Radio Astronomy in the Early Twenty-First Century

This introduction to Radio Astronomy explains coordinated worldwide efforts to develop techniques and locate equipment to study Earth-like planets and the origin and evolution of the Universe.

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Abstract: This paper serves as an introduction to the contributions in this Special Issue on “Advances in Radio Telescopes.” After a very short historical view of the emergence of Radio Astronomy, we refer to earlier IEEE special issues on this subject and mention recent instruments in the domain of millimeter wavelength radio telescopes, developments in very long baseline interferometry and the planned Square Kilometre Array (SKA). After a short discussion of site selection aspects for the new telescopes we conclude with a summary of the major astronomical and astrophysical problems which will be studied by the new instruments described in the following papers.

Keywords: Radio astronomy; radio telescope

I. Early Development of Radio Astronomy

In 1609, 400 years ago, Galileo Galilei started modern observational astronomy by adapting the recently invented “spyglass” to look at the Moon and planets. His discovery of moons orbiting Jupiter provided a major argument in favor of the Copernican system. To celebrate this occasion, the year 2009 has been declared “the year of astronomy” by the United Nations and the International Astronomical Union.

It is only 77 years ago that the wavelength domain of astronomy was extended to radio wavelengths by the serendipitous discovery of radio radiation from the direction to the Galactic Center by Jansky at Bell Telephone Laboratories. Being a radio engineer, he published his result in Proceedings of the IRE [1], which thereby became the professional journal to introduce the new science of radio astronomy to the engineering public. Astronomers barely took notice, but another radio engineer, Reber, built a parabolic reflector in his backyard and made a systematic survey of the sky at several frequencies between 160 and 480 MHz. His results were published in The Astrophysical Journal [2] in 1940. After the war, radar engineers in several countries, notably in England, Australia, and the United States, turned their attention to radio astronomy using their experience gained in the radar field. In The Netherlands, activities had from the onset the goal of detecting the spectral line of neutral hydrogen (HI) at a wavelength of 21 cm, which had been predicted by van de Hulst [3] in 1944. This line was detected in 1951 by Ewen and Purcell [4] at Harvard University and a few weeks later by Muller and Oort [5] in The Netherlands.

By the early 1950s, radio astronomy was becoming a serious and important part of astronomy, with major new telescopes being built in The Netherlands, Australia, and England. The IRE devoted the January 1958 issue of the Proceedings to radio and radar astronomy, 25 years after Jansky’s discovery. Apart from summarizing the status of the field, considerable attention was given to the structure and planning of the newly established National Radio Astronomy Observatory in Green Bank, WV [6].

II. Radio Telescopes

Radio telescopes bring together the state of the art in several areas of electrical and mechanical engineering, including the theory, construction, and control of large antennas, low-noise microwave amplifiers and detectors, digital correlators, signal processing, and computer algorithms for data reduction, analysis, and display. New
devices and applications developed at radio observatories are of interest to other disciplines, and indeed the IRE/IEEE has on several occasions featured radio and radar astronomy and its instrumentation in its Journals. In 1964, a Special Issue on Radio and Radar Astronomy was published jointly in the Transactions on Military Electronics (July–October 1964) and Transactions on Antennas and Propagation (December 1964), which contained a paper on parametric amplifiers and descriptions of the latest large radio telescopes. A special issue of the Transactions on Antennas and Propagation (July 1970) on Millimeter Wave Antennas and Propagation featured the description of ten radio telescopes for millimeter waves with diameters of up to 20 m.

In the early 1970s, several new large radio telescopes had come into operation and new observing techniques were being exploited. Examples are earth-rotation synthesis, very long baseline interferometry, and pulsar observation. The status of the field was reviewed in a Special Issue of the Proceedings of the IEEE in September 1973.

After the detection of the molecule carbon monoxide (CO) at 2.6 mm wavelength in the interstellar medium in 1970, followed by detection of more than 100 other atoms and molecules, development of large millimeter-wavelength telescopes became a major activity at several observatories, culminating in the operation of telescopes of up to 45 m diameter and extension of the frequency range into the submillimeter wavelengths by the end of the 1980s. Again, the IEEE featured these and other developments in radio astronomy in a Special Issue of the Proceedings of the IEEE on Radio Telescopes in May 1994. Highlights here were the large millimeter telescopes of Japan and the French/German Institute de Radio Astronomie Millimetrique (IRAM), the Very Long Baseline Array of the National Radio Astronomy Observatory (NRAO), the upgrade of the 300-m-diameter Arecibo telescope, and the description of low-noise superconductor–insulator–superconductor (SIS) receivers for millimeter wavelengths.

