attain resolutions of better than three tenths of a second of arc (one hundred micro-degrees), good enough to distinguish between a pair of car headlamps at a distance of 1 000 kilometres. To have the same resolving power at a typical wavelength of 20 centimetres, a radio telescope would need a dish more than 100 kilometres in diameter.

Rather than trying to build ever larger dishes, radio astronomers have solved this problem by the technique of interferometry. The basic idea is that two small telescopes can be made to imitate a much bigger telescope (Figure 1) by linking them electronically. The imaginary line drawn between the telescopes is known as the baseline. Each telescope observes the same radio source simultaneously, and the signals are brought together and combined to achieve a resolving power equivalent to that of a single large aperture of width equal to the baseline length.

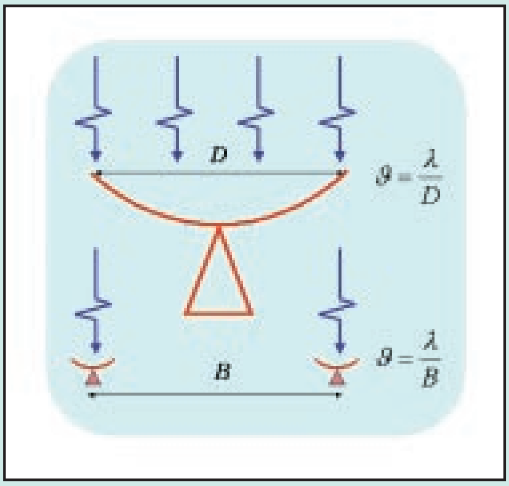


Figure 1.

In an extension of the basic technique, several telescopes can be linked together to form an "array". Each telescope can be thought of as a small segment of a much larger dish. During the course of a day the rotation of the Earth causes each telescope to sweep out a complete ring of the large aperture. By including a sufficiently large number of telescopes in the array and using sophisticated image reconstruction techniques, the whole aperture can effectively be filled. The signals can be processed by computer to make a picture of the radio source, whose resolution depends on the longest baseline in the array. This technique of "aperture synthesis" was pioneered by Sir Martin Ryle at Cambridge University in the 1950's, and is now used in some form in all large multi-telescope arrays.

VERY LONG BASELINE INTERFEROMETRY (VLBI)

In the radio wavelength domain the electrical fields of the cosmic radiation can be measured directly, as opposed to other parts of the electromagnetic spectrum (e.g. optical) where only the energies are measured. This makes the storage of signals of individual telescopes possible on magnetic tapes in order to be interferometrically combined at a later date at a central facility (Figure 2). This allows the baselines to be arbitrarily long, up to the limit set by the scattering effects of interstellar matter on the radio signals. In practice, baselines of 10 000 km are regularly obtained with ground-based arrays, and up to 30 000 km with the orbiting radio telescope, HALCA (Highly Advanced Laboratory for Communication and Astronomy), launched by Japan in 1997 as the main element of the VLBI Space Observatory Programme (VSOP). The importance of VLBI to astronomy and astrophysics lies in the extremely high angular resolving power achieved, providing the sharpest view of the Universe available from any part of the electromagnetic spectrum.

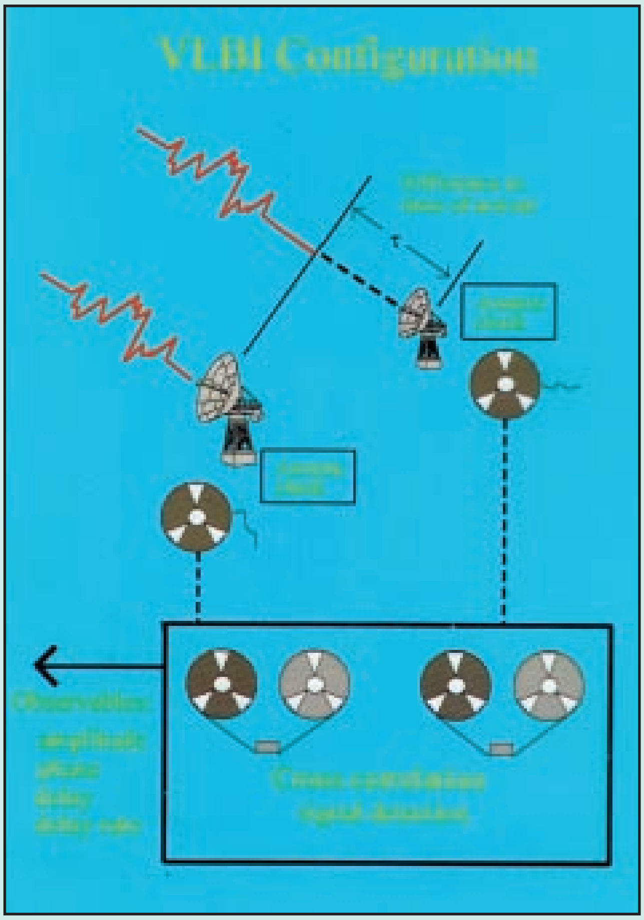


Figure 2.

Structures in radio sources can be investigated which subtend an angle at the Earth of less than 100 nano-degrees, equivalent to the size of a golf ball on the surface of the Moon. This technique allows astronomers to peer deep into the centres of other galaxies at the edge of the universe, and to measure motions of radio emitting gas swept along by the exhaust jets from massive black holes in galactic nuclei or by winds blown out from stars.

FOCUS ON PARTICIPATING INFRASTRUCTURES IN THE EUROPEAN VLBI NETWORK (EVN)

There are several VLBI arrays in the world working in the fields of astronomy, astrometry [1], and geodesy [2]. In Europe, most VLBI observations are done by the European VLBI Network (EVN), a consortium of 13 institutes who, between them, operate 15 radio telescopes in Finland, Germany, Italy, the Netherlands, South Africa, Spain, Sweden, the UK, Poland, and China, and the data processor at the Joint Institute for VLBI in Europe located in the Netherlands.

This is the most sensitive VLBI array in the world. Together, these individual centres form a distributed large-scale facility, an intercontinental radio telescope. The EVN is supported by the IHP Programme in order to provide access to its facilities (telescopes and data processor) for new and inexperienced users from Member States and associated States. The EVN often combines with the MERLIN array in the UK (see below) to create a very sensitive regional array, and with US Very Long Baseline Array to form a "global" array for high quality imaging. In addition, the EVN occasionally observes together with the Arecibo 300-m telescope in Puerto Rico, and the NASA 70-m Deep Space Network antenna near Madrid. ***http://www.evlbi.org/evn.html***

ASTRON (THE NETHERLANDS)

The Westerbork Synthesis Radio Telescope (WSRT) is an array of fourteen 25-meter telescopes laid out on a 3 km east-west line in northern Netherlands (Figure 3). After more than 30 years of service, the WSRT is completing a major upgrade to ensure its future as a state-of-the-art observing facility for competitive national and international research programs. For EVN observations it operates in a phased-array [3] mode with the equivalent collecting area of a 94-m diameter telescope. The frequency coverage of the WSRT ranges from 250 to 8 400 MHz. In addition to its EVN participation, the WSRT operates as a stand-alone interferometer for research programs in spectral line [4], continuum [5] and pulsar [6] astronomy. The primary funding source for the WSRT is the Netherlands Foundation for Scientific Research (NWO). ***http://www.astron.nl***

Figure 3.

INSTITUTE OF RADIO ASTRONOMY (ITALY)

The Institute for Radio Astronomy (IRA) is responsible for radio telescopes at three sites in Italy, two 32-m diameter antennas (at Medicina near Bologna and Noto in Sicily, see Figures 4 and 5), and a 64-m antenna whose construction is about to begin near Cagliari in Sardinia (*see The Future: page 21*). The two 32-m telescopes are used for VLBI research in astrophysics and geodesy, and for single dish programmes of spectral line, continuum and pulsar research.

