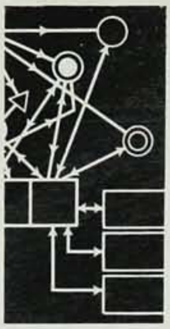

# INSTRUMENTATION FOR RADIO ASTRONOMY

by J. P. Wild

*Equipment used to detect and measure extraterrestrail radio emanations appears in a bewildering variety of sizes and shapes. Yet the various radiotelescopes can be classified by form and function under a very few heads, a procedure that allows intercomparison of performance and range.*

THE WORLD'S FIRST radiotelescope designed specifically for astronomical observations was built in 1937, a few years after Karl Jansky's pioneering discovery of radio waves from the Milky Way. The radiotelescope was conceived by Grote Reber[1] who built the instrument practically unaided in his own back yard at Wheatstone, Illinois. It consisted (figure 1) of a 31-ft parabolic reflector which focused the radio waves arriving from a small region of the sky onto a focal dipole. The signals were then amplified and detected in a high-frequency receiver and the output registered on a pen recorder. Reber's radio telescope (preserved at the National Radio Astronomy Observatory, Green Bank, W. Va.) stands as the prototype of the giant instruments that exist today.

Since the early discoveries the succession of spectacular advances in radio astronomy has been made possible largely through the attainment of greater and greater resolving power and sensitivity. The progressive improvements have come about through two lines of attack: the development of unified structures such as paraboloid mirrors of increasing size and precision; and the application—pioneered in 1946, independently by J. L. Pawsey[2] and Martin Ryle[3] and their colleagues—of the classical principles of interferometry to the development of arrays of increasing size and sophistication. The result is that now radio astronomical observations are being taken with an extraordinarily diverse variety of radiotelescopes. This diversity never fails to amaze and confuse the interested public, scientists in other disciplines, the funding agencies, and often indeed radio astronomers themselves. Perhaps we should regard the present era of radio astronomy as one of experimentation and rapid evolution; an unusual feature of radio astronomy is that this stage has to be passed through with instruments of enormous proportions.

In this review we shall consider the different classes of radiotelescopes in turn and attempt to assess their relative capabilities. In the course of this process we shall cite a few representative examples of actual major instruments in each class; each is now in operation or under construction. An attempt has been made to give reliable data on these instruments in a form suitable for intercomparison. (The author is indebted to D. E. Yabsley for his help in supplying the more elusive data.) These performance data (especially on angular resolution) may sometimes be at variance

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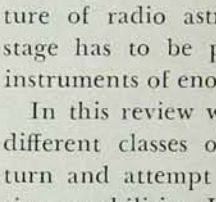


J. P. Wild graduated from Cambridge University in 1943. After service as a radar officer in the Royal Navy he joined the Division of Radiophysics of the CSIRO at Sydney, Australia, and is now director of the Division's Solar Radio Observatory at Culgoora.

with figures quoted by their designers; this arises partly because different criteria are used by different people but partly no doubt from the inadequacy of the data available to the author. The figures should therefore be taken as a guide to the different classes of instruments and not as definitive data on particular instruments.

Side by side with the development of antennas and systems for producing high resolving power has come the development of low-noise receivers. Their advance has played a vital part in the evolution of radiotelescopes, but that is a story beyond the scope of this review.

### *Antenna specification*

The performance of the antenna of a radiotelescope may be specified in the first place by three definite quantities, each of which depends on wavelength:

**Angular resolution.** This determines the detail of the radio "image" formed by the telescope. We shall specify it by the angle between two directions just discernible by the radiotelescope. This angle $\theta$ is conveniently given by the Rayleigh criterion that

$$\theta = \frac{\lambda}{D} \text{ radians}$$

$$= \frac{3438\lambda}{D} \text{ minutes of arc.}$$

where $\lambda$ is the wavelength and $D$ the total width of the aperture. The angle $\theta$ is approximately the half-power width of the beam; in the case of arrays with many antennas the beamwidth may be reduced to about $0.7\theta$ if a greater but reasonable side-lobe level can be tolerated.

**Efficiency.** With an ideal filled-aperture radiotelescope (such as a paraboloid mirror uniformly "illuminated" by its feed) radiation is received only through the narrow beam whose width is approximately the resolution angle $\theta$. Such an antenna is said to have an efficiency of unity. With other types of radiotelescope, the resolution of a filled-aperture instrument is attained by the use of an aperture of the same overall dimensions but of much smaller area; for example, a thin ring can be used to simulate a filled circle of the same diameter. Such apertures are called unfilled or *dilute*. Dilute apertures receive additional radiation from directions other than those within the desired beam, the extraneous radiation being cancelled out in the final image; nevertheless the noise fluctuations due to the extraneous radiation cannot be eliminated and so the signal-to-noise ratio of the image is inferior to that obtained with a filled aperture *in the same time and bandwidth* by a factor $E$, say. The factor $E$ is called the efficiency of the radiotelescope. As will be discussed later, it depends partly on the dilution factor of the aperture and partly on the number of image points being formed simultaneously.

**Comparative effective area.** With simple systems the amount of radiation received from a point source of given flux density is determined by the effective (collecting) area that the antenna presents to the incoming radiation. In an ideal filled aperture the effective area is equal to the geometrical area of the aperture. In the general case the corresponding area is given by the product: (area of the filled aperture required to produce the same resolution) $\times$ (efficiency $E$). This area, which depends (through $E$) on the number of image points being found simultaneously as well as the aperture, we shall call the "comparative effective area".

Thus in efficiency and comparative effective area we have two different measures of the sensitivity of a radiotelescope. The two are significant in different circumstances: for the detection of sources of large angular size (that is, more extended than the resolution beam) one seeks maximum efficiency; for small (unresolved) sources, maximum effective area.