Since the early 1990s, an important aspect of radio astronomy instrumentation has been the extension of observing capabilities at millimeter wavelengths, exemplified by the interferometer systems of IRAM [7], OVRO [8], BIMA [9] (these last two instruments recently combined into CARMA [10]), Nobeyama [11], and CSIRO [12]. The submillimeter domain has been opened up by the California Institute of Technology [13], James Clerk Maxwell Telescope [14], Heinrich Hertz Telescope [15], South Pole Telescope [16], Submillimeter Array [17], and the satellite telescope Herschel. The need for significantly higher sensitivity and angular resolution in the millimeter and submillimeter wavelength range led to the nearly coincident proposals for large millimeter arrays in the United States, Europe, and Japan. Eventually these proposals were combined into one large system, which is currently under construction at the Atacama Large Millimeter Array (ALMA) (5000 m altitude) in the Atacama Desert of northern Chile. The Atacama Large Millimeter Array (ALMA) will consist of 50, possibly up to 64, paraboloidal reflectors of 12 m diameter and less than 25 μm surface accuracy, which form a synthesis array with baselines varying from 15 m to 14 km. An additional compact array of 12 7-m dishes plus four 12-m reflectors provides total power and short spacing information on objects of large angular extent. ALMA is described in this issue. From 2012, it will enable observations in the frequency range 30–950 GHz with more than two orders of magnitude improvement both in sensitivity and angular resolution.

During the past decade, plans for greatly improving the observing capability in radio astronomy at meter and centimeter wavelengths have received increasingly prominent consideration. This activity results from the need for greater sensitivity and higher survey speed, required to pursue a range of astronomical and cosmological questions. The high angular resolution provided by very long baseline interferometry (VLBI), and the frequency resolution achieved by digital correlators during the 1990s, must be combined with greatly increased sensitivity. This will extend investigation to greater depths of space allowing studies of the earliest epochs in the evolution of the cosmos. Conceptually, much of this development has been centered on an instrument with a collecting area of one square kilometer, the Square Kilometre Array (SKA), also featured in this issue. In particular, the study of the early universe in the “light” of the neutral hydrogen line (rest frequency 1420 MHz) requires observations in the hundreds of megahertz because of the large red-shift at which the material in the early epoch of the universe is seen. The globally designed and proposed SKA has the support and participation of institutes in 19 countries and will be the next big international radio telescope after ALMA. As part of the development of the required new technologies, and in an effort to be selected to host the instrument, several countries are actively involved in the design and construction of so-called SKA pathfinders. These are themselves significant radio telescopes, and their description fills a considerable part of this Special Issue.

The frequency range of anticipated SKA studies extends approximately from 80 MHz to 10 GHz, possibly up to 25 GHz. In the range below ~2 GHz, there is a relatively new requirement for wide instantaneous fields of view to provide increased speed in sky surveys. These surveys are required to catalog increasing numbers of sources, HI features, pulsars, etc., and also to allow investigations to cover the whole sky. Maximization of the sky coverage improves statistical analyses and increases the probability of success in searches for transient events such as supernovas. The increased speed is provided by the formation of a number of simultaneous beams. At the lower frequencies, this is achieved using large horizontal arrays of receiving elements from which the beams can be formed by combining received signals with appropriate phasing. As
frequencies increase toward 1 GHz, it is convenient to use paraboloidal reflector antennas with phased array feeds that provide multiple simultaneous beams. At frequencies above \( \sim 2 \) GHz, the requirement for cryogenically cooled front-ends necessitates the use of paraboloidal reflectors, mostly with single-beam feeds. Wide system bandwidths, required to maximize the sensitivity for continuum observations, have resulted in further development of feeds and low-noise input stages.

