European Review, Vol. 10, No. 2, 285–299 (2002) © Academia Europaea, Printed in the United Kingdom

The big ears of radio astronomy

FRANCIS GRAHAM-SMITH

Jodrell Bank Observatory, University of Manchester, Jodrell Bank
SK11 9DL, UK. E-mail: fgs@jb.man.ac.uk

The special value of radio astronomy lies in the probing of extreme conditions in the universe, including the highest energies and the lowest temperatures. Radio waves can penetrate clouds of gas and dust to reveal objects in the universe and, in particular, in our Galaxy that cannot be seen by visible light. To achieve the highest resolution, radio telescopes in widely separate parts of our globe combine their reception to produce a synthesized image. This is a splendid example of international collaboration. Among the images visualized are pulsars, derived from the remnants of supernovae explosions, and quasar sources powered by black holes.

Big ears or big eyes? Radio telescopes are listening to, and looking at, the Universe by detecting and measuring radio waves. Optical telescopes do this with light, but light is only a small part of the electromagnetic spectrum, which happens to penetrate and shine through the Earth's atmosphere. Radio waves over the whole familiar range – from VHF radio, through the television bands and radar, to the microwaves used in communications with spacecraft – are all reaching us from the depths of space.

Over the last half-century we have realized that to understand the origin, the present state and the future of the Universe, astronomers must use a wide variety of tools operating across the full range of the electromagnetic spectrum. Radio astronomy is particularly important because:

(i) The Universe contains matter in many different forms, which are revealed in different ways by light, radio, X-rays and gamma rays. Radio waves provide a vital probe of extreme conditions, including the highest energies and the lowest temperatures.

(ii) Just as radar penetrates fog, radio waves penetrate the obscuring clouds of dust and gas in our Galaxy and throughout the Universe.

(iii) Radio telescopes, like optical telescopes, produce images, but with finer detail than is currently possible with astronomical instruments in any other waveband.

(iv) The atmosphere is transparent to radio waves, so that radio telescopes can be used on the surface of the Earth, without the complication and expense of operation in space.

Some examples may be useful. Our Galaxy is a beautiful spiral galaxy, much like our near neighbour, the Andromeda Nebula. How do we know this, when most of the Milky Way is hidden behind dark clouds? Radio waves from gas molecules in the spiral arms come to us from across the whole disc, giving us a complete map. Again, the centre of the Galaxy, which was only recently seen with some difficulty in infrared light, was first seen by radio to contain gas orbiting at enormous speeds around a central black hole.

The life cycle of the stars, condensing from gas and shining like our Sun with nuclear energy, ends for many with a massive explosion – a supernova. Radio telescopes follow this evolution one stage further: the supernova leaves an inert remnant, a neutron star, which may become a *pulsar*, a pulsating source of radio waves. Only a few of these can be seen optically or with orbiting X-ray telescopes, but some 1500 have now been detected by radio astronomy. Pulsars are amazing objects; they are extremely condensed stars only 20 km across but with the mass of a normal star, spinning rapidly, some like a humming top at hundreds of revolutions per second. They have the strongest magnetic fields known anywhere in the Universe, and they act like dynamos to generate charged particles with energies far higher than any available in our terrestrial particle accelerators.

Far beyond our Galaxy, and beyond the familiar picture-book galaxies such as the Andromeda Nebula, there are the *quasars*. These were discovered and accurately located by radio telescopes, and are now being investigated by the whole range of infrared, optical, X-ray and gamma-ray telescopes. Quasars are the active centres of galaxies, powered by black holes (see Charles' article in this issue of *European Review*), which we now believe exist at the centres of most galaxies (including our own, but luckily ours is not very active!). They are so powerful that they act as beacons, marking out the most distant recognizable parts of the Universe, where galaxies are young and newly formed.

Even further away, and therefore even younger, is the expanding remnant of the Big Bang fireball, which was the origin of our Universe. The remains of this fireball surround us today; it is called the Cosmological Microwave Background. Originally very energetic, it is today so dilute that it produces no light and can be seen only by radio telescopes.

Over the last half-century, radio telescopes have provided a unique window on this amazing and complex Universe. How do radio telescopes work, and what are the plans of radio astronomers for the next half-century?

The conventional picture of a radio telescope is a 'Big Ear,' a large steerable dish that collects radio waves and concentrates them on a receiver at a focal point. Large radio telescopes that fit this picture include the 100 m diameter dish at Effelsberg, Germany, the 76 m Lovell Telescope at Jodrell Bank, UK and the 300 m Arecibo fixed reflector, Puerto Rico. They are vital tools in astronomy. Their importance can be measured by the recent decision to resurface the Lovell Telescope to allow it to operate over a wider band of radio frequencies, and by the building of the new 100 m Robert C. Byrd telescope at Green Bank in the USA. These big dishes are used to pick up the weakest radio signals, from distant galaxies or pulsars, and to hunt for unusual signals that might indicate the existence of extraterrestrial intelligence. However, radio astronomy now demands detailed images of radio sources, like the familiar pictures of optical astronomy, and even the biggest dishes cannot do this acting alone. One of their main tasks now is to provide an element of the large multiple telescope arrays that are essential in modern astronomy. It is these arrays that provide the images of the radio sky.

