13 November 1959, Volume 130, Number 3385 SCIENCE

National Radio Astronomy Observatory

The early history and development of the observatory at Green Bank, West Virginia, are reviewed.

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On 17 October 1957, a group of several hundred representatives of science, education, and federal, state, and local governments gathered in the high-school auditorium at Green Bank, West Virginia, to participate in ground-breaking ceremonies for the National Radio Astronomy Observatory. This event followed by two weeks the launching of the first artificial satellite, on 4 October, and in some minds the Green Bank activities were an indication of the immediate reaction of the United States to this tremendous step into the space age. The near coincidence of these dates is interesting, but no significance should be attached to it. The ground-breaking ceremonies at Green Bank were only one step in a long train of events which hark back to the discovery of radio astronomy by Karl G. Jansky in 1932.

Early History

Accounts of Jansky's discovery have been recorded on numerous occasions (*1*). In brief, Jansky was studying the effects of atmospheric radio interference on transatlantic communications at the Holmdel, New Jersey, station of Bell Telephone Laboratories, when he noticed certain signals with peculiar characteristics that could be explained only if they were originating from outside the earth's atmosphere in a direction fixed in space. Jansky's equipment (Fig. 1), which operated at 14.6-meter wavelength, was not capable of extreme directional precision, but Jansky was able to fix the position of this celestial radio transmitter in the sky at roughly 18 hours of right ascension and $-10°$ declination, which is approximately toward the center of our own galaxy or Milky Way system.

Little attention was paid to Jansky's discovery by professional astronomers, and throughout the 1930's the only continuing activity in this new branch of astronomy was carried on by Grote Reber, operating equipment designed and built by himself at his home in Wheaton, Illinois (Fig. 2). Reber's results were published in a series of papers that clearly showed the existence of sources of radio interference or static in the plane of our Milky Way (*2*).

During World War II, tremendous strides were made in developing electronic components, particularly for radar, and during this time the sensitivity of the receivers for such equipment was improved greatly over that of the receivers available to Jansky and Reber. Throughout the war years numerous persons, by chance or otherwise, made astronomical observations, but time was not available to pursue an orderly investigation of the astronomical phenomena (*3*). When hostilities ended, however, scientists returned to examine these phenomena, and by the late 1940's, centers of radio astronomy had been established in several countries, including particularly England, the Netherlands, France, Australia, Canada, and the United States. Scientists behind the Iron Curtain were also interested in this new branch of astronomy, but their areas of activity and interest were not immediately known to us in the United States.

During the occupation of the Netherlands in World War II, a young Dutch radio astronomer, H. C. van de Hulst, predicted from theoretical considerations that a radio emission at a wavelength of approximately 21 centimeters should be produced by the neutral hydrogen in our galaxy with sufficient intensity that it could be observed with equipment then deemed feasible. The first observations of this hydrogen radiation were made by H. I. Ewen and E. M. Purcell at Harvard University (*4*). Because hydrogen is the most abundant element in the universe, this observational confirmation of van de Hulst's prediction was of great significance, because, essentially, a signature had been found amid all the random noise or static coming to us from outer space. For readers more familiar with the optical portion of the spectrum, it should be noted that the 21-centimeter hydrogen emission is analogous to the absorption lines in the solar and stellar spectra, which are also identified with chemical elements on the earth.

This impetus to astronomy had prompt effects in a number of countries. The British, spurred on by A. C. B. Lovell, had started to build a radio telescope with a steerable paraboloid 250 feet in diameter. They recognized the significance of the hydrogen radiation and forthwith proceeded to revise the design for the giant telescope at Jodrell Bank in order that it might be used to make observations at this rela-

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tively short wavelength. In the Netherlands, work was started on a 25-meter telescope, and in Australia preliminary plans were initiated for the design of a large steerable paraboloid. Meanwhile, in the United States, the 50-foot telescope of the Naval Research Laboratory was the only large instrument capable of efficient work at wavelengths as short as 21 centimeters. Other institutions, including Cornell University, Harvard College Observatory, the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, and Ohio State University, had active programs in radio astronomy, but none of these institutions were planning construction of a steerable paraboloid larger than the 50-foot instrument at the Naval Research Laboratory.

This was essentially the state of affairs in January 1954 when a conference was called in Washington, jointly sponsored by California Institute of Technology, the Carnegie Institution of Washington, and the National Science Foundation (*5*). This conference was called to take advantage of the presence in the United States of several distinguished radio astronomers from other countries. At the conclusion of the conference it became clear to the United States scientists that radio astronomy in the United States was not keeping up with progress being made in other countries, and that unless this trend were reversed, the United States would drop further and further behind, into a most unsatisfactory, secondary position. This state of affairs was all the more deplorable in view of the noteworthy contributions from the United States: Jansky's discovery of radio astronomy; Reber's exploratory observations; advances in electronic technology; and the first observation of the 21-centimeter hydrogen emission by Ewen and Purcell. There was general agreement that the principal need in the United States was for improved observational equipment having capabilities at least as good as those that were already, or soon would be, available in other countries.

At this point the National Science Foundation (*6*) entered the picture. The foundation is a unique agency in the federal government. It was founded by an act of Congress in 1950 to insure that science would have proper attention at the federal level of government, and, particularly, to provide a mechanism for supporting those areas of science in which it appeared that the United States was lagging behind other countries. Within the foundation the plight of the United States radio astronomer was recognized, and in order to provide a mechanism for giving more attention to the problem, an advisory panel for radio astronomy was established, in May 1954, with M. A. Tuve serving as chairman.

During that spring there were discussions among radio astronomers in the United States on the pressing problem of obtaining better observing facilities. Some colleges and universities decided to build radio telescopes as part of their academic establishments. Other institutions tentatively suggested pooling their efforts, thereby making possible the construction of larger, more costly facilities than could be afforded singly. During such discussions between B. J. Bok, J. B. Weisner, J. P. Hagen, and other representatives of Harvard, Massachusetts Institute of Technology, and the Naval Research Laboratory, Julius A. Stratton suggested the establishment of a radio observatory to be operated on behalf of all United States scientists; a somewhat analogous research institution was already in existence at the Brookhaven National Laboratory, which is operated by Associated Universities, Inc., under contract with the Atomic Energy Commission (*7*). The Brookhaven National Laboratory is essentially a postgraduate research center active in all domains of science related to nuclear energy. A permanent staff of scientists is augmented by visitors who come for terms varying from a few weeks to as much as a year or more.

Acting on Stratton's suggestion, a group of scientists directed informal inquiries to Associated Universities, seeking assistance in bringing the matter to a point at which a decision could be made on the feasibility of establishing such an observatory. A conference was held in New York on 20 May 1954, attended by representatives of astronomy and other closely related fields of science and engineering, at which this question was formally raised, in a memorandum, "Survey of the Potentialities of Cooperative Research in Radio Astronomy," prepared on 13 April 1954 by D. H. Menzel, director of Harvard College Observatory. The conference concluded that a three-step program was in order, involving: (i) a feasibility study on objectives and organization, sites, and facilities; (ii) final design of facilities and equipment; and (iii) construction of the observatory. The National Science Foundation representatives agreed with the others present that a national observatory would solve many of the problems confronting workers in radio astronomy in the United States, and a tentative commitment was made on behalf of the foundation to support a feasibility study on the establishment of such an observatory. On the basis of the 20 May conference and subsequent discussions with Menzel and Tuve, L. V. Berkner, president of Associated Universities, organized a steering committee for a feasibility study; John P. Hagen served as chairman, and other members were

