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A new radio interferometer and its application to the observation of weak radio stars

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A new type of radio interferometer has been developed which has a number of important advantages over earlier systems. Its use enables the radiation from a weak 'point' source such as a radio star to be recorded independently of the radiation of much greater intensity from an extended source. It is therefore possible to use a very much greater recorder sensitivity than with earlier methods. It is, in addition, possible to use pre-amplifiers at the aerials, and the resolving power which may be used is therefore not restricted by attenuation in the aerial cables.

Besides improved sensitivity, the new system has a number of other advantages, particularly for the accurate determination of the position of a radio source. Unlike earlier systems the accuracy of position finding is not seriously affected by rapid variations in the intensity of the radiation. It also has important applications to the measurement of the angular diameter and polarization of a weak source of radiation.

The new system has been used on wave-lengths of 1·4, 3·7, 6·7 and 8 m for the detection and accurate location of radio stars, and for the investigation of the scintillation of radio stars. It has also been used in a number of special experiments on the radiation from the sun. The results which have been obtained in these experiments have confirmed the advantages predicted analytically.

1. INTRODUCTION

One of the most important experimental problems in radio astronomy is concerned with the detection and location of weak radio stars. An improvement in the accuracy with which their positions may be determined might allow identification with faint visual bodies, or might enable their annual parallax or proper motion to be detected.

The observation of a large number of radio stars would make it possible to carry out a detailed analysis of their distribution in space. It has already been shown that one of the most satisfactory methods for observing radio stars makes use of a radio interferometer arrangement associated with a special type of receiver (Ryle 1950). Observations with this type of apparatus have enabled a number of radio stars to be located, but the extension of these methods to allow the observation of weaker stars presents considerable difficulty. At the same time it is unlikely that the accuracy of the early methods of position finding can be greatly improved without the use of systems of considerably greater aperture.

It is the purpose of this paper to describe a new type of interferometer which has considerable advantages both for the detection and for the location of weak radio stars, and to compare its performance with other systems which have been used. Consideration is also given to the factors which limit the detection of radio stars by present-day methods.

The results of observations carried out with the new system are not discussed in detail in the present paper; some of the earlier results have already been described (Ryle, Smith & Elsmore 1950; Smith 1951). The various methods of determining the position of a radio star by measurements with interferometer systems are discussed in a separate paper (Smith, in preparation).

2. The new phase-switching system

(a) *General description*

Previous interferometer aerial systems used at Cambridge for the observation of the sun and radio stars have made use of two aerials spaced on an east-west line (Ryle 1950). The new phase-switching system also makes use of two spaced aerials to produce an interference pattern, but a switch is arranged so that an additional half-wave-length* of cable may be introduced into one of the aerial cables; by this means it is possible to displace the interference pattern so that the new maxima correspond to the minima of the original pattern. The two reception patterns are indicated in figure 1, where the envelope of the interference patterns is determined by the reception pattern $A(\theta)$ of the individual aerials. ($A(\theta)$ is a function which will be used to represent the effective area of each aerial for reception of radiation incident from a direction θ; it therefore takes account of any directivity in the axial plane, the plane normal to the line joining the two aerials.)

The power receptivity of this system when the aerials are in phase is given by

$$A(\theta)\,[1+\cos\{(2\pi d/\lambda)\sin\theta\}], \tag{1}$$

where θ is the angle between the source and the axial plane, d is the spacing between the aerials and λ is the wave-length.

* It is important that the phase-switching be carried out by the insertion of a half-wave-length into one of the aerial cables, and not by the more symmetrical method of transferring a quarter-wave-length from one aerial cable to the other. In the latter case the parallel impedance of the two aerials will not be the same in the two positions of the switch unless the impedances of the two aerials are exactly equal. A variation of the parallel impedance may modify the internal noise power of the receiver, and as will be shown later this variation will produce a false deflexion of the recorder. This condition cannot arise if 'half-wave' switching is used.

With the aerials connected in anti-phase, the receptivity is

$$A(\theta)\,[1-\cos\{(2\pi d/\lambda)\sin\theta\}]. \tag{2}$$

If the analysis is restricted to angles near the axial plane of the interferometer, these expressions may be simplified to

$$A(\theta)\,[1\pm\cos(2\pi d\theta/\lambda)]. \tag{3}$$

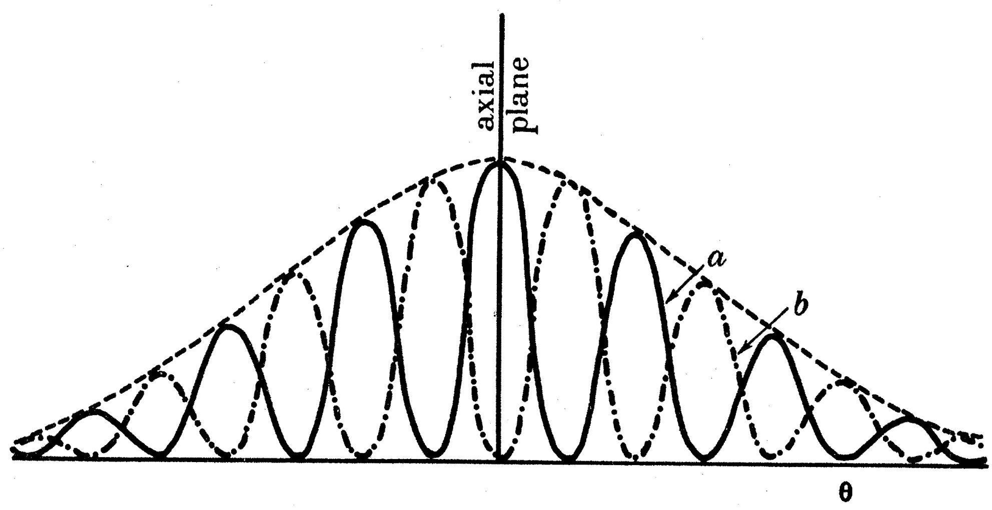

FIGURE 1. Reception pattern of two spaced aerials: (*a*) connected in phase and (*b*) connected in anti-phase.

Suppose now that a point source of radiation which produces a power flux p at the aerial is situated in a direction θ; the powers intercepted by the aerial system in the two conditions are given by

$$pA(\theta)\,[1+\cos(2\pi d\theta/\lambda)] \quad \text{and} \quad pA(\theta)\,[1-\cos(2\pi d\theta/\lambda)].$$

If now the system is switched rapidly between the two conditions, the aerial power will contain an alternating component whose magnitude is the difference between the powers intercepted in the two switch conditions

$$2pA(\theta)\cos(2\pi d\theta/\lambda). \tag{4}$$

If the aerial system is connected to a receiver having a square-law detector* the output voltage will contain a steady component which includes the noise power generated in the receiver itself, together with a square-wave alternating component whose amplitude is

$$2GpA(\theta)\cos(2\pi d\theta/\lambda),$$

where G is a constant which includes the amplification of the receiver and the constant of the detector. Thus, by the addition of an amplifier which responds to the alternating component from the detector, but not to the steady component, it is possible to obtain an alternating output voltage related to the power received from the point source. By combining this voltage with a reference signal derived from

* A more detailed analysis shows that for any type of detection the same result is obtained when the noise power from the source represents a small fraction of the total noise power in the input circuit of the receiver.

the aerial phase-changing switch, it is then possible to produce a direct current whose magnitude and sign depend on the intensity and direction of the point source. A block diagram of the complete system is shown in figure 2.

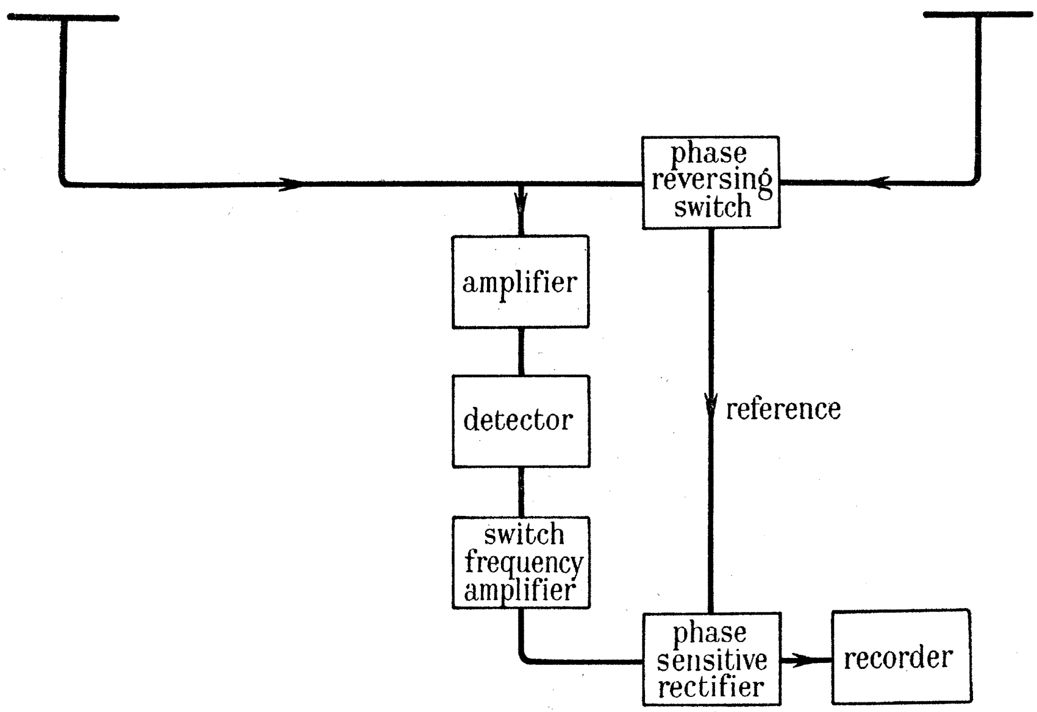

FIGURE 2. Block diagram of the phase-switching system.