The Medicina 32-m telescope (Figure 4) was completed in 1983 with funding from the Consiglio Nazionale delle Ricerche (CNR). The telescope operates in the frequency range 1.4 to 22 GHz. Planned technical improvements include the capability to rapidly change observing frequency.

The Noto 32-m telescope (Figure 5) was completed in 1988 with funding from the CNR. The telescope currently operates in the frequency range 0.327 to 22 GHz. Technical improvements in progress include installing an active reflector surface on the telescope utilising 250 actuators behind new panels. This will allow the frequency range to be extended up to 100 GHz. ***http://www.ira.cnr.it***

Figure 4.

Figure 5.

JOINT INSTITUTE FOR VLBI IN EUROPE (THE NETHERLANDS) – RADIONET COORDINATOR

The Joint Institute for VLBI in Europe (JIVE) is the central institute for the EVN, providing the data processing facilities for EVN observations at its location at the headquarters of ASTRON in Dwingeloo. The data processor (commissioned in 1998) is the most advanced of its type in the world and can replay tapes from up to 16 telescopes simultaneously (Figure 6). On-going development work is expanding the capabilities for advanced continuum, spectral line, and pulsar research. The performance of the EVN is continually monitored at JIVE providing direct and critical feedback to the telescopes. Institute staff also support individual users from the astronomical community in Europe with expert advice and assistance with proposal preparation, preparing observations, data calibration and analysis. Funding for institute operations comes from research organisations in Italy, Spain, Sweden, the Netherlands, and the UK. ***http://www.jive.nl***

Figure 6.

JODRELL BANK OBSERVATORY (UK)

The University of Manchester's Jodrell Bank Observatory (JBO) is funded by the UK's Particle Physics and Astronomy Research Council (PPARC) and operates two facilities used for VLBI. The 76-m diameter Lovell Telescope is one of the major elements of the European VLBI Network (Figure 7). It became operational in 1957 as the first of the world's large telescopes. It is currently undergoing its second upgrade and is receiving a new surface and drive system that will enable it to operate from a few 100 MHz up to 8 GHz. ***http://www.jb.man.ac.uk***

MERLIN (the Multi-Element Radio-Linked Interferometer Network) is a network of 6 radio telescopes distributed over England with a maximum separation of 217 km (Figure 8). The 32-m telescope at Cambridge and the 25-m MkII telescope at JBO regularly participate in VLBI observations and the combined use of MERLIN+EVN is in increasing demand. A major upgrade to MERLIN has just been funded (e-MERLIN). This will connect the telescopes with fibre-optic cables enabling the use of much wider bandwidths and resulting in a factor of 30 increase in sensitivity, thus producing one of the most powerful radio imaging instruments in the world. ***http://www.merlin.ac.uk***

AX-PLANCK-INSTITUTE FOR RADIOASTRONOMY (GERMANY)

The 100-m Effelsberg radio telescope (Figure 9), operated by the Max-Planck-Institut für Radioastronomie (MPIfR), Bonn, is situated near Bad Münstereifel in the Eifel region of Germany. It is the largest individual element of the EVN, and was completed in 1972. The telescope operates in the frequency range from 400 MHz up to 90 GHz, and is used for astronomical VLBI research at centimetre and millimetre wavelengths, geodetic VLBI research, and single dish spectral line, continuum and pulsar research. The MPIfR also operates a 9-station data processor for millimetre wavelength VLBI observations and VLBI geodesy. The MPIfR is an institute of the Max-Planck Society in Munich, which is financed by the German Federal and State governments.
http://www.mpifr-bonn.mpg.de

Figure 7.

Figure 8.

Figure 9.

METSÄHOVI RADIO OBSERVATORY (FINLAND)

Metsähovi Radio Observatory (MRO) is a research institute of Helsinki University of Technology. The 14-meter diameter radio telescope is covered by a radio-transparent protective membrane or radome (Figure 10). Observatory operation started in 1974 and the telescope was upgraded in 1992-1995. Radio astronomy observations can be made in the frequency range of 10--150 GHz. The observatory is mainly funded by Helsinki University of Technology and the Finnish Academy of Sciences.
http://kurp-www.hut.fi

NATIONAL ASTRONOMICAL OBSERVATORY (SPAIN)

The 14-m radio telescope at Yebes near Madrid is enclosed in a radome (Figure 11, picture taken from within the radome) and operates at 2.3, 8.4, 41-49 GHz. It was completed in 1976 with funding from the Instituto Geografico Nacional of Spain (IGN). It is used for research in VLBI (astronomy and geodesy) and mapping and monitoring of molecular emission. A 40-m telescope is under construction on the same site (*see The Future: page 21*). ***http://www.oan.es***

ONSALA SPACE OBSERVATORY (SWEDEN)

The Onsala Space Observatory (OSO) operates the 26-m diameter decimetre-wave telescope (erected 1964, shown in Figure 12 in the foreground), and the radome-enclosed 20-m millimetre wave telescope (commissioned 1975; Figure 12 background). The observatory gained the status of the Swedish National Facility for Radio Astronomy in 1990; it is funded by the Swedish Research Council (Vetenskaps Rådet). The telescopes are used for astronomical research, including VLBI, over a frequency range from 900 MHz to 6.7 GHz (26-m) and 22 GHz – 115 GHz (20-m). A suite of receivers for all the radio astronomy bands between 5 GHz and 115 GHz will soon be installed on the 20-m telescope. The 20-m telescope is used for VLBI and single dish astronomy, and used at 2.3/8.4 GHz for geodesy-VLBI measurements of Earth rotation parameters and polar motion, and for astrometry. ***http://www.oso.chalmers.se***

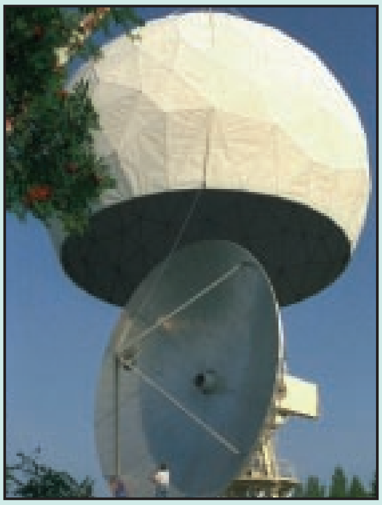


Figure 10.

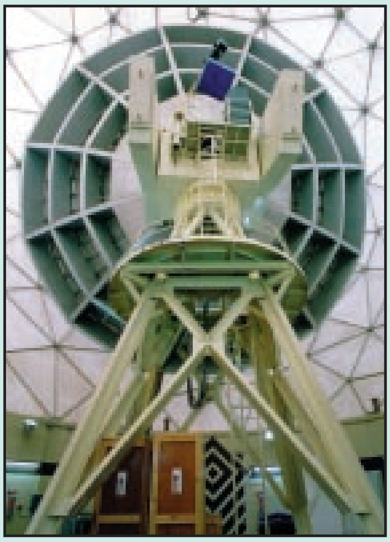


Figure 11.

Figure 12.

TORUN CENTRE FOR ASTRONOMY (POLAND)

The Toruń Centre for Astronomy (TCfA, Nicolaus Copernicus University) operates a 32-m radio telescope near Toruń at frequencies from 750 MHz to 30 GHz. The telescope (Figure 13) was completed in 1994 and put into operation in 1996 with funding from national sources including the Ministry of Higher Education and the State Committee for Scientific Research. Significant additional funding for telescope instrumentation came from the European Commission via grants for cooperation with the European VLBI Network. Planned developments include the construction of a focal plane array for an all-sky survey at 1 cm wavelength (in collaboration with the Jodrell Bank Observatory), and a 22 GHz receiver for observations of water masers [9] in our Galaxy.
http://www.astro.uni.torun.pl

Figure 13.

