THE DISTRIBUTION OF RADIO BRIGHTNESS OVER THE SOLAR DISK AT A WAVELENGTH OF 21 CENTIMETRES

I. A NEW HIGHLY DIRECTIONAL AERIAL SYSTEM

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Summary

A new aerial system of very high resolving power has been designed for use in determining the distribution of radio brightness across the solar disk at a wavelength of 21 cm. Thirty-two aerials with paraboloidal reflectors are evenly spaced in an east-west direction over a distance of about 700 ft., and are connected by a branching system of balanced open-wire transmission lines to a receiver. The aerial system produces multiple beams each 3′ of arc wide and spaced 1·7° apart. The rotation of the Earth causes one after another of the aerial beams to scan the disk of the Sun. The record obtained from the radio receiver gives a one-dimensional brightness distribution over the solar disk.

I. Introduction

The poor resolving power of radio aerial systems used in radio astronomy is in marked contrast with the high resolution obtainable with optical telescopes, and is the main limiting factor in astronomical studies by means of radio waves. Until recently even a relatively large astronomical object like the Sun could not be resolved by the aerial systems in use.

The radio-frequency emission from the Sun has been studied intensively in recent years, and several different components of the radiation have been discovered. One of these is constant over months or years, and has been identified with thermal radiation from the undisturbed or " quiet " Sun. A determination of the brightness distribution of this component would be valuable in providing information about physical conditions in the solar atmosphere.

Another component, prominent at decimetre wavelengths, has been called the " slowly varying " component of the solar radiation. Its variations show a good correlation with visible sunspot area.

Radio observations during solar eclipses, commencing with those of Covington (1947), have shown that small areas of enhanced radio brightness often occur in the vicinity of sunspots, and there is little doubt that these areas are the source of the slowly varying component of the solar radiation. Eclipse observations are rare, however, and do not reveal the changes with time of these regions of enhanced brightness. Insufficient information is available,

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therefore, to test theories regarding the nature of these regions. Their presence at decimetre wavelengths produces difficulties in interpreting eclipse records, and has prevented a clear determination of the brightness distribution of the quiet-Sun component over the solar disk. The most useful eclipse observations have been made at the highest frequencies where the variable component of the solar radiation is small.

At decimetre wavelengths frequent observations are necessary to separate the quiet-Sun and slowly varying components, hence an aerial of very high resolving power is required.

II. Aerial Systems of High Resolving Power

For a detailed study of the solar disk, the aerial system should have a beam width much less than the angular diameter of the Sun, say 1/10 of this or about 3′ of arc. An aerial system 1000 wavelengths wide is required to achieve this resolution. At a wavelength of 2 dm., this is about 700 ft. It would be impracticable to construct a steerable aerial system of such a size and of conventional design.

High resolution in one angular coordinate requires the aerial to be large in only one direction and is therefore very much easier to achieve than a pencil beam. The aerial beam is then fan-shaped and in radio astronomical work this has the great advantage that the aerial need not be steered, but instead the Earth's rotation may be used to sweep the aerial beam across the object to be studied. If the aerial system has the form of a uniform strip, it produces a single main beam. The Sun would pass through this beam only once each day. If the system has the form of a non-uniform strip, then more than one main beam may be produced. An extreme form is the two-aerial interferometer which has a large number of beams of equal amplitude. The latter arrangement, however, is not useful for finding the brightness distribution across an extended object like the solar disk because the spacing between adjacent beams is only double the width of each beam.

A modified form of the two-aerial interferometer was used by Stanier (1950), who varied the spacing between the two aerials and from the different interference patterns derived a brightness distribution for the quiet Sun at a wavelength of 60 cm. Undetected areas of enhanced brightness on the disk may produce serious errors in the results obtained by this method.

III. Principle of a New Aerial System

For an aerial system in which there is a number of elements arranged at uniform intervals along a straight line, the polar diagram takes the form of multiple beams having a separation from each other which is inversely proportional to the spacing between adjacent elements. Such an arrangement is suitable for studying the Sun, as beams of the required narrowness can be produced and sufficient elements used so that the Sun will be in no more than one aerial beam at any time. Such a system is analogous to a diffraction grating or, less directly, to a multiple-beam optical interferometer. A maximum response is obtained when the optical path to adjacent aerials is the same or differs by an integral number of wavelengths. The directivity of systems such as this (in terms of received power) is given by

$$\Phi(\theta)=\frac{\sin^2 Np}{N\sin^2 p}, \qquad \text{(1)}$$

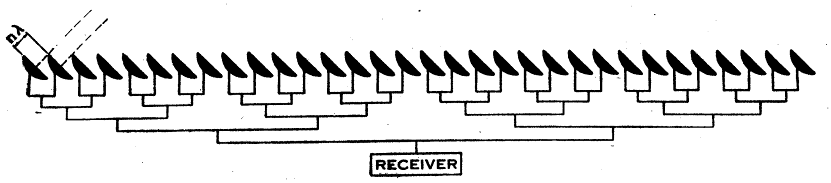

Fig. 1.—General arrangement of the aerial system and transmission lines. A maximum is obtained when n is integral.