The difficulty is that we cannot make our 'big ears' big enough. Obviously, the larger the collecting area the more sensitive it can be for weak radio signals: for example, tracking the feeble signals from Pioneer 10 as it left the Solar System was only possible for the largest dishes. However, for radio telescopes also to make detailed images of objects in the same way as optical telescopes, they must have comparable angular resolution (the ability to discriminate fine detail) – painting a picture with minute detail needs a fine brush; therefore, the radio telescope must have a narrow beamwidth.

The beamwidth of a telescope at any wavelength cannot be less than the ratio of the wavelength to the overall dimensions of the telescope aperture (the ratio gives the width in radians: one radian equals 57 degrees). The wavelengths used in radio astronomy are typically between 1 cm and 1 m, i.e. up to one million times the wavelength of light. Even the largest single dish at the shortest wavelength may be only a few thousand wavelengths across, giving a beamwidth of about one arc minute (1/60 degree), far short of the tenth of an arc second or better that is expected of modern optical telescopes. Radio telescope arrays can, in fact, achieve much greater angular resolution than optical telescopes, but to do this they must use overall dimensions of hundreds or even thousands of kilometres. This is obviously impossible for a single telescope aperture, but it is now routinely achieved by the simultaneous use of widely separated individual telescopes in an interferometer array. The technique of using comparatively small telescopes connected together as elements of a large array is called *aperture synthesis*.

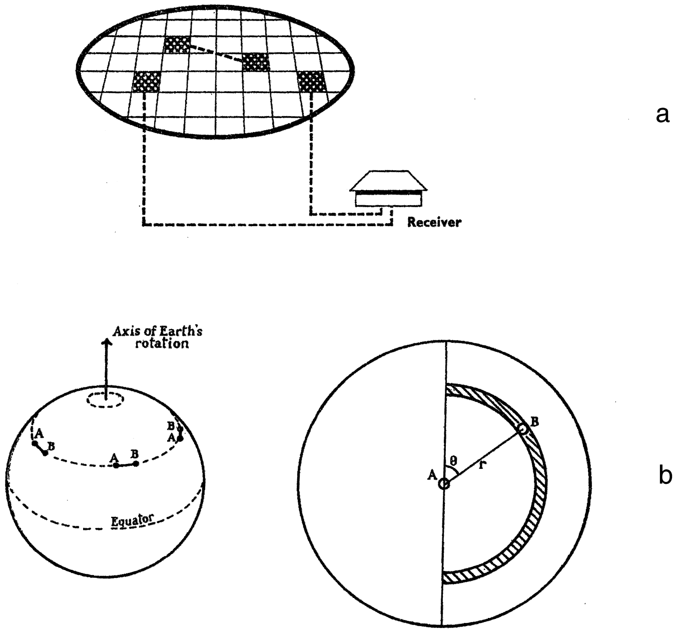

Figure 1. Aperture synthesis. (a) The original concept: small elements are used in pairs to build up a large aperture. (b) Earth rotation: over a period of 12 hours, an east–west line of antenna elements synthesizes a large aperture; the ellipticity of the synthesized aperture depends on the latitude of the observatory.

Aperture synthesis

The original idea of aperture synthesis, as conceived by Martin Ryle in Cambridge, UK, for which he received the Nobel Prize, is to build up a large telescope area by dividing it into elements that cover the whole area, but which are individually small enough to be occupied by practical telescope elements. In the original concept, only two such elements need to be used at any one time, connected to a single receiver. The pair of telescope elements, forming an interferometer, would be moved to cover in sequence all possible paired spacings in the aperture to be synthesized. Ryle then realized that interferometer spacings along an east–west line would be sufficient to cover the full aperture, since the rotation of the Earth would, during the course of a day, provide all the necessary orientations of any spaced interferometer pair (see Figure 1).

Three major radio telescopes, which are still in use, follow closely the original concept of aperture synthesis. The Ryle Telescope in Cambridge uses eight 13 m telescopes on an east–west line extending to 5 km. The Westerbork Synthesis Radio Telescope in the Netherlands uses fourteen 25 m diameter dishes in an east–west array 2.7 km long. The Australian Telescope Compact Array (ATCA) uses six 22 m telescopes on an east–west line 6 km long. The most powerful modern array, the Very Large Array (VLA) in New Mexico, uses twenty-seven 25 m diameter dishes disposed on three arms, each 20 km long and separated by 120 degrees. This system relies less on Earth rotation, since it is possible to synthesise a considerable proportion of the complete aperture in a short observation, without requiring the 12 hour observation of a full aperture synthesis.

