*Mon. Not. R. astr. Soc.* (1966) **134**, 87–95.

# THE OPERATION OF THE CAMBRIDGE ONE-MILE DIAMETER RADIO TELESCOPE

*B. Elsmore, S. Kenderdine and Sir Martin Ryle*

(Received 1966 February 11)

*Summary*

The new radio telescope at Cambridge uses the technique of synthesis to produce an aperture one mile in diameter, giving beamwidths of 80″ and 23″ arc at its two observing frequencies of 408 and 1407 Mc/s. This paper describes how the telescope may be used (i) to obtain accurate positions of point sources, (ii) to determine the angular structure of extended sources, and (iii) to make a complete survey of very weak radio sources over a limited area of sky.

1. *Introduction.* The new Cambridge radio telescope (Ryle 1962) is based on a method of two-dimensional aerial synthesis in which the rotation of the Earth is used to vary the projected axis of an east–west interferometer on the sky. Observations made with equatorially mounted aerials over a continuous 12-hour period, enable an elliptical ring of a large equivalent aerial to be synthesized and by repeating the observations with different separations of the two aerials, the complete elliptical aperture may be reconstituted. For observations near the pole, the equivalent instrument is circular with a diameter equal to $D$, the maximum separation of the aerials; for observations at other declinations, the minor axis of the equivalent instrument is reduced by $\sin\delta$. A more favourable weighting function can be used than that provided by a circular aperture of uniform illumination giving a resolution better than that of a circular aerial of diameter $D$ by an amount which is of the order of 25%.

Since observations over the whole observing period are used in the derivation of each map point, the signal to noise ratio in the final map is very much better than might be expected from the use of the two small aerials (of diameter $d$) and corresponds to that appropriate to the use of an aperture of area $3Dd$, when the same total observing time is used (Ryle & Hewish 1960). In this way instruments of very large resolving power and sensitivity can be built; furthermore it becomes possible to design an instrument in which the resolving power and sensitivity can be matched at the most suitable observing wavelength, where the overall system noise relative to the signals from the sources under investigation has a minimum value. In this way the combined effects of noise and of weak confusing sources may be reduced to a very small value. A series of observations made to test this method of synthesis has been described (Ryle & Neville 1962) in which a circular beam of 4′·5 arc was obtained at a frequency of 178 Mc/s.

A brief account of the new telescope has already been given (Ryle 1962). The instrument consists of three equatorially mounted paraboloids 60 ft in diameter, on an E–W axis, one being rail mounted as shown in Fig. 1; the maximum spacing is approximately 1 mile. By combining the signals from the moving aerial with those from each of the two fixed aerials, two interferometric spacings may be obtained simultaneously; the use of a larger number of fixed aerials and a shorter rail would reduce the observing time still further, but would be less economical than the present design.

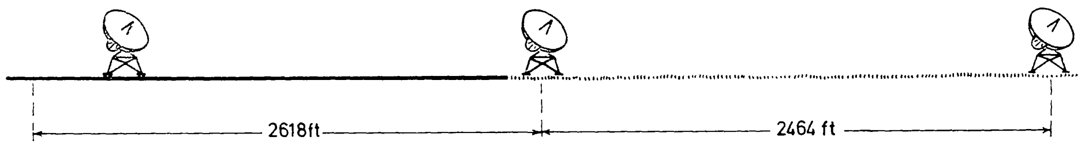


FIG. 1. *Diagram showing the arrangement of the three aerials.*

The instrument operates simultaneously at frequencies of 408 and 1407 Mc/s; at high declinations, the beams are circular with half-power beamwidths of 80″ and 23″ arc respectively.

Normally, 12-hour observations, from H.A. = $18^h$ to $06^h$, are made with the moving aerial in each of sixty-four different positions, with a displacement of approximately 2/3 the diameter of the aerials between each observation; this overlap allows the whole area of sky within the 0·4 contour of the envelope polar diagram to be scanned in the computer without any difficulties arising from grating responses (Ryle & Hewish 1960); this area has a diameter of approximately 3° 15′ at 408 Mc/s and 1° at 1407 Mc/s.