To express this point quantitatively: The signal-to-noise ratio of a radio image of a weak "extended" source is given by

$$E \frac{T_S}{T_N} (t \, \Delta f)^{\frac{1}{2}}$$

Where $T_S$ is the brightness of the source averaged across the beam, $T_N$ the receiver noise temperature, $t$ the time of observation and $\Delta f$ the receiver bandwidth. On the other hand, the signal-to-noise ratio of an image of a weak "point" source, that is, one not resolved by the instrument, is given by

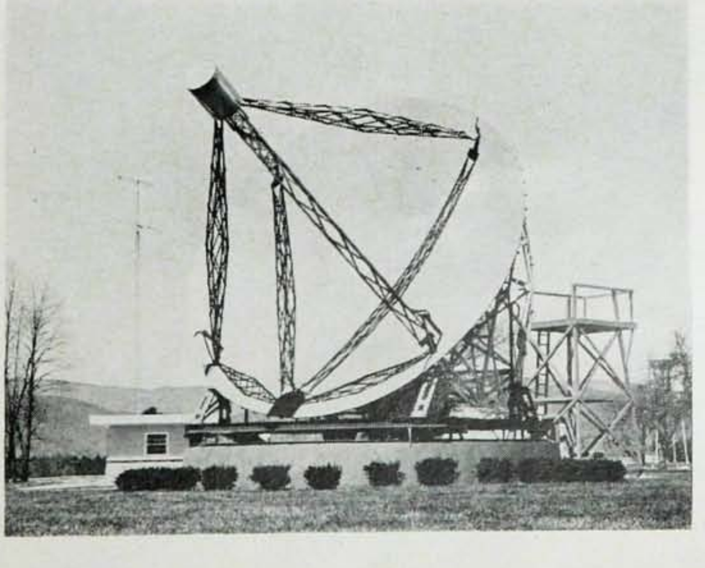
$$A \frac{S}{k \, T_N} (t \, \Delta f)^{\frac{1}{2}}$$

where $A$ is the comparative effective area, $S$ is the flux density of the source (one polarized component), and $k$ is Boltzmann's constant.

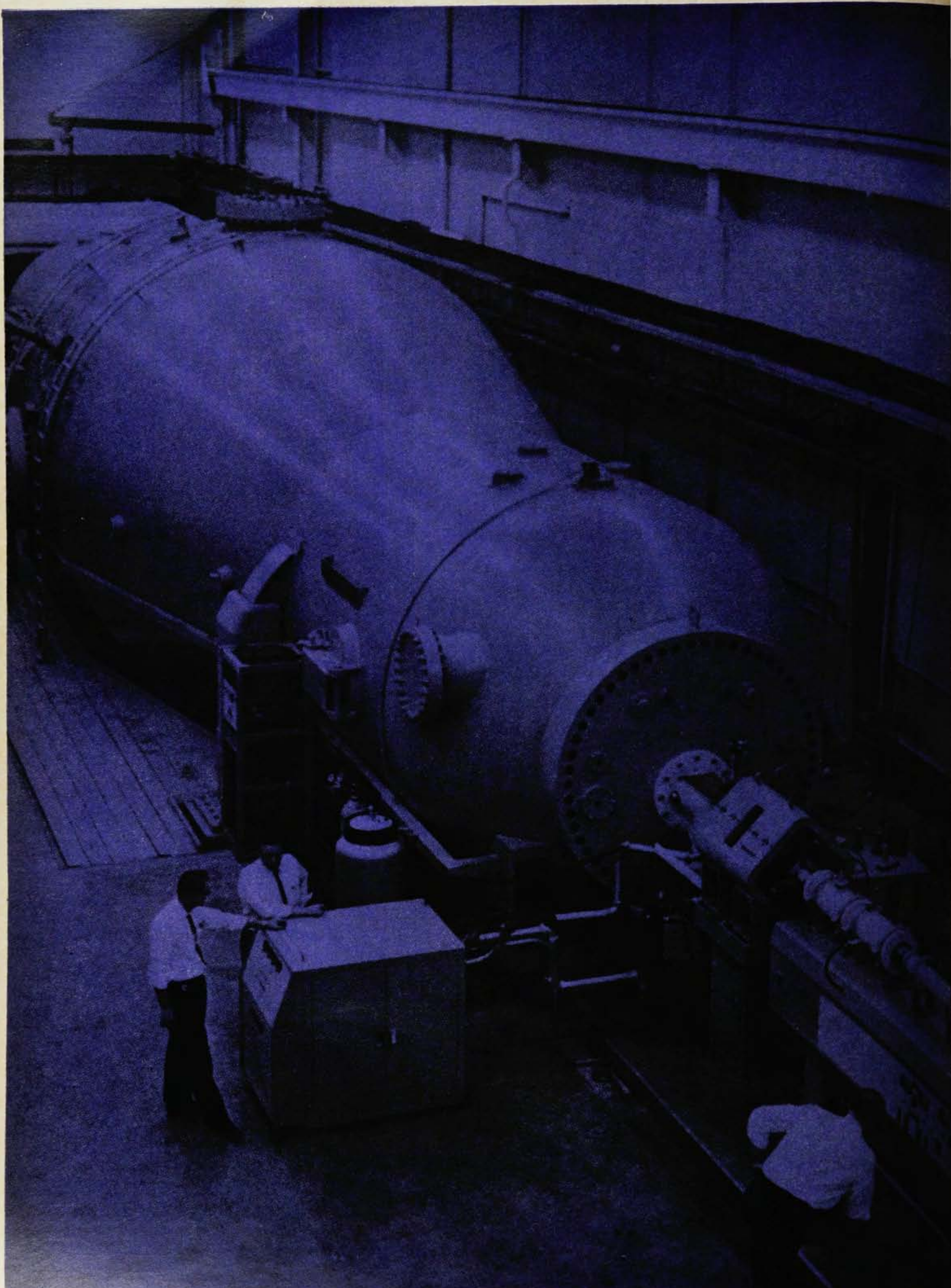
Besides the three quantitative measures given above there are other factors which determine the usefulness of a radiotelescope. Among these are its flexibility for pointing to different directions in the sky, for operating with different receivers and at different wavelengths, for yielding immediate data at a rapid rate and for measuring polarization.

### *Paraboloid antennas*

Conceptually the simplest form of radiotelescope is the kind, like Reber's



GROTE REBER'S original radiotelescope. The 31-ft parabolic reflector is now preserved at the National Radio Astronomy Observatory, Green Bank, West Virginia. —FIG. 1



MP Tandem Test Facility at High Voltage Engineering Corporation.

## New opportunity for heavy element research:

# Uranium ions accelerated to 200 MeV by HVEC Emperor Tandem.

Uranium ions have been accelerated to record-high energies exceeding 200 MeV during heavy-ion performance tests of the first completely assembled Model MP "Emperor" Tandem. The tests were carried out at HVEC's MP Tandem Test Facility at Burlington.

Calculations indicate that uranium ions at the energies achieved can create coulomb excitation in the nucleus of stationary uranium atoms. This is the first instance of uranium ion acceleration to energy levels sufficiently high for bombardment and examination of the nuclei of even the heaviest naturally occurring elements.