The next stage of development towards greater angular resolution is represented by MERLIN, the Multi-Element Radio Linked Interferometer, at Jodrell Bank, UK (see Figure 2). This was developed from pioneering experiments on long-baseline astronomy at Jodrell Bank in the 1950s and 1960s, which showed that sub-arcsecond resolution was not only technically achievable but also necessary for mapping some of the most interesting and most distant astronomical objects. MERLIN uses six telescope elements spread across England from Cheshire to Cambridge, covering a total distance of 217 km; this is the diameter of the full aperture obtained by Earth rotation synthesis. MERLIN is often used at a wavelength of 6 cm (a radio frequency of 5 GHz); the angular resolution is then 0.05 arcseconds, which coincidentally – but usefully – is the same as that of the Hubble Space Telescope.

The separate telescope elements of MERLIN are connected by radio links, so that they can be used in the same way as the close spaced arrays, such as the Ryle Telescope, which are directly connected by cables. A further stage in aperture synthesis is to obtain even better angular resolution by using spacings ten times larger again in Very Long Baseline Interferometry (VLBI). The separate elements are now so far apart that they cannot be directly connected, even using radio links; instead, the signals received by each telescope element are recorded on magnetic tape and are brought together subsequently in a processing centre. A prime example of VLBI is the European VLBI Network (EVN), which includes 13 radio telescopes located in nine European countries and uses a central data processor at the Joint Institute for VLBI in Europe (JIVE), located in the Netherlands. Further collaborating sites can be used to extend the EVN; westwards to include several radio telescopes located in the USA, and eastwards to telescopes in Russia, Ukraine and China. It is even possible to use baselines larger than the diameter of the Earth by adding a space-borne antenna such as that on the Japanese satellite HALCA. A selection of sites to be used in an individual observation depends on the demands of the particular observation; the combination becomes a single distributed radio telescope on a continent-wide (or even transglobal) scale.

The telescope apertures achieved in this progressive expansion of the concept of aperture synthesis are very sparsely covered, even after including the effect of Earth Rotation. In a large single dish, the parabolic shape concentrates to the focus

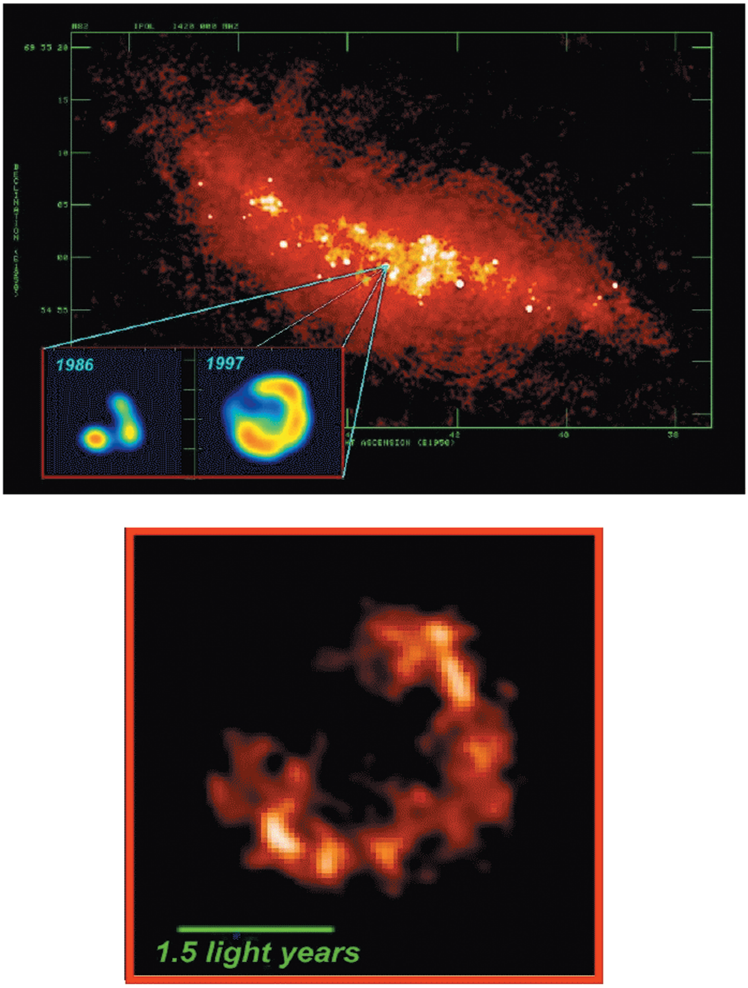

Figure 2. (Top) Radio image of the nearby galaxy M82 made with the MERLIN radio telescope in the UK. On the fuzzy background of radio emission from the galaxy in general are bright spots, which are the remnants of catastrophically exploding stars, or 'supernovae'. Supernovae are particularly frequent in this galaxy – about 1 every 30 years – because M82 has an unusually large number of massive stars. These stars live fast and die young, by exploding. In the inset are images made by combining data from all the radio telescopes in Europe of the youngest supernova remnant, which apparently exploded in 1957. Observed in 1986 and 1997, the exploding fragments have grown in size in the ten year interval at a speed of about 20 000 km s^{-1}. (Bottom) A highly detailed image of the same explosion, observed in November 1998, obtained from a 'World Array' of radio telescopes some 12 000 km in diameter. The pictures are 30 times more detailed than those of the Hubble Space Telescope, and are equivalent to a curious Dutchman in a cafe in Amsterdam being freely able to read a newspaper over the shoulder of a lounger in another café in London.