The instrument may however also be used for investigating the structure of a source whose angular size is much smaller than the envelope pattern and whose intensity is much greater than that of other sources within this area. Under these circumstances a relatively small number of different positions of the moving aerial along the full length of the rails may be used to provide the same resolving power without difficulties arising from grating responses. This method was employed in some observations of the intense sources in Cygnus and Cassiopeia, and a number of other sources (Ryle, Elsmore & Neville 1965a, b).

In the special case of a source of very small angular size, observations at a single spacing may be used to derive an unambiguous position with considerable accuracy. A full account of this method of observations is given elsewhere (Elsmore & Macdonald 1966).

The receiving system is described in section 2 and the types of observation mentioned above are described in section 3.

The telescope may also be used as a transit instrument to achieve an intermediate resolution for survey work using a one-dimensional synthesis. Here the aerials are directed at a fixed hour angle for observing periods of up to 24 hours. On successive days the position of the moving aerial is altered so that the projected spacing of the pairs of aerials on the sky is changed, but the orientation remains constant; in this way a rectangular aperture of dimensions $D \times d$ may be synthesized. The observations thus give a map of a strip of sky with a highly elongated beam whose orientation depends on the H.A. used.

The different ways in which this method may be applied, and its use to carry out a relatively fast survey of rather more intense sources than those reached with the full two-dimensional synthesis are described in a separate paper (Bailey & Pooley 1966).

2. *Description of the receiving system.* The receiving and recording system used follows that developed in earlier synthesis systems (Scott, Ryle & Hewish 1961); there are however important additional problems associated with the need to observe at large hour angles and with the much greater resolving power now available.

In order to be able to carry out the aerial synthesis it is necessary to record, for each pair of relative positions of the aerial elements, the amplitude and phase of the correlated signals from the two aerials. As in previous instruments which have already been described this may be done by using two phase-switching receivers (Ryle 1952) which are fed from the two aerials (i) in phase and (ii) in phase quadrature.

Since the noise contributions from the ground and the receiving preamplifiers are uncorrelated, the noise fluctuations in the output of a phase-switching receiver fed with the two signals in antiphase, are uncorrelated with those from a receiver fed in phase; by combining the outputs from two receivers fed in phase and in antiphase for each of (i) and (ii) an improvement in signal to noise ratio of $\sqrt{2}$ may be achieved. The arrangement of hybrid-networks is shown in Fig. 2 and is similar to that used in the survey of the North Pole region (Ryle & Neville 1962).

For an E–W interferometer of spacing $l$, and an observing wavelength $\lambda$, the path difference from a source at declination $\delta$ when observed at hour angle $H$ is given by:

$$l \cos\delta \sin H. \tag{1}$$

Two difficulties are now apparent:

(a) *Path difference.* The path difference encountered with large values of $l$ and H.A. must be corrected if a finite receiver bandwidth is to be used; for a frequency response which is uniform over a bandwidth $\Delta f$, the receiver output will fall to zero if the paths of the two signal channels differ by $c/\Delta f$ and to avoid large corrections it is desirable to introduce a compensating path such that the difference is less than $c/2\Delta f$. Since the path difference from the source to the two aerials varies with $H$, this compensating path must be varied throughout the 12-hour observing period.

It should be noted that although an appropriate correction can be made for the centre of the area of sky under observation, an error will occur for sources at the edges of the reception pattern of the individual aerials; at the half power points the maximum error in path is given approximately by

$$\frac{D}{2d}\frac{c}{f}$$

where $D$ is the maximum value of the spacing $l$, and $d$ is the diameter of the aerial elements. It is thus clear that the maximum bandwidth which can be used is given by

$$\frac{\Delta f}{f} \leqslant \frac{d}{D}.$$

In the present instrument $d/D \sim 0{\cdot}01$ permitting the use of bandwidths of 4 and 14 Mc/s at the two operating frequencies of 408 and 1407 Mc/s; in practice both systems have been used with a 4 Mc/s bandwidth.