FEDERAL OFFICE FOR CARTOGRAPHY AND GEODESY (GERMANY)

The 20-m Radiotelescope Wettzell is located in the Bavarian Forest close to Kötzting, Germany (Figure 14). The telescope is operated by the Federal Office for Cartography and Geodesy (Bundesamt für Kartographie und Geodäsie -BKG), Frankfurt/M together with the Technical University of Munich in the context of the Research Group Satellite Geodesy (Forschungsgruppe Satellitengeodäsie – FGS). The telescope is heavily engaged in geodetic observing programs, which are coordinated by the International VLBI Service for Geodesy and Astrometry (IVS). The observing frequencies are 2.3 and 8.4 GHz. The presence of the FGS in the consortium of EVN institutes facilitates interaction between the astronomical and geodetic research communities. ***http://www.ifag.de***

Figure 14.

HALCA, THE ORBITING RADIO TELESCOPE

The first dedicated Space VLBI mission VSOP (VLBI Space Observatory Programme) is led by the Institute of Space and Astronautical Science (ISAS, Japan). Its main element, the 8-metre orbital radio telescope on board the satellite HALCA (Highly Advanced Laboratory for Communication and Astronomy) orbits the Earth with a period of 6.4 hours (Figure 15). On the ground, about 40 radio telescopes participate in VSOP observations, including the European VLBI Network (EVN), the NRAO Very Long Baseline Array (VLBA, USA) and other telescopes in Australia, Japan, Russia and USA. Tracking, navigation and data processing support is provided by ISAS, NASA, the Canadian Space Agency, the Herzberg Institute of Astrophysics (Canada) and NRAO. The mission began in-orbit operations in February 1997. ***http://www.vsop.isas.ac.jp***

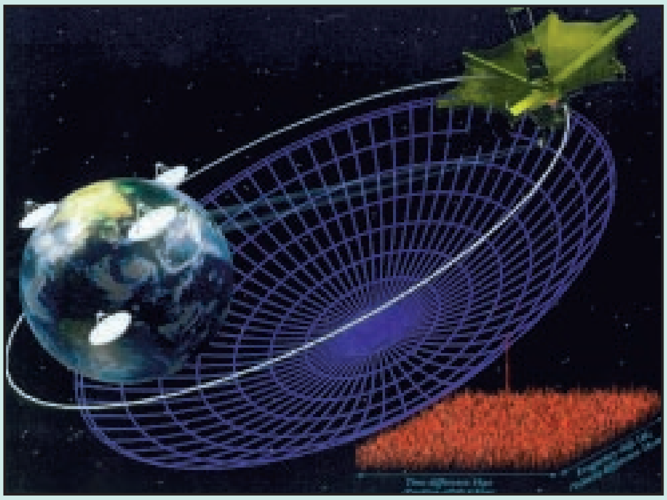


Figure 15.

SCIENTIFIC HIGHLIGHTS OF EVN RESEARCH

The EVN provides a "zoom lens" as large as Europe to focus on the very centres of distant galaxies and examine the often violent eruptions of radio emission taking place. These are laboratories for high-energy physics on energy and size scales that are unimaginable on Earth. The unique capabilities of the EVN are its sensitivity – greater than that of any other VLBI array due to the presence of the 70 – 100-m class telescopes – and its ability to observe in so-called non-standard and thus unique frequency bands. High sensitivity allows detection of very weak cosmic radio sources and opens up new fields of research; the non-standard frequencies target particular spectral lines and provide a wealth of astrophysical information not available in continuum observations. These two points feature strongly in the list of science highlights.

HUBBLE DEEP FIELD

One of the major questions in astrophysics is whether all galaxies harbour a massive black hole at their centres, and if so, how does the activity associated with these black holes evolve with cosmic time since the Big Bang. VLBI is a powerful technique to discriminate black holes from bursts of star formation. Figure 16 shows the Hubble Deep Field in optical light (greyscale) with contours of radio intensity measured at lower angular resolution with the Westerbork Telescope superimposed in yellow. The inserts show three faint radio sources in the field detected with the EVN on 10 milli-arcsecond [7] scales. Of particular interest is the central faint source (flux density 1.8 x 10^{-30} W/Hz/m^2) which is associated with a very red, dust-enshrouded starburst galaxy at a very great distance. This may arise from a low luminosity active nucleus but a compact starburst cannot be completely ruled out. Future observations employing the full sensitivity of the EVN will allow sources 4 times fainter than these to be imaged. These wide-field high sensitivity imaging techniques were pioneered in the EVN and have wide application in studying not only faint extragalactic objects but also stars in our own Galaxy.

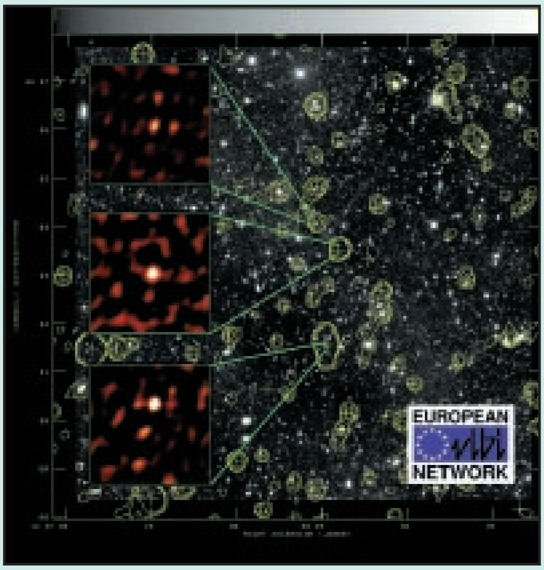


Figure 16.
Courtesy of Michael Garrett, JIVE

MERGING GALAXIES, ARP220

An example of the end-phase of star formation in a distant galaxy is seen in Arp220. Sensitive global VLBI observations using the large telescopes in Europe and the VLBA/VLA in the USA reveal the presence of 12 radio supernova remnants [8] deep in the centre of the western nucleus of the starburst galaxy Arp220. These are the bright points in the right panel of Figure 17. Optical and infra-red observations are unable to see this region due to the immense amount of dust throughout this merging system. Low resolution radio imaging with MERLIN reveals only the presence of two large emitting regions associated with the two nuclei of the system (left panel). It is only sensitive, high resolution global VLBI that reveals the true nature of the radio emission as supernova remnants and demonstrates that active star formation, evolution and death is occurring in Arp220.

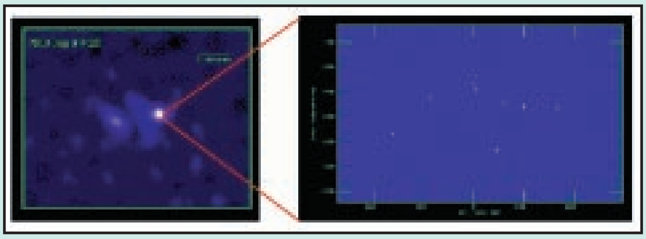


Figure 17.
Courtesy of Philip Diamond, JBO

GRAVITATIONAL LENS, MG J0414+0534

The gravitational field of a galaxy can act as a magnifying glass. The alignment of a distant light source, an intervening massive object (the physical lens), and the observer produce the phenomenon of gravitational lensing: the gravity bends the light and can create multiple distorted images of the distant object. One of the most interesting cases is the quadruple gravitational lens MG J0414+0534. VLBI observations using a global array which included EVN, NASA and US-VLBA telescopes, show the features presented here (Figure 18.) in false colour. The centre panel shows the four lensed images at low resolution. The other four panels show high resolution images of each of the lensed objects. A double core-jet is evident, strongly magnified and distorted by the gravitational field of two lensing galaxies.