Now consider the effect of a slow variation of θ, which might be caused by the rotation of the earth; the relative powers from the aerial system in the two positions of the phase-changing switch will alter, and the amplitude of the square-wave component and hence of the direct-current output from the phase-sensitive rectifier will undergo a periodic variation in time proportional to $2GpA(\theta)\cos(2\pi d\theta/\lambda)$.

If the output current is used to operate a recording milliammeter, a trace having the form shown in figure 3 will be produced.

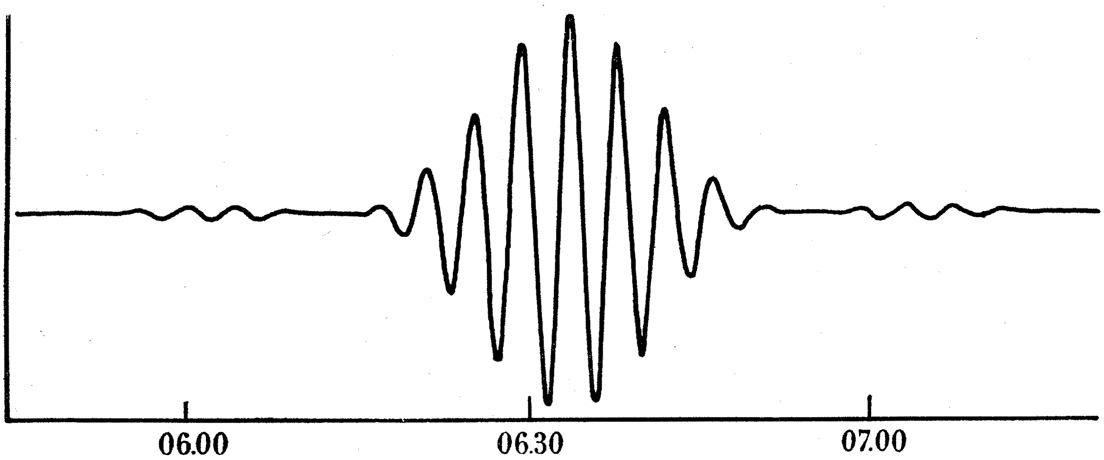

FIGURE 3. Record of the intense radio star in Cassiopeia obtained with the phase-switching system on a wave-length of 3·7 m.

So far it has been assumed that the incident radiation is due to a single point source; it is now necessary to consider the effect of radiation from an extended source, which subtends an angle which is not small compared with the separation (λ/d) of successive maxima of the interference pattern. Let the intensity emitted by a strip bounded by the directions θ and $(\theta + \mathrm{d}\theta)$ be represented by $P(\theta)\,\mathrm{d}\theta$. Then the power intercepted when the aerials are connected in phase is

$$\int P(\theta)\,A(\theta)\left[1+\cos\left(\frac{2\pi d\theta}{\lambda}\right)\right]\mathrm{d}\theta,$$

and with the aerials in anti-phase is

$$\int P(\theta)\,A(\theta)\left[1-\cos\left(\frac{2\pi d\theta}{\lambda}\right)\right]\mathrm{d}\theta.$$

If the variation across the source of the receptivity of each aerial individually, $A(\theta)$, is neglected, the powers intercepted may be written

$$A(\theta)\int P(\theta)\left[1\pm\cos\left(\frac{2\pi d\theta}{\lambda}\right)\right]\mathrm{d}\theta. \tag{5}$$

For a source of uniform 'brightness' and angular width $2\Delta\theta$, the quantity $P(\theta)$ may be replaced by $p'/2\Delta\theta$, where p' represents the total intensity of the radiation emitted by the source. The powers intercepted by the aerial when the centre of the source is in a direction θ_1 are then

$$\frac{p'A(\theta)}{2\Delta\theta}\int_{\theta_1-\Delta\theta}^{\theta_1+\Delta\theta}\left[1\pm\cos\left(\frac{2\pi d\theta}{\lambda}\right)\right]\mathrm{d}\theta=\frac{p'A(\theta)}{2\Delta\theta}\left[2\Delta\theta\pm\frac{\lambda}{\pi d}\cos\left(\frac{2\pi d\theta_1}{\lambda}\right)\sin\left(\frac{2\pi d\Delta\theta}{\lambda}\right)\right]. \tag{6}$$

An extended source of radiation therefore produces a steady component, $Gp'A(\theta)$, at the output of the receiver, together with an alternating component of magnitude

$$\frac{Gp'A(\theta)}{\Delta\theta}\frac{\lambda}{\pi d}\cos\left(\frac{2\pi d\theta_1}{\lambda}\right)\sin\left(\frac{2\pi d\Delta\theta}{\lambda}\right).$$

The latter component will be amplified and will produce, from the phase-sensitive rectifier, a proportional direct current which may be used to operate the recorder. The steady component will have no effect on the phase-sensitive rectifier and will therefore produce no deflexion of the recorder; as will be seen later, however, it is of importance when considering automatic control of the receiver gain.

As the earth rotates, θ_1 will increase and the recorder deflexion will vary periodically; the phase of the variations will be the same as would be produced by a point source situated at the centre of the extended source, but the amplitude will be smaller than that from a point source giving rise to the same total flux by a factor

$$\frac{\sin\left(\frac{2\pi d}{\lambda}\Delta\theta\right)}{\frac{2\pi d}{\lambda}\Delta\theta}.$$

By measuring the amplitudes of the traces obtained with two different values of d, it is therefore possible to deduce $\Delta\theta$, the half-width of the source; a comparison between this method of measuring the angular diameter of a source and methods which have been described previously in which the total aerial power was measured is given in § 3 (*d*).

From equation (5) it is apparent that the amplitude of the trace is in fact proportional to one term of the Fourier transform of the angular distribution of intensity across the source*; the angular periodicity of the term is determined by the spacing between the aerials and is given by d/λ. A similar analysis, based on the use of a 'total power' recording system, has already been applied to the measurement of the distribution of radio 'brightness' across the undisturbed solar disk (Stanier 1950; Ryle 1950). The same experiment, on a longer wave-length, has recently been carried out by Machin (1951) using the phase-switching system.

(b) The elimination of the background radiation due to the galaxy

It is now possible to apply these results to find the effect of the background radiation from the galaxy on measurements made with the phase-switching system. Suppose that the average intensity of the background radiation is deduced for a number of strips running parallel to the axial plane, and extending over the reception pattern of the primary aerials. Let $f(\theta)$ represent the variation of this average intensity with θ. (For the case of an east-west interferometer, the strips will be parallel to the meridian, and will extend in declination through an angle determined by the north-south coverage of each aerial.) In the absence of any point sources of radiation the deflexion of a recorder used with a phase-switching system will be proportional to the amplitude of the component of the Fourier transform of $f(\theta)$ having a periodicity in angle of d/λ. If the background radiation varies in angle in a continuous manner, the residual periodic variation of the trace can be made indefinitely smaller by increasing the separation (d) between the aerials.

In any practical system it is clear that the function $f(\theta)$ may contain small terms having angular periodicities comparable with d/λ, and that confusion may therefore arise between a genuine radio star and the small irregularities in the background radiation. The importance of this possible limitation depends not only on d/λ but on the area and shape of the individual aerials of the interferometer. The use of a second alternative value of the aerial spacing (d), however, always makes it possible to discriminate between irregularities of this nature and genuine sources of small angular diameter, and no trouble has been encountered with this limitation in practice.

The effectiveness of discriminating against the background radiation in this way may be compared with that obtained with a simple 'pencil-beam' aerial. In the latter case any irregularities having an angular structure comparable with the angular width of the reception pattern will be difficult to distinguish from a radio

* The relation between the magnitude of the varying component of power intercepted by an interferometer and the Fourier transform of the distribution across the source was first pointed out by McCready, Pawsey & Payne-Scott (1947).

star. A 'pencil-beam' aerial system would therefore have to have an aperture of about twice the *separation* between the aerials of an interference system ($2d$) to have the same discrimination.

It is clear that because the background radiation does not produce a deflexion on the record, it is possible to use a very much greater recording sensitivity than is possible with a 'total-power' recording system. As the sensitivity is increased one of two factors may prevent the detection of further radio stars:

(i) The random fluctuations on the record may mask the traces due to radio stars whose flux is less than a certain value.

(ii) The traces from adjacent radio stars may overlap to produce a resultant trace whose amplitude and phase are related to the intensities and positions of two or more radio stars. Under these conditions no accurate position or intensity can be determined for the individual stars, yet they cannot be regarded as an irregularity in the unresolved background radiation, since in principle they could be resolved by observations with a number of different aerial spacings.