The MP heavy-ion performance tests were initial. We believe that further optimization of the system will allow demonstration of the machine's capability to accelerate uranium ion beams to energies of several hundred MeV . . . and the possibility of causing other interactions, including nuclear fission.

Such significant achievements are opening up entirely new fields of heavy element research . . . and offer the promising prospect that, with the Tandem Van de Graaff, nuclear scientists will soon be free to choose *any* specific pair of nuclei from among the multitude of possible pairs for controlled collisions and precise experimental examination.

Seven MP Tandems have already been ordered from HVEC. Five are now being installed. They will join the more than 30 Tandem Van de Graaffs now engaged in important research throughout the world. This wide acceptance of the Tandem as a basic tool for nuclear research is due to its inherent precision, versatility and ease of particle choice for nuclear experimentation. The MP Tandem is the most recent embodiment of the Tandem concept. It offers, for the first time, a proven and comprehensive approach to heavy element research.

A new booklet describing the MP heavy-ion performance tests contains a number of very interesting photomicrographs of recorded particle tracks. For a free copy and detailed information about HVEC particle accelerator systems and components, write to our offices at Burlington, Massachusetts or Amersfoort, The Netherlands.


500X photomicrograph of uranium ions accelerated by MP Tandem striking photographic emulsion plate at 10 degree incidence. Note frequent collisions with atomic nuclei in emulsion.

MP Tandem accelerator being installed at Yale University has accelerated proton beams of 20 microamperes in the range from 10 to over 20 MeV. Acceptance tests are now in progress.

MP Tandem accelerator being installed at Atomic Energy of Canada Ltd. Chalk River Laboratories achieved 15 MV terminal voltage during initial test of the electrostatic structure.

**HIGH VOLTAGE ENGINEERING**

## RADIO ASTRONOMY

*(Continued)*

prototype, that collects radiation with a paraboloid mirror and focal feed. To point in different directions across the sky the mirror is erected on either an equatorial or an altitude-azimuth mount; a less costly but less flexible alternative is to mount the mirror on a horizontal east-west axis for transit observations. With a paraboloid antenna a region of the sky is surveyed by scanning, the image being built up point by point.

The wavelength of operation can be changed simply by changing the focal feed and associated receiver head. At long enough wavelengths the aperture operates at full efficiency ($E = 1$) apart from a factor (usually 0.5 to 0.6) which depends on the illumination of the mirror by the feed. The shortest wavelength of operation is determined primarily by the surface accuracy. As the wavelength is reduced, the efficiency remains constant until the surface errors become appreciable in comparison with the wavelength after which the efficiency diminishes rapidly. We shall specify this effect by the wavelength $\lambda_0$ at which the efficiency is reduced to one half of its long-wavelength value.

To optimize the performance/cost ratio, a different specification is called for at different wavelength ranges: at long wavelengths the emphasis is on sheer size while at short wavelengths surface accuracy is the prime requirement, and the collecting area is limited in consequence. Historically one may cite the Jodrell Bank 250-ft telescope (1956) and the Naval Research Laboratory 50-ft telescope at Washington (1953) as early examples which helped to pioneer the two classes. Subsequently (1961) the construction of the Parkes 210-ft telescope demonstrated the feasibility of using very large mirrors at wavelengths as short as 6 cm. This trend will surely continue.

The first five entries of table 1 give the main characteristics of some of the outstanding instruments now in operation (see also figures 2, 3, 4). The table shows that paraboloids can now achieve a resolution in the vinicity of 1 min of arc near 1 cm wavelength, 5 min of arc at 10 cm, and 40 min of arc at 1 meter.

At all except the shortest wavelengths, higher resolving power can be obtained by other methods discussed below. Yet large parabolic antennas are always likely to remain an essential tool of radio astronomical research for the following reasons:

- They are "filled" apertures and consequently the quality of the images they record is uniform and optimum, whether for sources of small or large angular size, simple or complex. They are ideal for recording very weak sources that "fill" their beam, and especially for the detection of sources emitting and absorbing spectral lines.
- They present their full face to different parts of the sky so that the resolution and image quality are independent of position.
- They can be used over a wide

**Table 1. Examples of Radio Telescopes with Filled Apertures**

| *Observatory* | *Description* | *Geometric area* m²* | *"Minimum" wavelength† ($\lambda_0$) cm* | *Resolution at $\lambda_0$ minutes of arc* | *Sky coverage* |
|---|---|---|---|---|---|
| Green Bank (USA) | 300 ft-diam paraboloid[4] | 6560 | 17 | 6.4 | Transit |
| Jodrell Bank (UK) | 250 ft-diam paraboloid[5] | 4550 | 40 | 18 | Complete |
| Parkes (Australia) | 210 ft-diam paraboloid[6] | 3220 | 5 | 2.7 | 60 deg around zenith |
| Green Bank (USA) | 140 ft-diam paraboloid[7] | 1425 | 1.5 | 1.2 | Complete |
| Lebedev (USSR) | 72 ft-diam paraboloid[8] | 380 | 0.8 | 1.25 | Complete |
| Arecibo (Puerto Rico) | 1000-ft spherical mirror fixed in ground[9] | 73000 | (42)# | (4.7)# | 20 deg around zenith |
| Nançay (France) | Vertical spherical mirror 300 × 35 meters; Tilting plane reflector[10] 200 × 40 meters | 7000 (200 × 35) | 10 | 1.6 × 9.8 | Transit ± 7½ deg |

* This column corresponds to the effective area at long wavelengths assuming the hypothetical condition of uniform illumination. In practice the illumination is tapered toward the edges of the mirror and the effective area is approximately half this value. For some spherical mirrors, such as Arecibo, this factor is somewhat lower.

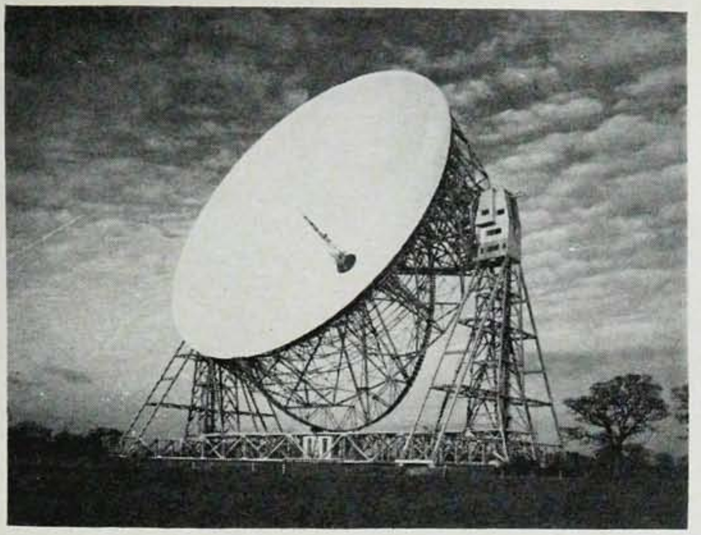
† The approximate wavelength at which surface errors of the dish reduce the efficiency to ½ the long-wave value. Shorter wavelengths are possible with further reduction of efficiency.

