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FOREWORD

Again we have a volume appearing within less than a year of its predecessor. Furthermore, it will be separated only by months from publication of the next volume. This rather closely packed appearance of volumes reflects the abundance of extremely interesting material, all of which we are pleased to present in these *Advances*.

The first review, by Erickson and Kerr, deals with the technology and observations of the "passive" branch of radio astronomy. This branch, much more important than the "active" one, offers a beautiful example of the interrelationships among astronomy, physics, chemistry, and, last but not least, advanced electronic technology.

The next two reviews deal with widely different aspects of microscopy. Misell considers the role of image defects in the image formation of the transmission-type electron microscope, with particular attention to the influence of inelastic scattering in the specimen. This subject was of great interest to your editor many years ago and I welcome this thorough treatment of it. The author deals with the deterioration of contrast, rather than that of resolution, and points to the role of radiation damage in the specimen affecting the image quality.

Swanson and Bell, in their review, discuss the present status of field emission microscopy of metals. The rapid growth in this area required several previous reviews; as our last one was published 12 years ago, the time appeared ripe to consider the advances since that time. Swanson and Bell examine the theoretical, experimental, and technological aspects of recent progress.

The last review in this volume, by Granatstein and Feinstein, deals with the multiple scattering and transport of microwaves in turbulent plasmas. Some aspects of this subject were treated in earlier reviews in this series (Bowles, 1964; McLane, 1971). The importance of the subject, both for electromagnetic wave propagation and for controlled thermonuclear research, amply justifies this presentation.

As has been our custom, we list again future reviews, together with their prospective authors:

The Effects of Radiation in MIS Structures	Karl Zaininger
Small Angle Deflection Fields for Cathode Ray Tubes	R. G. E. Hutter and H. Dressel
Sputtering	M. W. Thompson
Interpretation of Electron Microscope Images of Defects in Crystals	M. J. Whelan

Optical Communication through Scattering Channels	Robert S. Kennedy
Hollow Cathode Arcs	J. L. Delcroix
Channelling in Solids	R. Sizmann and Constantin Varelas
Physics and Applications of MIS-Varactors	W. Harth and H. G. Unger
Ion Implantation in Semiconductors	S. Namba and Kohzoh Masuda
Self Scanned Solid State Image Sensors	Paul K. Weimer
Quantum Magneto-Optical Studies of Semiconductors in the Infrared	Bruce D. McCombe and Robert J. Wagner
Gas Discharge Displays	R. N. Jackson and K. E. Johnson
Photodetectors for the 1μ to 0.1μ Spectral Region	David H. Seib and L. W. Aukerman
High Resolution Nuclear Magnetic Resonance in High Superconducting Fields	H. Sauzade
The Photovoltaic Effect	Joseph J. Loferski
The Future Possibilities for Neural Control	Karl Frank and Frederick T. Hambrecht
Electron Bombardment Ion Sources for Space Propulsion	Harold R. Kaufman
Recent Advances in Hall-effect Research and Development	D. Midgley
Semiconductor Microwave Power Devices	S. Teszner
The Gyrator	K. M. Adams, E. Deprettére, and J. O. Voorman
Electrophotography	M. D. Tabak and J. L. Thourson
Microwave Device Technology Assessment	Jeffrey Frey and Raymond Bowers
The Excitation and Ionization of Ions by Electron Impact	John W. Hopper and R. K. Feeney
Whistlers and Echoes	Robert A. Helliwell
Experimental Studies of Acoustic Waves in Plasmas	J. L. Hirshfield
Multiphoton Ionization of Atoms and Molecules	J. Bakos
Auger Electron Spectroscopy	N. C. Macdonald and P. W. Palmberg

Suggestions about future reviews and authors proved to be most useful. We would like to repeat our invitation for more suggestions.

L. MARTON
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CONTENTS

Multiple Scattering and Transport of Microwaves in Turbulent Plasmas

V. L. GRANATSTEIN AND DAVID L. FEINSTEIN

Technology and Observations in Radio Astronomy

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I. Introduction

Radio astronomy is a branch of physics which deals with matter and energy under conditions that are unattainable on Earth. Several decades ago, when scientific work in radio astronomy began, the observed phenomena seemed very strange and unrelated to physics or optical astronomy. In the late 1950s and early 60s, optical identification of radio sources began, hydrogen line observations of galactic structure were related to optical observations, and radio data became an integral part of astronomical knowledge. In the past few years, the increased sophistication of radio techniques has led to solid, quantitative knowledge. Concurrent developments in plasma physics have provided a theoretical framework through which some of these quantitative data can be understood. The radio observations often provide the most crucial tests of a theory and the unexplained phenomena suggest fruitful avenues of theoretical research. Radio astronomy is therefore taking its place as a vital part of physics. In an analogous way, the discovery of new interstellar molecules and an understanding of the processes involved in their formation are closely tied to chemistry, and perhaps to elementary biology.