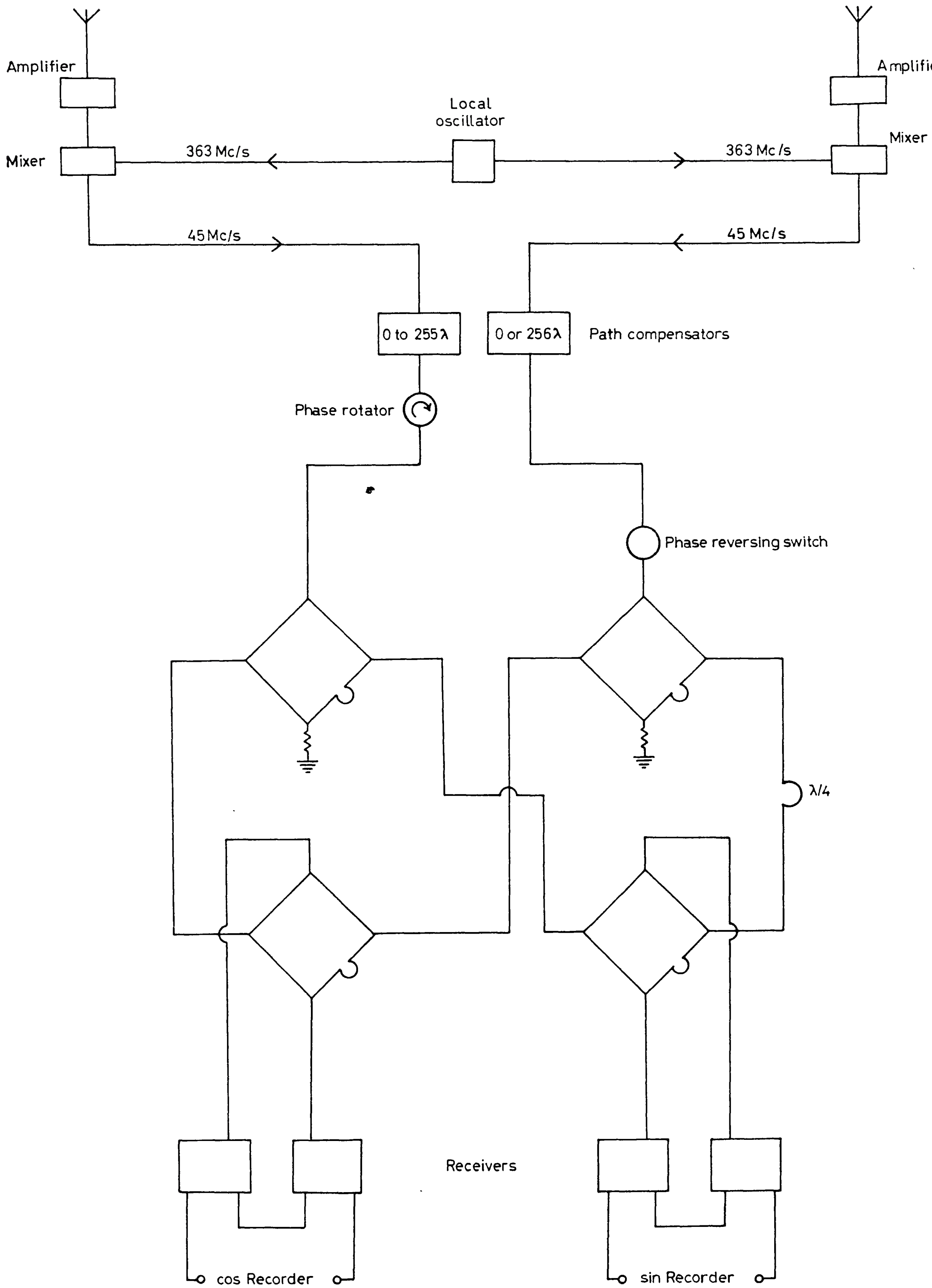


FIG. 2. *The receiving and recording arrangements for one pair of aerials. Each of the hybrid networks consists of three λ/4 sections and one 3λ/4 section.*

(b) *Phase rotator*. It is evident from (1) that at a frequency of 1407 Mc/s and with spacings of $\sim$ 1·6 km the rate of change of phase may be as high as 3 radians/s. If the output from the phase-switching receivers were to be recorded adequately, a sampling interval not greater than 0·5 s would have to be employed. The use of such a high sampling speed would lead to severe difficulties both in handling the large amount of punched paper tape, and in the time taken to read it into the computer.