# The minimum wavelength so far used with full aperture is 70 cm, giving a resolution of 8 min of arc.

range of wavelengths, and the wavelength can be readily changed.

- They lend themselves to extremely low-noise observations, both because a single low-noise receiver can be used at the focus and because radiation from the ground can be reduced to an extremely low level.
- Their circular symmetry makes them ideal for measurement of polarization.

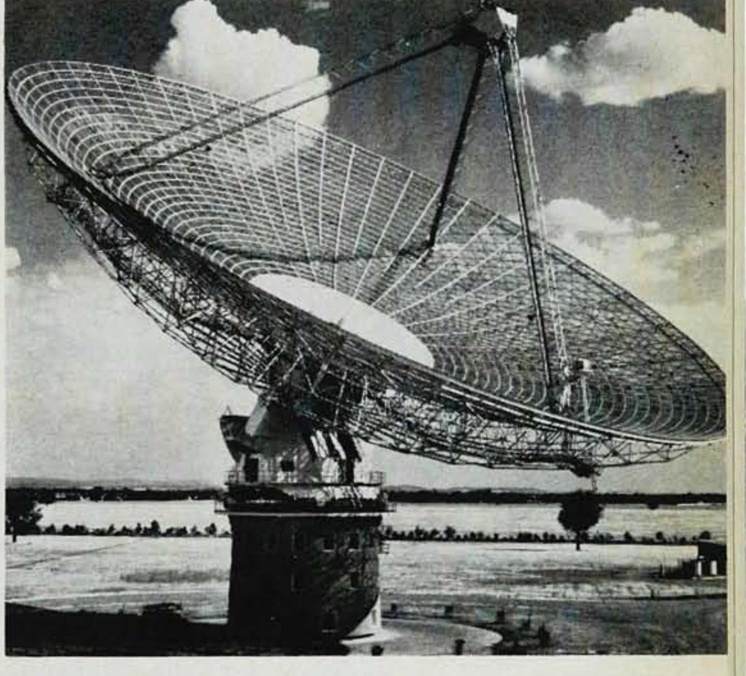
As has been said, paraboloid antennas are normally used in radio astronomy with a single feed element and receiver. However, their sensitivity is potentially capable of being increased considerably (that is to give efficiencies >> 1) by the use of a cluster of focal feed elements (suitably corrected for aberrations), thus allowing many points of the sky to be examined simultaneously. The author is unaware of any application of this technique in radio astronomy, except for a plan to use triple feeds for the Arecibo spherical mirror discussed below.



**250-FT DISH at Jodrell Bank. This completely steerable paraboloid was the first giant reflector. —FIG. 2**

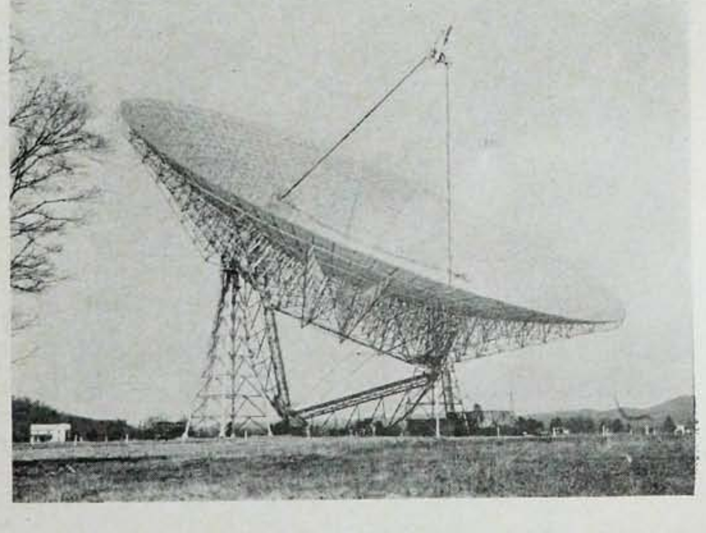
### *Other filled-aperture designs*

Mechanical problems inherent in the design of steerable paraboloids more than a few hundred feet in diameter have led to development of other kinds of filled apertures for instruments of rather greater specialization. One design, exemplified by the 1000-ft radiotelescope at Arecibo (Puerto Rico), consists of a vertically directed spherical dish built in a natural bowl-shaped hollow in the ground (see table 1 and figure 5). The spherical surface allows one to move the beam to different parts of the sky (to within 20 deg of the zenith) by moving the position of the feed. A special and rather tricky feed is used to eliminate the spherical aberration thus introduced. The instrument is designed for relatively long wavelengths and so far 70 cm is the shortest wavelength at which the full aperture has been used.



**PARKES 210-FT dish (Australia) combines size and centimeter-wave precision. —FIG. 3**

Another approach to filled apertures, introduced by J. D. Kraus,[11] is to fix the objective mirror in a vertical position on the ground and direct the celestial radiation onto it by using a tiltable plane mirror centered on the same meridian as the objective mirror. With this arrangement transit obser-



**300-FT TRANSIT telescope at Green Bank is the largest existing paraboloid. It is suitable for decimeter-wave studies. —FIG. 4**