These advances have been brought about primarily through technical developments. The technical advances which have been most important to radio astronomy are in the development of large aperture antennas, highly stable, low noise amplifiers, and data processing techniques. In this article we will attempt to show the ways in which technological developments have stimulated scientific discoveries. However, it should not be assumed that this is always a premeditated process; important scientific discoveries have often occurred quite serendipitously when powerful new instruments became available.

In this article we will attempt to give some discussion of most aspects of the science of radio astronomy. In our discussion of technological developments, we will confine ourselves to those subjects to which radio astronomers have been the most important direct contributors. Many of the techniques most vital to current research in radio astronomy were developed primarily for other purposes. The application of such techniques to astronomy will be mentioned but a discussion of their development is beyond the scope of this article.

II. Radio Astronomy Techniques

A. Observational Considerations

Before discussing the development of techniques for radio astronomy, we shall briefly outline the main observational factors which determine the types of equipment and technology that are required. In this paper, we consider only the "passive" branch of radio astronomy, in which radio energy emitted by celestial bodies is received at the Earth. The "active" branch, in which radar transmissions are used, is extremely important for solar system research but it is limited to the nearer bodies in the solar system because the strength of the received echo is inversely proportional to the fourth power of the distance of the echoing object (*1*).

The main energy received is in the form of a continuum, extending over a wide frequency range, but a substantial number of spectral lines from interstellar atoms and molecules have also been detected. The observer's problem is to measure the variation of intensity as a function of position in the sky and also of frequency. For a number of sources, variations on several time scales must also be taken into account, but usually the intensity and position appear to be constant to our present accuracy of measurement.

Except at long wavelengths, the received signals are weak and the highest possible receiver sensitivity is required. The radiation has the character of random noise and is similar to the noise generated inside a receiver or in the environment of an antenna. The astronomical signal produces an increase in the noise level at the output of the receiver, and has no other distinguishing characteristics. Under most circumstances the radiation is randomly polarized, but some sources show linear or circular polarization. Often the degree of polarization is quite low, and spurious polarization effects in the instruments must be kept to a minimum. Because the wavelengths are long in comparison with those common in optical or ultraviolet astronomy, adequate angular resolution can only be obtained with structures of large physical size or interferometers with large separations between the component parts. Attempts to increase resolving power have played an important part in the entire history of radio astronomy.

Until recently there was no radio analog of the optical photograph, and it was necessary to work with point-by-point measurements. Systems now exist which can effectively form images, but they are necessarily complex. One type can scan rapidly over a strong source such as the Sun. In the other case a long period of observation is required to build up a detailed "picture" of some particular area of the sky. In an analogous way a wide spectral range can only be observed slowly. Even with a multichannel receiver a single observation can cover only a very small fractional bandwidth without replacement or extensive retuning of receiver components.

Radio astronomers commonly express the strength of the received radiation in terms of temperatures. The *antenna temperature* corresponding to a cosmic source is defined as the temperature of a terminating resistor which could replace the antenna and which would produce the same receiver output as the source in the frequency band of the observation. The *brightness temperature* or surface brightness of that part of the sky under observation can be obtained from the antenna temperature if the antenna efficiency is known. The average brightness temperature of the radio sky varies from about 10,000 K at 30 MHz to a few kelvin above 1 GHz.

The strength of a discrete source whose angular size is smaller than most antenna beamwidths is usually specified in terms of its *flux density*. This is a measure of the total power received at the Earth from the source in a unit area and bandwidth. The conventional "flux unit" (f.u.) is 10^{-26} W m^{-2} (Hz)$^{-1}$. The flux density, S, of a radio source can be characterized by a power law in frequency ν

$$S = k\nu^{\alpha}, \qquad (1)$$

where k and α are constants. For most radio sources, α is -0.7 to -0.8. If α is not constant, the source is said to have a "curved" spectrum.