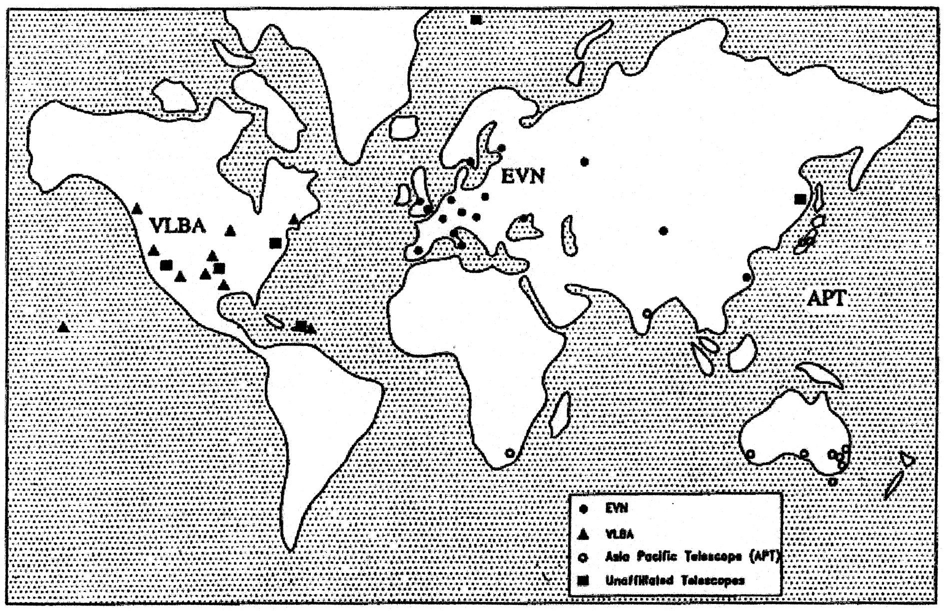

Figure 3. The world of very long baseline interferometry: the networks of telescopes forming the European VLBI Network (EVN), US Very Long Baseline Array (VLBA), and the Asia-Pacific Telescope (APT).

all the radiation falling on the reflector surface: in contrast, only a small part of the full aperture of a synthesis telescope is actually collecting radio waves. In any telescope, a partially blocked or unfilled aperture distorts all images by diffraction; these effects are very much larger in synthesis telescopes. The effects are, however, precisely calculable, and can be removed by sophisticated image processing techniques. These techniques are routinely available, and remarkably little is lost in image quality compared with images from a perfectly filled aperture. The layout of the network is important in minimizing the effect of the unfilled aperture: the arrangement of the component telescopes should include small as well as large spacings.

The sensitivity and angular resolution of aperture synthesis telescopes allow the observation of very weak radio sources. The sensitivity depends on the size of the component telescopes; the unique capability of the European EVN depends on the inclusion of several 70–100 m class radio telescopes in the network, together with its ability to observe in a wide range of frequency bands.

Operating the European VLBI Network (EVN)

Aperture synthesis has provided imaging capabilities far beyond the reach of any single optical or radio telescope. As in many other branches of astronomy, this has been achieved by a remarkable growth of a new international culture, in which the efforts and resources of astronomers in many different observatories are combined in a common objective, and the capabilities of large facilities become available to any astronomer who writes a good proposal. The next stages of development in radio astronomy will necessarily follow the same path. Before we look at the new aperture synthesis techniques, which will be involved in the next generation of radio telescopes, it is instructive to describe the EVN and its mode of operation.

The world map of Figure 3 shows the network of telescopes making up the EVN, along with the two other VLBI networks: the VLBA in the USA and the Asia Pacific Telescope (APT). Although these three are organizationally distinct, they use common techniques and elements of each can be combined to produce a worldwide network with higher resolution than any one of them. Recorded data from any of these networks can also be combined with data from other smaller-scale networks; this combination of scales reduces the problem of gaps in interferometer spacings, allowing a true representation of both small and large scale components of a radio source.

The EVN is a part-time array; its radio telescopes operate in VLBI mode for about 25% of the year, with the remainder of the time the individual constituent telescopes working on local astronomical observations. A number of unaffiliated radio telescopes participate on a case-by-case basis with the EVN, including the Arecibo telescope in Puerto Rico, NASA's Deep Space Network antennas near Madrid, and the Hartebeesthoek radio telescope in South Africa.