# RADIO ASTRONOMY

*(Continued)*

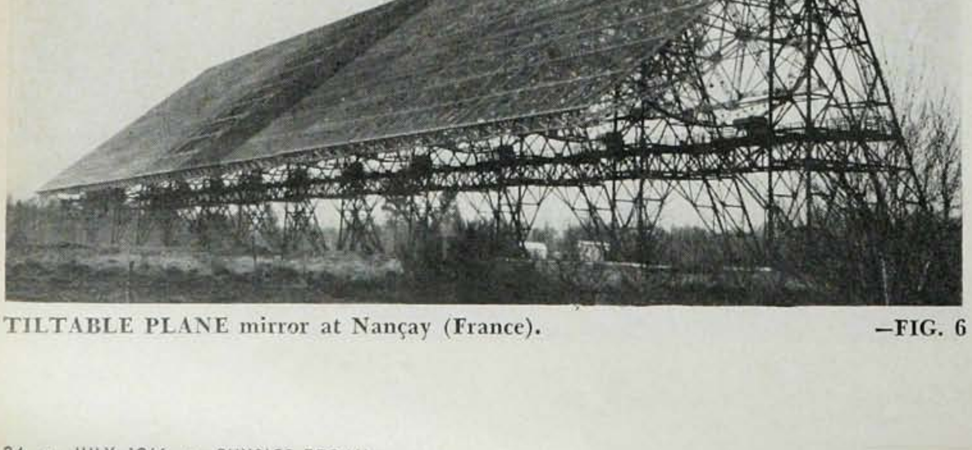
vations can be made over a wide range of elevations. It is obviously economical to make the objective mirror rectangular with its width much greater than its height; the resulting beam shape is then correspondingly elongated. A large instrument of this class is now in operation in France at the Nançay Observatory (see table 1 and figure 6). Vertical swing is provided by the tilting mirror, and limited azimuth coverage is made possible by moving the focal feed which is conveniently close to the ground. The maximum effective area is similar to that of a 300-ft paraboloid, yet the surface accuracies are such that wavelengths as short as 10 cm can be used with reasonable efficiency.

**1000-FT SPHERICAL** mirror at Arecibo (Puerto Rico). —FIG. 5

Mention should also be made of what is historically the earliest type of filled-aperture antenna—the broadside array—a type which has often been used in radio astronomy. It consists of many small closely-packed aerial elements arranged in a rectangular matrix. The array may be mounted on a rigid structure for full or transit steering; or it may be deployed on the ground and the beam shifted by inserting appropriate phases into each antenna line. The latter alternative offers immediate advantages both for rapid beam swinging (by electronic phasing) and for the simultaneous recording of a large number of image points.

### *Dilute apertures—image synthesis*

Although there is no theoretical limit to the size and therefore the resolution of filled-aperture telescopes, a practical limit is eventually set by engineering or financial considerations. The need for still higher resolution, especially at the longer (decimeter and meter) wavelengths, has led to the development of a variety of instruments whose apertures are of much smaller area than the full aperture required to obtain the same resolution and yet which are capable of producing proper two-dimensional images. Such dilute apertures divide naturally into two classes of instrument distinguished by whether they are used to build up an image point by point (let us call it "image synthesis") or Fourier component by Fourier component (let us say "aperture synthesis").



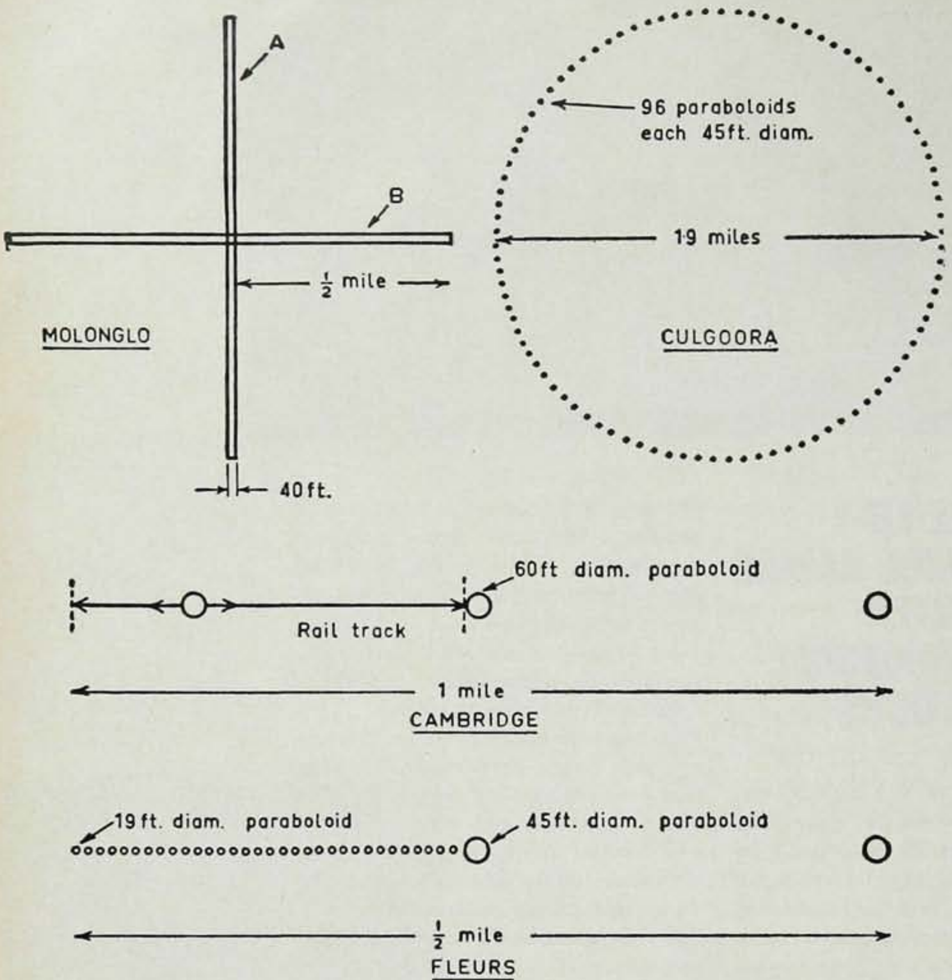
**TILTABLE PLANE** mirror at Nançay (France). —FIG. 6

The first radiotelescope of dilute aperture to be developed with image synthesis was the Mills Cross[12] which consists of two linear arrays A and B (figure 7) arranged in the form of a cross. Since arm A has high resolution in the north-south direction and low resolution in the east-west, it receives radiation only within a thin fan-shaped beam elongated in the east-west direction. Arm B has a similar beam elongated north-south. Hence when the signals from arms A and B are combined in a *correlator* (that is, the voltages are multiplied together), the output signal represents radiation received only from the overlapping part of the two crossed fan beams, that is from a sharp pencil beam. The beam of a Mills cross is the same as that produced by a full aperture of square shape with sides equal to the half-length of the arms. When a single correlator is used, the effective collecting area is equal to $1/\sqrt{2}$ times the total area of the two arms. This area can be made very large so that the instrument is very sensitive for high-resolution surveys of point sources. However the area is small compared with the full aperture of equivalent resolution: the efficiency is correspondingly low and the instrument comparatively insensitive to sources of large angular extent. These remarks apply to all dilute aperture instruments.