It may be seen from (1) however, that at any time the *range* of frequencies present in the output of the phase-switching receivers is relatively small; it depends on the range of $\delta$ and $\alpha$ accepted by the envelope pattern of the individual aerials. At H.A. = 0, the frequency is independent of small variations of $\alpha$ but is given by

$$\frac{l\Delta\delta}{\lambda}\sin\delta\,\frac{dH}{dt},$$

where the envelope pattern extends to $\pm\Delta\delta$ in declination; at H.A. = $18^{\mathrm{h}}$ and $06^{\mathrm{h}}$, the frequency range is determined by the width of the envelope pattern in H.A. and is given by

$$\frac{l\Delta\alpha}{\lambda}\cos\delta\,\frac{dH}{dt},$$

where the envelope pattern covers a range $\pm\Delta\alpha$ in R.A.

For a symmetrical envelope pattern, the range of frequencies covered is thus approximately the same throughout the 12-hour track, and is very much less than the actual frequencies occurring near H.A. = 0; by suitable treatment it should therefore be possible to record all the information required with a sampling interval considerably longer than that required to record the receiver output directly.

The minimum sampling frequency then permitted is determined by the frequency range present which is

$$\sim\frac{D}{\lambda}\Delta\delta\,\frac{dH}{dt}.$$

Since $\Delta\alpha\sim\Delta\delta\sim\lambda/d$ this sampling frequency is

$$\sim\frac{D}{d}\,\frac{dH}{dt}$$

which is just the rate at which the position of one aerial relative to the other moves by its own width. Thus the minimum sampling rate corresponds to the requirement that observations are made at sufficient interferometric arrangements to reconstitute the full aperture.

In order to achieve this economy in data sampling, a phase rotator is incorporated in the path from one element, so that a continuous phase shift approximately equal to those of the arriving signals may be injected. As in the case of the path compensator, a continuous adjustment of the phase rotator speed is necessary.

It is clear that both phase rotator and path compensator could be combined in the radio frequency path from one of the aerials, but in practice it is more convenient to incorporate them in the I.F. path, so that conversion to I.F. may be made at the focus of each of the three aerials. If this is done the path compensation may conveniently be carried out by including integral numbers of $\lambda_{IF}$, which is a length sufficiently small to satisfy the requirements of section 2 (a) above, and which does not itself introduce any phase change. The phase rotator, which is also included in the I.F. path from one aerial must of course be driven at a rate appropriate to the wavelength of the incoming signals. The system is shown in Fig. 2; for simplicity only one pair of aerials has been included.

With this system it is only necessary to sample the output signals from the phase-switching receivers every 20 s.

The instructions for both the path compensator and the phase rotator are provided by a punched paper control tape, which is also used to instruct the digital recorder and paper tape punch when to sample the record. The same tape provides this information for both pairs of spacings and for each of the two operating wavelengths; it also provides the signal which instructs the three aerials when to start and stop sidereal tracking.

Eight-bit digital converters are used on the shafts of each recorder, which provide a cosine and sine track for each of the two spacings on each wavelength.

3. *The methods of observation.* Three different types of observation employing two-dimensional synthesis have been made, in addition to the one-dimensional synthesis which is described elsewhere (Bailey & Pooley 1966).

(a) *The determination of the position of an unresolved source.* 12-hour observations with a single spacing may be used to provide an unambiguous position in both co-ordinates of a source of small angular size. Using the largest spacing available, positions have been obtained with an accuracy of about 1″ arc —the ultimate accuracy being at present largely determined by the difficulty of establishing the precise geometry of the instrument.

The method is described in detail in another paper (Elsmore & Macdonald 1966), where it is shown that the effect of nearby weaker sources is small owing to the large effective area of the synthesized ring aerial.

Any angular structure which is sufficient to be detected with the maximum resolution of the instrument is immediately apparent from the records of these observations, and further observations at smaller spacings may then be made to provide a map of the source as described in 3 (b) below. In practice two spacings are normally observed simultaneously and the structure of barely resolved sources can often be obtained from a single 12-hour observation.