The relative importance of these two factors which determine the ultimate limit of detection will be discussed in greater detail in § 3 (a). Some further properties of the phase-switching system will first be discussed.

(c) *The general relationships for the phase-switching system*

It is now important to consider the behaviour of a phase-switching system in the general case where the two aerials are not identical; these differences might arise if the two aerials had different reception patterns, or if the attenuation factors of the two cables were unequal.

Suppose that a point source produces a power flux p_s at the aerials, and that a mean flux p_g per unit solid angle is incident from the background radiation. If A and A' represent the effective areas of the two aerials for radiation incident from the direction of the point source, then the powers available from the two aerials are

$$Ap_s + p_g\lambda^2, \quad A'p_s + p_g\lambda^2.$$

As will be seen later, there are certain applications of the phase-switching system in which the two aerials have very different reception patterns; under these conditions it may be necessary to consider the different area of sky covered by each aerial. If the effective values of the incident flux from the background are represented by p_g and p'_g, the aerial powers may then be written

$$Ap_s + p_g\lambda^2, \quad A'p_s + p'_g\lambda^2.$$

If now the aerials are connected to the receiving system with cables having attenuation constants α and α', the power available at the input of the receiver with the aerials in-phase and with the source on the axial plane of the interferometer is

$$\tfrac{1}{2}\{\sqrt{(\alpha A p_s)} + \sqrt{(\alpha' A' p_s)}\}^2 + \tfrac{1}{2}\lambda^2(\alpha p_g + \alpha' p'_g).$$

When the aerials are connected in anti-phase the power will be

$$\tfrac{1}{2}\{\sqrt{(\alpha A p_s)} - \sqrt{(\alpha' A' p_s)}\}^2 + \tfrac{1}{2}\lambda^2(\alpha p_g + \alpha' p'_g).$$

If the receiving amplifier generates a noise power P_N, the total power at the input of the receiver in the two positions of the phase-changing switch will be

$$\tfrac{1}{2}p_s\{\sqrt{(\alpha A)} \pm \sqrt{(\alpha' A')}\}^2 + \tfrac{1}{2}\lambda^2(\alpha p_g + \alpha' p'_g) + P_N. \tag{7}$$

This result may be interpreted in terms of a steady component of noise power

$$\tfrac{1}{2}p_s(\alpha A + \alpha' A') + \tfrac{1}{2}\lambda^2(\alpha p_g + \alpha' p'_g) + P_N, \tag{8}$$

and an alternating component

$$2p_s\sqrt{(\alpha\alpha' AA')}. \tag{9}$$

The latter component may be used to produce an output current which will vary sinusoidally as the position of the point source changes due to the rotation of the earth. The steady component of noise power determines the amplitude of the statistical fluctuations on the record, and therefore determines the limiting sensitivity of the system.

Some applications of this result will now be examined.

(d) *The use of pre-amplifiers*

In order to obtain good discrimination against the background radiation, and to determine the positions of radio stars as accurately as possible, it is important to use the maximum possible separation between the aerials. Apart from observations with the 'cliff' type of interferometer (McCready, Pawsey & Payne-Scott 1947), the use of a large separation introduces considerable attenuation (α) in the cables from the aerials. At the shorter wave-lengths, where the total noise power at the input of the receiver is mainly due to the internal noise P_N, an increase of α would seriously reduce the overall sensitivity of the system, and accurate observations of the weaker radio stars would therefore be impossible.

It is clear that if an amplifier were installed at each aerial, having a gain somewhat greater than $1/\alpha$ and a noise power comparable with that of the main receiver, then the limiting sensitivity would be the same as if there were no attenuation. In the earlier experiments, in which the total aerial power was measured, the use of pre-amplifiers would not have been possible unless their gains and noise powers remained extremely constant. It will now be shown that these difficulties do not occur with the phase-switching system; the system therefore enables weaker radio stars to be detected, and also permits an indefinite increase of the resolving power which may be realized.

Suppose that the two pre-amplifiers have gains β and β', and that they generate noise powers P_N and P'_N. If a point source situated in the axial plane of the interferometer produces a flux p_s, and if, as before, the background radiation produces an effective flux per unit solid angle of p_g and p'_g, then the total noise power available at the input of the main receiver in the two positions of the phase-changing switch is

$$\tfrac{1}{2}p_s\{\sqrt{(\alpha\beta A)} \pm \sqrt{(\alpha'\beta' A')}\}^2 + \tfrac{1}{2}\lambda^2(\alpha\beta p_g + \alpha'\beta' p'_g) + \tfrac{1}{2}\alpha\beta P_N + \tfrac{1}{2}\alpha'\beta' P'_N. \tag{10}$$

(If $\alpha\beta \gg 1$ the noise power generated in the main receiver may be neglected.)

This result may be interpreted as a steady component of noise power

$$\tfrac{1}{2}p_s(\alpha\beta A + \alpha'\beta' A') + \tfrac{1}{2}\lambda^2(\alpha\beta p_g + \alpha'\beta' p'_g) + \tfrac{1}{2}\alpha\beta P_n + \tfrac{1}{2}\alpha'\beta' P'_n, \tag{11}$$

and an alternating component

$$2p_s\sqrt{(\alpha\alpha'\beta\beta'AA')}. \tag{12}$$

Since only the latter component is effective in producing a deflexion of the recorder, it may be seen that in the absence of a point source no deflexion is produced even if the aerials, cable attenuation, amplifier gains or noise powers are unequal or vary with time. The amplitude of the trace produced by a point source is a function of the geometric mean of the overall gain of the two halves of the system, and as will be seen in the next section it is unnecessary to adopt any elaborate arrangement for equalizing the gains or noise powers of the pre-amplifiers.

(e) The absolute measurement of power flux with the phase-switching system

It is clear that the amplitude of the trace produced by a radio star is a function of the overall gain of the system whether pre-amplifiers are used or not, and it is therefore important to examine the problem of obtaining absolute measurements of the intensity of a radio star over long periods of time.

When measuring the total aerial power, the automatic balancing system which is mentioned in §3(*a*) enabled absolute measurements to be made without the necessity for accurate stabilization of the gain of the receiver; a similar result can be obtained with the phase-switching system by incorporating an automatic-gain control circuit having a response time which is long compared with the switching period. There is little difficulty in designing such a circuit to maintain the mean noise power at the detector constant to within 1 %.

First consider the application to a phase-switching system without pre-amplifiers. By reference to equation (8) it can be seen that the gain G of the amplifier will be continuously adjusted so that

$$G[\tfrac{1}{2}p_s(\alpha A+\alpha' A')+\tfrac{1}{2}\lambda^2(\alpha p_g+\alpha' p_g')+P_N] = C,$$

where C is a constant determined by the setting of the gain control. The amplitude of the trace produced by the passage of the radio star will then be

$$2Ggp_s\sqrt{(\alpha\alpha' AA')} = \frac{2gp_s\sqrt{(\alpha\alpha' AA')}\,C}{\tfrac{1}{2}p_s(\alpha A+\alpha' A')+\tfrac{1}{2}\lambda^2(\alpha p_g+\alpha' p_g')+P_N},$$

where g represents the amplification of the remaining circuits following the detector (i.e. the switch-frequency amplifier, the phase-sensitive rectifier and recorder circuits). In practice $g \ll G$, and there is little difficulty in design to ensure that g is sufficiently stable.

Except for observations of the most intense radio stars with very large aerial systems, $p_s A \ll p_g \lambda^2$, and the amplitude on the record may be written

$$\frac{2gp_s\sqrt{(\alpha\alpha' AA')}\,C}{\tfrac{1}{2}\lambda^2(ap_g+\alpha' p_g')+P_N}.$$

Since A, A' are constants depending only on the dimensions of the aerial structure, and since α, α' represent the attenuation constants of the cables, it can be seen that for a given gain setting C, the deflexion sensitivity depends only on $\lambda^2 p_g$ and P_N, and is not dependent on the maintenance of constant gain of the main amplifier. The two limiting cases are of interest.

(i) $\alpha\lambda^2 p_g \gg P_N$

For wave-lengths greater than about 3 m, the aerial power available at the input of the receiving amplifier may be appreciably greater than the noise power of the receiver itself. (In the absence of pre-amplifiers, this condition may only arise for comparatively small resolving powers, where the cable attenuation (α) is small; the use of pre-amplifiers will be discussed later.) If $\alpha\lambda^2 p_g \gg P_N$, it can be seen that the recorder sensitivity is independent of the noise power generated in the receiver, and depends (apart from the characteristics of the aerials and cables) only on the average intensity of the background radiation within the solid angles of the two aerials. The flux from the radio star is, in effect, compared with that from the galactic background, and when the aerial characteristics are known an absolute measurement is available without knowledge of the characteristics of the receiving amplifier itself. For absolute measurements of the intensity of a number of radio stars it is, of course, also necessary to determine p_g in different directions; this may conveniently be done by making recordings of the total aerial power.

(ii) $P_N \gg \alpha\lambda^2 p_g$

At the shorter wave-lengths (< 2 or 3 m), the noise power generated in the receiver itself (P_N) normally exceeds that from the aerial. Under these conditions the recorder sensitivity does not depend on the direction of observation, but is a function of P_N. Fortunately, it is very much easier to maintain the input noise power of an amplifier within small limits than it is to maintain its gain, and there is little difficulty in practice in maintaining the noise power within 5 to 10 % despite large variations in the supply voltage.