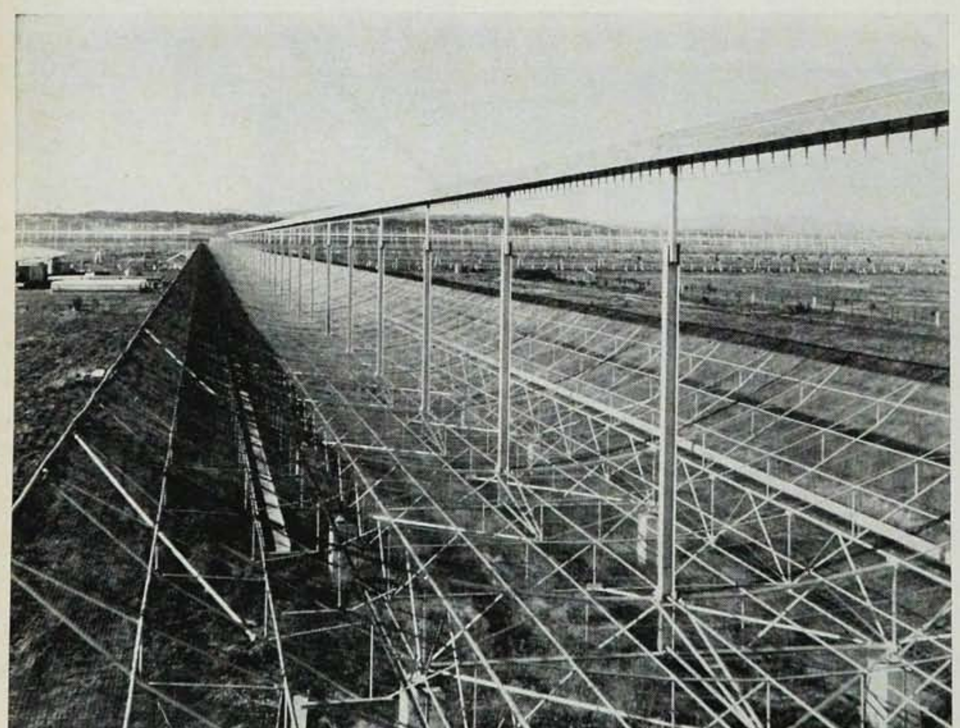
The parameters of a representative large cross array—now being constructed by Mills[13] and his colleagues at Molonglo Observatory in Australia—are given in table 2. This instrument has 1-mile long arms (figure 8) and yields a 3 min of arc beam at 73.5 cm. To achieve this resolution with a full aperture one would be faced with the forbidding prospect of building a half-mile square aperture.

It can simply be shown that half of one of the arms of a cross can be removed without affecting the resolution of the instrument and several such T-shaped arrays have been or are being constructed.

We have seen that the cross configuration is equivalent to the perimeter of a square. Another form of dilute aperture is obtained by using




**CONFIGURATIONS** of the four dilute-aperture instruments discussed. —FIG. 7



MILLS CROSS at Molonglo (Australia). Each arm measures 40 ft by one mile.—FIG. 8

## RADIO ASTRONOMY

*(Continued)*

the perimeter of a circle and methods have been worked out[14] for combining the received signals in such a way that a pencil beam is generated with the same resolution as a circular filled aperture of the same diameter (see figure 9). This configuration has the advantage of circular symmetry as regards beam shape, side-lobes and the distribution of directions from which noise fluctuations are received. Such an aperture has been adopted in a radiotelescope under construction at Culgoora (Australia) designed predominantly for observations of the sun (see table 2 and figure 7).[14] It consists of 96 steerable paraboloids each 45 feet in diameter arranged around a circle 3 km in diameter. It operates at the long wavelength of 3.75 meters and the resolution is 4.3 min of arc. The sun can be followed for 4 hours each day and the diameter of the instantaneous field of view is 2 deg. Outside this field, grating responses are present owing to the finite spacing beween antennas.

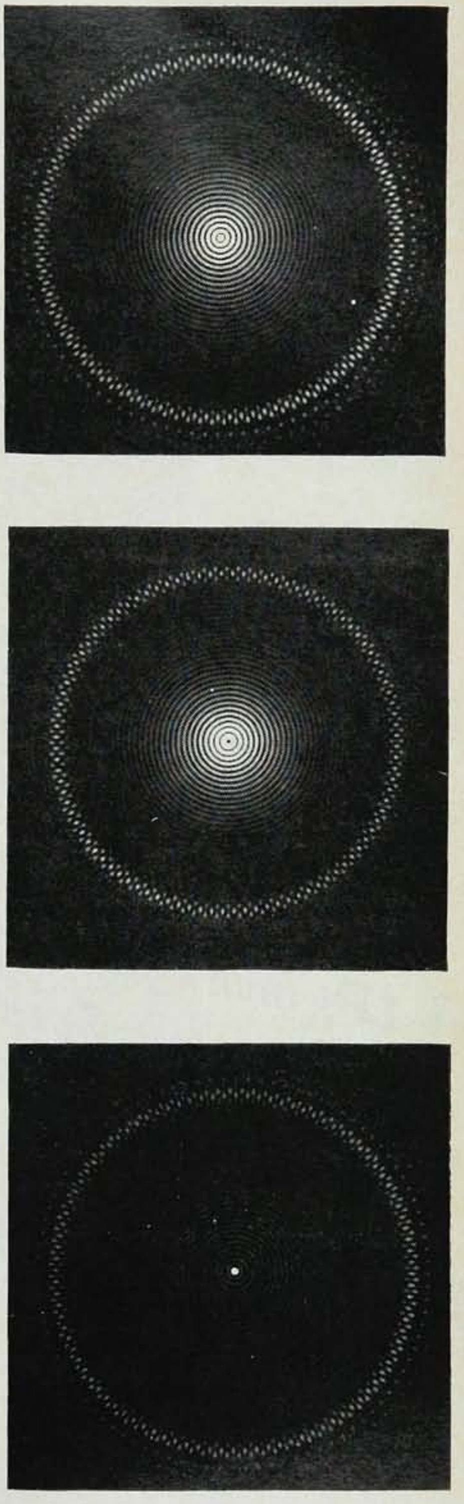
With image-synthesis systems, such as the two described above, the direction of the pencil beam is varied simply by changing the phase at each antenna (for example, by changing the length of cable between antenna and mixing point).