Since α is usually negative and the brightness temperature of the sky decreases with frequency, antenna temperatures generally fall with increasing frequency. At high frequencies low noise techniques are extremely important while at longer wavelengths angular resolution is the most important consideration.

In the past few years the greatest technical advances have been made in three areas: (1) The surface tolerances of parabolic telescopes with apertures in the 100 m range have been improved; this allows operation at wavelengths of a few centimeters. A few years ago most telescopes of such sizes were limited to wavelengths greater than about 20 cm. These improvements, along with the development and common use of low noise preamplifiers, have resulted in an order of magnitude increase in the frequency range available for sensitive observation. This has led to the discovery of spectral lines from many interstellar molecules and to rapid development of the new field of interstellar chemistry. (2) Very high angular resolutions have been achieved. Radio sources can now be completely mapped with angular resolutions of a few arcseconds and some partial information can be obtained concerning fine structure to a limiting resolution of about 10^{-3} arcsec. A wealth of information concerning the detailed structure of radio sources is becoming available. (3) Observations from above the Earth's atmosphere have become available. The entire electromagnetic spectrum from zero hertz to the most energetic gamma rays can now be examined in at least a rudimentary fashion. This promises to revolutionize our knowledge of astrophysics. Already, correlations between the radio and the x-ray emissions from highly energetic electrons have been found. The shells of gases expelled from stars which have undergone supernova explosions have been observed optically, in the decimetric wavelength range, and at hectometric wavelengths. Millimeter wavelength and infrared observations provide clues concerning completely unforeseen processes in the nuclei of galaxies.

B. Single Telescopes and Spectroscopy

A single radio telescope has the virtue of simplicity, easy steerability, and great flexibility in wavelength. These characteristics give rise to a wide range of applications. The angular resolution achievable with a single telescope is limited to about one arcminute. Deflections of the structure due to gravitational, thermal, or wind loading effects generally combine to limit either the useful aperture or the minimum wavelength, so that single steerable telescopes can be no more than a few thousand wavelengths in diameter. This implies beamwidths of an arcminute or more, and the most interesting structural features of many types of radio sources are unresolved by such beamwidths. Different techniques are therefore required to obtain higher resolution, and these will be described in the next section. On the other hand, high resolution instruments are usually restricted in their applications, each being designed for specialized purposes.

Single telescopes have been widely used for mapping extensive regions of the sky at various wavelengths, both in the continuum and in the stronger lines. Aperture synthesis techniques are now taking over much of the mapping work. This is especially the case for continuum studies; the use of these techniques for mapping of spectral line sources is only just beginning. Most of the pulsar work has been done with single telescopes. However, the principal application of single dishes now and in the foreseeable future is in the field of spectroscopy, i.e. in the discovery and study of a wide range of interstellar radio lines. In fact, all the detection and searching for lines as well as the greater part of the work on the characteristics of spectral line sources has been done with single dishes. These studies require the combination of a large collecting area and the ability to operate over a large range of wavelength. The particular suitability of a single dish comes from the ease with which receiver changes can be made when only a single feed point is involved.

In the 1960's, the largest steerable dishes were those at Jodrell Bank, England [250 ft (76 m) in diameter], and at Parkes, Australia [210 ft (64 m)]. Larger dishes with limited steerability were built at Arecibo, Puerto Rico [1000 ft (305 m)], and Green Bank, West Virginia [300 ft (91 m)]. These were used in their original form down to wavelengths of 18, 6, 50, and 21 cm, respectively. All have been, or are being, resurfaced to extend their operating ranges to somewhat shorter wavelengths. The biggest steerable telescope has been recently completed at Bonn, with a diameter of 100 m and an expected minimum wavelength near 2 cm. Some large telescopes in current use are shown in Figs. 1 through 5.

The present trend is towards the development of bigger millimeter-wavelength telescopes, as the greatest interest in searching for new interstellar spectral lines is now in this wavelength range. The biggest mm-wave telescopes at present are the 36 ft (11 m) dish of the National Radio Astronomy Observatory at Kitt Peak, Arizona, and the 22 m instrument at the Crimean Astrophysical Observatory. The latter however has not yet been greatly used for spectral line work. Several countries are planning the construction of bigger and more precise mm-wave dishes, and the limiting factors involved in telescope accuracy are being very carefully examined. For example, the principle of homologous deformation (*2*), in which a structure maintains similarity of shape under gravitational loading while changing its zenith angle, has been already used to some extent in the Parkes and Bonn telescopes; it will be the fundamental basis of design in future installations. The status of single-dish technology has recently been reviewed by Findlay (*3*).

