Radio Astronomy: A Large Antenna Array

D. S. Heeschen

Radio observations of celestial objects are of fundamental importance to a better understanding of the universe. This has been amply demonstrated by the recent history of astronomy. But the radio "picture" of the universe attainable today is still blurred and confused by the relatively poor resolution and sensitivity of radio telescopes. In fact, the capability of radio telescopes is, with some outstanding exceptions, roughly equivalent to that of the human eye observing the sky at optical wavelengths. Radio astronomy today can be compared with optical astronomy before the invention of the telescope. The resolution of the largest radio telescopes approaches, but does not quite reach, the resolution of the human eye. The total number of objects that can be observed with radio telescopes is about the same as the number that can be seen with the unaided eye. Finally, the observable dynamic range of intensity, from the brightest objects to the faintest that can be detected, is about the same with the unaided eye as it is with the most sophisticated radio telescopes.

Higher resolution has always been a major goal of the development of instruments for radio astronomy. In the 1950's and early 1960's, the need for resolution led to the extensive development and use of radio interferometers, particularly at the radio observatories in Cambridge and Manchester, England; Sydney, Australia; and the California Institute of Technology. In the most recent developments, a resolution of 0.005 second of arc has been achieved (*1*). But even the very sophisticated interferometers have serious disadvantages, in that either they produce high side-lobe levels or fan beams which limit their usefulness, or else they are very slow instruments. At present, there is no instrument which will produce high-resolution radio "pictures" of a source or region of sky. Such "pictures" are needed for two basic reasons: (i) to study the detailed polarization and brightness structure of celestial objects, and (ii) to allow the measurement of faint sources of radiation without confusion due to the blending of neighboring sources.

The report of the Panel on Astronomical Facilities of the Committee on Science and Public Policy of the National Academy of Sciences (*2*) stated " . . . that the primary need in radio astronomy is a very powerful high-resolution instrument." It recommended construction, by the National Radio Astronomy Observatory (NRAO), of a large array that would achieve a resolution of less than 10 seconds of arc at centimeter wavelengths. In response to this recommendation, the NRAO has designed, and now proposes construction of, a very large array (VLA) of radio telescopes (*3*). The VLA will consist of 36 parabolic antennas operated synchronously to produce radio maps with 1 second of arc resolution. Its high resolution, sensitivity, and speed will provide unique capabilities for research in radio astronomy. These capabilities are one to two orders of magnitude greater than those of any other existing or planned instrument. With the VLA it will be possible, for example, to investigate the detailed brightness and polarization of extragalactic radio sources with a resolution of 1 second of arc and negligible side-lobe effects, to a flux density level of about 10^{-4} flux unit (*4*).

The design of the VLA is based on the principle of aperture synthesis developed by Ryle (*5*). An interferometer measures one term of the two-dimensional Fourier series representation of the brightness distribution of a source or region of sky to which the interferometer is pointed. The particular term measured is specified by the apparent separation and orientation, as seen from the source, of the two elements of the interferometer. By changing the separation or orientation of the elements, a different Fourier component is measured. Thus, many Fourier components can be measured with a two-element interferometer by successively moving one element to different positions relative to the other. A single telescope of large aperture can thereby be synthesized by using just two telescopes of much smaller aperture, one of which must be movable.

This scheme has two disadvantages: it is slow, and it is inefficient to move antennas frequently. To obtain a map of a region of sky of diameter β with a resolution α requires measuring the order of $(\beta/\alpha)^2$ Fourier components, a number that is typically 10^4 or more. It would be extremely slow and awkward to obtain that many measurements with a single interferometer in the manner described above—for example, 10^4 moves of one element would be required. The process can be speeded up simply by the use of an array of antennas. The number of independent interferometers, and therefore the number of Fourier components that can be measured simultaneously, increases about as the square of the number of antennas in the array. In addition, the need to move antennas can be reduced by taking advantage of the earth's rotation. Both the apparent separation and orientation of a pair of antennas, as seen from a point fixed on the celestial sphere, change as the earth rotates. Therefore, even without physically moving the antennas, it is possible to measure a range of Fourier components with a given pair by tracking the source under observation across the sky.