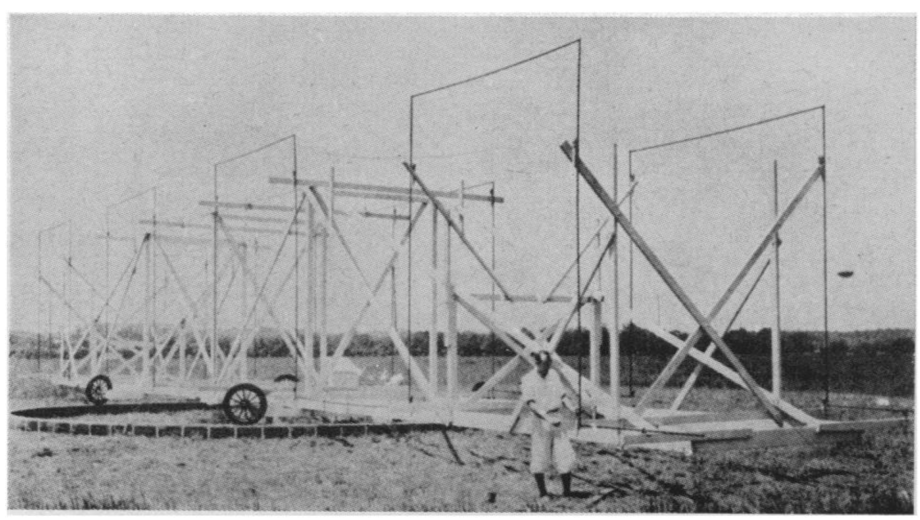

Fig. 1. Karl G. Jansky and his 14.6-meter rotatable directional antenna. The important discovery that some stars produce radio waves was made by Jansky, a Bell Laboratories scientist, while he was exploring atmospheric disturbances which it was thought might interfere with transoceanic telephone service. His discovery, in 1932, marked the birth of the fast-growing science of radio astronomy. [Courtesy Bell Telephone Laboratories]

Bart J. Bok, Armin J. Deutsch, Harold I. Ewen, Leo Goldberg, William E. Gordon, Fred T. Haddock, John D. Kraus, Aden B. Meinel, Merle A. Tuve, Harry E. Wells, and Jerome B. Weisner. Throughout the feasibility study the steering committee gave valuable assistance and advice. During the second year of the study, Bart J. Bok served as chairman of the committee.

Meanwhile, the trustees of Associated Universities had authorized the expenditure of $2000 to defray preliminary expenses, and this made possible a meeting of the steering committee in July 1954. The committee reviewed a research proposal, to be made to the National Science Foundation for a grant to support the feasibility study. The principal objectives of the study were as follows: to make (i) a survey of opinion among scientists who are now active or interested in the field of radio astronomy, in order to set up a program of research objectives; (ii) an examination of the various suggestions made regarding the major items of equipment, to gain some understanding of the technical problems of design and construction that would have to be solved, and to be able to compare performances and costs; (iii) an examination of possible sites and their comparative desirability, judged by the requirements of the research program and staff, the availability of housing and transportation, meteorological factors, sources of radio interference, accessibility to other centers of intellectual activity, and any other factors shown to be important by the first two parts of the study; (iv) an examination of any other expenditures essential to the establishment of a functional radio astronomy observatory—for example, access roads, power lines or power generating equipment, and laboratory buildings; (v) preliminary estimates of the costs involved in phase ii, preliminary proposals of methods to finance these costs, and consideration of how much time to allow for completing this phase; and (vi) preliminary estimates of the organization and staff necessary to operate the completed facilities and proposals on budgets, personnel policies, and methods of promoting cooperation among interested institutions.

On 18 February 1955, the National Science Foundation granted $85,000 to Associated Universities to support the feasibility study, and active work started. I served as principal investigator or project director.

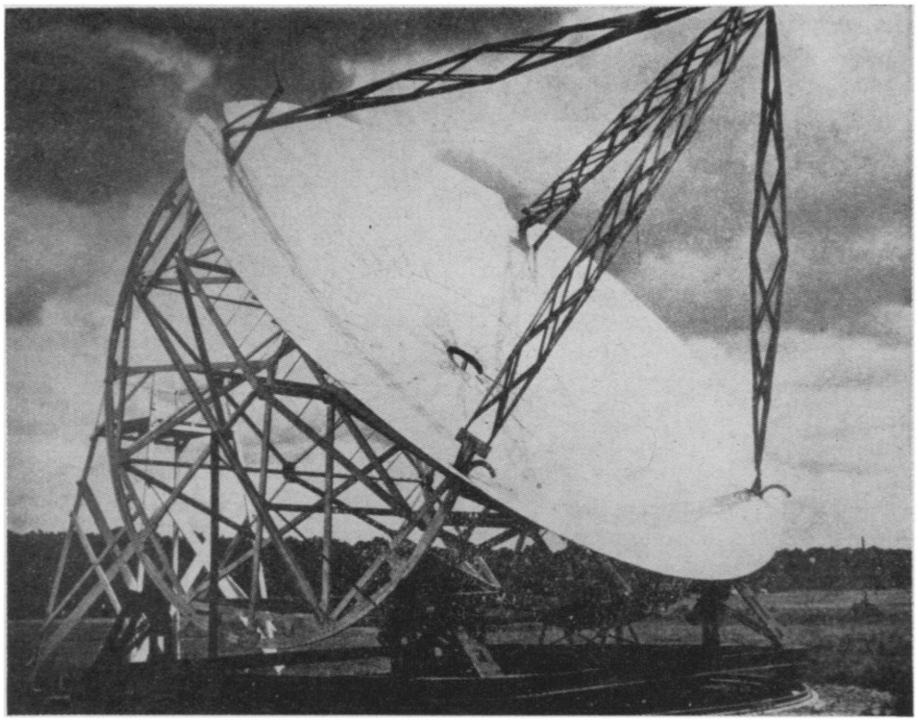

Fig. 2. The Reber telescope. Grote Reber designed and built this telescope at Wheaton, Illinois, soon after the announcement of Jansky's discovery. The telescope was moved to the National Bureau of Standards in the early 1940's, where this photograph was taken by Reber.

The study efforts were channeled into three areas: (i) organization and operation; (ii) facilities; and (iii) site. All of these obviously would be affected by the research objectives for the observatory. In order that this question might be crystallized promptly, early in the spring of 1955 B. J. Bok contacted all of the United States scientists engaged or interested in radio astronomy, and from their comments developed a statement of research objectives. It was recognized that the observatory should provide facilities for research at long wavelengths; on the other hand, it was recognized that research tools for short wavelength were more costly, and that these, particularly, should be made available.

It was agreed that research at 21-centimeter wavelength should be pursued at the observatory, with radio telescopes having high gain and resolution, and that such research should include studies of the structure of our own and other galaxies, the hydrogen clouds associated with peculiar stars, globular clusters, and absorbing clouds of dust, as well as measurements of the Doppler red shift. Early work by F. T. Haddock and his colleagues at the Naval Research Laboratory had revealed the possibility of making thermal emission studies throughout the microwave region. A critical problem was that of spectral classification of radio sources, based on measurements of the radio brightness at a number of wavelengths distributed over as wide a band as possible. Many research problems were suggested for learning more about the solar system. For some studies of the moon, planets, and sun, only receiving equipment is necessary; other studies require that the radio telescope be fitted as a radar, capable of transmitting as well as receiving.

From these considerations, the steering committee proposed that a series of steerable paraboloid telescopes be planned for the observatory. First in this series was to be an instrument (of 140-foot diameter, it was subsequently decided) with very high precision in its reflector surface, in its position indication, and in its capabilities for tracking celestial objects. The consensus was that such a precision instrument would be the most satisfactory all-purpose research tool. The committee felt that the observatory should also have an active instrumentation program, covering antenna theory and design, electronic tubes and other components, receivers, and information theory and data handling.

Underlying these research programs was a basic question of organization.