Single telescopes have normally been paraboloids, but the Bell Telephone Laboratories have had great advantages from a horn which they have used at 21 cm and other wavelengths. A well-designed horn picks up very little thermal radiation from the ground nearby, and so it can form part of a very

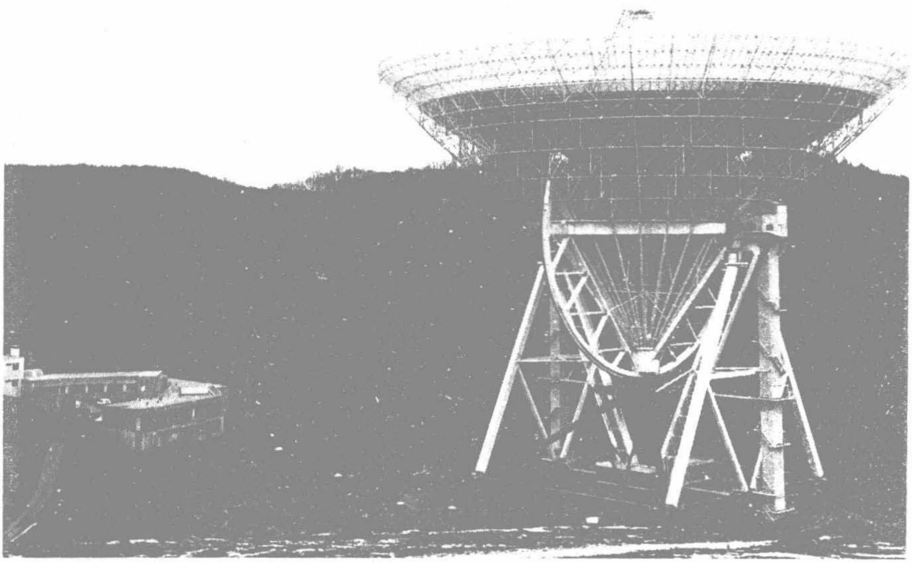

FIG. 1. The 100 m telescope of the Max-Planck-Institut für Radioastronomie at Bonn. This recently completed antenna is the newest major facility in radio astronomy.

low noise system. Also, the performance of a horn is accurately calculable, which is important for absolute flux or brightness measurements.

Historically, radio astronomy receivers have been developed for special needs at particular wavelengths, each covering only a small frequency range. Technical developments are pushing down the lower limits of wavelength, and the needs of spectral line investigators are closing the gaps in the available frequency coverage. Before long, receivers with good sensitivity should be available over the whole wavelength range accessible from the ground.

In the quest for high sensitivity, parametric amplifiers have been extensively used in many frequency ranges. Masers have received less attention, in spite of their inherently low noise properties, partly because of their greater complexity under field conditions, and partly because the pickup of thermal emission from the ground and from feed system losses prevents the full potentiality of the maser from being realized. Experiments are now being carried out at the shortest wavelengths with detectors of the style used in the infrared, such as indium antimonide crystals and Josephson detectors.