The EVN was formed in 1980 by a consortium of five of the major radio astronomy institutes in Europe. For several years all development and funding were provided by a growing number of individual members. The scale of operations and the need for a large communal data processing centre led, in 1992, to the funding by the Netherlands Government and national research councils in the UK, Italy, France and Sweden of the processor and user support centre. In 1993, the EVN Consortium directors initiated the establishment of a legal entity, the Joint Institute for VLBI in Europe (JIVE), at Dwingeloo in the Netherlands to manage the design and construction of the data processor and then to run it as a user centre. Design and construction were a multinational effort of European radio astronomy institutes and industry, together with an American partner institute, and took nearly seven years to complete. In 1992, the EVN was recognized as a Large Scale Facility by the European Commission, and since then has received a number of awards to enable a broader community of users to access the facility. The EVN is governed by a Board whose members are the directors of the participating institutes. Day to day operations are carried out by a Technical

Operations Group and a Programme Committee. The Programme Committee meets three times a year to evaluate proposals for observing time submitted by scientists in Europe and elsewhere in response to widely circulated Calls for Proposals. The selection of observing programmes is based on scientific merit and technical feasibility. The member institutes agree to commit at least 45 days of observing time per year to observations within the framework of the EVN, including joint observations of the EVN with other networks; in practice, the amount of observing time has risen to about 90 days per year because of the pressure of excellent observing proposals. With recent equipment upgrades, the EVN is now operating at a remarkably high sensitivity level, between three and five times better than that of the VLBA. For several years the EVN was used mainly to study the structure of quasars and active galactic nuclei, using observing frequencies of 1.4/1.6 GHz and 5 GHz. More recently, receivers at 6 GHz were installed, to allow mapping of cosmic maser emission from methanol and excited OH in regions of star formation. The EVN now performs a broad range of scientific observations extending from nearby stars to the far reaches of the early Universe.

Recent highlights of EVN results, as noted in an ESF Report (September 2000), are governed to a large extent by the unique capabilities of the EVN mentioned above. They include the study of the expanding and decelerating supernova SN1993J and the discovery of large numbers of supernovae in starburst galaxies, such as M82 and Arp220. A major success of VLBI has been the identification and subsequent explanation of the class of radio source known as Compact Symmetric Objects (CSOs). These were found among the very powerful and distant radio sources with a double structure. The twin lobes of the CSOs are separated by only some tens of light-years, but are nevertheless expanding outwards at more than 10% of the velocity of light. They are therefore very young radio sources, only a few hundreds of years old, and appear to be the progenitors of classical double radio sources.

Measuring the position of stars relative to a distant and unchanging background of quasars is called astrometry. The positions change with time, partly because we move on the Earth's journey around the Sun and on our Sun's journey around the Galaxy, and partly because the stars themselves move, for example in orbit around other stars. Remarkable astrometric accuracy has been achieved in radio interferometry, especially by MERLIN and the EVN. A 12 year EVN observing programme of radio-emitting stars has now established a firm and unmoving reference frame, with respect to which measurements of moving stars can be made – the International Celestial Reference Frame. The programme linked the reference frame established by ESA's astrometric satellite Hipparcos to the International Celestial Reference Frame. The mean astrometric positional accuracy achieved in the EVN programme is 360 μarcsec, equivalent to 1 m at the distance of the Moon. The highest precision is for the close binary σ^2CrB, with uncertainties of 120 μarcsec in position, 50 μarcsec in annual proper motion and 100 μarcsec in its trigonometric parallax. The precision obtained can be compared with $\sim$1000 μarcsec obtained by the Hipparcos satellite and the best ground-based astrometry. All this means that the distances and motions of stars can be determined with unprecedented accuracy.

The next stage: The Square Kilometre Array

The technical developments that have led to the current generation of radio telescopes are part of a revolution that has transformed all fields of observational astronomy, ranging from nearby stars to distant radio galaxies and the cosmic microwave background. The revolution has been rapid: observational cosmology, in particular, is a young subject, but today's astronomers are already on the brink of probing the origin and evolution of the Universe as a whole (see Liddle's article in this issue of *European Review*). The age of the Universe is known to be about 15 billion years old. The evolution of the Universe from a uniform fireball to the stars and galaxies of the familiar night sky took place in the first tenth of this time. X-ray, optical and radio telescopes are presently observing objects in the last nine tenths of this time. The next generation of telescopes will probe into the earliest era in which the elements were created and the structure of the Universe was determined.

Planning for the next generation of facilities leads to the conclusion that a revolutionary new instrument at radio wavelengths is needed, one with an effective collecting area more than 30 times greater than the largest telescope ever built. Such a telescope will reveal the dawn of galaxy formation, as well as a plethora of other new discoveries in all fields of astronomy. Technological developments in computing and radio frequency devices make it possible for such a telescope to be built within the next two decades. The international radio astronomical community is proposing that such a telescope, with a million square metres of collecting area, should be the next major radio telescope to be built. The project is known as the Square Kilometre Array (SKA). It will have a sensitivity 100 times that of the VLA.