Should the observatory be a self-sufficient institution, or should it be divided, with its laboratory and supporting facilities located in some urban center and with only the observing equipment and a minimum of supporting facilities located at a remote site? Examples of this latter arrangement are quite common among optical observatories; for example, the Pasadena office and laboratories of the Mount Wilson and Palomar observatories, and the Tucson laboratory of the recently established Kitt Peak National Observatory. On the other hand, there are examples of self-sufficient observatories, both optical and radio. The probable isolation of the new observatory and the objective of continual interplay between the laboratory and the observing programs turned the decision in favor of a self-sufficient organization.

The organization of the observatory, its transition from a construction phase to an institution actively engaged in research, and the results of these researches are not treated in this article. It suffices to mention that Otto Struve has been appointed the first director. A permanent staff has been slowly built up, and these scientists, plus visitors, have carried on various astronomical observational researches since early in 1959. The prospects are bright for realization of our hopes for the National Radio Astronomy Observatory.

Site

The steering committee listed eight specifications for the site.

1) *Radio noise*. The level of radio noise or interference on wavelengths below 10 meters (frequencies greater than 30 megacycles per second) must be extraordinarily low. The fundamental sensitivities to which the radio telescopes can operate on any frequency are directly proportional to the ratio of external noise to desired signal. Therefore, the usefulness of the site is directly proportional to the amount of interference noise. To avoid noise the following conditions are necessary: (i) the number of inhabitants close by, within "view" of the telescopes, who might generate noise in the course of their daily work, should be as small as possible. (ii) The telescopes should not "view" high-tension power lines, which radiate radio noise through corona discharges or other means. (iii) The site should be in a valley surrounded by as many ranges of high mountains in as many directions as possible, to attenuate direct radio propagation from neighboring radio stations and to reduce diffraction of tropospheric propagation into the valley. (iv) The site should be at least 50 miles from any city or other concentration of people or industries and should be separated from more distant concentrations by mountain ranges. (v) The site should not be near commercial air routes, with aircraft frequently flying over, or in a region where commerce or industry are likely to intrude and grow in the future.

Quietness of the site must be assured for the future—for example, by appropriate zoning regulations to permit control over the installation and use of equipment, devices, or systems of any type that might emit radio noise.

2) *Location south*. The site should be as far south as possible, with a southern obstruction not exceeding a few degrees, to permit observation of the center of the Milky Way and other objects having southern declinations. A site anywhere in the United States could view all celestial objects in the northern celestial sphere but not all celestial objects in the southern celestial sphere. The more southerly the site, the more of the sky it can view.

3) *Location north*. The site should be in northern latitudes to permit researches that involve auroras, ionospheric scintillation, and polar blackouts.

4) *Ice and snow*. The site should not be in an area of excessive snow and ice that would create great snow and ice loads on the radio telescopes. Snow and ice need not be entirely absent, but they should be at a minimum to prevent excessive "down-time" of radio telescopes.

5) *Winds*. The site should not be in a region subject to violent winds and tornadoes. Because telescopes have large exposed areas, it is very difficult or impossible to construct them to withstand tornadoes or hurricanes. Moreover, strong winds are usually accompanied by periodic gusts of such force that they might cause dangerous vibration in large structural units.

6) *Humidity*. The climate should be reasonably mild, and high humidity is undesirable. Since the radio telescopes operate in the open, maintenance during excessively long cold periods becomes difficult and introduces problems of operation. Moreover, high humidity speeds the physical deterioration of materials and increases problems of electrical insulation.

7) *Size*. The site should be large enough to allow adequate separation among the installations of many types and sizes of telescopes and arrays; the latter require a relatively flat space of 1 or more square miles. A total area of as much as 5000 to 10,000 acres should be available for eventual use by the observatory.

8) *General surroundings*. Within the limits set by the basic requirements, the site should provide as many as possible of the attributes of a university campus. These include, of course, the physical means for research—laboratories and shops, libraries, and conference rooms. It would also be stimulating and helpful if scientists working in related domains of science were nearby—mathematicians, engineers, chemists, and physicists, to name only a few.

The site should provide or be accessible to housing and other necessary facilities for visiting scientists and for the permanent staff and their families. In addition, access to other amenities, such as stores, theaters, and recreational areas, is desirable.

Within the limits of the basic requirements, the site should be easy to reach by plane, rail, or automobile.

A ninth specification was added by the National Science Foundation's advisory panel on radio astronomy—namely, that the initial search be limited to within about 300 miles of Washington, D.C.

Some of the specifications are mutually contradictory or incompatible. It was therefore necessary to attach an index of importance to each. Beyond all question, the most important specification is the level of radio noise or interference at the site. Throughout all of the discussions about the site there was a strong sense that more was involved than merely the selection of a location for the new observatory. It could be foreseen that an excellent site would be a national asset that would become more valuable with the passage of years, *provided* that means could be promptly initiated to reduce, or at least to hold to the present levels, radio interference from man-made sources. Indeed, radio astronomers located near urban centers find that the present levels of interference forbid many relatively simple experiments. The steering committee envisaged a situation in which these scientists could move their apparatus to the observatory site and

Fig. 3. Helicopter view of the central portion of the National Radio Astronomy Observatory site, looking eastward from above the location for the 140-foot telescope. The 85-foot Howard E. Tatel telescope appears in the distance, and at the far right the works area and the incomplete residence hall and laboratory buildings may be seen. [Naval Radio Research Station, Sugar Grove, W.Va.]

proceed with their researches because of the low levels of interference, without using costly facilities of the observatory. With this potential use of the observatory site in mind, one finds a deeper significance in the specification for the size of the site.

The search procedure was relatively simple at the outset. The risk of hurricane-wind damage to the large radio telescopes eliminated the Atlantic coastal area from consideration. The U.S. Weather Bureau furnished data on all tornadoes recorded in the period 1916-1950. These data show that few tornadoes have occurred in a large region from northern Maine, through north and central New York, north-central Pennsylvania, and an oval-shaped area, about 300 miles long and 100 to 150 miles wide, extending in a southwest-northeast direction from eastern Kentucky and Tennessee, through West Virginia and the western edge of Virginia, almost to the Pennsylvania border. Of these relatively tornado-free regions, all but the last was eliminated because of problems of winter ice and snow, and because of distances of more than 300 miles from Washington, D.C.

The search area, thus limited, is characterized by mountain ridges that run in a general northeast-southwest direction. A wide valley or cove among these mountains would thus offer a site having many of the desired characteristics. In particular, the rough mountain terrain would guarantee a relatively low density of human population and, hence, of man-made radio interference. Furthermore, the mountains would serve as partial shields against some more distant sources of man-made interference, and against winds.

An *ad hoc* panel was organized, composed largely of persons having some direct knowledge of the search area, as well as an interest in the proposed observatory. Members of the *ad hoc* panel were H. L. Alden, J. E. Campbell, C. E. Cutts, E. R. Dyer, R. M. Emberson, H. I. Ewen, F. T. Haddock, J. P. Hagen, William Hardiman, R. A. Laurence, William McGill, W. A. Nelson, P. H. Price, C. K. Seyfert, and P. van de Kamp.

This *ad hoc* panel compiled a list of more than two dozen possible sites. Independent inquiries were also addressed to the U.S. Forest Service, the U.S. Park Service, the Geological Survey, the Tennessee Valley Authority, the Army Map Service, and the Real Property Disposal Office of the U.S. General Services Administration. Through the early stages of the search there was some hope that a suitable site could be found on land already owned by the federal government. This hope faded and died because the search showed that any oasis of relatively flat land had been discovered by settlers more than a century earlier, and that all these coves and valleys have been in private hands for many years.

Finally there were 30 site possibilities that seemed worthy of closer examination. Many were eliminated by visual inspection, usually because of existing urban and industrial centers close by.