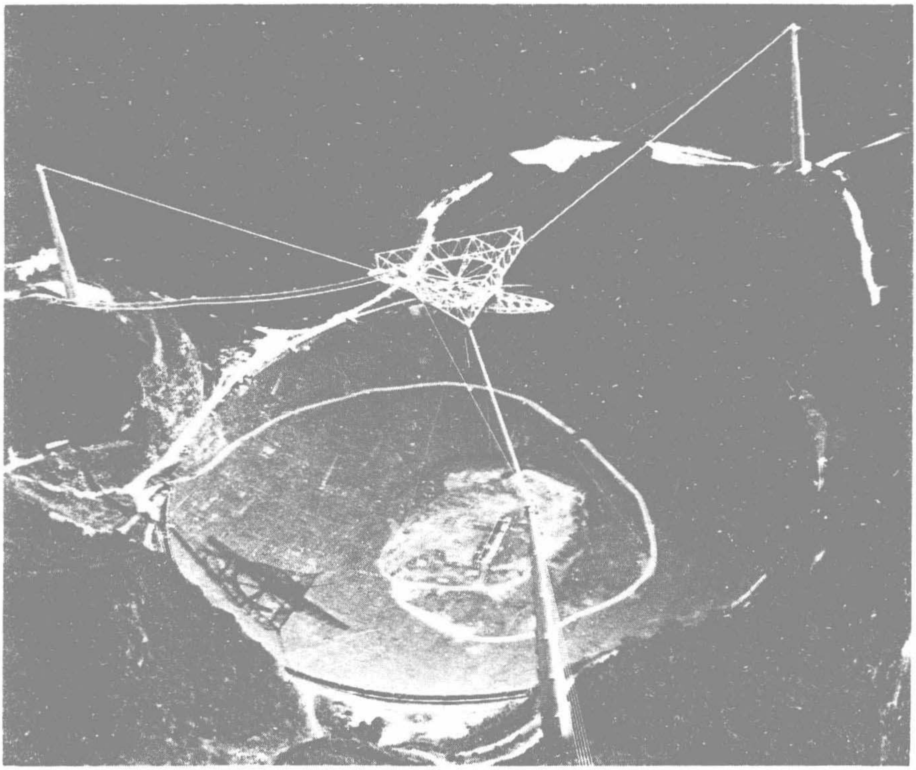

FIG. 2. The Arecibo 1000 ft (305 m) antenna. In this antenna the spherical reflector surface is immobile and supported by the Earth. Correction for spherical aberration is performed by the feed and beam steering to zenith distances of 20° is accomplished by movement of the feed system only.

At millimeter wavelengths, the atmosphere is a limiting factor, and there are only a few spectral "windows" where the absorption due to water vapor and oxygen is low enough to allow successful ground-based observations (Fig. 6). Everywhere in this wavelength range dry climates and mountain sites offer an advantage, but observations between the windows or at even shorter wavelengths will have to be carried out from above the atmosphere. In this case, large structures will be required and an eventual observatory on the Moon might be utilized.

Successul work in microwave spectroscopy depends on a good blend of telescope performance and electronics expertise. The great importance of the latter is indicated by the fact that most of the known lines (except for the early discoveries of HI, OH, NH_3, and H_2O) have been found with the facilities of one organization, the National Radio Astronomy Observatory, at Green Bank and Kitt Peak.