The highest angular resolution in radio astronomy is obtained with VLBI. Here we want to mention two advances in the technology used in VLBI. In VLBI, the received signals at each of the antennas in the interferometer array are converted to intermediate frequency, digitized, and then recorded for subsequent cross-correlation. First, in recent years, the use of magnetic tape for recording the signals has been widely replaced by use of computer-type magnetic disc packs [18]. Although the capacity of discs is continuously improving, parallel recording with multiple drives is still required for competitive data rates. The units currently in use in VLBI provide a much greater capacity than was available on a tape. This has allowed increasing the data rate and, correspondingly, the signal bandwidth, as well as increasing the running time between changes of the recording units. The error rates in the data are also very much lower than with magnetic tapes, and the random access methods for disks have greatly improved the efficiency of playback at the correlator. Secondly, in the European VLBI network (EVN), some observations are now being made with real-time connections between the antennas and the correlator using optical fiber links, thus avoiding the requirement for recording the signals [19]. This is referred to as electronic VLBI (eVLBI) and all continents have been connected this way, in some cases even simultaneously. Not only does the real-time connectivity allow for rapid response science, for example, on radio transients, but it has also been demonstrated to be operationally more reliable, as the feedback loop on data quality with the participating antennas can be closed during the observations. The cost of usage of long-distance fiber links is, however, a practical consideration in this method. Moreover, there are current operational limitations that prevent VLBI being done exclusively in this way. For example, the limited correlator capacity requires that certain demanding experiments be done in multiple passes, for example, to process full spectral resolution or multiple field centers. For the future, more correlator capacity and buffering mechanisms are envisioned that will lift these limitations and allow more experiments to benefit from the progress in eVLBI.

There are also large new single-element radio telescopes featured in this issue. The Green Bank Telescope (GBT) of the NRAO is a 100-m-diameter, offset-feed antenna. The Five-Hundred-Meter Aperture Spherical Telescope (FAST) under construction in China is an “Arecibo type” system, i.e., one with a fixed reflector. Both of these instruments feature computer-controlled adjustment of the positioning of the reflector panels. In the GBT, this allows use at frequencies up to \( \sim 100 \) GHz. In FAST, it allows coverage of a range of pointing centered on the zenith and the shaping of the surface to paraboloidal form, which greatly simplifies the feed requirements.

An essential feature of all these instrumental programs is the constantly improving capacity of digital signal processors that control the formation of multiple beams and facilitate the operation of wide-band correlators and advanced imaging procedures. Continuing gains through “Moore’s law” are necessary for the eventual application of collecting areas approaching one square kilometer. Processing power is also necessary for mitigation of expected radio-frequency interference in the received signals, as the wide observing bandwidths require coverage of frequencies allocated to other services.

### III. Site Selection for the new Telescopes

The penetration into the submillimeter wavelength range, and the return to meter wavelengths at much higher sensitivity and instantaneous all-sky coverage, increase the need for careful selection of telescope sites. While radio observations are not hampered by daylight, there are other serious natural and man-made impediments to interference free operation. In the submillimeter domain, the major problem is caused by the strong absorption of the received radiation by atmospheric water vapor. Several absorption lines of water occupy parts of the millimeter and submillimeter spectrum and observations are only possible in the frequency “windows” between these. But even there, the absorption is significant and increasing with frequency. This requires (sub)millimeter telescopes to be located on high sites in dry and cloud-free areas. For this reason, the first dedicated millimeter telescope (the 11-m-diameter reflector of the NRAO) was placed in 1967 at 2000 m altitude on Kitt Peak in Arizona and not at the home site of the NRAO in Green Bank, WV. Later major (sub)millimeter telescopes have been located well above 2500 m on mountains in southern Spain, Arizona, and, in particular, Hawaii. ALMA, mentioned above, is being constructed at 5000 m altitude in the arid Atacama Desert of northern Chile, where long periods of clear sky and extremely low water vapor density are common.

Observations at long wavelengths (centimeters to meters) are made in the domain where commercial use of the electromagnetic spectrum is abundant. In addition, radio emission from vehicles can easily suppress the weak astronomical signals. For this reason, many observatories are protected against such interference by zones of limited transmission, where transmitters and industrial activities are curtailed or banned. With the advent of the SKA and other similarly sensitive instruments, operating at frequencies from less than 100 MHz to a few gigahertz,
the need for an interference-free location is more serious
than ever. Both the large instantaneous sky coverage and
the extreme sensitivity require these telescopes to be
located in remote and thinly populated areas. Thus the two
candidates for the site of the SKA are the Karoo desert in
the northern part of the Cape Province of South Africa, and
the desert of Western Australia, some 600 km northeast of
Perth. Both countries are prepared to establish protection
against interference over regions of several hundreds of
kilometers in diameter. For completeness, it should be
mentioned that the earth’s ionosphere hinders observations
decimeter and meter wavelengths. Thus it is ad-
advantageous to locate telescopes in areas least hampered by
ionospheric anomalies. Both South Africa and Western
Australia offer this advantage.

IV. RADIO ASTRONOMICAL
CONSIDERATIONS

A. Meter and Centimeter Wavelength Astronomy

To help define the requirements of the SKA, consid-
eration has been focused on five key science projects which
include a range of interests as follows.