STAR FORMATION AND METHANOL MASERS

Our present picture of star formation is that proto-stars accrete matter from a rotating disc and shed angular momentum by ejection of material in a bipolar flow. Observational evidence for this simple picture can only come from detailed high resolution studies at milli-arcsecond levels of objects in our own Galaxy. Only masers [9] can be observed at this kind of resolution thanks to their high brightness and compact sizes. Onsala Space Observatory has recently completed a survey of methanol masers including detailed mapping with the EVN in 15 Galactic sources. The masers trace either rotating discs in Keplerian motion around a high central mass, or shocked clumps within outflows. A striking example is found in NGC 7538 (Figure 19); a straight string of masers with a linear velocity gradient provides the first reliable detection of a proto-stellar disc around a high mass star.

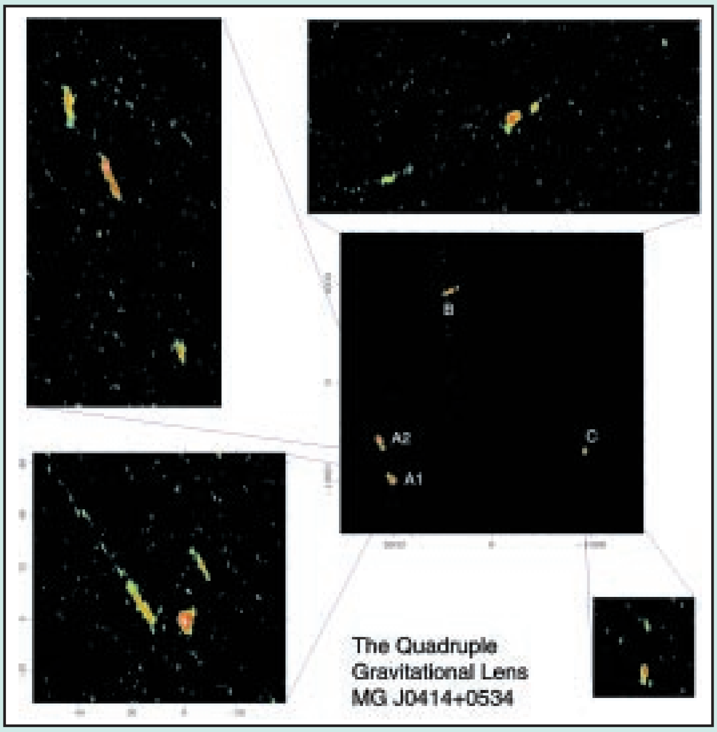


Figure 18.
Courtesy of Eduardo Ros, MPIfR

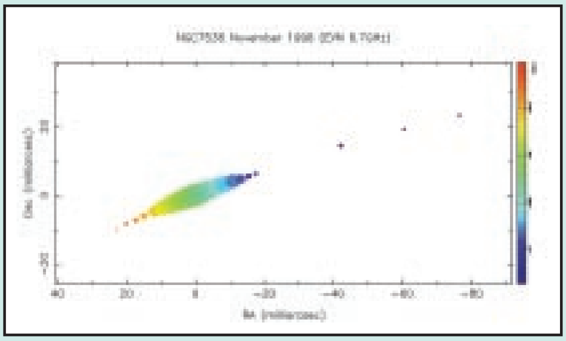


Figure 19.
Courtesy of Roy Booth, OSO

HIGH REDSHIFT QUASAR OBSERVED WITH SPACE VLBI

In Figure 20, images are shown of the high redshift quasar [10] 0014+813 obtained with the EVN only (left panel), and the Space VLBI VSOP observation with HALCA plus the telescopes of the European VLBI Network and the Green Bank 43-m telescope (right panel). Space VLBI data make visible the fine structure of the source which is too compact to be distinguished by any other astronomical technique. The bars in lower-right corners of the images show the angular extent corresponding to a linear size of 60 light years ($6x10^{14}$ km) at the distance of this quasar.

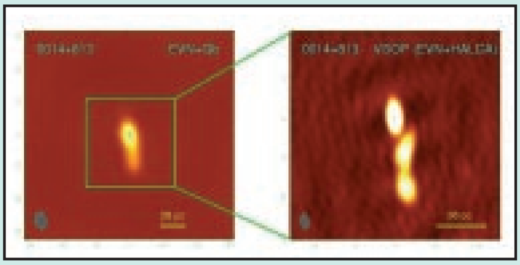


Figure 20.
Courtesy of Leonid Gurvits, JIVE

1144+35, AN ACTIVE RADIO GALAXY

The current model for the active nucleus [11] of a galaxy involves an accretion disk [12] and torus [13] on scales of a few light years around a central black hole. Material accreting onto the black hole can be ejected in the form of relativistic plasma along the rotation axis of the black hole. In this galaxy, the nucleus is the brightest feature in the top right of Figure 21; the other radio emission reveals the jets, the one to the left being seen more clearly. The left-going jet appears to have a cylindrical sheath structure whose top and bottom edges can be seen clearly. This can be explained if it consists of two different components, a fast central spine and a surrounding shear-layer moving at slower but still relativistic speeds.

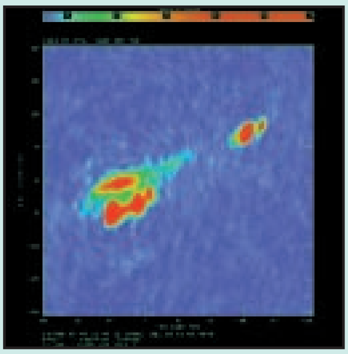


Figure 21.
Courtesy of Gabriele Giovannini, IRA

ATOMIC HYDROGEN ABSORPTION TOWARDS NGC 3894

Much of the material in the torus in an active galaxy should comprise atomic gas detectable in absorption towards the bright inner radio jets. Figure 22 shows integrated absorption profiles for atomic hydrogen towards a number of locations in an elliptical galaxy called NGC 3894. The structure of the hydrogen is complicated with several distinct components present along the lines of sight to the approaching and receding jet.

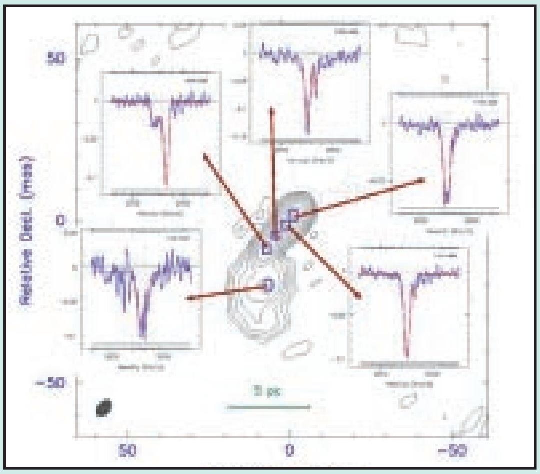


Figure 22.
Courtesy of Alison Peck, MPIfR

SS433

All that remains of a star that exploded as a supernova many aeons ago is the "debris" called W50, seen in Figure 23 panel a) and, at the centre of the debris, a black hole or neutron star which shows itself as a very compact radio source designated SS433 in panels b, c, and d. The radio source shows up as a twin precessing jet of material moving outwards at one quarter of the speed of light along the axis of rotation of the black hole or neutron star (panel b), and as emission in the equatorial plane (panel c). The jets have clearly had a major impact on the shape of the debris which is much more extended in the direction of the jets than in the orthogonal direction. Panel d shows a zoomed image of the central region of the radio source with arrows depicting the wind driving the equatorial emission.