Simply put, the goals of SKA are as follows:

- To probe the structure and kinematics of the Universe at a time before the dawn of galaxies: to understand the physics of the early Universe and how galaxies arose.
- To chart the formation and evolution of galaxies from the epoch of formation: to measure the evolution of the properties of galaxies,

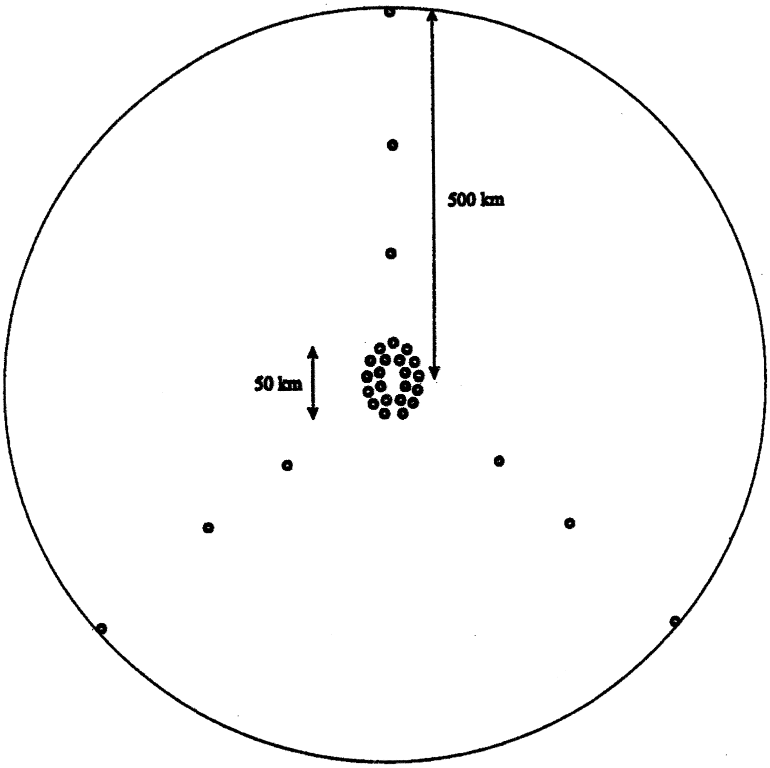

Figure 4. An example configuration for the Square Kilometre Array. The collecting area (one million square metres) is spread over a synthetic aperture 1000 km in diameter. Approximately 80% of the collecting area is contained within a centrally condensed inner region, yielding extremely high surface brightness sensitivity at arcsecond scale resolution. The outer antennas provide a higher angular resolution mode. In this configuration, there are 30 individual antenna stations, each with a 200 m diameter collecting area.

including dark matter, trace the history of star formation, and explore the origin of cosmic magnetic fields and their role in galaxy evolution.

- To understand key astrophysical processes relating to the process of star formation and the physical and chemical evolution of galaxies by studies of the local Universe.
- To trace the physical mechanisms that give rise to planetary systems, to understand the evolution of our own solar system, and to engage in definitive experiments to answer the question, ‘Are we alone?’
- To conduct exhaustive tests of general relativity, and explore the properties of nuclear matter within neutron stars.

The specification demands wavelength coverage from several metres to about one centimetre. Using new technologies, the SKA will become the premier imaging instrument of its generation in any wavelength region. With a spatial resolution better than the Hubble Space Telescope, and a field of view larger than the full Moon, the SKA will be a discovery instrument comparable only with the Next Generation Space Telescope (NGST), which will operate in the optical and the near-infrared wavebands. The SKA can be expected both to drive the agenda for, and to complement in essential ways, much of the programme of the NGST.

The new techniques that have opened the possibility of such dramatic advances are already being developed in existing synthesis arrays such as MERLIN. These advances in technique concern all the elements of the receiver system, from the amplifiers at the antennas, through the transmission systems, to the correlators and data processing. The basic determinants of the sensitivity of an interferometer array are the noise temperature of the individual detectors, and the radio frequency bandwidth. Cooled amplifiers with very low noise are now routinely used, but the bandwidths are limited both by the ability to transmit broadband signals to the central processor and by the capacity of the processor itself. Using bandwidths up to 1 GHz, the available sensitivity can be improved by more than an order of magnitude. Using the full bandwidth requires, however, two further components that have only recently become available: fibre-optic links, and very fast multiple channel digital correlators. These are proposed for eMERLIN, the next stage of improvement of MERLIN, which will go a long way to demonstrating the techniques required for the SKA.

Radio telescopes are increasingly affected by man-made radio-frequency interference. The wide-band, ultra-high-sensitivity SKA will need to make many observations outside the designated and protected radio astronomy bands, which only make up about 1% of the radio spectrum, and so it must incorporate interference mitigation techniques. The most powerful of these depend on recent advances in digital receiver techniques, which make it possible to dissect a receiver band into many independent channels, allowing the rejection of interfering signals. These techniques, which have already been demonstrated in radio observations, are important in many other applications, such as media services and communications, because of the increasingly dense signal environment in which they operate.