(*f*) *The absolute measurement of power flux when pre-amplifiers are used*

The use of pre-amplifiers not only allows a very considerable extension of the limiting sensitivity and resolving power which may be used, but also increases the range of wave-lengths over which the recorder sensitivity is determined by the galactic background radiation. Previously it was shown that the sensitivity would be controlled by the galactic background as long as $\alpha\lambda^2 p_g > P_N$. With pre-amplifiers the limit is given by $\lambda^2 p_g > P_N$. For example, observations with an aerial separation of 100λ would only be controlled by the background on wave-lengths greater than about 8 m (the precise figure depends, of course, on the type of aerial cable used). If pre-amplifiers are used, the sensitivity will be controlled by the background with any aerial separation and with low-grade cables, at wave-lengths as short as about 3 m. It is, however, now necessary to examine the effects of inequality in the gains or noise powers of the two pre-amplifiers.

(i) $\lambda^2 p_g \gg P_N$

The noise power at the input to the main receiving amplifier will be

$$\tfrac{1}{2}\lambda^2 p_g(\alpha\beta + \alpha'\beta'),$$

where $\beta\beta'$ are the gains of the two pre-amplifiers. (The noise power generated in the main receiver may be neglected provided $\alpha\beta \gg 1$.)

The alternating component of noise power due to the radio star is given by

$$2p_s\sqrt{(\alpha\alpha'\beta\beta'AA')},$$

and the deflexion of the recorder will be

$$\frac{4gp_s\sqrt{(\alpha\alpha'\beta\beta'AA')}\,C}{\lambda^2 p_g(\alpha\beta+\alpha'\beta')}.$$

It can thus be seen that, providing the overall gains ($\alpha\beta A$) of the two halves are equal, the deflexion sensitivity is independent of the gains of the pre-amplifiers.

Now suppose that one-half has a gain equal to half that of the other (e.g. $\beta = \frac{1}{2}\beta'$). The deflexion will be reduced by a factor $\frac{2}{3}\sqrt{2} = 0{\cdot}94$. Thus a deterioration of 2 : 1 in the gain of one pre-amplifier will only produce a 6 % change in the overall sensitivity of the system. In practice the total gain of the pre-amplifiers need only be sufficient to overcome the attenuation constant of the cables ($\alpha\beta \gg 1$), and the maintenance of a gain stability considerably better than 2 : 1 is very simple.

(ii) $P_N \gg \lambda^2 p_g$

At the shorter wave-lengths the gain of the main receiving amplifier is determined by the total noise power from the two pre-amplifiers $\frac{1}{2}(\alpha\beta P_N + \alpha'\beta' P'_N)$, and the deflexion of the recorder due to a radio star of intensity p_s is given by

$$\frac{4gp_s\sqrt{(\alpha\alpha'\beta\beta'AA')}\,C}{(\alpha\beta P_N + \alpha'\beta' P'_N)}.$$

If the gains and noise powers of the two pre-amplifiers are equal, the sensitivity depends only on the value of this noise power. If the gain of one pre-amplifier falls by a factor of 2, the overall sensitivity decreases by 6 %; a similar change would be produced by an increase of the noise power of one pre-amplifier by 12 %. As has already been stated, the maintenance of such figures of stability presents no great difficulty.

3. Comparison of the phase-switching system and other systems for observing radio stars

(a) *The detection of radio stars*

The problem of detecting a weak 'point' source of radio waves has already been considered in some detail (Ryle 1950); it was there shown that a lower limit may be set to the intensity of the detectable radio stars by any one of the three following experimental difficulties.

(i) The difficulty of measuring the small radio-frequency power produced in the aerial by the radio star owing to the random fluctuations on the record. The amplitude of these fluctuations depends first on the total noise power at the input of the receiver, which includes that due to the galactic background and that generated in the receiving amplifier itself, and secondly on the ratio of the band-widths of the receiving amplifier before and after the detector.

(ii) The difficulty of discriminating between the aerial power due to the radio star and the very much greater power due to the galactic background.

(iii) When sensitive receiving apparatus is used in conjunction with an aerial system of large resolving power an additional limitation may arise, which is due to the confusion between the traces produced by adjacent radio stars.

It was shown that the use of an interferometer aerial system provided a powerful method of overcoming the second difficulty, and allowed a discrimination which was comparable with that of a simple 'pencil-beam' aerial system having an aperture of twice the *spacing* between the aerials of the interferometer.

Two main types of interferometer have been used: (i) those in which the interference pattern is produced by two spaced aerials (Ryle & Vonberg 1946; Ryle 1950) and (ii) those based on the use of a single aerial mounted on a high cliff to produce interference by reflexion at the surface of the sea (McCready *et al.* 1947; Bolton & Stanley 1949; Stanley & Slee 1950). The latter type has the advantage of simplicity, and allows a large resolving power to be obtained without the use of two long and equal lengths of high-quality cable from the aerials, but it suffers from the disadvantage that observations are necessarily made at small angles of elevation, where refraction effects become serious. Observations with the spaced-aerial interferometer, on the other hand, are made when the radio star is near the meridian, and refraction effects are a minimum. The cable attenuation introduced when large resolving powers are used does not affect the limiting sensitivity when the phase-switching system is used, since pre-amplifiers may be mounted at the aerials.

The problem of measuring a small random radio-frequency power in the presence of a much larger noise power (P_N) generated in the receiving amplifier has been examined in an earlier paper (Ryle & Vonberg 1948), where it was shown that the additional power should be detectable if it exceeded $P_N/\sqrt{(Bt)}$, where B is the band-width of the receiving amplifier and t is the time-constant of the recorder circuits following the detector. The product Bt is commonly of the order of 10^5 to 10^6. In practice the necessity for very accurate stabilization of the gain of the amplifier makes it difficult to achieve a sensitivity as good as this, and in earlier observations at Cambridge of the radiation from the sun and radio stars an improved system of recording was used in which the output of a local source of noise power was continuously and automatically balanced against the aerial power (Ryle & Vonberg 1948). This system has been found to have a limiting sensitivity close to that expected theoretically,* and since the aerial power is measured absolutely, in a manner which is independent of the characteristics of the receiving amplifier, it has proved a most satisfactory way of measuring the total aerial power.

It is now important to examine the extension of these ideas to the detection of the much smaller power from weak radio stars. The aerial power due to the galactic background must now be considered with the receiver noise power as an unwanted background, which not only increases the statistical fluctuations on the record $(P_N+\lambda^2 p_g)/\sqrt{(Bt)}$, but may also introduce other difficulties which are discussed

* Since the aerial is connected to the receiver for only half the time in this system, the smallest detectable power is increased by a factor of $\sqrt{2}$, as compared with the theoretical limit; this loss does not occur with the phase-switching system, where the aerial system is connected all the time.

below. It should first be noted that the theoretical limit of detection set by the statistical fluctuations on the record may be very much smaller than was considered in earlier work on solar radiation. It is often possible to use a much longer recording time-constant t, determined only by the rate of movement of the interference pattern due to the rotation of the earth, and the corresponding statistical fluctuations on the record may represent less than $\frac{1}{1000}$th of the total aerial power. Even with the automatic balancing system mentioned above, other difficulties may arise when attempting to measure additional aerial powers of this magnitude.

A typical record obtained with a spaced-aerial interferometer and the total-power recording system mentioned above is shown in figure 4. The periodically varying component of aerial power due to the passage of the two most intense radio stars can be seen superimposed on the slowly varying component due to the galactic background. It is clear that records of this type are adequate for observing radio stars which produce an aerial power comparable with that due to the background radiation, but it would be difficult to make accurate observations of a radio star

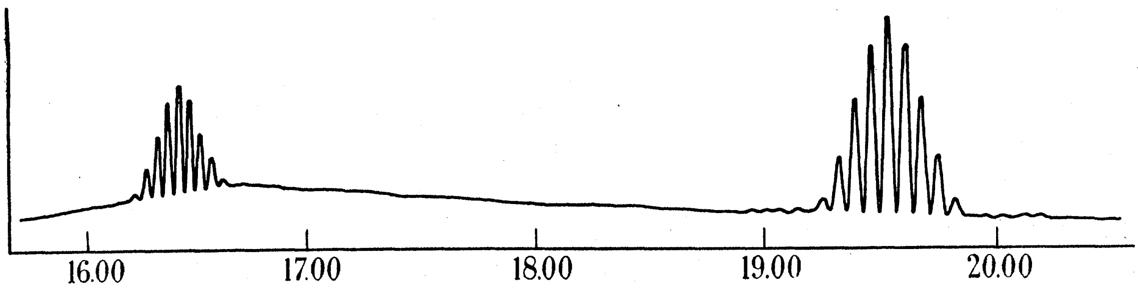

FIGURE 4. Record obtained with 'total-power' recording system showing the two most intense radio stars and background radiation.

which produces an aerial power of, say, $\frac{1}{20}$th of this value, because of the limit set to the maximum recorder sensitivity by the variation of the background component throughout the day. Whilst it would in principle be possible to incorporate a device for 'backing-off' the output current of the receiver by an amount which varied with the direction of observation, it would clearly be difficult to increase the sensitivity sufficiently to enable the observation of a radio star which produced an aerial power only $\frac{1}{1000}$th of that due to the background radiation. In the phase-switching system, no deflexion of the recorder is produced by the background radiation, and, as has already been shown, a very much greater recorder sensitivity can therefore be used.