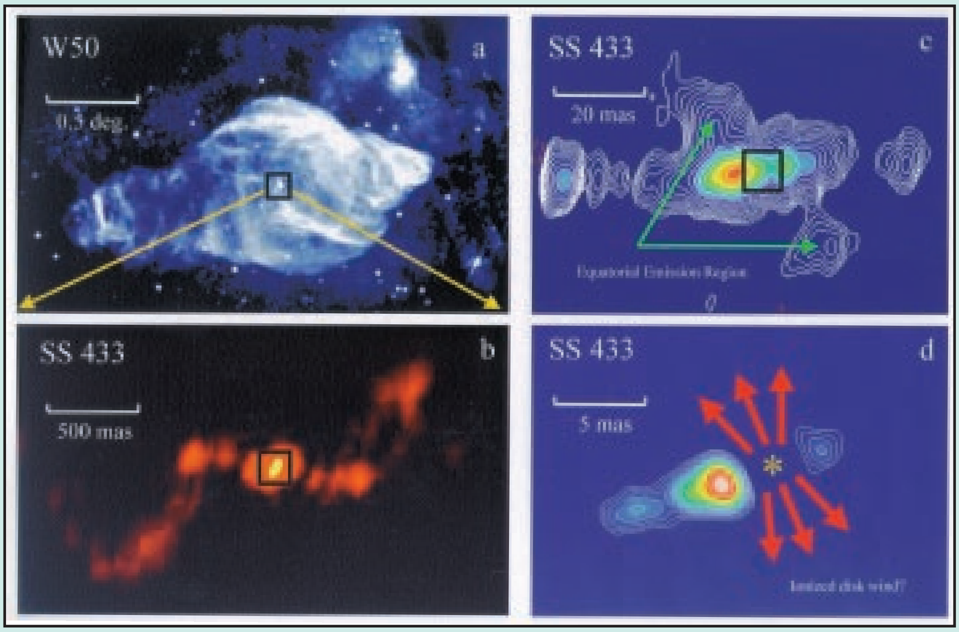


Figure 23.
Courtesy of Zsolt Paragi, FÖMI Satellite Geodetic Observatory, Hungary. Panel a) data from the VLA, panel b) from MERLIN, panels c) and d) from VLBI

THE FUTURE

Our vision for the development of radio astronomy, continent-wide, in the coming decade includes:

1) maintaining our distributed facility, the European VLBI Network (EVN), at the state-of-the-art

2) maintaining the individual national facilities at the state-of the-art by developing and operating front-line instrumentation for use in EVN and local-mode observations. This is also important in view of the fact that the individual national facilities provide the training grounds for the young engineers and astronomers who will develop and use the future large scale facilities

3) upgrading the EVN to a real-time connected array (e-EVN) using fibre-optic links provided by the academic communications networks, to enhance astronomical performance and improve reliability. Extending the European communications network to other countries including China, Japan, South Africa, and the US is extremely desirable

4) upgrading the MERLIN radio-linked interferometer in the UK to a fibre-linked array, e-MERLIN, to work in stand-alone mode and in combination with the EVN

5) developing and operating new, ***regional and/or national***, radio telescopes such as LOFAR centred in the Netherlands, the 64-m Sardinia Radio Telescope in Italy, and the 40-m Yebes telescope in Spain

6) developing and operating new, ***global***, radio telescopes: ALMA (Atacama Large Millimetre Array, 2012) and SKA (Square Kilometre Array, 2015)

7) participating in the development of the Astrophysical Virtual Observatory providing on-line access to the radio astronomy databases

8) participating in a second generation space VLBI mission.

Broadband communication networks are expected to play a central role in radio astronomy infrastructure in Europe. Development of infrastructure is required in particular to support:

1) transport of raw data from the telescope(s) to central data processing facilities at rates up to 10 Gigabit/sec from each telescope

2) distribution of data from the processing facilities to the users, and

3) “mining” of the databases.

NEW TELESCOPES FUNDED FOR CONSTRUCTION

1) 40-m Radio Telescope of the National Astronomical Observatory in Spain

The National Astronomical Observatory of Spain has started the construction of a new 40-m radio telescope in Yebes (Figure 24), next to the existing 14-m dish. The instrument will operate in the frequency range from 2 to 115 GHz, and will be used for research in astronomy (single dish and VLBI) and geodesy (VLBI) after its completion in 2003. The project is funded by the Instituto Geografico Nacional (IGN) of Spain.

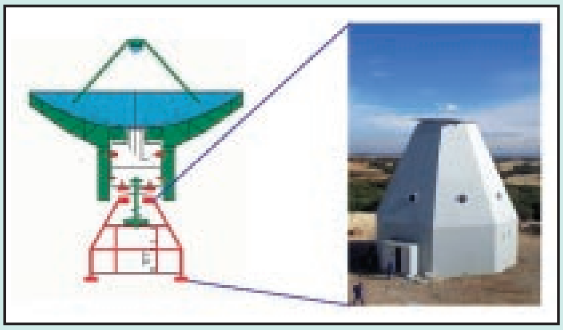


Figure 24.

2) 64-m Sardinia Radio Telescope

The CNR Institute of Radio Astronomy is about to start the construction of a 64-m diameter telescope (Figure 25) located at San Basileo near Cagliari in Sardinia. The facility will operate in the frequency range from 0.327 to 100 GHz and be used for astronomy (VLBI and single dish), VLBI geodesy, and spacecraft tracking. The telescope is expected to be completed in 2005/6, and the project is funded by the Consiglio Nazionale delle Ricerche and the Agenzia Spaziale Italiana. ***http://www.ca.astro.it/srt***

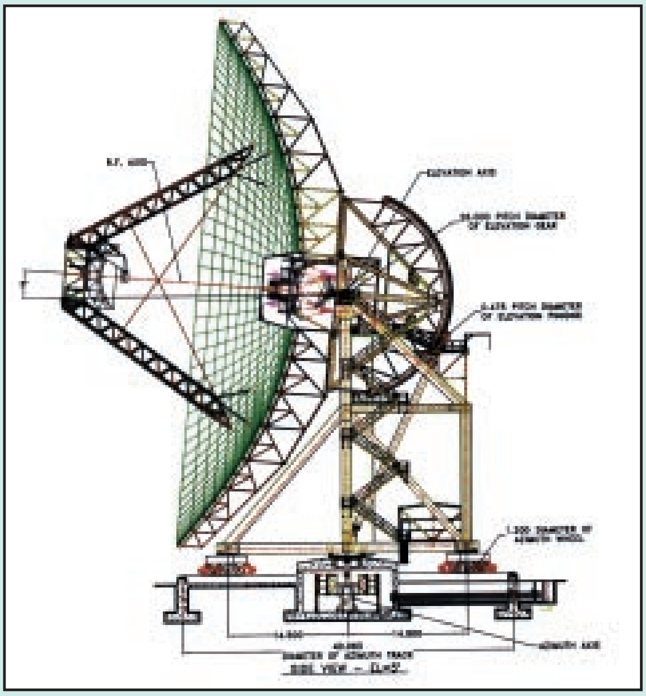


Figure 25.