The SKA will be an interferometric array with a maximum baseline of several hundred to a thousand kilometres. Figure 4 shows a possible arrangement of the elements of the array. In this arrangement, there is a central concentration that can be used as the equivalent of a single very large dish, while the outer elements provide higher angular resolution.

As currently envisaged, each station of the array will be some form of radio

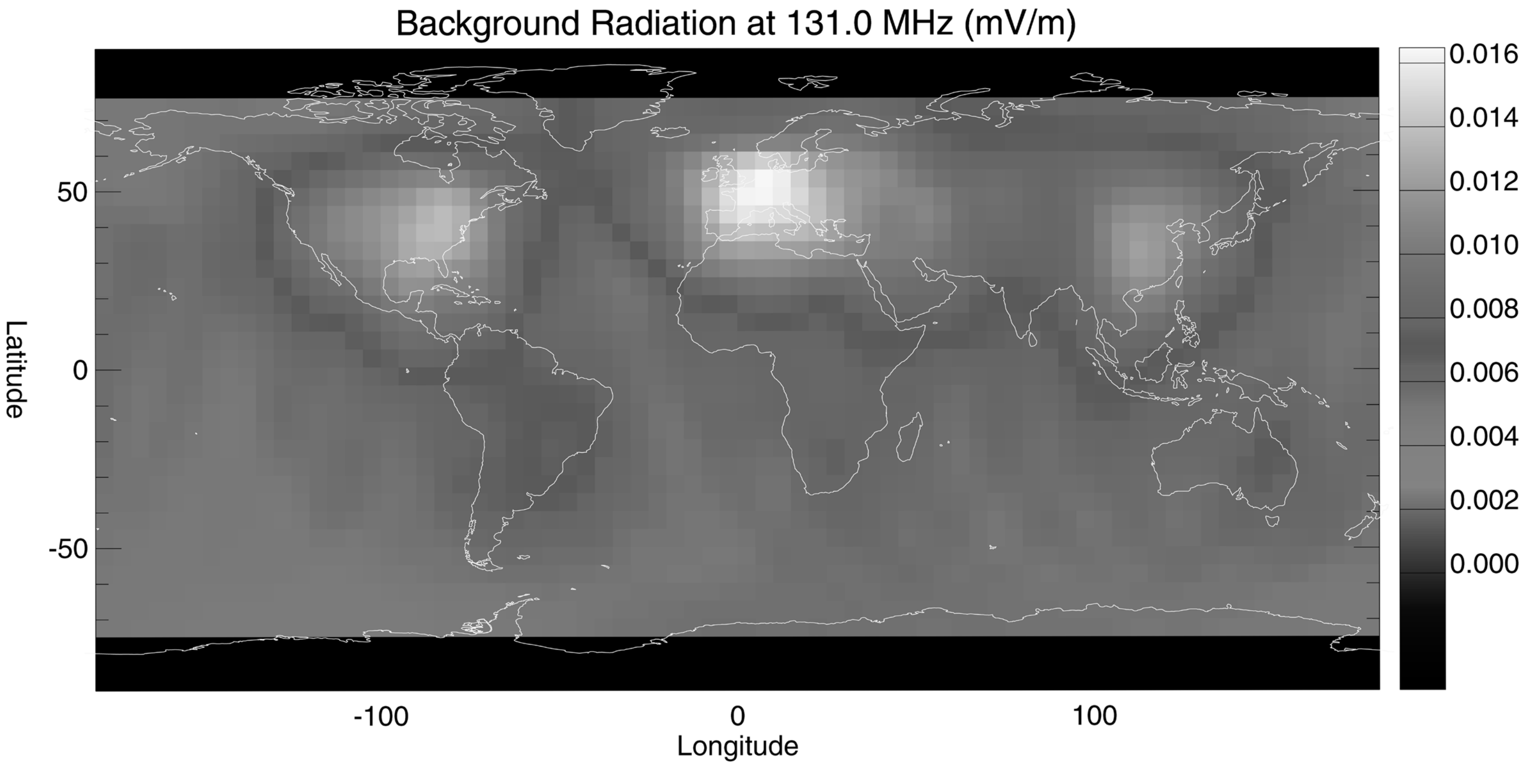

Figure 5. The global distribution of radio background emission in a 1 MHz band centred on 131 MHz. The quantity plotted is the median root-mean-square electric field measured by the FORTE satellite at 800 km altitude, averaged over several months and all local times. The FORTE satellite is a joint project of the Los Alamos National Laboratory and the Sandia National Laboratory.

telescope array with the collecting area being a circular aperture 200 m in diameter. It would be impractical and uneconomic to build such a station in the form of a single steerable dish, which would be factor of two larger in diameter than the largest existing fully steerable radio telescope. A single large dish also has the disadvantage of a narrow field of view. A large collecting area and a wide field of view must be achieved by constructing stations with arrays of smaller sub-elements, which might be small dishes or arrays of even smaller fixed elements. An example of such an array is the Allen Telescope Array, which is under construction in California for the specific purposes of SETI, the Search for Extraterrestrial Intelligence: this is an array of 300 dishes each 6 m diameter, making a collecting area of one hectare.