The five most promising sites were then subjected to a careful and detailed study. Counts were made of the total population within 20-mile and 50-mile radii for each site. Studies were made of existing and planned air ports, air lanes, and related aviation installations. The American Telephone and Telegraph Company supplied information on existing and planned installations that might raise the radio noise levels nearby. Finally, arrangements were made with the Naval Research Laboratory whereby suitable receiving equipment was made available to engineers of Jansky and Bailey, Inc., for the purpose of making radio-noise measurements. The data from these measurements were sufficient to permit assignment of a relative number or index for interference levels at the five sites.

On the basis of these detailed studies, the 18th possibility on the list, at Green Bank, West Virginia, stood out. The radio-interference measurements showed that the Green Bank site was in a class by itself. Also, it was first on the basis of the population studies and first on the basis of the location of nearby towns and cities, and it was tied for first on the basis of aviation activities.

The Green Bank site area (Fig. 3) consists of a triangular portion of Deer Creek valley, about 4 miles across at the southern base and extending about 3 miles northward. The average elevation is 2700 feet above sea level. Mountains rise in multiple folds in all directions, many to heights of 4000 feet.

The village of Green Bank, from which the site gets its name, is situated in Pocahontas County. The largest urban center is Marlinton, the county seat, which is about 30 miles to the south. Green Bank is slightly more than 200 miles west of Washington, D.C., about midway between Roanoke, Virginia, and Pittsburgh, Pennsylvania, and about 170 miles east of Charleston, West Virginia.

The steering committee unanimously recommended the selection of the Green Bank site for the proposed observatory. The committee further urged that nearly all of Deer Creek valley at Green Bank be acquired, to insure better local protection against interference, or, if direct purchase of all the land was not feasible, that suitable controls be arranged to insure continued suitability of the site for the National Radio Astronomy Observatory.

The National Science Foundation adopted the steering committee's recommendation and authorized Associated Universities to obtain purchase options. These were obtained by Richard F. Currence, of Marlinton, acting on behalf of Associated Universities. By mid-spring of 1956 he had about 6000 acres under option. Purchase of more land had been recommended by the steering committee, but to have sought additional options would have required price agreements that seemed unreasonable, and the option program was halted.

After completion of the contract between Associated Universities and the National Science Foundation, in November 1956, for the establishment and operation of the observatory, one of the first tasks was site procurement. It was decided to let the options lapse and to arrange for the U.S. Army Corps of Engineers to acquire the site on behalf of the foundation and the federal government. This decision brought an agency with vast experience in land problems to the important task of acquiring the site. The valley was divided into regions or zones, and the Corps of Engineers was instructed to start acquisition proceedings in the central zone and work outward until a total expenditure of about $550,000 had been made. At that stage, no more land was purchased. The site, thus determined, consists of about 2700 acres, bounded on the east by state route 28 and the villages of Green Bank and Arbovale, on the south by a ridge that extends southwest from Green Bank, and on the west by the irregular boundary of the national forest lands.

At the same time that the option program was initiated, steps were taken to protect the site from future encroachment of man-made noise. Through the good offices of Arthur D. Little, Inc., contact was made with the governor of West Virginia, William Marland, and he and members of his staff were briefed on the proposed observatory. The West Virginia officials were favorably disposed toward the plan, and they thought that a zoning act could be drafted that would give the observatory protection against the encroachment of local, unlicensed sources of radio interference. West Virginia legislative leaders were briefed on the problem, drafts were discussed and revised, and a special session of the Assembly and Senate convened on 9 August 1956. The legislature enacted the Radio Astronomy Zoning Act, which to the best of our knowledge is the first legislation anywhere in the world designed explicitly to protect research in radio astronomy and allied sciences.

This special zoning act also protects the naval station at Sugar Grove, West Virginia, located a little more than 30 air miles east and north of Green Bank. The observational environment desired by the Navy at Sugar Grove is similar to that desired for the National Radio Astronomy Observatory, and the two groups have worked closely together in seeking to eliminate or reduce the levels of radio interference from man-made sources.

The West Virginia zoning act is directed toward unlicensed, local sources. The Federal Communications Commission has jurisdiction over licensed, intentional transmitters. (Within the federal government, the Interdepartmental Radio Advisory Committee plays a regulatory role among federal agencies that is analogous to the relationship of the Federal Communications Commission to commercial broadcasters.) The special radio-noise problem at Green Bank and Sugar Grove was taken to Washington. After thorough hearings and several reviews had been completed, special rules were promulgated to establish a radio quiet zone for both Green Bank and Sugar Grove. This quiet zone is rectangular in area, approximately 100 miles across in the east-west direction, and 120 miles from north to south. The special rules provide that civil applications for new or revised transmitters in the quiet zone shall be brought to the attention of the director of the National Radio Astronomy Observatory, who is responsible for bringing the matter to the attention of the Navy at Sugar Grove and submitting a coordinated reply or comment to the Federal Communications Commission. (In the case of applications by a governmental agency, the case is handled between Green Bank and Sugar Grove by the Navy.) To date, this arrangement seems to be working smoothly.

Radio astronomers know aircraft can seriously interfere with the work at Green Bank. A metal airplane without any electronic equipment on board can serve as a mirror to reflect into the radio telescopes signals from ground stations that otherwise would be shielded by the mountain ridges. When the nearby aircraft is equipped with electronic equipment, including beacon, navigational, and other types of transmitters, the situation becomes quite serious. The primary emissions from such nearby transmitters completely mask any celestial radio signals at the same frequency. In addition, spurious emissions, which may be at frequencies above and below those of the primary emissions and which are of such low intensity as to be of no consequence in normal communications and navigational applications, are frequently of the same order of magnitude as the celestial signals sought by the astronomers. The hydrogen emission at 21 centimeters, or 1420 megacycles per second, and the lower frequencies that result from a Doppler red shift, unfortunately lie in a band assigned to aviation purposes. Thus, for example, the spurious signals from aircraft flying in the neighborhood of Green Bank will interfere with this important astronomical observing band, even if the aircraft transmitter's primary frequency is carefully set away from the hydrogen frequency. Because of this situation. Associated Universities has asked the National Science Foundation to seek some measure of protection against aircraft interference at Green Bank.

Since the first observation of hydrogen emission by Ewen and Purcell, radio astronomers have recognized that they were the receiving station for a peculiar type of communication system. If both man-made transmitters and receivers were used by the scientists, they could apply for a license that would assign a frequency for the experimental work. In the case of radio astronomy, including also many branches of geophysics, the transmitter is a natural phenomenon, emitting at frequencies independent of man and his neat allocations and assignments. Hence, a normal type of communication license is not helpful to the research programs, unless it is carefully written to coincide with the frequencies of the natural emitters. Essentially such a special research license has been and is being sought by several groups representing radio astronomers and allied scientists. For a number of years both the International Astronomical Union and the International Scientific Radio Union have urged that special frequency bands be assigned for research purposes. In the United States, the Federal Communications Commission has recommended, in docket No. 12263, that the 1400-to-1427-megacycle-per-second frequency band be reserved in-