3) ALMA

The Atacama Large Millimetre Array will bring aperture synthesis techniques (*see Focus on participating infrastructures in the European VLBI Network (EVN): page 11*) to millimetre/submillimetre astronomy and will enable precision imaging on sub-arcsecond scales. Europe, the USA and possibly Japan will collaborate to build this array of 64x12-m diameter antennas. Figure 26 is an artist's conception of the array. With its excellent site and state of the art receivers, ALMA will give a collecting area seven times larger than existing millimetre facilities and a speed up factor of about 500 for continuum observations. It is currently in the development phase with construction due to start in 2003, and expected completion in 2012. ***http://eso.org/projects/alma***

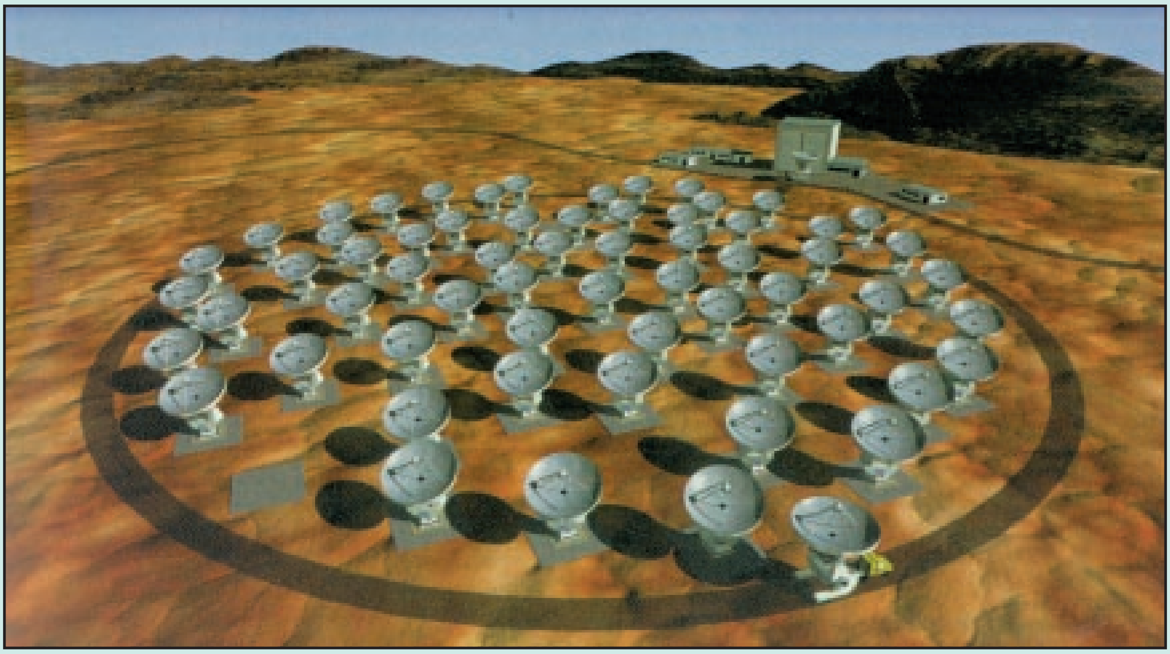


Figure 26.

Dream site in Northern Chile

At sea level, millimetre radiation is seriously attenuated by atmospheric water vapour and oxygen. ALMA will be built on an excellent site, Llano Chajnantor, at an elevation of 5 000m in the high Chilean Andes where the atmosphere is so thin and dry that even sub-millimetre radiation shines through, barely attenuated.

Science Goals

COOL RADIATION FROM DUST AND GAS

The millimetre universe is dominated by thermal emission from cool dust and gas and by spectral line emission from a host of interstellar molecules. The dust dominates regions of star formation, blocking out the optical light, so that these objects are only seen at infrared and sub-millimetre wavelengths. ALMA will facilitate the imaging of proto-planetary discs around newly forming solar systems.

DISTANT GALAXIES

The same dust obscuration applies to young galaxies at large distances in the early universe. As the galaxies formed, stars created heavy elements giving rise to dust which hides the newly formed stars from view. Those star-forming galaxies shine brightly at sub-millimetre wavelengths. ALMA will be able to image nearby star formation and star formation in distant galaxies in great detail at several hundred times the sensitivity that is possible today.

For objects in the earliest Universe, the velocity of recession increases, shifting the brightest emission from galaxies to sub-millimetre wavelengths. ALMA will enable us to get a picture of the galaxies as they existed long ago and the red-shift of their spectral lines will tell us their velocity and hence their distance.

SOLAR SYSTEM

Nearer home, the resolution afforded by ALMA represents very small linear scales. At the distance of the Sun, 10 milli-arcseconds (mas) represents a linear size of only 7 km. ALMA will be able to image the emission in the coma of a comet with unprecedented resolution. It will provide detailed images of planets and their satellites; with a resolution of 10 mas one will be able to detect sulphur dioxide in the plumes of the volcanoes on Jupiter's moon Io and probably discover other interesting trace constituents.

PLANNED NEW TELESCOPES

1) Square Kilometre Array (SKA)

The next generation of imaging radio telescopes is currently being constructed; this builds on the existing infrastructure by connecting the individual antennas to a central correlator with fibre-optic cables. By this method, the EVLA, e-MERLIN and the proposed e-EVN and LOFAR arrays will provide a large increase in sensitivity and capability over the existing instruments. However, in order to achieve the next step in sensitivity and to address the major science questions that will loom in the next decade or two even these improvements will not be enough.

The solution is the proposed Square Kilometre Array (SKA). SKA will have a collecting area of a million square metres, about 100 times larger than the most powerful radio telescopes that currently exist, and will operate at wavelengths of a few metres down to a few centimetres. SKA will transform astronomy. It will provide a tool that is 10 000 times faster than the best available today. It is hoped that it will provide a capability to simultaneously image at multiple points in the sky. It will enable the generation of radio images of almost every object that can be seen with optical telescopes.

In addition to its unique scientific contribution, there will be many areas of complementarity of the SKA with the Extremely Large optical/infra-red Telescope and ALMA which will be essential for the correct interpretation of the observations.

Science Goals

THE DARK AGES AND THE DAWN OF GALAXIES

The SKA will have the capability to look back in time and detect the first light in the Universe, to detect and study the so-called 'Epoch of Reionization' when the first stars were formed and then to study the formation of the first galaxies.

THE LARGE SCALE STRUCTURE OF THE UNIVERSE

SKA will be the most powerful imaging instrument for atomic hydrogen ever built. For the first time, it will be possible to image the large-scale structure of the Universe as defined by atomic hydrogen, its most ubiquitous component. For example, SKA may perform a large area 'shallow' survey of the relatively nearby universe detecting $\sim 10^7$ galaxies, as well as 'deep' surveys of small areas of sky to enable astronomers to trace the evolution of galactic properties from the distant to the nearby universe.

STAR FORMATION THROUGHOUT THE UNIVERSE

SKA will detect radio emission from starburst galaxies back to the epoch of galaxy formation thus enabling astronomers to probe the star-formation history of the Universe, unencumbered by the obscuring dust.

A CENSUS OF THE MILKY WAY

SKA will prove to be an immensely powerful tool for the study of objects in our own Galaxy. It will study all aspects of star-formation and stellar evolution. It will study exotic objects such as X-ray binaries [14] and their radio emission. It will revolutionize the study of pulsars, extending the current population census by an order of magnitude.

THE TRANSIENT SKY

With its wide field of view and the ultimate in sensitivity, SKA will be able to detect $\sim 10^6$ radio sources in a single beam. Who knows what transient sources might be observable? We might detect very powerful radio supernova remnants or 'hypernovae'; analogues of the Crab Nebula's giant pulses; flares from dwarf stars; weak gamma-ray burst afterglows or even intermittent ETI (extra terrestrial intelligence) signals.

THE SKA CONCEPT

SKA has been 'born global', astronomical institutes from all over the world, including many from Europe, have joined forces to create the SKA Consortium. An International SKA Steering Committee (ISSC) has been formed. It includes 6 European representatives, and will steer the project through design, funding and construction.

There are several possible choices for the appropriate SKA technology ranging from a few individual large dishes, to a multitude of individual small steerable antennas, on to advanced concepts such as flat, phased arrays. All concepts are being worked on and the ISSC expects to select the most appropriate for the SKA in 2005.