(b) *The mapping of individual sources.* It is often important to establish the distribution of radio brightness across a source whose angular extent may be considerably less than the area of the primary reception pattern. In many cases the source is considerably more intense than any other within this area. Under such circumstances it is convenient to synthesize a grating instrument, by observations at a limited number of spacings over the full range available. The response of such a system comprises a central beam having the same resolution as that of the completely synthesized instrument, which is surrounded by a series of rings of angular radii $\theta$, $2\theta$, $3\theta$ etc. where $\theta = \lambda/l'$ and $l'$ is the increment in spacing between successive positions of the moving aerial.

Providing that $l'$ is chosen to give a value of $\theta$ somewhat larger than the maximum extent of the source, no difficulties are caused by reception of the source in the grating responses; the presence of weaker sources within the envelope pattern may produce weak ring features on the map, but in many cases they are too weak to be of importance; they are in any case easily recognized.

In this way observations at 1407 Mc/s have been made with two, four and eight positions of the moving aerial, which are adequate for the study of sources whose extent is less than 90″, 180″ and 360″ arc respectively.

(c) *Complete mapping within the area of the envelope pattern.* Observations have been made using increments of 38·5 ft in the spacing of the aerials; the results have been used to obtain a map over the area of sky within which the response of the individual aerials exceeds 0·3 of its central value. In these observations sixty-five different positions of the movable aerial have been employed, which allow the completion of a map over an area about 4° in diameter at the frequency of 408 Mc/s and 65′ arc in diameter at 1407 Mc/s.

The first observations, which were made with preamplifiers of only moderate noise figure, were of an area of sky centred on $\alpha = 09^{h}\,40^{m}$, $\delta = +50°$ and the results are described in a separate paper (Kenderdine, Ryle & Pooley 1966). The results of the 408 Mc/s survey revealed about 100 sources, the weakest having $S_{408} \sim 25 \times 10^{-29}\,\mathrm{w\,m^{-2}\,(c/s)^{-1}}$.

4. *The reduction of the observations.* In all of the three types of observations described above, the data consist of one or more series of 12-hour observations of the in-phase and quadrature components of the correlated signals from two spaced aerials.

This information, in the form of a punched paper tape, is fed to the computer and converted to amplitude $A$ and phase $\phi$.

For each observation a reference point in the sky is chosen which for observations of individual sources is the best available radio position and for mapping observations is a point near the centre of the response pattern of the aerial elements. The variation of phase during the 12-hour period for a source at the reference point is computed, $\phi_0$ and $\phi - \phi_0$ together with the corresponding values of $A$ are plotted against time for the 12-hour run.

(a) *Observations of point sources.* A point source at the reference point gives a constant value of $\phi - \phi_0$ equal to the collimation error of the system. A point source differing in declination or right ascension by small amounts $\Delta\delta$ and $\Delta\alpha$ gives additional phase differences of

$$\Delta\delta \frac{d}{d\delta}\left(\frac{2\pi l}{\lambda}\cos\delta\,.\,\sin H\right) = -\Delta\delta\frac{2\pi l}{\lambda}\sin\delta\,.\,\sin H \qquad (2)$$

and

$$\Delta\alpha \frac{d}{d\alpha}\left(\frac{2\pi l}{\lambda}\cos\delta\,.\,\sin H\right) = -\Delta\alpha\frac{2\pi l}{\lambda}\cos\delta\,.\,\cos H. \qquad (3)$$

Thus by measuring the variation of $\phi - \phi_0$ throughout the 12-hour period, $\Delta\delta$ and $\Delta\alpha$ and hence the true position of the source may be found.

The presence of resolvable structure can be recognized by variations of $A$ and by more complex variations of $\phi - \phi_0$. Sources showing such structure may then be observed at intermediate spacings and a complete map obtained as described below.

(b) *Mapping observations.* The effect of subtracting $\phi_0$ from the observed $\phi$ is to reduce the data to a form identical with that for a survey centred at the pole. From this stage onwards the reduction both for deep surveys and for extended sources is therefore the same as that for a polar survey (Ryle & Neville 1962). The resultant map has as its centre the adopted reference point and differs from a polar map only in having an angular scale in declination which is reduced by $\sin \delta$.