Ryle and his colleagues at the Mullard Radio Observatory, Cambridge, England, first developed and put into use the techniques of aperture synthesis. With their present system, they are able, by using earth rotation and moving one antenna periodically, to synthesize an aperture 1.6 kilometers in diameter with just three antennas each 18.3 meters in diameter. They obtain a beamwidth of about 20 seconds of arc at their present operating wavelength of 20 centimeters. A similar instrument with three antennas of 25.9 meters in diameter is in operation at the NRAO. It synthesizes an aperture 2.7 kilometers in diameter and gives a beamwidth of 8 seconds of arc at its operating wavelength of 11 centimeters. Both instruments have

The author is director of the National Radio Astronomy Observatory, Green Bank, West Virginia.

proved to be extremely powerful tools for research in radio astronomy, and they clearly demonstrate that the technique of aperture synthesis is completely feasible.

However, these telescopes, each with only three antennas, are still very slow instruments. More than a month of observing is required to obtain a complete map of just one small region of sky. Although they provide the greatest resolution and sensitivity presently available to radio astronomy, except for interferometers with very long base lines which can achieve much higher resolution for a severely limited range of problems, they fall far short of what is needed.

The proposed VLA is a further extension of the technique of aperture synthesis to provide an increase of more than an order of magnitude in resolution, sensitivity, and speed. It will consist of 36 antennas, each 25 meters in diameter, arranged in an equiangular Y configuration. This configuration provides better performance of the array over a wider range of declinations than other possible configurations provide. The output of each antenna is correlated with that of every other antenna in the array. The 630 simultaneous correlator outputs, each representing one component of the complex Fourier transform of the brightness distribution of the region of sky under observation, are processed and accumulated in a central computer for a period of up to 12 hours during which the array tracks the region of sky as the earth rotates. Some 10^4 independent Fourier components, which are then transformed into a picture of the source or region observed, are obtained in 8 to 12 hours.

The individual antennas are paraboloids of revolution with solid surface permitting operation at wavelengths as short as 3 centimeters. Positioning and tracking of the antennas are under the control of the central computer.

Each arm of the Y configuration is 21 kilometers in length and has a pair of standard-gauge railroad tracks of that length. The characteristics of the array, particularly resolution and side-lobe levels, may be modified by moving the antennas along the arms of the Y on the track system. Thus, a variety of operating configurations will be available so that the performance of the instruments can be tailored to a particular program (Fig. 1).

Principal Characteristics of the VLA

Wavelength. Eleven centimeters is the primary design wavelength. The system is flexible enough to accommodate changes of wavelength with relative ease and for relatively low cost. In particular, provision for one shorter wavelength, to be operated simultaneously with 11-centimeter wavelength, has been made.

Resolution. Four configurations, giving resolutions of 1, 3, 9, and 27 seconds of arc at a wavelength of 11 centimeters, are available. Each of these configurations will allow pencil-beam mapping of a region of sky of radius 30 to 60 times the diameter of the synthesized beam. This observable field is limited by the effects of the finite bandwidth of the electronic system, an effect similar to the smearing of fringes in an optical interferometer. In the case of the configuration giving a resolution of 27 seconds of arc, the field is limited to a diameter of about 17 minutes of arc by the beamwidth of the individual elements of the array. Various other configurations are also readily available, including one which gives a fan-shaped beam with a resolution of 0.6 second of arc in its narrow dimension.

Side-lobe levels. The calculated maximum and mean side-lobe levels in various annular zones around the main beam (Table 1) arise from a wide variety of causes including missing information (not all of the needed Fourier components are measured), atmospheric and instrumental phase fluctuations, irregularities in the surfaces of the individual antennas, and many others. All known effects have been included in Table 1. The ultimate sensitivity of any antenna system for most kinds of observations is set by its resolution or its side-lobe levels, or both. Confusion, due to unresolved sources in the main beam or to spurious responses from sources in side lobes, is almost always the final limiting factor.

The side-lobe levels (Table 1) are very low—as low as those generally obtained with a high-quality parabolic antenna—and indicate that spurious responses will be a problem only when trying to work to the lowest flux density in the immediate vicinity of the three or four most intense sources. These low side lobes are an extremely important characteristic of the VLA and make it possible to obtain radio "pictures" with the highest resolution and sensitivity of the system.