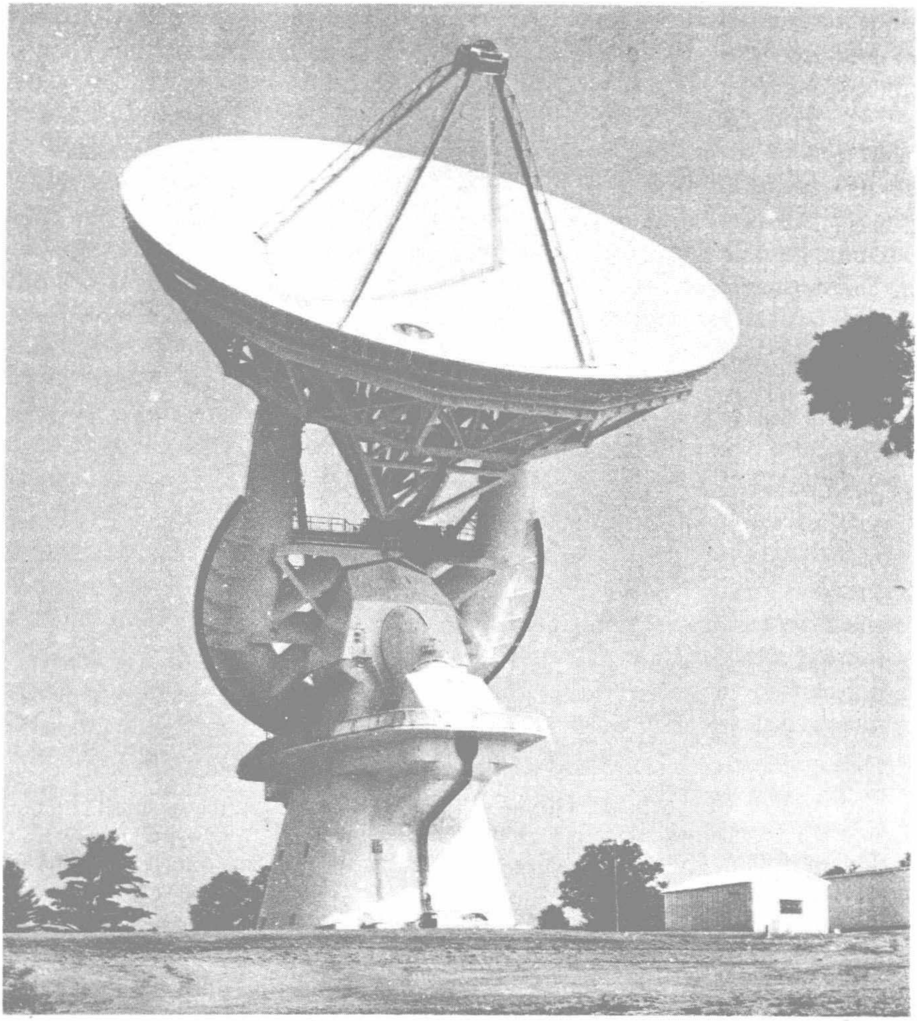

FIG. 3. The NRAO 140 ft (43 m) telescope at Green Bank, West Virginia. This telescope has been operated to wavelengths of 1 cm for the discovery of numerous molecular lines.

Radio astronomers must share an already overcrowded radio spectrum with many other users. The appropriate international organizations have recognized radio astronomy as a "service," entitled to receive some protected bands in the frequency allocation tables. In this way, a varying amount of protection has been obtained at some widely separated places in the continuum, and in narrow bands containing some of the most important lines. Good cooperation has generally been achieved in keeping these bands clear,

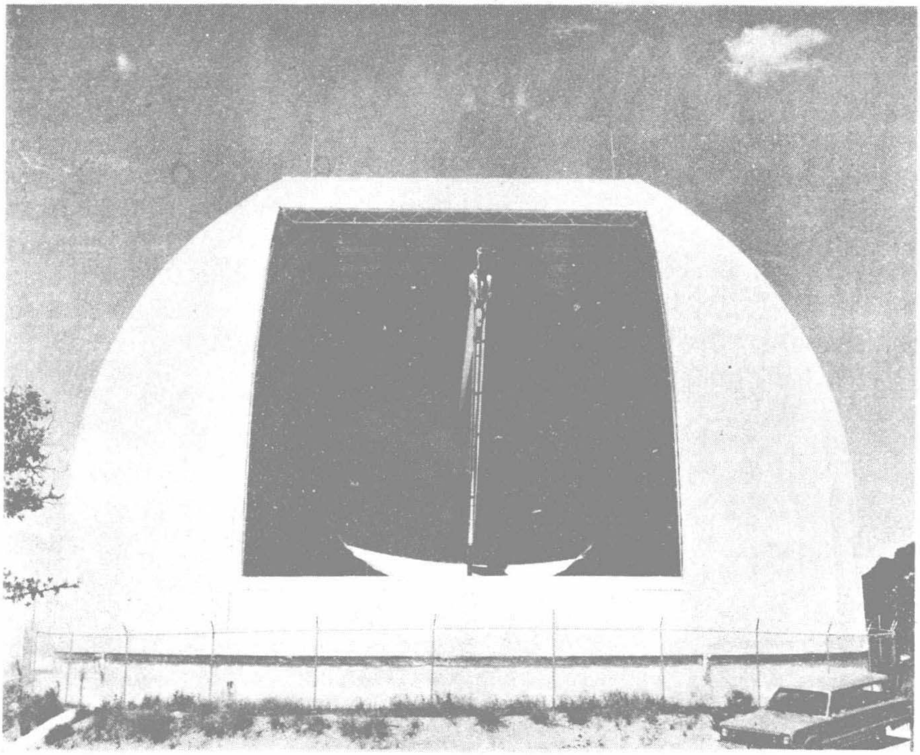

FIG. 4. The NRAO 36 ft (11 m) telescope at Kitt Peak, Arizona. This instrument operates to 3 mm wavelength. It has yielded observations of many millimeter wavelength radio sources.

on a worldwide, national, or sometimes a local basis. However, as the number of detected lines increases there will be growing difficulty in avoiding interference. Geographical isolation of observatories can help a great deal, but the greatest potential threat comes from the growing number of transmissions from Earth satellites or other space vehicles. Frequencies used for these services will be essentially unusable for radio astronomy anywhere on Earth, and there will come a time when some radio interstellar lines will be detectable only from the far side of the Moon. Radio astronomy needs the cooperation of all other groups who make use of the radio spectrum in order to survive as the vigorous science that it is today (*4*).

C. High Resolution Techniques

The attainment of higher angular resolution has occurred through the development of four radically different types of technique; aperture synthesis,