Access to as much of the sky as possible suggests a site for the SKA near the Equator. Further north would bring the Andromeda Nebula, the largest of our neighbour galaxies into the field of view, while further south would favour observations of the centre of our own galaxy and the two Magellanic clouds. The choice of site must eventually be made bearing in mind the configuration of the SKA, which will extend over some hundreds or thousands of kilometres, together with the system of fibre-optic links between the stations and access to communication links more generally.

A remote location is indicated by the need to minimize man-made radio interference. The SKA will operate over a wide range of frequencies, including low frequency bands that are already widely used in heavily populated areas. Figure 5 shows the worldwide distribution of radio background emission in a band at 131 MHz, measured by the FORTE satellite. Europe and the USA are clearly unsuitable for the SKA, while the Australian desert is one obvious candidate.

An international project

To realize a Square Kilometre Array at reasonable cost, a new means must be developed to construct the very large aperture individual radio telescopes at a small fraction of the cost of conventional technology. Research and development activities are underway at several international centres. Solutions under study include phased arrays, ‘smart’ antennas, large arrays of low-cost parabolic antennas, and novel concepts for very large, single-aperture antennas. Plans are well developed for construction of different prototype telescopes within the next several years. Convergence on the essential technological concepts for the SKA is expected by around 2005.

The time frame in which the Square Kilometre Array is needed to complement other next generation instruments will be in the years around 2010 and beyond. In September 1993 the International Union of Radio Science (URSI) established the Large Telescope Working Group to begin a worldwide effort to develop the scientific goals and technical specifications for a next generation radio observatory. Subsequent meetings of the working group have provided a forum for discussing the technical research required and for mobilizing a broad scientific community to cooperate in achieving this common goal. The project is rapidly gathering momentum in the international arena. In August 2000, 24 institutions from 11 countries signed a 'Memorandum of Agreement to Cooperate in a Technology Study Programme Leading to a Future Very Large Radio Telescope'. The Square Kilometre Array international planning meetings are occurring at a rapid pace. The workshop in Sydney, Australia in December 1997 was followed rapidly by meetings on the scientific goals and technical challenges in Calgary, Canada (July 1998), Green Bank, USA (October 1998), Amsterdam and Dwingeloo, the Netherlands (April 1999), Jodrell Bank, UK (August 2000) and Berkeley, USA (2001).

For historical reasons, radio astronomy has no international vehicle (such as an ESO or CERN) to promote coordination of activities among countries and to organize large multi-national facilities. As an ad hoc forum, the Organization for Economic Cooperation and Development (OECD) has established a Working Group on Radio Astronomy to consider whether specific actions by governments are necessary to make future large telescopes possible. Astronomers and funding agency officials from 15 countries have attended Working Group meetings, and have, in their Final Report to governments, identified millimetre wavelength arrays and the SKA as the main international megaprojects that are being discussed for development during the coming 10–20 years in most of the participating countries.

The Working Group identified one area that requires high-level government involvement even now if the planned large investments are to yield maximum scientific returns. This is the problem of radio interference and spectrum usage. SKA will have 100 times the sensitivity of current instruments, not only to celestial sources but also to man-made interference. In addition, to survey in redshift will require access to large portions of the radio spectrum. The Working Group concluded that these crucial needs are probably unachievable within the science system alone. It therefore falls to governments at a high level to initiate steps to evolve the current regulatory regime such that, by 2010, it will be possible, somewhere on Earth, to observe with the required sensitivity and bandwidths. The OECD delegations have accepted this challenge, and recommended to the triennial summit meeting of OECD science ministers in June 1999 that a special task force be formed to formulate and carry out appropriate measures to ensure that the desired observations are possible when SKA gets built. The initial thoughts are that this will require establishing one or more internationally recognized interference free zones in unpopulated areas of the world. Rigorous control of radio transmissions from satellites is essential: there is no place on Earth where radio telescopes can hide from space vehicles.

Further information on the European VLBI Network (EVN) may be found in a Report of the ESF Review Group on EVN and JIVE (September 2000). The opportunities for astronomical research with the SKA are set out in 'Science with the Square Kilometre Array', edited by A. R. Taylor and R. Braun, March 1999. The following web sites may be visited for the most recent information:

www.merlin.ac.uk
www.jb.man.ac.uk
www.jive.nl/jive/evn/evn.html
www.ras.ucalgary.ca/SKA/
www.atnf.csiro.au/ska/

About the Author

Francis Graham-Smith was Director of the Nuffield Radio Astronomy Laboratories at Jodrell Bank 1981–88 and British Astronomer Royal 1982–90. He is one of the pioneers of radio astronomy, starting at TRE Malvern and then moving to the Cavendish Laboratory, Cambridge University. His books include *Radio Astronomy* (1960), *Pulsars* (1977) and *Pulsar Astronomy* (1990).