Sensitivity. The sensitivity of the array may be limited by a combination of noise from the electronic system, confusion due to faint unresolved sources in the synthesized beam, and unwanted responses from sources in side lobes. The last two limits are in turn dependent on the number distribution of faint sources in the sky. Taking all three effects into consideration and assuming a number distribution of faint sources by extrapolation from the known distribution of brighter sources, the limiting sensitivity, for a signal-to-noise ratio of five in an 8-hour observation, is 2×10^{-4} flux unit in the configuration giving 1 second of arc resolution. The limiting sensitivity increases to 3×10^{-3} flux unit at a resolution of 27 seconds of arc because of increasing confusion in the synthesized beam. For comparison, the present limiting sensitivity of radio telescopes is at best about 5×10^{-2} flux unit.

Time required for an observation. To achieve the above resolution, side-lobe levels, and sensitivity requires an observing time of 8 to 12 hours, depending on the declination of the region observed. No changes in the positions of the elements of the array are required. Observations not requiring such low side-lobe levels may be obtained in shorter times. Similarly, observations requiring still lower side-lobe levels may be accomplished by successive measurements with the array elements in complementary configurations, at the expense of more total time.

Polarization. Individual elements of the array will simultaneously select either two linear or two circular polarization components of the incoming radiation. Appropriate combination of these will allow complete polarization synthesis of sources.

Sky coverage. The above performance of the array is equaled or exceeded at all declinations north of $-30°$, that is, 75 percent of the celestial sphere. This is particularly important because most existing or proposed high-resolution instruments give good performance only north of about $+30°$ declination, or 25 percent of the celestial sphere.

Spectral line observations. Because of the greater electronic complexity, an array is less convenient to use for radio spectroscopy than a single dishtype antenna is. However, the VLA can be used for spectroscopy, and, in exchange for the increased electronic complexity, much higher resolution is obtained than that achieved with a single antenna. For those spectral problems which require very low side lobes and resolution better than a few minutes of arc, the VLA will be unexcelled.

Flexibility. The correlated outputs of all possible pairs of antennas are separately available. Every antenna is movable to any position within the array configuration. The individual antennas of the array are altitude-azimuth mounted paraboloids of revolution with full sky coverage and operable to wavelengths as short as 3 centimeters. Thus, a very wide range of both electronic and geometric configurations can be achieved with, at most, minor modifications to the system. The system can, for example, be split into two or more smaller arrays to allow independent programs to be carried out simultaneously. In addition, the array is, by its nature, readily expandable to give increased resolution, sensitivity, or flexibility as future developments in radio astronomy dictate.

Site requirements for the VLA are relatively few and simple but quite restrictive. A rather flat, reasonably unoccupied site with dimensions of the order of 40 kilometers is needed. Both sky coverage and other characteristics of the array will depend in part on the geographic latitude of the site, which should be as far south as consistent with other requirements. Finally, the ultimate performance of the array will depend partly on the stability of the atmosphere and on its water vapor content. The site therefore should be at a high elevation. Fortunately, there are several regions in the southwestern United States which meet all of these requirements.

Table 1. VLA side-lobe levels. Maximum and mean are expressed in decibels.

Zone	Maximum	Mean
2–4″	−18.0	−26.0
4–8″	−20.1	−29.0
8–16″	−19.2	−31.1
16–31″	−14.5	−33.0
31–60″	−17.1	−35.4
1–17′	< −30	
17′–2°	< −40	
2–20°	< −70	
> 20°	< −90	

The facilities of the NRAO are available to any qualified scientist on the basis of the scientific merit of his proposed program and without regard to his institutional affiliation. The VLA will be operated under the same policy More than 70 percent of the observations with present NRAO telescopes are made by scientists not on the NRAO staff, and the same percentage will apply to the VLA.

The power of the proposed VLA for radio astronomy research is far greater than that of any other existing or proposed instrument. With a resolution of 1 second of arc, sensitivity of 2×10^{-4} flux units, polarization and spectral line capability, and the ability to obtain radio "pictures" with these characteristics and with reasonable speed, it would put the instrumental capability of radio astronomy on an equal footing with that of optical astronomy. For the first time, it would allow comparison of optical and radio data of similar resolution. It would extend the domain of radio astronomy to a larger volume of space, a wider range of physical phenomena and problems, and a wider variety of celestial objects. Its impact on all astronomy will surely be very great.