Apart from purely practical difficulties of this type, there are, however, more fundamental problems involved in detecting weak radio stars by 'total power' recording methods. No attempt will here be made to analyze these problems in detail, but two specific difficulties will be mentioned.

(i) As has already been shown (Ryle & Vonberg 1948), small variations of the aerial impedance will alter the effective load resistance in parallel with the input circuit and will thereby modify the internal noise power (P_N) generated in the amplifier. It was shown that a change of 10 % of the aerial impedance might displace the recorder by an amount corresponding to 5 % of the receiver noise power P_N. If observations of a radio star which produces an aerial power of only $P_N/1000$ are attempted, it is clear that small variations of the aerial impedance, such as are likely to occur in wet weather, will produce irregular variations on the recorder which may mask the small periodic trace due to the radio star. In the phase-switching system the impedance appearing across the input circuit of the receiver is the same in both positions of the phase-changing switch (provided that 'half-wave' switching is used); no component of the output noise power at the switching frequency will therefore be produced, even if one or both of the aerials is badly mismatched, and no deflexion of the recorder will therefore occur.

(ii) Even in the absence of difficulties associated with the noise power generated in the receiver, similar difficulties may arise when the aerial power produced by the radio star is only about $\frac{1}{1000}$th of that due to the background radiation. Small variations of the attenuation or reflexion loss in one of the cables from the aerials may produce sufficient variation of the total power from the galactic background to mask the periodic variations due to the movement of the radio star through the interference pattern. No deflexion of the trace of the phase-switching system is produced by the background radiation, and small variations of the cable loss will therefore not affect the record.

It has been shown that many of the difficulties encountered in the detection of weak radio stars by methods based on the measurement of the total aerial power have been overcome by the use of the phase-switching system. The limiting sensitivity determined by the random fluctuations on the record has been found to be in close agreement with that predicted theoretically for a total noise power equal to the sum of the aerial and pre-amplifier powers, and this limiting sensitivity is not affected by attenuation in the aerial cables. The use of aerial spacings of 100 to 200λ has allowed virtually complete elimination of the background radiation and inequalities or variations of the impedances of the aerials or the attenuation of the cables have no effect. The limit of detection with the phase-switching system is therefore determined either by the theoretical random fluctuations on the record, or by the confusion of the traces produced by adjacent radio stars. The relative importance of these two limitations depends not only on the intensity and distribution of radio stars and of the background radiation, but on the dimensions of the aerial system and on the wave-length used. It is outside the scope of the present paper to discuss the effect of these two limiting factors on the choice of aerial design, or of their corresponding effects on measurements of the positions of radio stars, but it is clear that at the longer wave-lengths, the solid angle for reception is likely to be large, whilst the random fluctuations on the record depend only on the background radiation from the galaxy; under these conditions the limitation set by confusion is likely to be the more serious. At short wave-lengths, on the other hand, the resolving power is likely to be greater, whilst the random fluctuations will be mainly due to the pre-amplifier noise power and are more likely to be the limiting factor.

In addition to improved sensitivity and available resolving power the phase-switching system has a number of other advantages over 'total power' recording systems, and these will now be discussed.

(*b*) *The determination of the position of a radio star*

Accurate measurements of the positions of radio stars have all been based on observations of the movement of the radio star through the reception pattern of an interference system. A discussion of the methods which may be used is given in another paper (Smith, in preparation). In observations with 'total power' recording systems, such measurements are best made by determining the times of successive minima of the recorded power. It is, however, clear that a marked improvement in the accuracy should be possible if measurements were made at a time when the *rate of change* of the recorded power was a maximum rather than a minimum.

In the phase-switching system, zero deflexion of the recorder occurs whenever the two signals from the aerials are in quadrature; at this time the rate of change of the recorder deflexion is a maximum and very much greater timing accuracy is therefore possible. Furthermore, since the addition of any two voltages in quadrature gives a resultant whose magnitude is unaltered if the phase of one voltage is reversed, the time at which zero deflexion of the recorder occurs is not altered if the two signals are of unequal magnitude; the 'time of cross-over' on the record is therefore not affected by inequalities in the effective area of the aerials, or by differences in the gains of the pre-amplifiers or in the attenuation constants of the cables.

Since the time of cross-over corresponds to zero amplitude of the switch-frequency component at the detector, the accuracy is also unaffected by non-linearity in the succeeding amplifiers or by changes in the intensity of the incident radiation. It therefore becomes possible to use a very great deflexion sensitivity, such that the maxima of the trace would correspond to perhaps 50 times full-scale deflexion of the recorder, and complete overload of the switch-frequency amplifier and subsequent circuits. If a very great deflexion sensitivity is used in this way, the time during which the recorder deflexion is changing is very small (perhaps only 0·01 of the total period of the trace), and it becomes possible to determine the cross-over time with an accuracy which corresponds to only 10^{-3} of the period of the pattern. This accuracy corresponds to a determination of the quadrature condition of the voltages from the two aerials to a fraction of a degree; with aerial separations of 100 to 200λ this error is equivalent to an error in the apparent right ascension of the source of a few seconds of arc.* Experimental records of this type are shown in figures 5 and 6.

(*c*) *Determination of the position of a source of variable intensity*

The ability to observe the time of cross-over, and hence the position of the source, in a manner which is independent of the intensity of the radiation is particularly important for investigating the diffraction effects caused by irregularities in the terrestrial ionosphere, and for observing the intense sources of radiation associated with sunspots. In both cases large and rapid fluctuations of intensity occur, and it is clear that serious errors will be introduced if attempts are made to estimate the apparent position of the source with a 'total power' recording system. Even with

* The determination of the *absolute* position of a source also requires a knowledge of the refraction effects in the terrestrial atmosphere, and of the positions of the electrical centres of the two aerials of the system.

very large and rapid variations of intensity the timing error involved in the phase-switching system can only be of the order of the time-constant of the recording system. In many cases the observed variations of intensity are considerably slower than this quantity, and the errors are correspondingly reduced. Phase-switching systems have been used in this way to determine the relation between the variation of apparent position and the variation of intensity of a radio star due to ionospheric diffraction (Ryle & Hewish 1950), and to investigate the angular movement of the effective centre of sources of sunspot radiation.

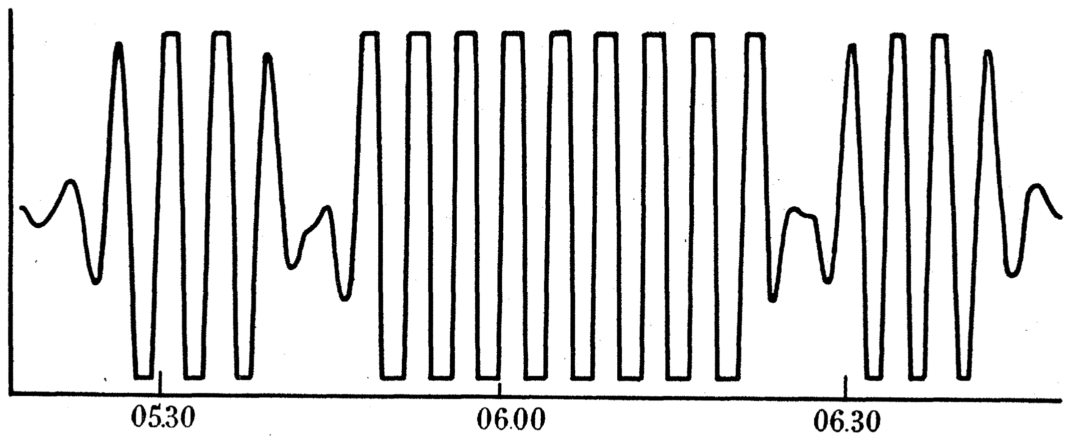

FIGURE 5. Typical record of intense radio star using increased recording sensitivity.

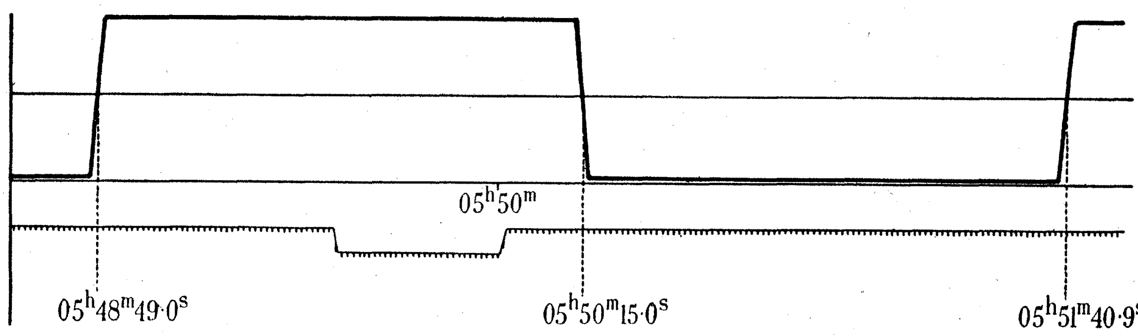

FIGURE 6. Typical high-speed record used for accurate determination of the position of a radio star.