When we come to compare the sensitivity of dilute with full apertures we have to remember that dilute-aperture arrays can very conveniently be connected so as to record signals arriving from several ($n$) directions simultaneously. This facility can be achieved by a branching network which connects each of $n$ receivers to all elements of the array with phases appropriate to the chosen direction of pointing—a technique introduced by Blum[15]. It reduces the time required to survey a given region of the sky by the factor $n$, and so increases the efficiency by a factor of $n^{\frac{1}{2}}$. This factor has been taken into account in listing efficiencies and comparative effective areas in table 2. The Molongo Cross will view 11 points simultaneously, the Culgoora circle 48. In the latter case the points will form a north-south row of points; special fast-acting phase changers will allow the 48 points to be rapidly swept in the east-west direction. By this means a two-dimensional picture of the sun with $48 \times 60$ points will be formed in a period of 1 sec, thus allowing rapidly varying phenomena to be recorded.

One may ask how far this procedure of multiple receivers can be taken to give continuing improvement of sensitivity. It can be shown that a two-dimensional array of $N$ antennas is fundamentally capable of yielding an image of $\sim N^2$ points. If this full potential were realized and if the antennas of the array were effectively butting against one another, the comparative efficiency would become of order unity—that is, the sensitivity of a filled aperture would be achieved. However the technical realization of this goal by using branching or electronic networks and receivers seems almost prohibitive for practical arrays with large $N$. The ultimate solution may be found in the use of optical analog displays in which the radio signals from each antenna are used to modulate a coherent beam of light in such a way that an optical image is formed directly. This technique was proposed for radio astronomy by D. J. McLean and J. P. Wild[16] and has been successfully demonstrated in a simulated radar application by L. B. Lambert, M. Arm and A. Aimette[17].

### *Dilute apertures—aperture synthesis*

Although the cost of dilute apertures of the kind suitable for image synthesis is enormously less than that of a filled aperture with equal resolving power, a stage must be reached where continued increase in size becomes limited by cost. On the other hand the alternative ("aperture synthesis") method of operating a dilute aperture allows one to build up an image gradually by recording with different parts of the aperture at different times; in the extreme case this can be done by using no more than two small antennas one of which is moved about on the ground so as to occupy each part of the desired aperture in turn: more precisely, to simulate a filled aperture of diameter $d$, the mobile antenna is required to cover sequentially a



**OBTAINING A PENCIL BEAM for image synthesis with dilute apertures (one method). Upper photo shows the radiation pattern obtained with the Culgoora circular array when all antennas are connected in phase. Middle photo shows the pattern when suitable phase shifts are inserted around the circle (note central dark spot). Lower photo shows the result of subtracting middle pattern from upper pattern. Outer fringes (inner diam: 2 deg) are from grating response. (Ref. 14 gives details.) Photos taken by D. J. McLean and R. N. Smart using an optical analog method. —FIG. 9**

**Table 2. Examples of Radio Telescopes with Dilute Apertures**

| *Observatory* | *Molonglo (Australia)* | *Culgoora (Australia)* | *Cambridge (U.K.)* | *Fleurs (Australia)* |
|---|---|---|---|---|
| Type of array | Cross*[13] | Ring*[14] | Simple interferometer[18] | Compound interferometer*[19] |
| Type of synthesis | Image | Image | Aperture | Aperture |
| Shortest wavelength (cm) | 73.5 | 375 | 21 | 21 |
| Maximum resolution (min of arc) | 3.1 | 4.3 | 0.5 | 1.0 |
| Number of receivers or correlators | 11 | 48 | 2 | 64 |
| Efficiency | $8 \times 10^{-2}$ | $7 \times 10^{-3}$ | $1.7 \times 10^{-2}$ | $6 \times 10^{-2}$ |
| Comparative effective area (m²) | $4.8 \times 10^4$ | $4.5 \times 10^4$ | $3 \times 10^4$ | $3 \times 10^4$ |
| Observation rate | 11 points in 5 sec (transit observations) | 2 deg field of $3 \times 10^3$ points in 1 sec | 1 deg field of $\sim 3 \times 10^4$ points in fifty 12-hour days ($\sim$500 points per day) | 1 deg diam field of $5 \times 10^4$ points in two 8-hour days |

* under construction

semicircular area of radius $d$ centered on the fixed antenna. The measured pattern of amplitude and phase as a function of position on the ground is then fed into a computer which works out the square of the Fourier transform of this pattern. The result is just the required image. The theory of this process is identical to that of Fraunhoffer diffraction in optics.

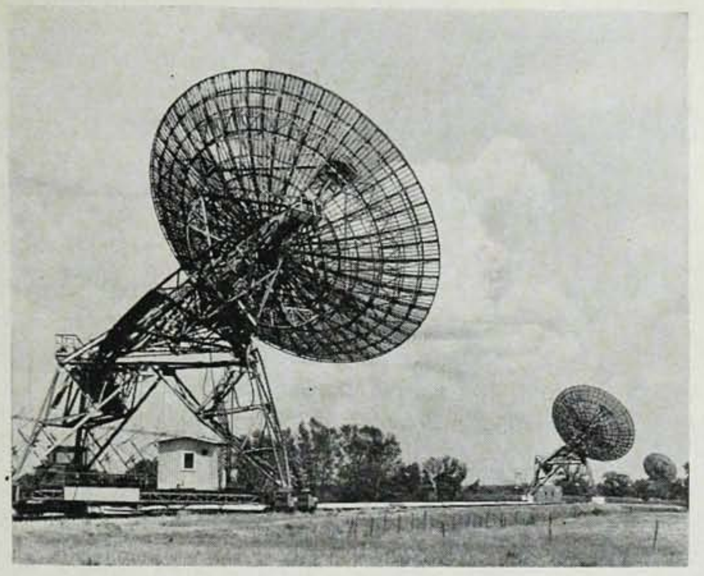
Almost unlimited resolution thus becomes possible with relatively simple equipment, but the time required to form an image can become unduly large.

A simple but powerful instrument of this kind is now being operated by Ryle and his Cambridge colleagues[18] who have consistently adopted and developed this method for many years. Two fixed antennas and one movable antenna, each a paraboloid of diameter 60 feet, are mounted along a base line 5000 ft in length and of fixed orientation (see table 2 and figures 7 and 10). The earth's rotation is then used to rotate the baseline through 180 deg in 12 hours of observation time. Some 50 different spacings on 50 different days are required to complete the image of one region of the sky about 1 deg in diameter—the diameter of the useful part of the beam of one antenna. The resolution is equivalent to that of an elliptically shaped filled aperture whose major axis is 5000 ft. In the optimum direction the resolution at 21-cm wavelength is 29 sec of arc. The ellipticity varies with the declination of the source region.