At a cost of about $50 million, the VLA is relatively expensive when compared to other astronomical instruments, although not so expensive in comparison to the cost of instruments in some other fields of research—space

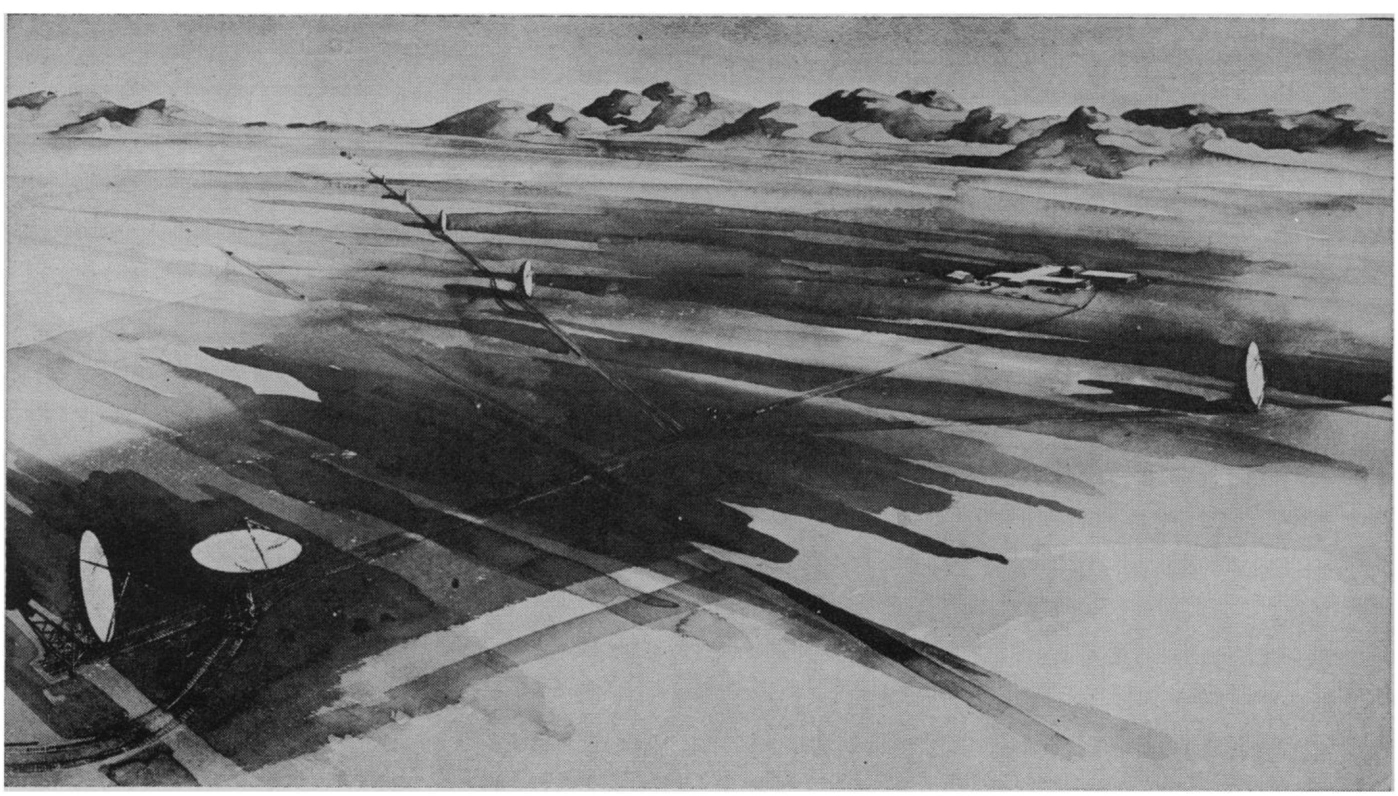

Fig. 1. Drawing of the VLA project.

or high-energy physics, for example. The potential reward, however, in new insights into the age-old questions of the universe, challenges the imagination, and I believe that it more than justifies the money and effort required.