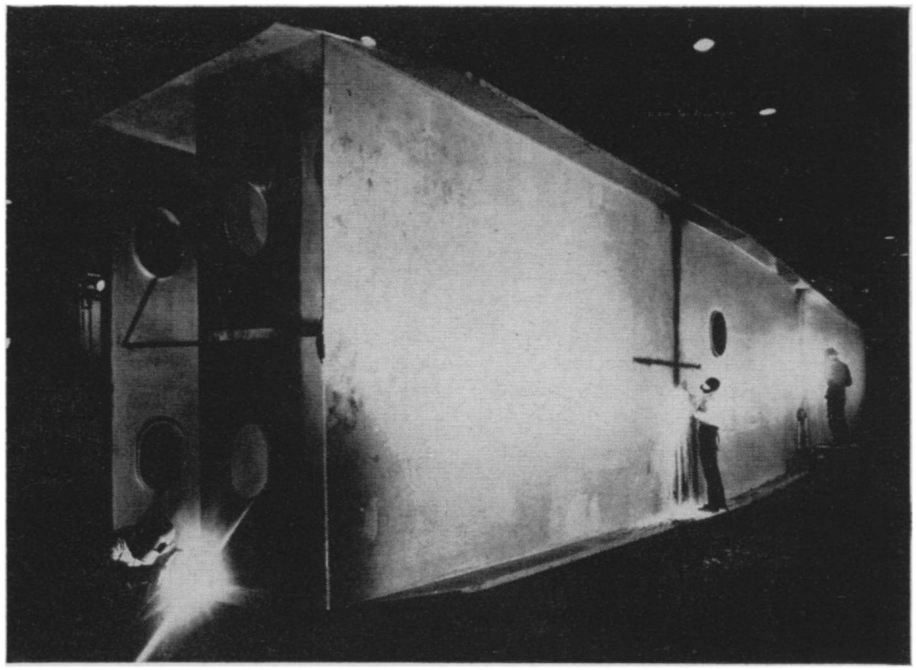

Fig. 4. Fabrication in the Bliss plant of part of the yoke for the 140-foot telescope. [E. W. Bliss Company]

ternationally for radio astronomical use.

This matter also found its way to the 9th Plenary Assembly of the International Radio Consultative Committee, meeting in Los Angeles during April 1959. The committee adopted the following recommendation (Docket No. 437-E [revised]): (i) that radio astronomers should be encouraged to choose sites as free as possible from interference; (ii) that administrations should afford all practicable protection to the frequencies used by radio astronomers in their own and neighboring countries; (iii) that particular care should be taken to give complete international protection from interference to observations of emissions known or thought to occur in the following bands:

Line	Line frequency Mcy/sec	Band to be protected Mcy/sec
D	327.4	322– 329
H	1420.4	1400–1427
OH	1667	1645–1675

(iv) that the bands allocated for standard frequency and time signal emissions at 2.5, 5.0, 10.0 and 20.0 megacycles per second should not include anything other than the standard frequency and time signal emissions, their use for reception in radio astronomy thus being permitted; (v) that consideration be given to securing adequate international protection of a number of narrow-frequency bands throughout the spectrum above 30 megacycles per second for the purpose of reception in radio astronomy (*8*); and (vi) that administrations, in seeking to afford protection to particular radio astronomical observations, should take all practicable steps to reduce to the absolute minimum amplitude harmonic radiations falling within bands of frequencies to be protected for radio astronomy.

To become effective, these recommendations must be adopted by the International Telecommunications Union. This treaty-making organization, in which the United States participates through an official delegation organized by the Department of State, is in session at Geneva as this article is being written. At Geneva, the requirements for scientific research are opposed by the pressures for allocations in the frequency spectrum to commercial, military, and other users. Obviously, an allocation of a portion of the frequency spectrum has great potential value, and the pressures at Geneva are correspondingly in evidence. It is understood that the U.S.S.R. favors the adoption of the International Radio Consultative Committee recommendations, but other nations are awaiting an indication of the United States' position. The official instructions of the United States delegation on this matter have not been made public. It is hoped that a strong, affirmative stand to protect basic research will be taken. The situation is critical because the International Telecommunications Union convenes only at about 10-year intervals. If protective measures are not taken now, research in radio astronomy and allied sciences throughout many portions of the frequency spectrum will be doomed during the next decade.

Site Planning and Development

As part of the feasibility study, the New York firm of Eggers & Higgins planned the development of a typical site in order to bring some realism to the estimates of the work that would have to be done. After the site in West Virginia was selected, it seemed better to engage a firm more familiar with the local building situation. Accordingly, under its contract with the National Science Foundation, Associated Universities engaged the firm of Irving Bowman & Associates, of Charleston, West Virginia, to perform the necessary architectural and engineering work at Green Bank. It was made clear that the special technical problems related to the radio telescopes and other research equipment were not a part of the Bowman assignment.

Advantage was taken of a relatively high ridge that extends across the central portion of the site in a general east-west direction. A plan was developed whereby most of the observatory buildings would be located at the eastern end of the ridge, close to route 28. Radio telescopes of the steerable paraboloid variety would be placed further west along the ridge, thus minimizing through distance any interference from automobile traffic on the highway. An access road was designed and constructed along the central ridge.

The electric power distribution system found in the Green Bank area was marginal, even if no additional loads were added by the observatory. The Monongahela Power Company advised that long-range plans called for a complete revision and modernization of the system. This revision was accelerated because of the observatory's requirements. As this report is being written, a new 66-kilovolt line is being constructed along the Greenbrier River, approximately 7 miles west of the site. A substation will feed a 12-kilovolt branch that comes east to the observatory. Where this feeder line comes over the nearest mountain ridge within "view" of the radio telescopes, the normal line is replaced with shielded cable in order to minimize radio interference. A second transformer station, located on the east bank of Deer Creek and naturally shielded from the radio telescopes, will convert from 12 kilovolts to the 4160-volt power that is distributed through an underground conduit system, parallel to the observatory road. Transformers are provided at each telescope, building, or other major installation. The total observatory power requirements, including those of the 140-foot telescope (described in more detail below), have been estimated at slightly more than 1 megawatt. The system being installed by the Monongahela Power Company is capable of delivering 3 megawatts.

Water at Green Bank is obtained from wells, usually drilled to a depth of slightly more than 100 feet. The supply is modest by commercial standards but should be adequate for the normal observatory requirements. The complex of residence hall and cafeteria, laboratory, and works area or shop buildings is served by three wells that supply an elevated 100,000-gallon tank. This arrangement offers some degree of fire protection and is certainly capable of handling the normal daily peak loads.

Building Program

During the feasibility study, the steering committee reviewed the types of activities that would be carried on at the new observatory and recommended that four types of buildings be included in the site development plan. First was the obvious requirement for a control building, or its equivalent, for each radio telescope, to serve as a base of operations for radio astronomers and to house the electronic equipment required for the receivers and data storage and processing. Second, a laboratory building in combination with administrative offices would be needed. Third, construction of shops for maintenance of the observatory, as well as for the construction of special equipment, was deemed advisable; and fourth, housing was required, particularly for visiting scientists.

As the Army Corps of Engineers acquired the site, some farm houses became available for use. The first of these was remodeled as a field office and has been in use since May 1957. Other houses were converted to provide office space for the radio astronomers and laboratory space for the physicists and electronic engineers. Other houses were remodeled to serve as family dwellings, and the largest has served as a dormitory. All of these farm houses will probably continue to be used for housing for a number of years. It is entirely unreasonable to expect scientific visitors to the observatory to make personal investment in a residence, and when these visitors come with families too large to be accommodated in the rooms or apartments available at the new residence hall, the only possible solution is to have an individual residence available.

The hypothetical site development undertaken by Eggers & Higgins as part of the feasibility study included preliminary plans for the buildings at Green Bank. These preliminary plans were subsequently revised in accordance with more precise estimates of the requirements for the observatory. Portions of three buildings have now been completed at Green Bank. A decision was made to combine all of the maintenance shops, warehousing, and similar activities in one building, of which one wing would be of special construction with high, clear spans to permit work to be done indoors on large and bulky equipment. Budget limitations would not permit construction of this special wing in the initial phase of the program. This so-called "works area" building was completed in the fall of 1958. Immediately upon its completion, the research equipment development department, under John W. Findlay, moved into a portion of the building. A conference room, carpenter shop, machine shop, and stock room were also provided, in addition to the necessary boiler room, electric power center, and area for the maintenance of work vehicles at the site.