The method described allows accurate observations of the position to be made at each half-period of the interference pattern; an extension of this method to allow a continuous record to be obtained of a source whose intensity and apparent position are both varying has also been used (Hewish, in preparation).

(*d*) *The measurement of the angular diameter of a source*

It has been shown that when an extended source is observed with an interferometer having an aperture d, the amplitude of the trace produced by a phase-switching system, and the amplitude of the *variable component* of the trace produced by a total power recording system, are proportional to one term of the Fourier transform of the intensity distribution; the angular frequency of the term is given by d/λ. If the source has a uniform distribution of intensity, and a width $2\Delta\theta$

(e.g. a square source), the amplitude of the trace relative to that produced by a point source emitting the same total power is given by

$$\frac{\sin \frac{2\pi d}{\lambda} \Delta\theta}{\frac{2\pi d}{\lambda} \Delta\theta} = \gamma.*$$

Previous measurements with total power recording systems have taken advantage of the fact that provided observations are made of the received power at both maxima and minima of the interference pattern, their ratio $(1+\gamma)/(1-\gamma)$ enables a determination of γ without a knowledge of the total intensity of the source. It is therefore possible to deduce the angular diameter with a single value of the aerial spacing d. Observations with the phase-switching system give a trace whose amplitude is proportional to γ, and it is therefore necessary to compare the amplitudes obtained with two different aerial spacings before the angular diameter can be deduced.

It is now important to compare the practical difficulties of the two methods, with particular reference to the determination of very small angular diameters, and those of sources of small intensity. It is first useful to show (table 1) how the quantities γ and $(1+\gamma)/(1-\gamma)$ vary with $2\Delta\theta/(\lambda/d)$.

Table 1

$2\Delta\theta/(\lambda/d)$	γ	$(1+\gamma)/(1-\gamma)$
0	1·0	∞
0·01	0·9999	12200
0·02	0·9993	3040
0·05	0·996	485
0·1	0·984	121
0·2	0·936	31
0·3	0·86	14·3
0·4	0·76	7·3
0·5	0·64	4·1
0·6	0·51	3·0
0·8	0·23	1·6
1·0	0	1·0

The resolving power of either system is determined by the largest value of γ or $(1+\gamma)/(1-\gamma)$ that can be measured. In the phase-switching system this limit is set by the accuracy with which the overall gains of the systems at the two different spacings are known. The total-power system is limited by the accuracy with which the minimum power may be found, and is therefore affected by inequalities in the gains of the two aerials (or the losses in their cables) and by uncertainty concerning the contribution of the galactic background radiation.

Early observations of the angular diameter of the intense sources of radiation associated with sunspots were made with interferometers having apertures of 100 to

* A circular source which is small compared with λ/d will produce a trace equal to that from a 'square' source whose width is 0·82 × its angular diameter.

200λ. Since the diameters of these sources are of the order of 3 to 10 min. of arc, it was only necessary to work with values of $2\Delta\theta/(\lambda/d)$ of 0·1 to 0·5, and no special difficulties were encountered in equalizing the gains or cable losses of the two aerials. Furthermore, since the intensity of the radiation emitted by these sources was normally considerably greater than that from the galactic background, there was little difficulty in estimating the effective zero level on the record when determining the minimum power from the sun.

If attempts are made to extend such observations to measure the angular diameter of radio stars, two serious limitations are encountered with total-power recording systems:

(i) The angular diameters are known to be very much smaller than those of sunspots, and present estimates of the maximum diameters using interferometers of aperture 100 to 200λ have involved maximum/minimum ratios of the interference pattern of about a hundred. An increase of the aerial spacing would of course allow the same resolving power to be obtained with a smaller ratio, but the additional cable attenuation would decrease the ratio of signal to random fluctuations on the trace, and therefore again introduce a limitation to the resolving power; pre-amplifiers could only be used if it were possible to ensure that their gains remained equal to within 1 %.

Although the problem of cable attenuation does not arise in 'cliff' type interferometers, other difficulties are encountered in this method, both because of the effects of imperfect reflexion at the surface of the sea (Stanley & Slee 1950) and because of the geographical difficulties of obtaining a sufficiently high cliff site.

(ii) Both 'cliff' and spaced aerial interferometers using total-power recording suffer from an even more serious limitation when observing sources of small intensity; the uncertainty of determining the deflexion produced by the background radiation then makes it impossible to obtain an accurate measure of the minimum power received from the source. For this reason it is likely to be difficult with existing systems to make any estimate of the diameter of a source which produces an aerial power less than about 1 % of that due to the background radiation, whilst a source which produces a power of 10 % could probably only be resolved if its angular diameter exceeded $0{\cdot}25\,(\lambda/d)$.

Both of these difficulties are largely overcome by the use of the phase-switching system. Since no deflexion is produced by the background radiation, the intensity of the source does not present a limitation provided that it can be observed satisfactorily in the presence of the random fluctuations on the record. The limiting resolving power is then determined solely by the accuracy with which the overall gain of the system is known at the two aerial spacings; if the gain remains constant to within 5 % when the aerial spacing is changed, it is possible to resolve a source whose diameter is about $0{\cdot}15\,(\lambda/d)$. Increased resolution is possible if the overall gain can be determined directly by observing another source (such as a more remote radio star) whose angular diameter is less than that of the source under investigation. In addition, the use of simple pre-amplifiers makes it possible to operate with a very much greater aerial spacing than was possible with a total-power system.

(e) *The measurement of the polarization of the radiation from a radio star*

The measurement of the polarization of the radiation from a weak source, in the presence of a large unpolarized background radiation, has already been discussed in some detail (Ryle & Vonberg 1948, Ryle 1950). It was shown that the use of an interferometer aerial system in which the planes of polarization of the two aerials could be altered, allowed a complete analysis of the polarization of the radiation from a source of small angular diameter, in the presence of intense unpolarized radiation from the galactic background. The application of the phase-switching system to this method has similar advantages to those considered in the detection of weak radio stars, and makes it possible to detect a very small degree of polarization. If the aerials are arranged to respond to a circularly polarized component, no deflexion of the recorder will be produced either by the background radiation or by randomly polarized radiation from the radio star; it therefore becomes possible to use a very much greater recording sensitivity.

In another application which has been used to study the instantaneous polarization of the radiation from sunspots, a phase-switching system has been used in conjunction with a conventional crossed-aerial polarization system. No deflexion is produced by the background radiation or by randomly polarized radiation from the sun, but the occurrence of a circularly polarized component produces a proportional deflexion whose direction depends on the sense of the polarization. In this way a continuous record can be obtained of the instantaneous changes of polarization.

(f) *Freedom from man-made interference*

The incidence of man-made interference, particularly the radiation from unsuppressed ignition systems of cars and aircraft, presents one of the most serious practical limitations to the detection sensitivity of 'total power' systems.

From equation (9) it can be seen that the output deflexion in the phase-switching system is a function of the product of the powers intercepted by the two aerials. An interfering signal which is received by only one aerial will not therefore deflect the recorder. This property enables a very considerable immunity from local sources of interference to be obtained with the large aerial systems used for detecting radio stars. As an example the present system which has been used at Cambridge on a wave-length of 3·7 m consists of two aerials having an aperture of 20λ and separated by a distance of 0·5 km; the reception pattern of each aerial therefore extends over about $\pm 1\frac{1}{2}^\circ$ in an east-west plane, and a source of interference cannot lie in both reception patterns unless it is at a distance greater than about 10 km. Sources much nearer than this, which would cause serious interference with a total-power system whenever they passed through the reception pattern of either aerial, do not therefore affect the phase-switching system. At distances greater than 10 km the intensity of the interference is of course greatly reduced, particularly for sources at ground level, for which the received power falls off as the fourth power of the distance.

(g) *Control of the primary reception pattern of the phase-switching system*

It was shown in equation (12) that the recorder deflexion was proportional to $\sqrt{(\alpha\alpha'\beta\beta'AA')}$. The envelope of the interference pattern is thus determined by the geometric mean of the reception patterns of the individual aerials. Where the two halves of the interferometer are identical, the envelope of the pattern on the record will therefore correspond to the power reception pattern of each aerial. The ability to control the overall reception pattern by independent adjustments to either aerial has some important possibilities both for improving the effective resolving power of the system, or for reducing side lobes. One application of this feature is related to the detection of radio stars at the longer wave-lengths, where the limit of detection is usually determined by confusion between adjacent radio stars and not by the limiting sensitivity of the system. Under these conditions a decrease of the solid angle for reception without necessarily increasing the total area of the aerials would allow an increase in the number of sources which could be detected. By using aerials of equal area, one of which has a large aperture in the north-south plane, whilst the other has a large aperture in the east-west plane, it becomes possible to reduce the effective solid angle for reception without increasing the total area of the system.