References and Notes

1. B. G. Clark, M. H. Cohen, D. L. Jauncey, *Astrophys. J. Letters*, in press.
2. "Ground-based astronomy, a ten year program," *Nat. Acad. Sci.–Nat. Res. Council Publ.* (1964).
3. *The VLA, A Proposal for a Very Large Array Radio Telescope* (National Radio Astronomy Observatory, Green Bank, West Virginia, 1967); submitted to NSF in January 1967, the proposal is available from Clearinghouse for Federal Scientific and Technical Information, Springfield, Virginia.
4. One flux unit is equal to 10^{-26} watt m^{-2} hz^{-1}.
5. M. Ryle, *Nature* **194**, 517 (1962).
6. The NRAO is operated by Associated Universities, Inc., under a contract with NSF.

Capillary-Tube Scanner for Mechanized Microbiology

A photoelectric scanner measures growth in agar-filled capillaries and gives a new approach to microbiology.

Robert L. Bowman, Philip Blume, Gerald G. Vurek

We are reporting an instrumental method for counting viable bacteria and determining their antibiotic susceptibilities. The instrument counts the light-scattering pulses from developing colonies in a capillary tube filled with agar containing various nutrients. New or larger scattering pulses are produced by growth of organisms but not by inert scattering points. Antibiotics added to the agar inhibit growth or fail to modify it according to the susceptibility of the organisms. The system will reduce the burden of colony-counting and accelerate the determination of antibiotic sensitivities. The time saved in determining antibiotic sensitivity of organisms isolated from clinical specimens permits rational antibiotic therapy to be instituted earlier. Multiple parallel tests are feasible through the use of cheap disposable capillaries that require small amounts of both sample and reagent, and little laboratory space. The hazard of contamination is low because the samples are held in gelled agar inside sealed capillaries.

We have used methods of manual manipulation to permit easy variation of the techniques, but the extension to automated procedures can be accomplished easily. The sample is suspended in gelled agar, as in conventional pour plates, so that problems arising from motile organisms are reduced, and the growth dynamics of each colony derived from a viable organism in the original sample can be studied. The volume occupied by the organisms is so small that, at least for the first few hours of incubation, the capillary represents a large reservoir for nutrients and sink for metabolites. Mixed populations grow independently in dilute suspensions. Although a trained microbiologist can count and obtain partial identification of microcolonies soon after a pour plate is prepared (*1*), the man-hours involved are so great that this procedure is not used routinely. Petri-dish scanners and counters have been made, but they are expensive, bulky, and complex (*2*). The compact, inexpensive capillary system and the information made available by repeated scans and by analysis of the pulse-height distribution can provide a useful and powerful tool for research as well as for clinical testing.

Instrumentation and Method

Figure 1 is a schematic representation of the equipment we are developing. Light from a linear tungsten filament lamp (*3*) is focused by a microscope objective (3.2×) into the center of the filled capillary. Another objective (3.5×) collects light scattered from material within the capillary and directs it through a stop to a photomultiplier (*4*). The axes of the illuminating beam, the capillary, and the observation line are coplanar. The photoelectric signal is recorded graphically or registered on a counter whenever the amplitude exceeds a predetermined threshold. A synchronous motor-driven carriage translates the capillary through the light beam, and the recorded charts or accumulated counts of successive scans of a capillary can be compared directly.

The details of the equipment used for many of the studies to be described below are shown in Fig. 2; the photomultiplier housing is at the left, the drive motor and capillary carriage are in the central foreground, and the illuminating optics are at the right. Six separate capillary holders were used so that we could follow the development of growth within several capillaries without disturbing the orientation of the tubes in their holders. The holders were designed to be replaced precisely on the carriage with semikinematic mounts. During use, a cover (removed for the photograph) encloses the carriage region to reduce the effect of room light. An earlier apparatus (*5*) used the light scattered at a right angle from a laser-source to indicate the presence of microcolonies, but that unit was put aside when we found the coplanar forward-scattered light signal measured with the new apparatus was adequate. In addition to the unit shown in Fig. 2, we are using equipment that has essentially the same configuration except that the capillary carrier holds several tubes that can be scanned successively (*6*).

The chance that colonies will not be counted because of coincidence loss depends on the concentration of colonies and the volume of the region formed by the intersection of the illuminating beam and the observing "beam." We selected the size of our viewing stop so that coincidence losses

Dr. Bowman is chief, Dr. Blume is staff scientist, and Dr. Vurek is senior investigator at the Laboratory of Technical Development, National Heart Institute, Bethesda, Maryland 20014. Dr. Blume's present address is: Department of Laboratory Medicine, University of Minnesota, Minneapolis 55455.