The weighting function used in the combination of the different spacings may of course be varied depending on the type of observation; an excitation which has an approximately Gaussian distribution falling to 30% at the maximum spacing $D$ has generally been used, and this gives a theoretical reception pattern about 25% narrower than that of a uniformly excited circular aperture of diameter $D$, with a first and second side lobe response of $-5$ and $+3$%. At the two operating frequencies of 408 Mc/s and 1407 Mc/s the reception pattern has a width in R.A. at half intensity of 80″ and 23″ arc respectively. For both point source and mapping observations the effects of day-to-day precession are automatically taken into account by precessing the reference point to the date of each observation. The effects of errors in spacing and orientation of the interferometer elements may also be taken into account by adjustments to the reference point as described in the appendix.

The effect on these observations of refraction by a horizontally stratified atmosphere or ionosphere is extremely small. Refraction effects due to curvature of the ionosphere and gradients in its electron density are discussed in another paper (Elsmore & Macdonald 1966), where the electrical phase stability of the system is also examined.

Some of the results obtained with the instrument have already been described (Ryle, Elsmore & Neville 1965a, b); the results of observations made to determine the accurate positions of sources in order to search for optically related objects have also been given (Parker, Elsmore & Shakeshaft 1966, Elsmore & Macdonald 1966). Further observations of the structure of extended sources are described by Macdonald & Neville (1966). An account of the results obtained with the first observations made using the full synthesis of a one-mile instrument are described in a paper by Kenderdine, Ryle & Pooley (1966).

## APPENDIX

The error in orientation and spacing of the interferometer elements may be specified by Cartesian components of a displacement vector. Thus let the east aerial depart from its supposed position by distances of

$x$, towards the east;

$y$, in the equatorial plane at right angles to $x$, measured positive towards the north;

$z$, below the equatorial plane.

Since the displacement is very much smaller than the size of the aerials its effec at any time is to introduce a phase change which is constant for the whole area c sky being observed and given by

$$\phi = \frac{2\pi}{\lambda}(x\cos\delta\sin H + y\cos\delta\cos H + z\sin\delta).$$

By comparison with equations (2) and (3) such a phase change would appear as a change in source position by

$$\Delta\delta = -\frac{x}{l}\cot\delta$$

$$\Delta\alpha = -\frac{y}{l}.$$

Thus by moving the position of the reference point by the same amount before using it to calculate $\phi_0$, the $x$ and $y$ errors are taken into account. The height error $z$ gives for a given declination a collimation error indistinguishable from those arising from other effects; it is thus automatically taken care of if the collimation error is derived from observations on a source at, or near, the declination of the area being mapped.

The determination of these errors in practice is discussed fully elsewhere (Elsmore & Macdonald 1966).

*Mullard Radio Astronomy Observatory,*
*Cavendish Laboratory,*
*Cambridge:*
1966 *February.*

## *References*

Bailey, J. A. & Pooley, G. G., 1966. *Mon. Not. R. astr. Soc.*, in preparation.
Elsmore, B. & Macdonald, G., 1966. *Mon. Not. R. astr. Soc.*, in preparation.
Kenderdine, S., Ryle, M. & Pooley, G. G., 1966. *Mon. Not. R. astr. Soc.*, in press.
Macdonald, G. & Neville, A. C., 1966. In preparation.
Parker, E. A., Elsmore, B. & Shakeshaft, J. R., 1966. *Nature, Lond.*, **210**, 22.
Ryle, M., 1952. *Proc. R. Soc.*, A, **211**, 351.
Ryle, M., 1962. *Nature, Lond.*, **194**, 517.
Ryle, M., Elsmore, B. & Neville, A. C., 1965a. *Nature, Lond.*, **205**, 1259.
Ryle, M., Elsmore, B. & Neville, A. C., 1965b. *Nature, Lond.*, **207**, 1024.
Ryle, M. & Hewish, A., 1960. *Mon. Not. R. astr. Soc.*, **120**, 220.
Ryle, M. & Neville, A. C., 1962. *Mon. Not. R. astr. Soc.*, **125**, 39.
Scott, P. F., Ryle, M. & Hewish, A., 1961. *Mon. Not. R. astr. Soc.*, **122**, 95.