4. Some illustrative practical examples of the phase-switching system

In this section an attempt will be made to illustrate some of the results, which have been demonstrated analytically in earlier sections, by experimental records obtained during observations at Cambridge. These observations have been made on wave-lengths of 1·4, 3·7, 6·7 and 8 m with a number of different types of aerial system. Most of the observations on 3·7 m have been made with an interferometer which covers a narrow strip near the meridian extending from the North pole to the equator (Ryle *et al.* 1950). This system allows daily observations of a considerable number of radio stars in the northern hemisphere to be made. In another series of observations on 1·4 m two parabolic mirrors of diameter $6{\cdot}5\lambda$ and spacing 205λ have been used to provide a system capable of more accurate position finding (Smith 1951). Observations on a wave-length of 8 m have been made with an interferometer having an aerial spacing of 60λ. In addition, a number of experiments have been made to investigate the scintillation of radio stars on all four wave-lengths.

(a) *Elimination of the background radiation*

Examples of records obtained with the phase-switching system have already been given in figures 3, 5 and 6. Examination of these records and of that shown in figure 9 (in which full-scale deflexion of the recorder corresponds to an aerial power of about 5 % of that due to the galactic background) shows the absence of any slow variations due to the background radiation which are visible in records such as figure 4 obtained with the same aerial system and a 'total power' recording system. In one of the series of observations made to investigate fluctuations of intensity caused by the diffraction effects in the terrestrial ionosphere, it was necessary to make continuous observations of the intense radio star in Cassiopeia (Ryle & Hewish 1950). To avoid complications of rotatable aerial structures, a phase-switching system was used with an interferometer in which each aerial had a sufficiently large solid angle for reception to observe the radio star in Cassiopeia continuously (power gain ≃ 4). A section of the record obtained with this system is shown in figure 7; full-scale deflexion corresponds to about 3 % of the aerial power due to the galactic background.

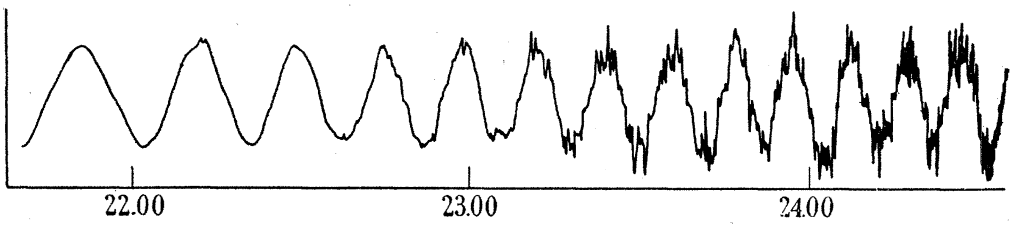

FIGURE 7. Record obtained with phase-switching system using very simple aerials (gain ≃ 4) to observe the radio star in Cassiopeia continuously.

In order to obtain a more exacting test of the effect of a comparatively localized area of increased background radiation, some special tests were carried out. Since, apart from the weak radiation from four of the extra-galactic nebulae (Ryle *et al.* 1950) no such localized areas are known, a series of observations was made of the sun in the presence of very weak sunspot radiation. Observations were made with the 1·4 m interferometer (aerial spacing 205λ), both with the 'total-power' recording system and with the phase-switching system. The results of some of these observations are shown in figure 8. During the first half of the time during which the sun was in the reception pattern of the aerials, the total-power system was connected, and the record shows both the galactic background radiation and the unresolved increase due to the radiation from the undisturbed solar disk. A small periodic component due to the small sunspot can also be seen. During the latter half of the record, the phase-switching system was used with a sensitivity approximately ten times as great; no deflexion associated with the galactic background or the undisturbed sun is visible, but the periodic component due to the sunspot is correspondingly greater.

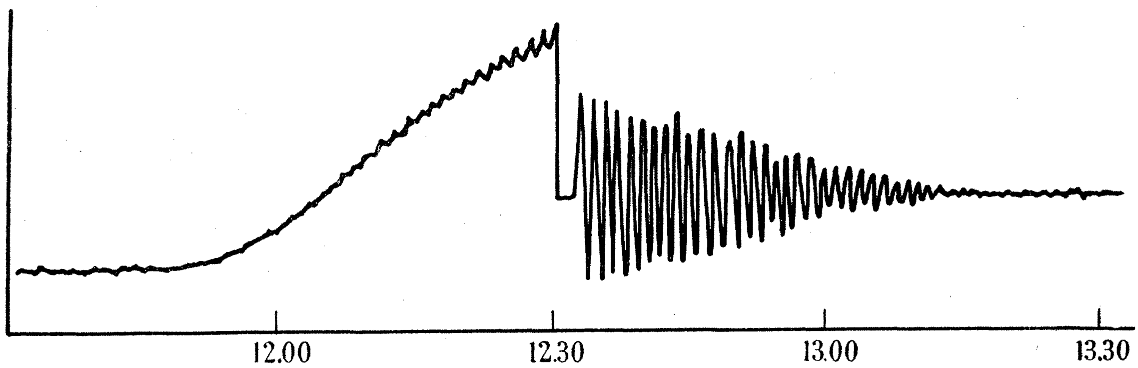

FIGURE 8. Observations showing radiation from undisturbed sun, and very small variable component from a minor sunspot: (*a*) 11.30–12.30 'total power' recording, (*b*) 12.30–13.30 phase-switching system.

From the results of such observations on the sun it can be seen that the use of an interferometer with the phase-switching system provides a satisfactory method of eliminating any likely distribution of the background radiation from the galaxy.

(b) The limit of detection

It was shown in § 3 (*a*) that the intensity of the weakest detectable radio star might be limited either by the random fluctuations on the record, or by confusion between the traces produced by adjacent radio stars. In particular, the relative importance of these two limitations depends on the size of the aerials, and on the wave-length.

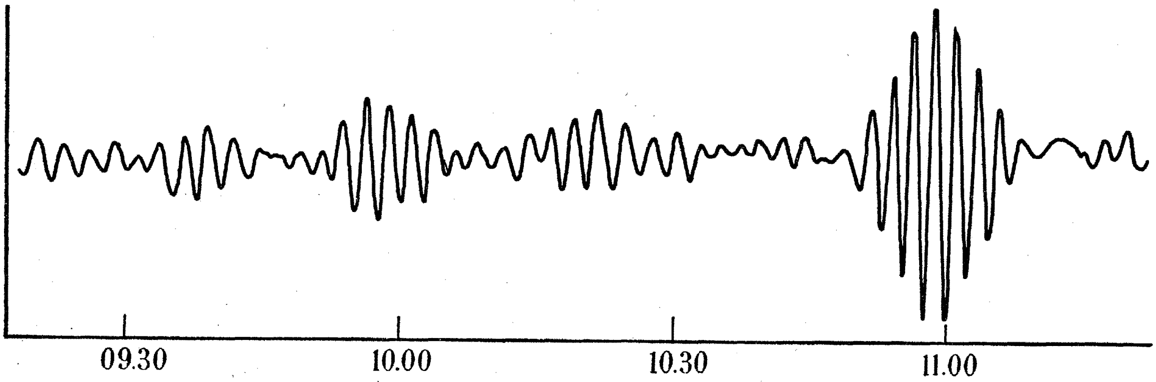

FIGURE 9. Section of record obtained with 3·7 m interferometer, showing a number of weak radio stars.

A typical section of record obtained with the 3·7 m interferometer is shown in figure 9. It can be seen that the random fluctuations are considerably smaller than the amplitude of the smallest trace which can be reliably identified. It is, in fact, found that many of the unidentified variations repeat from day to day and are therefore not due to random effects, but to the superimposition of the traces from a number of weak radio stars. Observations with this system are therefore limited entirely by confusion.

Observations with the 1·4 m interferometer, on the other hand, show that there is no confusion between any traces which are visible above the random fluctuations.

In § 2 (*e*) and (*f*) it was shown that absolute intensity measurements with the phase-switching system did not involve accurate stabilization of the gain of the receiving amplifier, and that at the longer wave-lengths the sensitivity was also independent of the noise power of the pre-amplifiers. In a series of observations on 3·7 m (where the background radiation produces a power approximately equal to that of the pre-amplifier) it was found that the deflexion sensitivity remained constant to within 5 % over a period of a year, although no special precautions were taken to stabilize the gains of the pre-amplifiers.

(c) The determination of the position of a source

An example of the type of record used for accurate determination of the position of a radio star was shown in figure 6. In the absence of ionospheric diffraction the accuracy of such observations is limited by the stability of the differential phase-angle of the aerials and pre-amplifiers and of the differential length of the aerial cables. Experiments have shown that extremely good stability can be achieved. In one particular series of observations with the 3·7 m interferometer over a period of 8 months no variation of the apparent position of the two intense radio stars could be detected greater than the limit set by the residual ionospheric diffraction. These results indicated a stability of phase of the aerials, pre-amplifiers and cables of better than 8° (corresponding to a variation in the apparent right ascension of the radio star of 40 sec. of arc).

In another series of experiments on 1·4 m (where the ionospheric diffraction effects are smaller), a phase stability of 5° was observed, corresponding to a variation in the apparent right ascension of 15 sec. of arc.

It was shown in § 3 (*c*) that the phase-switching system allowed accurate observations to be made of the position of a source of variable intensity. Observations of the variation of the apparent position of a radio star due to ionospheric diffraction have already been described (Ryle & Hewish 1950). Similar observations have also been made to investigate the movement of the effective centre of the intense sources of radiation associated with sunspots. An example of such a series of observations is shown in figure 10, in which the variation of intensity and apparent position of the source of 3·7 m solar radiation is shown.