The choice of the SKA site is crucial. The SKA must be able to image a wide range of surface brightness and so will need a large fraction of the array to be within a few tens of kilometres.

Equally, the need to image compact objects requires a significant fraction of the array spread over many thousands of kilometres. In order to observe at the sensitivity levels required, any site(s) will need to provide adequate protection from harmful levels if interference.

Formal requests for funding are to be submitted to the partner organizations' governments in 2008 and to start construction in 2010. The target date for 'first light' is 2015.

Figure 27 is an artist's conception of one of about 30 "patches" of the SKA. The total collecting area in the 30 patches is to be about 1 million square metres. ***http://www.skatelescope.org***

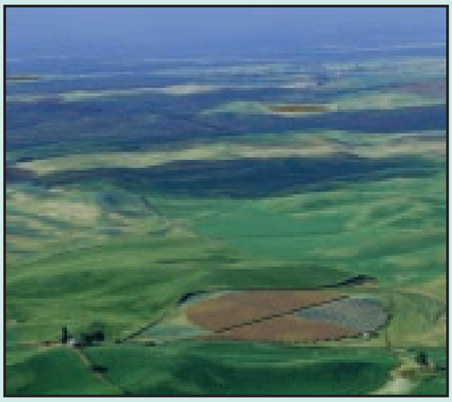


Figure 27.

2) LOFAR

The Low Frequency Array (LOFAR) is a radio telescope that will operate at the lowest frequencies accessible from earth (the range from 10-240 MHz). LOFAR will consist of up to 100 stations like the one shown in the artist's conception in Figure 28, which is some 200 meters in diameter. The receiving elements are relatively simple active dipole antennas. After detection, the signals will be immediately digitised, making LOFAR essentially the first in a new generation of software (radio-) telescopes. The most challenging aspect is the design, development and construction of the digital signal processing- and data transport-network to cope with the expected data rates of tera-bits/sec. The telescope is being developed by ASTRON, based in Dwingeloo (the Netherlands) together with its partners the Naval Research Laboratory in Washington DC (USA) and MIT's Haystack Observatory (USA). Strong interest in LOFAR has also been expressed by astronomers and solar and ionospheric physicists in other European countries. ***http://www.lofar.org***

Figure 28.

INFRASTRUCTURE COOPERATION NETWORK IN RADIO ASTRONOMY – RADIONET

RadioNET was established in 2000 to coordinate new initiatives in the field of Radio Astronomy in Europe. Particular emphasis is being given to initiatives in radio interferometry at centimetre and millimetre wavelengths to obtain detailed images of cosmic radio sources. The Infrastructure Cooperation Network includes the major radio astronomy facilities in Europe working at centimetre wavelengths and forming the distributed facility, the European Very long baseline interferometry Network (EVN), as well as a number of facilities working at millimetre wavelengths. Instrumental developments in radio astronomy in the future are focusing primarily on greatly increasing the sensitivity of the measurements by increasing the collecting area of the telescopes (Atacama Large Millimetre Array, Square Kilometre Array).

Partnership

RadioNET has 11 partners – all radio astronomy institutes – in Finland, France, Germany, Italy, the Netherlands, Poland, Spain, Sweden, and the UK. Nine of the partners are members of the Consortium managing the European VLBI Network. There are also two members of RadioNET from outside Europe – the Australia Telescope National Facility in Australia and the Herzberg Institute for Astrophysics in Canada – that participate together with the ASTRON institute in the Netherlands in the activities concerning the Square Kilometre Array. The partners meet formally once a year to review progress in all the initiatives and to hear comments from the users of the EVN, and representatives of the European Commission and the European Astronomical Society (EAS). At other times of the year, RadioNET organizes meetings and workshops as part of its coordination activities. Once a year, a Round Table meeting takes place under the auspices of the EAS with its counterpart in optical/infrared astronomy, OPTICON, to discuss priorities for ground-based astronomical instrumentation and other issues.

Activities of the Infrastructure Cooperation Network

RADIONET is focusing on coordinating the more effective use of the European VLBI Network to improve the quality and quantity of access by the scientific community. It also concentrates on building up the necessary scientific, technical and organisational consensus for the future major facilities in radio astronomy: ALMA and SKA. Specific activities of RadioNET are to:

1) improve the inter-operability and reliability of the EVN telescopes and thereby achieve sustained reliable operation during VLBI observations;
2) develop plans for upgrading the EVN to a fibre-linked array to take advantage of the advances made in information technology;
3) disseminate knowledge of VLBI techniques, and provide a forum for presenting new results via EVN Schools and Symposia;
4) facilitate system studies of the impact of the ALMA science case on the technical and operational design of the array during its design and development phase;
5) finalise the scientific case for the SKA, coordinate its technical development, and map out the collaborations leading to a formal proposal for the facility;
6) joint activities with the Infrastructure Cooperation Network in Optical and Infra-red Astronomy, OPTICON.

TRANSNATIONAL ACCESS

With support from the Access to Research Infrastructure activities within the 3rd, 4th and 5th Framework Programmes, the EVN has provided and continues to provide access to its facilities for non-experts. This takes the form of simultaneous observations of cosmic radio sources with the EVN telescopes, correlation of the data using the EVN Mk4 data processor at JIVE, full financial and technical support (via dedicated JIVE Support Scientists) for external users who visit EVN and JIVE facilities in order to prepare, schedule, analyse or participate in EVN observations.

RTD PROJECTS

Radio astronomy has always profited from its position at the interface of electronics, communications technology, image processing, and science. Taking advantage of advances in related technologies has led to a million-fold increase in the sensitivity of radio telescopes over the last 60 years. At the same time, the requirements of the new generation radio telescopes have led to innovative applications of basic technology that often find their way into the market-place. Two RTD projects in radio astronomy are contributing to the further development of technology and techniques needed for state-of-the-art radio astronomy in Europe. More can be expected in the future in relation to the new telescopes described in *The Future (see page 21)*.

FP4: Enhancing the European VLBI Network of radio telescopes

This project was completed at the end of 2001, and involved four main elements:

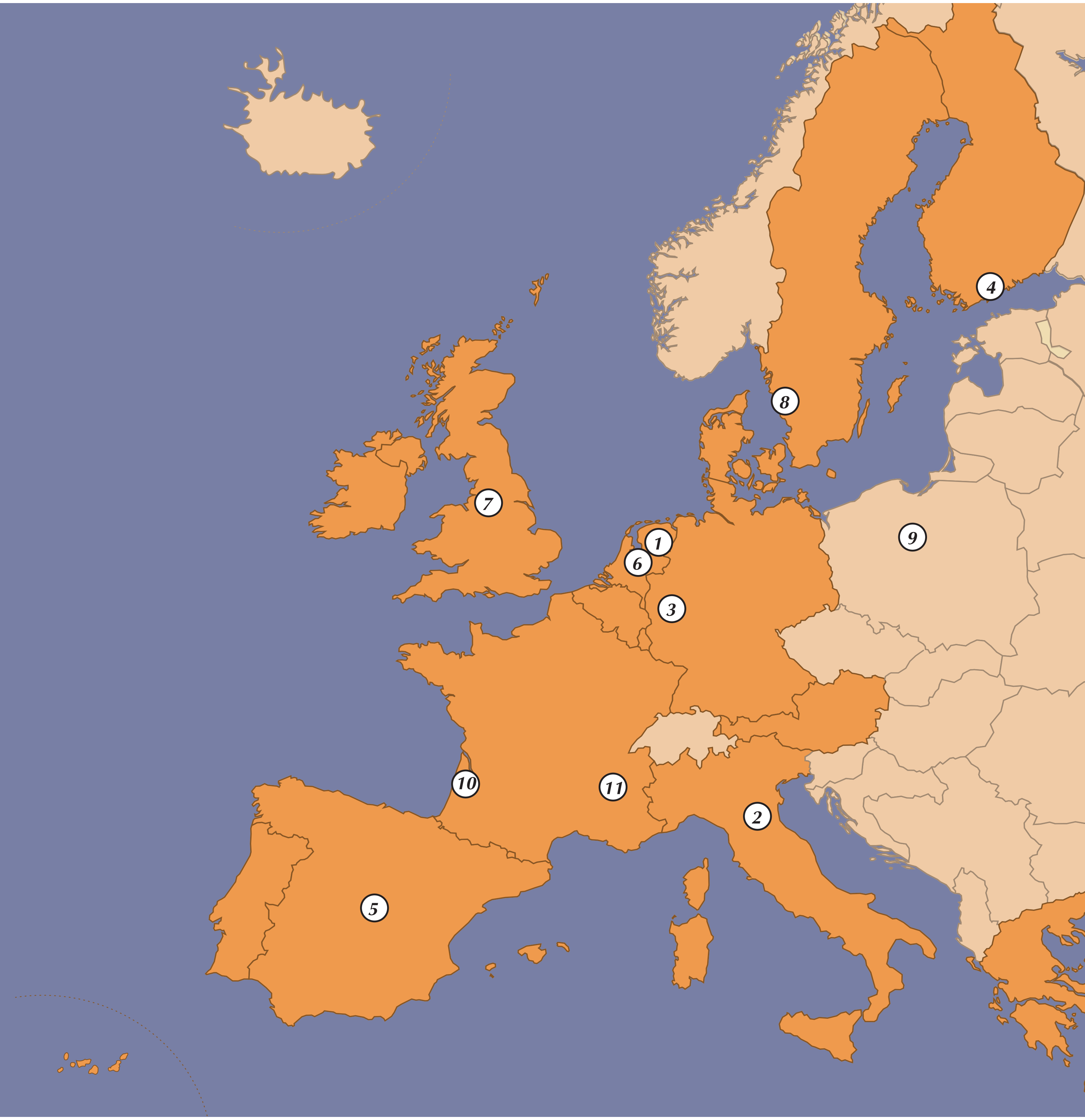
- development of a prototype post-correlation integrator subsystem for the EVN Data Processor at JIVE. This involves high speed readout electronics to allow the full design capabilities of the data processor for multiple field centre correlation, pulsar gating and high spectral resolution to be exploited.
- development of a prototype radio astronomical receiver (detector) which can operate in an increasingly hostile radio frequency interference (RFI) environment. Algorithms were developed to reduce the harmful effects of RFI.
- development of new experimental techniques to take advantage of new and unique hardware capabilities of the data processor at JIVE.
- a study of optical fibre data transfer between the radio telescopes and data processor (e-EVN), with the eventual goal of replacing tape recorders.

FP5: Faraday

The prime objective of the FARADAY project is to undertake the research and development required to produce two-dimensional receiver arrays to be installed at the foci of radio telescopes. Such arrays will bring new capabilities both to single radio telescopes and, in the longer term, to interferometers. The partners in FARADAY are Jodrell Bank Observatory (UK, coordinator), Institute of Radio Astronomy (Italy), ASTRON (NL), Toruń Center for Astronomy (Poland) and the Australia Telescope National Facility in Australia. At the heart of the project is the design of monolithic microwave integrated circuits (MMICs) using levels of integration not previously employed for cryogenic applications in the band 20-40 GHz or for phased arrays in the 2-5 GHz band. There are four sub-projects:

1) Cryogenic horn arrays for continuum survey work at ~30 GHz . The aim is to deliver an 8-horn prototype array with 6 to 10 GHz bandwidth and to produce a feasibility study for a 100-horn array. The prototype will be tested on the Toruń 32m Telescope.
2) Cryogenic horn arrays for spectroscopy in the band 21-26 GHz. A heterodyne design will be adopted with a down-converter integrated into each channel. The deliverables are a 5-element prototype array (to be tested on the Medicina or Noto radio telescopes) and a feasibility study for a 50-horn spectroscopic array at 40-50 GHz.
3) Non-cryogenic actively phased arrays at 2-5 GHz. Beam-forming circuitry and amplification will be integrated in the MMIC design. The deliverables are a 16-element 2-beam prototype array to work in the frequency range 2.5 to 5 GHz and a feasibility study for a 16-beam phased-array in the band around 5 GHz, generically suitable for any large European telescope.
4) Data analysis software. Flexible and transportable software tools for the acquisition and analysis of data from horn arrays will be produced.

MEMBERSHIP OF RADIONET



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Glossary

[1] **Astrometry:** The measurement of the positions and motions of objects in the universe

[2] **Geodesy:** The measurement of the size and shape of the Earth and changes therein.

[3] **Phased array:** coherent, in-phase combination of signals from an array of telescopes or detectors in the focal plane of an individual telescope.

[4] **Spectral line emission:** Spectral line radiation is generated at specific frequencies by atomic and molecular processes. The most important line at radio frequencies is that of neutral atomic hydrogen at 1420.405 MHz.

[5] **Continuum emission:** Most of the power emitted by a radio source is in the form of continuum radiation, the power spectrum of which varies only slowly with frequency.

[6] **Pulsar:** A pulsating source of radiation first discovered at radio wavelengths. The radiation is emitted in a narrow beam by a neutron star spinning once every few milli-seconds to few seconds. Rather like the rotating beam of a light-house, we see the pulsar when its beam sweeps across the Earth.

[7] **milli-arcsecond (mas):** 1 milli-arcsecond is about 300 nano-degrees in angular measure.

[8] **Supernova remnant:** The debris left over after a star explodes at the end of its life. The debris expands outwards with a velocity of about 10 000 km/sec sweeping up interstellar material as it goes, and eventually slowing down.

[9] **Maser:** A small number of spectral lines show very intense emission from radio sources of small angular diameter. These are generated by the maser (microwave amplification by the stimulated emission of radiation) process, similar to a laser but at radio frequencies rather than optical. Examples are the hydroxyl radical, and the water, silicon monoxide and methanol molecules.

[10] **Quasar:** A galaxy in which the optical emission from the nucleus overwhelms that from the rest of the galaxy so that it appears point-like. Quasars are the most powerful energy sources in the universe, found mostly at great distances from us.

[11] **Active galactic nucleus:** A galaxy with a substantial amount of its emission originating in the nucleus of the galaxy. Quasars are extreme examples of Active Galactic Nuclei.

[12] **Accretion disk:** A rotating disk around a compact object created by matter falling towards the central object under the influence of gravitational attraction. Accretion disks are thought to exist around massive black holes in the centres of galaxies and around neutron stars and stellar-mass black holes in binary systems.

[13] **Torus:** A doughnut-shaped structure composed of gas and dust, thought to rotate at a distance of a few light years around the central massive black hole in the centre of a galaxy.

[14] **Xray binary:** Two stars in orbit around each other, one of which is a very compact neutron star or black hole. Gas drawn off the larger of the two stars to orbit around the compact object is heated to high enough temperatures (10^7 degrees) that X-ray radiation is emitted.

ALMA	Atacama Large Millimetre Array
AVO	Astrophysical Virtual Observatory
EVN	European VLBI Network
LOFAR	Low Frequency Array
MERLIN	Multi-Element-Radio-Linked-Interferometer Network (UK)
SKA	Square Kilometre Array
VLA	Very Large Array (USA)
VLBA	Very Long Baseline Array (USA)
VLBI	Very Long Baseline Interferometry
WSRT	Westerbork Synthesis Radio Telescope (NL)

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