The laboratory building envisioned by the committee for the observatory will have a central section plus three wings. One wing is to accommodate the special laboratories required in the development of the electronic equipment required for the research programs. A second wing will consist of a large auditorium, and the third wing will provide accommodations for research astronomers, as well as large computer facilities. The central part will accommodate all the administrative offices, including the offices of the director and his immediate staff and offices of some of the research astronomers, the library, several conference rooms, and the miscellaneous requirements for the research establishment. For budgetary reasons, only the central section of the laboratory was included in the first phase of construction. This will be ready for

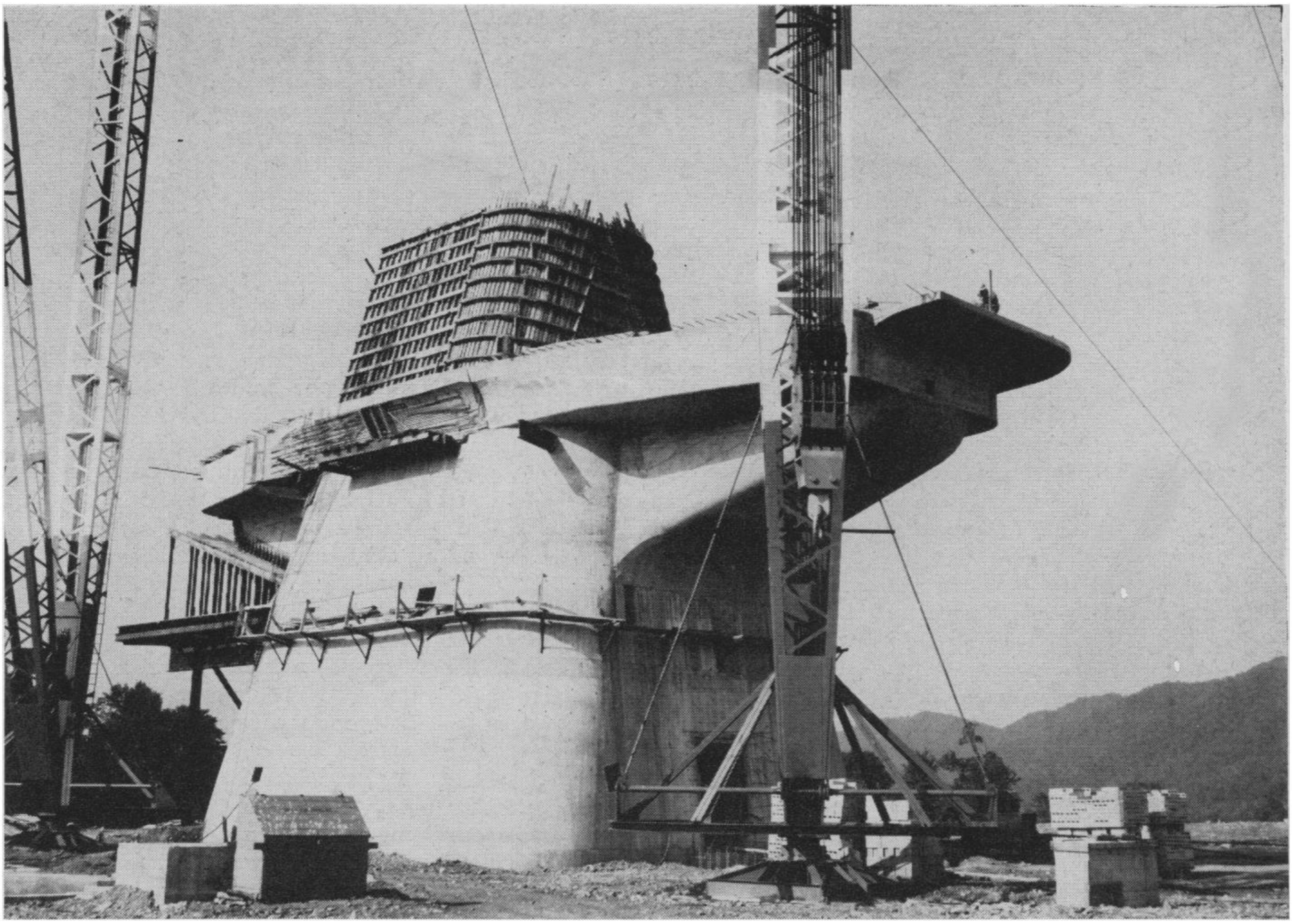

Fig. 5. View from the northeast of the nearly completed foundation for the 140-foot telescope. The two huge derricks will be used to lift the subassemblies of the telescope into position. [National Radio Astronomy Observatory]

occupancy early in the fall of 1959, when the research equipment development group will move from its temporary quarters in the works area building and will occupy most of the laboratory's first floor. A small engineering office concerned with the construction of the 140-foot telescope and with similar problems will also be housed on the first floor. On the second floor, Otto Struve will have his offices, adjacent both to the administrative department, under Frank J. Callender, and to the astronomy department, under David S. Heeschen.

The residence hall, which also will be ready for occupancy in the fall of 1959, provides four apartments on the first floor, together with a cafeteria that will be adequate to provide meals for the observatory staff, which, it is now estimated, will ultimately be something more than 100 persons. The second floor of the residence hall provides 16 bedrooms, each with an individual bath. It is planned that each of these rooms will be occupied by a single individual, but they are large enough to accommodate two people at times of special meetings and symposia. The ultimate plans for the observatory provide for at least twice this much residence hall space, as well as for additional residences to supplement the renovated farm houses.

Telescope Program

The feasibility study for the observatory ended with a proposal for a series of six radio telescopes of the steerable paraboloid variety, as follows: (i) a 600-foot telescope, the largest completely steerable instrument at the observatory; (ii) a telescope of 250- to 300-foot aperture; (iii) a 140-foot telescope of the highest attainable precision; (iv) two telescopes of the "standard" 60-foot or 84-foot size, both to be devoted to observational research programs; and (v) a relatively small (28 feet in diameter) telescope to be devoted primarily to pattern measurements and to the testing of receivers or other components under development at the observatory. It was also agreed that arrays and similar antenna devices would be installed at the observatory. However, these devices are less costly than steerable paraboloids, and it seemed best to treat them as expendable equipment that would be designed and built to meet the needs of particular research programs.

Early in the study it was recognized that radio astronomers require telescopes of high resolution, in order to be able to distinguish between two sources close together in the sky, and of high gain, to assist in the detection of the very weak celestial signals. Hence, a premium was placed on telescopes of large aperture. From purely structural considerations, the consensus of engineers consulted on the matter was that a paraboloid several thousand feet in diameter could be mounted to be fully steerable. But the cost would be very great. Accordingly, the steering committee decided that a structural design study should be undertaken for construction of a paraboloid of the more modest size of 600 feet. The work was undertaken by Jacob Feld (*9*). Feld was asked to consider a paraboloid surface true to within 1 inch over the entire 600-foot aperture, and true to within ⅝ inch over the inner 300 feet of the aperture, as minimum goals, and a tolerance of ¼ inch over the entire surface as the desired goal. This reflector was to be mounted in a manner such that it could be pointed anywhere in the sky with an accuracy of 7 seconds of arc, and the maximum permissible angular rate of motion was to be at least 30° per minute. The Feld study, which was completed in July 1955, showed that it was technically feasible to build a steerable parabolic telescope. But Feld also found that the extreme tolerances imposed difficult structural problems, and he concluded that the most practical telescope design would probably be one that would incorporate various types of servo devices to keep the components of the telescope structure in the proper shape and adjustment.

By the summer of 1956 it became clear that the Navy would probably build a large radio telescope at Sugar Grove that might be available on a limited basis for astronomical research. Accordingly, plans for constructing fully steerable paraboloids in the 300-foot and 600-foot size range have been virtually abandoned for the observatory. However, certain astronomical problems require telescopes with very large equivalent apertures, and thought has been given to the possibility of installing very large antennas that would offer the large aperture at the expense of sky coverage or steerability.