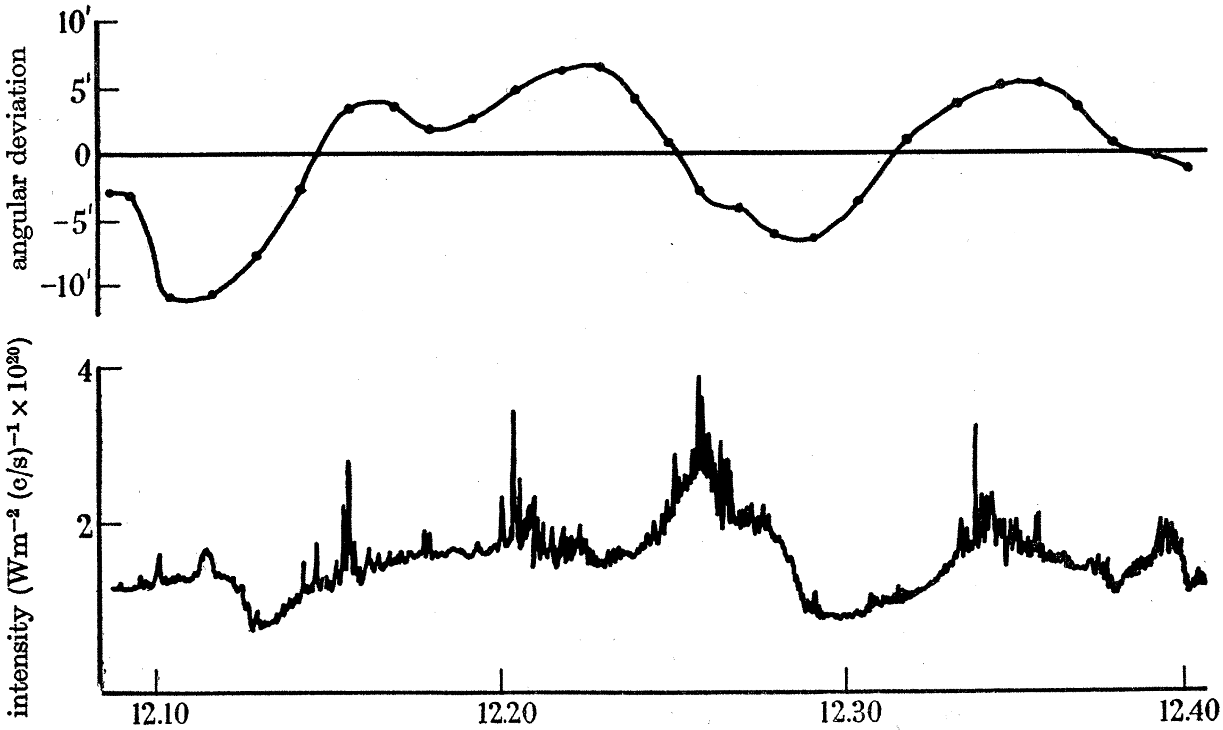

FIGURE 10. Record showing variation of intensity and deviation of apparent position of source of 3·7 m radiation associated with sunspot, 23 January 1951.

(*d*) *The reduction of man-made interference*

Figure 11 shows part of a record obtained with the 3·7 m interferometer in the presence of serious local interference generated in the reception pattern of one of the aerials. The first trace shows the record obtained with the 'total-power' recording system; the second trace shows that obtained with the phase-switching system, whose gain has been adjusted so that the deflexion sensitivity is the same as that of the 'total-power' system.

(e) Control of the primary reception pattern

It was shown in § 3 (g) that by the use of two aerials having different primary reception patterns the effective reception pattern of the interferometer could be improved. An example of this property of the phase-switching system is given in figure 12, which shows the observed envelope pattern of an interferometer in which each aerial consisted of six full-wave dipoles specially arranged to produce a restricted east-west coverage. For comparison the calculated reception pattern which would have been obtained with six aerials arranged as a conventional broadside array at each end of the interferometer is also shown.

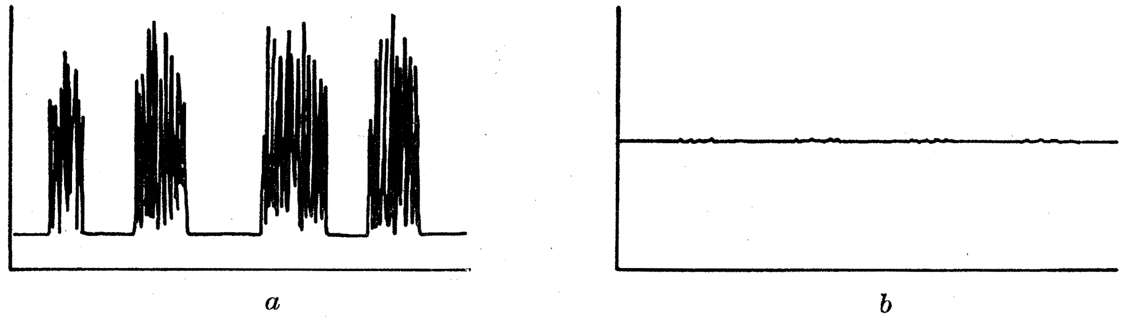

FIGURE 11. Records showing the effect of local interference on observations with (a) the 'total power' system and (b) the phase-switching system.

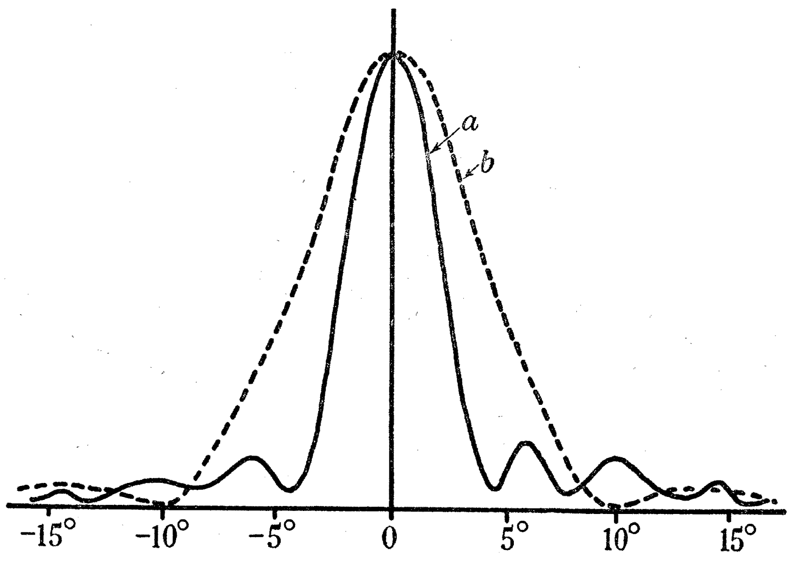

FIGURE 12. Envelope of reception pattern of interferometer in which six full-wave dipoles were used at each aerial: (a) special spacing of aerials; (b) uniform aperture.

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The action of X-rays on ferrous and ferric salts in aqueous solutions

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The action of X-rays on the ferrous-ferric system has been studied under a variety of conditions.

The H atoms and OH radicals formed primarily by the action of the radiation on the water react according to

$$Fe^{3+} + H \rightarrow Fe^{2+} + H^{+} \quad \text{and} \quad Fe^{2+} + OH \rightarrow Fe^{3+} + OH^{-}.$$

Experiments carried out in the presence of molecular hydrogen, where the latter reaction competes with the reaction $H_2 + OH \rightarrow H_2O + H$, permit us to deduce that the specific rate constant of the reaction between OH radicals and ferrous ions is about *five times* greater than that of the corresponding reaction with hydrogen molecules.

The study of the pH dependence of the reaction has led to the assumption that molecular hydrogen ions, $H^{+}_{2(\text{hydr.})}$, intervene in this process undergoing the reaction

$$Fe^{2+} + H^{+}_{2(\text{hydr.})} \rightarrow Fe^{3+} + H_2,$$

and that these ions exist in the equilibrium: $H + H^{+}_{(\text{hydr.})} \rightleftharpoons H^{+}_{2(\text{hydr.})}$. Experimental evidence and some theoretical considerations which have led to the assumption of H_2^+ in aqueous systems have been discussed in detail.

In the presence of molecular oxygen the hydrogen atoms react according to $H + O_2 \rightarrow HO_2$, followed by reactions of the latter radical (cf. Haber & Weiss 1934).

A comparison of the experimentally determined yields under different conditions with the absolute (chemical) yields as derived from the proposed mechanism has led to the estimation of the energy (W_{H_2O}) required for the production of a radical pair (H + OH) by the action of X-rays on water. This has been found to be $W_{H_2O} = 19{\cdot}4 \pm 0{\cdot}4$ eV.

INTRODUCTION

The action of X-rays on aqueous solutions of ferrous sulphate has been the subject of several investigations.

However, different investigators (Fricke 1927; Fricke & Morse 1929; Shishacow 1932; Miller 1948, 1950; Krenz & Dewhurst 1949; Amphlett 1950) seemed to