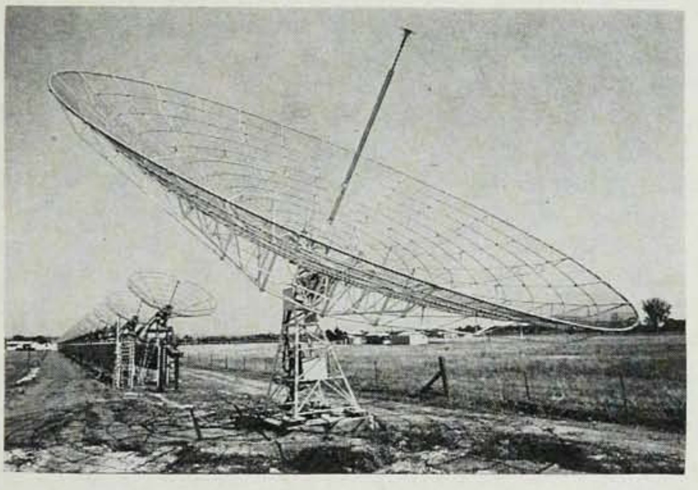
At first sight the efficiency of such a simple system might appear to be very low because the antennas are small and very many separate positions are required to survey a region of sky. However the simultaneous formation of the image over an extensive region containing many picture points acts in compensation. The comparative effective area of a linear two-antenna system that makes use of the earth's rotation is in fact roughly equal to the total area swept out by the mobile aerial as it moves along the baseline. It thus achieves with relatively simple equipment (plus a computer) the sensitivity of an array of vast dimensions, such as an image-synthesis instrument that uses a single receiver. (The potential of the large array remains much greater, however, since it can be operated with many receivers.) A limitation of simple aperture-synthesis systems is the extremely long time (months) required to form an image even though the sensitivity may be great enough to allow a suitable image to be formed in a much shorter time.

The next degree of complexity in aperture-synthesis techniques is to be found in the use of a large number of antennas (for example, in a linear array) and making many simultaneous correlations. This arrangement leads to the production of images of the same quality as those obtained with two-antenna systems but in a time shortened by a factor equal to the number of correlators. Such an instrument is now being constructed by W. N. Christiansen and his colleagues[19] at Fleurs (Australia).

The Fleurs telescope (see table 2; figures 7 and 11) will involve no moving antenna. Sixty-four correlations at different east-west spacings between 0 and 2400 ft will be simultaneously and continuously recorded. The east-west line will again be spun relative to the celestial sphere by the earth's rotation so that a complete image of a given region would in principle be obtainable in a period of 12 hours. However, a second identical arrangement will eventually be used along a north-south line; this will reduce the foreshortening effects that would otherwise impair the resolution in some directions. The correlators will be shared



**APERTURE-SYNTHESIS** interferometer at Cambridge (England) consists of three 60-ft paraboloids. The one in foreground moves on rails. —FIG. 10



**COMPOUND INTERFEROMETER** under construction at Fleurs (Australia) will operate by aperture synthesis at 21-cm wavelength. —FIG. 11

between the two arrays (for example, on alternate days) and the resulting performance will allow a field of approximately 1 deg diameter to be surveyed at 21-cm wavelength with a maximum resolution of 1 min of arc in a period of two eight-hour days. The image will not be entirely free from grating responses owing to the periodicity of the array. These responses, which can lead to ambiguities in the recorded image, will be capable of removal by the addition of two more antennas in each arm.

If the complexity of aperture-synthesis instruments is increased one stage further, the apertures would essentially resemble the same kinds of dilute aperture that are used for image synthesis. We saw in the previous section how image synthesis systems using arrays of $N$ elements achieve their full potential sensitivity when a branching network feeding $\sim N^2$ receivers is used. The same array system may equally be used as an aperture synthesis instrument of about the same sensitivity, in which case $\sim N^2$ correlators are needed. The technical complexity of the latter is probably the less forbidding of the two but requires extravagant use of a large computer and is less flexible in operation. An alternative to the use of $\sim N^2$ correlators is to record the voltage signals at each antenna directly on tape (preserving the detailed phase relationships); this procedure greatly reduces the technical complexity but greatly intensifies the computer load. A further alternative is the use of optical analogue displays referred to previously. For an instrument of this kind the distinction between image synthesis and aperture synthesis finally disappears.

### *Summary and conclusions*

The resolution and sensitivity characteristics of the selection of modern radiotelescopes discussed in this review are summarized in tables 1 and 2. It is interesting to note that their resolutions fall mainly in the range between 1 and 10 min of arc irrespective of wavelength. Full-aperture mirrors dominate the wavelength range below 20 cm; the range between 20 cm and 70 cm is shared by both dilute and full apertures while at longer wavelengths dilute apertures are without rival.

Generally speaking the steerable paraboloid is the most flexible type of radiotelescope allowing a wide range of astronomical programs to be undertaken and yielding images whose quality is independent of the angular size and complexity of sources being studied.

Greater size but less flexibility is obtainable with fixed mirrors. For still greater size, arrays of many elements can be used to generate fine pencil beams. Such arrays are technically more complex than single mirrors but have certain useful features: they lend themselves to multibeam operation and rapid scanning, and there is no mechanical limit to their size.

Many kinds of arrays are possible. When the prime requirement is high efficiency (e.g. for the study of weak extended sources, radar, etc.) one chooses a filled-aperture array; when the need for high resolution outweighs the need for efficiency one chooses a dilute-aperture array of the kind which generates pencil beams, such as a cross or a ring. Such arrays can be built with very large effective area and so are suitable for high resolution surveys of weak point sources. Their efficiency is low for single-beam operation but can be improved by multiple-beam operation; potentially, when very many beams are used, their efficiency can attain that of a single-beam full-aperture system, though the full potential has not yet been approached in current instruments.

Arrays can also be used to form images by correlating the signals received from the different combinations of pairs of antennas, in which case the image is synthesized from its Fourier components. With this system it is no longer necessary for the whole aperture to exist simultaneously; indeed the aperture can, in the extreme case, be synthesized by two relatively small antennas, one of which is mobile. For a given cost such a system is capable of yielding the highest possible angular resolution, but at the sacrifice of a very low rate of observation.

The general conclusion may perhaps be drawn that in its present state of development radio astronomy is best served by a wide diversity of instruments—such as, indeed, now exists. As resolving power, sensitivity and the rate of gathering information continue to increase the demand for more sophisticated multiple receiving systems is likely to become the most pressing technical problem. □

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