1) The detection and study of Earth-like planets
   including examination of planetary atmospheres
   for complex carbon biomolecules.

2) Strong-field tests of gravity by observing a pulsar
   in orbit around a black hole, a combination that is
   likely to be found as many more pulsars are
discovered.

3) The origin and evolution of cosmic magnetism,
   through characterization of magnetic fields in
   galaxies and clusters to red-shift distances \( z > 3 \).
   Observations would be based on measurements of
   Faraday rotation and the Zeeman effect.

4) Galaxy evolution and cosmology through compre-
   hensive HI surveys to \( z \sim 1.5 \) and studies of star
   formation.

5) The epoch of reionization in which luminous ob-
   jects first formed and re-ionized the intergalactic
   medium, providing a feature in the HI spectrum
   that should be observable at meter wavelengths,
   \( \sim 100 \text{ MHz} \).

B. Millimeter Wavelength Astronomy

ALMA fills in the gap between optical/infrared tele-
scopes and the frequency range typified by the SKA. The
reason that ALMA’s frequency range is scientifically
interesting is that radiation at millimeter and submilli-
meter wavelengths is caused by different physical mecha-
nisms than those that produce the emissions at longer and
shorter wavelengths. In contrast to meter wavelengths, at
which most of the astronomical signal energy is generated
by the synchrotron mechanism in which high-energy
electrons interact with cosmic magnetic fields, in the

millimeter and submillimeter range, thermal emission
processes in the relatively cold material play an increas-
ingly prominent role.

There are three major ALMA science requirements.
These are the ability to:

1) detect a Milky Way galaxy at red-shift \( z = 3 \) in a
   line of carbon monoxide or ionized carbon;

2) image the gas kinematics in protostars and proto-
   planetary disks around Sun-like stars at the dis-
   tance to molecular clouds in Ophiuchus or Corona
   Australis (150 parsecs);

3) provide precise images at an angular resolution of
   0.1 arcsecond.

These requirements necessitate a telescope with a wide
range of angular resolution and brightness temperature
sensitivity. The layout of ALMA as a multielement syn-
thesis array, with a variable density of elements and hence
a variable angular resolution, provides the possibility to
choose the optimal telescope configuration for each of
these science requirements.

In the nearby universe, ALMA will provide an unpre-
cedented ability to study the processes of star and planet
formation. Unimpeded by the dust that obscures visible
light, millimeter and submillimeter observations are able
to reveal the details of young, still-forming stars and are
expected to show young planets in the process of
developing.

Molecular lines become an increasingly important
component of the astronomical emissions as the frequency
increases. They provide detail about the complex chem-
istry of the giant clouds of gas and dust that spawn stars
and are highly suitable for investigation of planetary
systems. Submillimeter lines that emanate from the most
distant universe include red-shifted lines emitted in the far
infrared. These become observable in the submillimeter
region, thereby providing a window to the physics of
galaxies during early epochs of the Universe.

The frequency ranges of instruments like ALMA and
the proposed SKA are largely complementary, and together
they provide a wide access for astronomical investigation.
As the frequency increases above \( \sim 30 \text{ GHz} \), the effects of
the Earth’s atmosphere become increasingly limiting; and
above \( \sim 100 \text{ GHz} \), observations are largely limited to a
number of atmospheric “windows.” One terahertz is an
approximate upper limit for radio astronomy from the
Earth’s surface. Radio techniques are being used in the
supra terahertz regime on satellite-borne telescopes, also
represented in this Special Issue.

APPENDIX

SOME ASTRONOMICAL TERMS
AND UNITS

• A jansky [Jy] is a unit of flux density
  \( 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1} \).
• An astronomical unit [AU] is the distance from the Sun to the Earth \(1.5 \times 10^8\) km.

• A parsec [pc] is a unit of distance, about 3 lightyears, \(3 \times 10^{13}\) km. One parsec is the distance of an object with annual parallax of 1 arcsec as seen from the Earth. It is thus tied to the astronomical unit.

• Redshift \(z\) is a measure of cosmic velocity. The special relativistic Doppler effect is written as

\[
1 + z = \left(\frac{c+v}{c-v}\right)^{0.5},
\]

where \(c\) is the light velocity and \(v\) the radial velocity of the object.

• \((u,v)\)-plane: In interferometry, the baseline of any antenna pair is conventionally represented by parameters \((u,v)\), which are, respectively, the East–West and North–South components of the baseline projected normal to the field center and measured in wavelengths. Thus, \((u,v)\)-coverage represents the extent of the spatial frequency response of the instrument.

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**REFERENCES**