The 140-foot telescope was proposed as a general-purpose research instrument. The exact size of this instrument has no significance. The 50-foot telescope at the Naval Research Laboratory has a reflector that is sufficiently true to permit work at radio wavelengths as short as 1 centimeter. The precision instrument for the National Radio Astronomy Observatory was to be about three times as large and to be of such quality as to permit work at wavelengths at least as short as 3 centimeters.

The specifications for the instrument have gone through several revisions, each more specific than the former and intended to make the telescope more useful for a variety of research purposes. The 140-foot paraboloid will have a focal length of 60 feet and, hence, a focal-length/diameter (f/d) ratio of 0.43. For all positions and in winds up to 16 miles per hour, the surface is to be true to ¼ inch. The surface will be of aluminum plate, ¼ inch thick, and composed of 72 panels; the individual panels are to be true to $\frac{1}{16}$ inch. These panels are to be mounted on adjustable shoes. Hence, for one position of the telescope and in the absence of strong winds or thermal effects, the user should be able, with great patience, to adjust the entire surface to about $\frac{1}{16}$ inch. To measure or survey a surface as large as the 140-foot paraboloid with this degree of precision is a problem of some difficulty.

The supports that will hold the radio-frequency horns and other electronic equipment at the focus of the paraboloid are to accommodate a load of 1000 pounds in a manner such that gravity deflections will not exceed ⅛ inch as the telescope scans the sky.

The paraboloid will be supported on an equatorial mount that will permit approximately the same sky coverage that is available with the Palomar 200-inch optical instrument. Because the total moving mass above the polar axis will exceed 2000 pounds, for this axis an "oil-pad" or hydrostatic bearing system is specified. At the north end of the polar shaft, a segment of a 22-foot-diameter sphere will rest on the equivalent of three pads. At the south end of the shaft, a cylinder 5 feet in diameter will be held by four pads that may be adjusted somewhat like the jaws of a four-jawed chuck.

This combination of bearings offers a simple means of aligning the polar shaft parallel to the axis of the earth. The drive and control system is to have an over-all precision of 10 seconds of arc, for good environmental conditions and slow rates of motion. In addition to automatic tracking rates, to compensate for the diurnal rotation of the earth and for the slow motions of the sun, moon, and planets relative to the stars, the telescope will be capable of scanning areas of the sky at rates as high as 8° per minute and with a pattern similar to the scan of the picture on a television tube. The telescope will also be capable of faster rates, up to 50° per minute, which in some future experiments may be controlled in order to keep the telescope pointed at a fast-moving object, such as an artificial satellite. The requirements for close

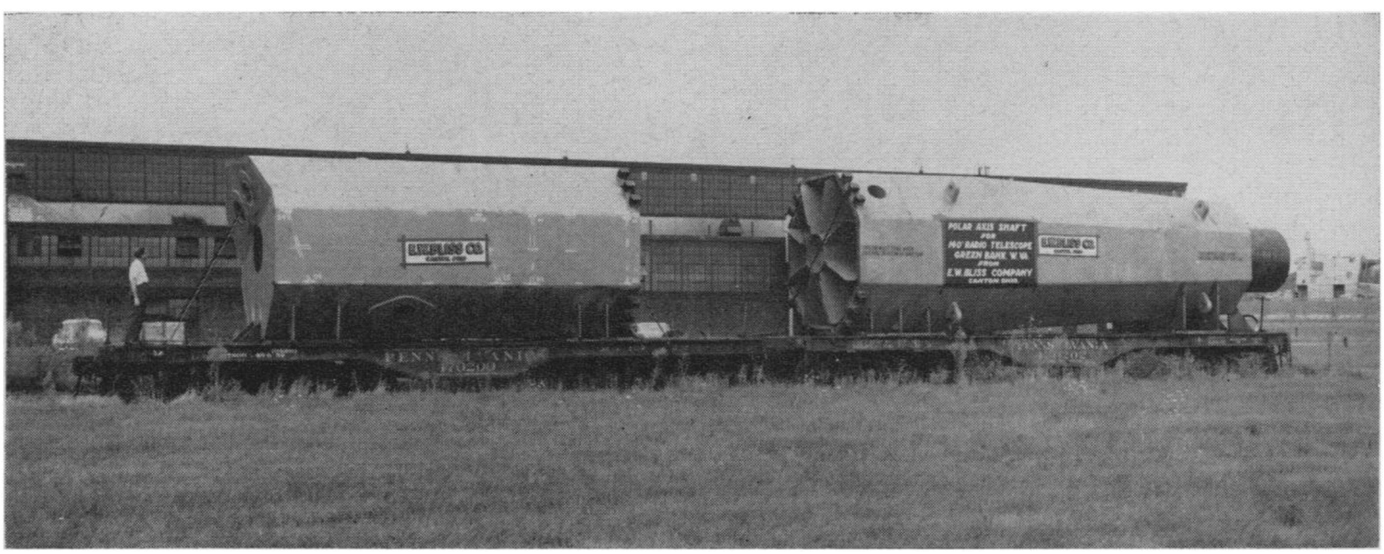

Fig. 6. Two sections of the polar shaft for the 140-foot telescope, ready for shipment from the Bliss plant to Green Bank, West Virginia. The shaft has to be sent in sections because the complete assembly will not pass through railroad tunnels along the route. [E. W. Bliss Company]

surface tolerances and great positional precision have placed a premium on rigidity of structure of the telescope.

The basic design of the telescope is the work of N. L. Ashton. An *ad hoc* advisory group consisting of T. C. Kavanagh (chairman), P. P. Bijlaard, J. G. Bolton, N. A. Christensen, A. M. Freudenthal, F. T. Haddock, M. B. Karelitz, D. P. Lindorff, E. F. McClain, E. J. Poitras, B. H. Rule, J. O. Silvey, and H. E. Tatel reviewed and assisted with the work. The Franklin Institute prepared the preliminary designs for the polar shaft bearings, and T. W. Brown developed a design for the drive and control system. The Canton division of the E. W. Bliss Company has the prime contract for construction of the telescope (Fig. 4). Darin & Armstrong, Inc., of Detroit, holds the subcontract for the field work at Green Bank. The Electric Boat Division of General Dynamics Corporation holds the subcontract for the drive and control system.

The foundation for the telescope, which will also serve as a control building to house the necessary auxiliary apparatus for the research scientists, is nearing completion at Green Bank (Fig. 5). Meanwhile, the first major component of the telescope, the polar shaft, was shipped from the Bliss plant on 29 August (Fig. 6). Because of the mammoth size of the instrument, final machining and assembly must be completed in the field.

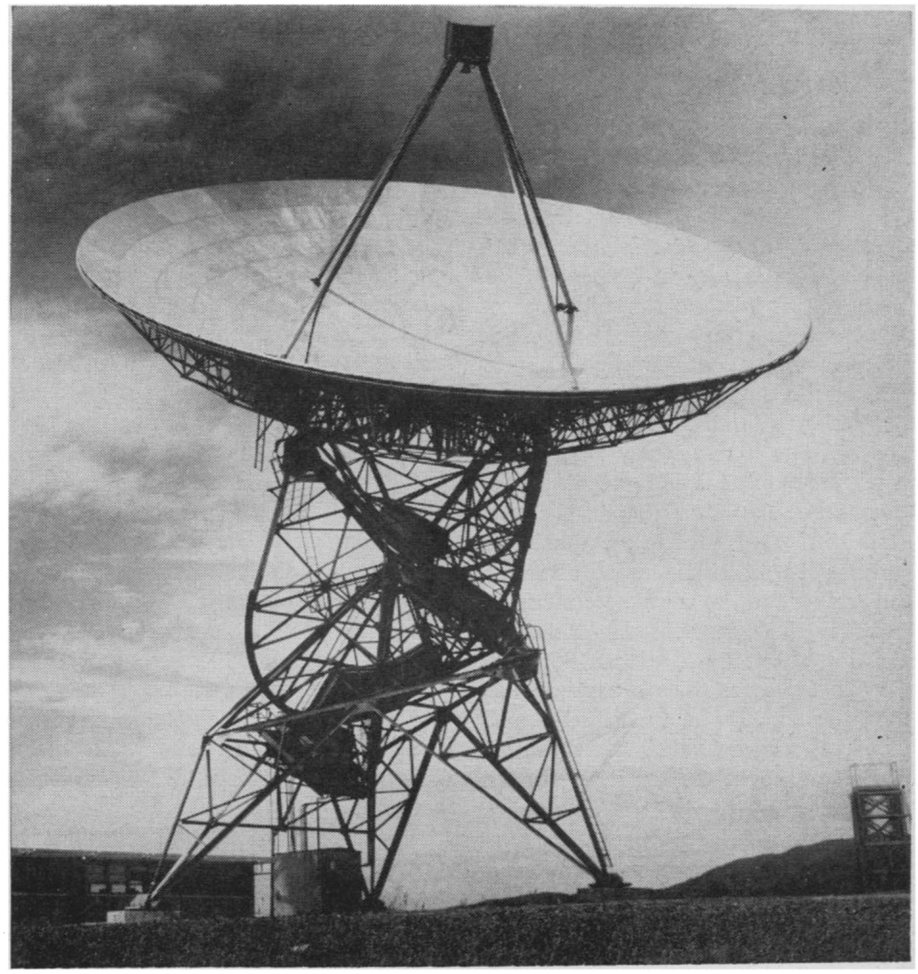

Fig. 7. The Howard E. Tatel 85-foot telescope. The control building is to the north. Some electronic components are mounted in the cylindrical container behind the horn feed at the focus. When the telescope is turned far to the east, an elevator provides access to the equipment at the focal point.

In order that astronomical observations could be started at the National Radio Astronomy Observatory prior to the completion of the 140-foot telescope, and in recognition of the expressed need for access to a telescope of intermediate size by scientists at several institutions, a decision was made to purchase an 85-foot telescope from the Blaw-Knox Company. This instrument (Fig. 7) is on an equatorial mount, the basic design for which was suggested by M. A. Tuve and his colleagues at the Department of Terrestrial Magnetism, Carnegie Institution of Washington. The late Howard E. Tatel was one of the principal contributors to this design, and the National Radio Astronomy Observatory telescope has been named in his memory. Analysis of the mount reveals that it is, essentially, a series of nearly equilateral triangles: there are three concrete bases in the ground, two on the north side and one at the south; the polar shaft is the axis of a right-circular cone, its apex coinciding with the south end of the polar shaft and its base forming the truss for the polar drive gear, the sides and base being built up of triangular elements; and the heavy frame from the north end of the polar shaft to the ends of the declination shaft forms an important triangular configuration. These are examples of the triangular systems to be found in the telescope structure. The reflector is a paraboloid with an f/d ratio of 0.43, the same as that of the 140-foot telescope. This coincidence is desirable because a feed designed to operate with one reflector will also match the other. The reflector surface is made up of panels covered with aluminum sheet. The tolerances are such that the telescope may be used effectively at wavelengths as short as 3 centimeters. The drive and control system provides an accuracy of about 2 minutes of arc; the power components for this system are located in a shielded metal house beneath the telescope.

Electronic components that must be near the pickup feed are located in a weatherproof container supported behind the focus of the paraboloid. Other electronic components are located in metal boxes or sheds mounted behind the reflector near the declination bearings. The receiver indicators, data storage and processing equipment, and related apparatus are located in the control building, which is on the north side of the telescope.

A dual feed, operating at 3.75- and 21-centimeter wavelengths, was obtained from Jasik Laboratories. At the start of observational work with the telescope, early in 1959, it was found that a 3.75-centimeter receiver, procured from Ewen-Knight Corporation, and a 21-centimeter receiver, procured from Airborne Instruments Laboratory, could be operated simultaneously, without noticeable cross interference. Subsequently, a 75-centimeter feed and receiver, both designed and built by the National Radio Astronomy Observatory research equipment development department, have been added, and simultaneous observations at three wavelengths are now routine procedure.

Four other instruments at Green Bank are worthy of note. Reber's original telescope was requisitioned by the government during World War II. In 1955 it was located, completely dismantled, at the Boulder laboratories of the National Bureau of Standards. Because of the historical significance of the telescope, arrangements were made through the National Science Foundation for the transfer of the telescope to the National Radio Astronomy Observatory. The telescope is now being completely refurbished and rebuilt under Reber's personal supervision. The telescope will be mounted in the altazimuth form, as it was at the Bureau of Standards, rather than in the simple meridian form, as it was built by Reber in Wheaton, Illinois, more than 25 years ago. This telescope has a parabolic reflector some 30 feet in diameter and, therefore, will be valuable for experimental purposes, as well as for its historical interest.

A precision 12-foot parabolic spinning reflector with an f/d ratio the same as that of the 85- and 140-foot telescopes was found at a British firm. This reflector has been mounted on an old radar turret that provides 360° of azimuth motion, but only some limited motion in altitude. The 12-foot reflector will be used primarily for test purposes, particularly for pattern measurements in developing feeds and supports.

The feasibility study pointed out that the observatory would have a responsibility for establishing standards of measurements for radar astronomy. Because a horn is more susceptible to theoretical calculations than any other type of antenna, J. W. Findlay is constructing a large horn as part of the observatory's standardization program. The horn will be 120 feet long, with a 13- by 17-foot aperture; appropriately, it has been called the "little big horn." The horn will lie in a fixed position, selected so that the bright radio source, Cas A, will transit once each day.

An interferometer, consisting of two 38- by 38- by 50-foot corner reflectors situated on a 2000-foot east-west baseline, has been in operation for about a year. The interferometer is designed for use at low frequencies to record such phenomena as the sudden emissions from Jupiter.

The receivers for the radio telescopes will always be subject to improvement and modification, to take advantage of improved electronic components and techniques, and to meet the particular requirements of the individual research programs. For these reasons, the receivers and related electronic components are generally treated as items in the annual operating budget, rather than as a part of the capital equipment. The basic observational data—receiver output, telescope position, and time—are available in digital form to permit storage and processing by electronic computers. The receiver output is also normally recorded in strip form to permit immediate visual inspection by the research scientists.

Summary

The existence of the National Radio Astronomy Observatory and the researches already accomplished there are the result of the foresight and wisdom of United States scientists, the National Science Board, and the Congress, who joined forces to make possible this new national asset. Continued effort will be needed to insure that the observatory will always have the finest possible research instruments and that the site will be a haven of radio quiet. Visiting scientists in some instances may wish to bring equipment with them for studying special problems. Within its means, the observatory will provide supporting facilities, including receivers and other electronic devices, computers, laboratories and shops, and housing. Scientists interested in more details concerning arrangements for visitors should direct their inquiries to the National Radio Astronomy Observatory, P. O. Box 2, Green Bank, West Virginia.

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7. Associated Universities, Inc., is a nonprofit corporation chartered by the Board of Regents of the State of New York to acquire, plan, construct, and operate laboratories and other facilities, either under contract with the government of the United States or its agencies or otherwise, for research, development, and education in the physical, biological, and social sciences, including all aspects of the field of nuclear energy and its engineering and other applications, and to educate and train technical, research, and student personnel. The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation. The work reported in this article is supported by the National Science Foundation.
8. The committee commented that radio astronomers in a number of countries have indicated their desire to use for this purpose one frequency band at each of the following approximate positions (not necessarily in harmonic relation):

Frequency (Mcy/sec)	*Bandwidth (Mcy/sec)*
40	± 0.75
80	± 1.0
160	± 2.0
640	± 2.5
2560	± 5.0
5120	±10.0
10240	±10.0

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