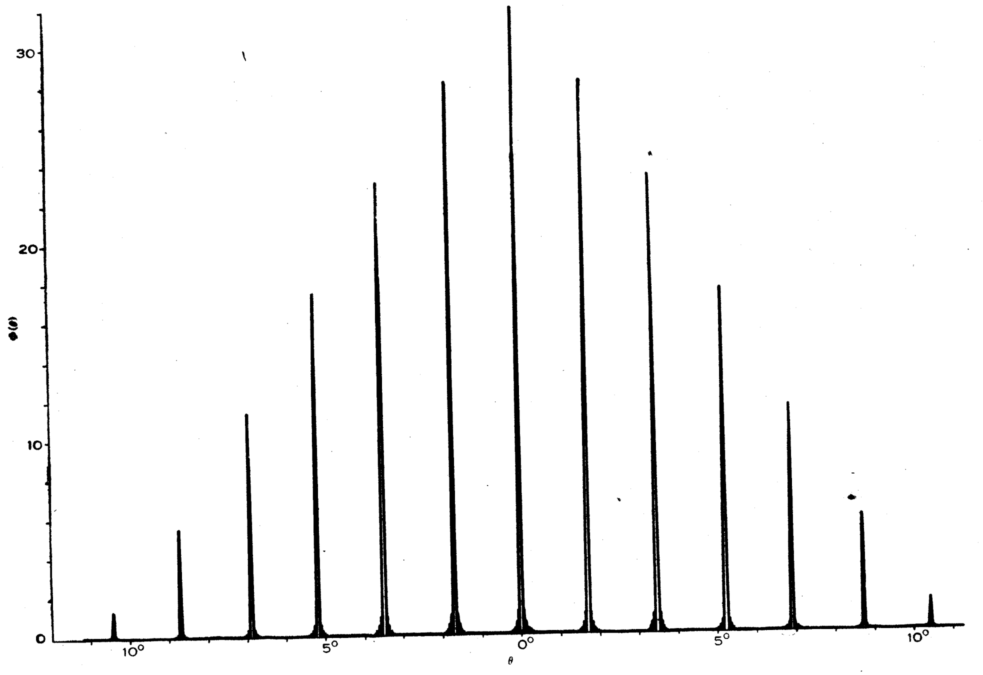

Fig. 2.—Directional diagram of the 32-aerial interferometer.

where $p=\pi d \sin \theta/\lambda$,

$\Phi(\theta)$ = the power received by the system from a point source, relative to the power received by one of its elements,

N = number of elements in the system,

d = spacing between adjacent elements,

λ = wavelength,

θ = angle between the normal to the system and the direction of the ray.

A system of this type operating at a wavelength of 21 cm. has been built in Sydney. It consists of 32 elements arranged over a distance of about 700 ft. in a straight line, roughly in an east-west direction. A schematic diagram of the system is shown in Figure 1.

The fan-shaped beams have a calculated beam width of $2\cdot9'$ of arc between half-power points and there is a spacing of $1\cdot7^\circ$ between adjacent beams. A representation of the beam system is shown in Figure 2. The envelope to the family of beams corresponds to the directivity pattern of the individual aerials of the system. Since these individual aerials can be steered, the envelope is movable and can follow the Sun as it passes through the large number of aerial beams during the course of a day. (Both the beam width and the angle between adjacent lobes increases, however, as the angle made with the normal to the line of the aerial system increases.)

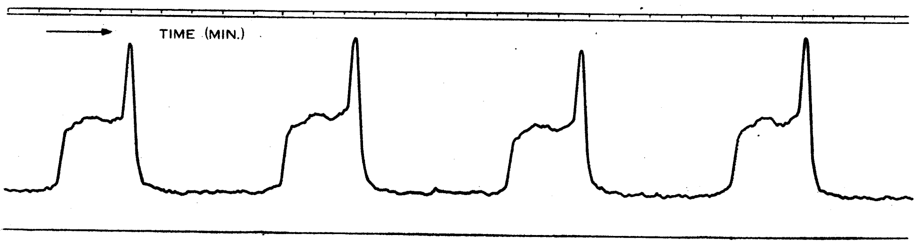

Fig. 3.—A typical record of the passage of the Sun through several aerial beams.

The radio-frequency energy from the aerials is amplified in a radio receiver and the output fed to a recording milliammeter. As the Sun passes through a beam of the aerial, the deflection of the meter at any instant is proportional to the energy being emitted from the narrow strip of the solar disk in the aerial beam at that instant. A series of records which gives the one-dimensional brightness distribution across the solar disk is obtained. A typical record is shown in Figure 3.

IV. A Modified Form of the Aerial for Circular Polarization

In the arrangement described above, the polarization of all the aerials is horizontal, and that of the complete system is the same. A modified form of the system has also been used. Adjacent aerials are polarized in mutually perpendicular planes and the complete system resolves the incident radiation into circularly polarized, right- and left-hand, components. The aerials are connected in the way shown in Figure 4, so that there is a 90° change in polarization between one aerial and the next, the change being progressive from one end of the system to the other. For directions in which there is a difference of $\frac{1}{4}$ wavelength in the optical path to adjacent aerials, circularly polarized radiation falling on the aerials will induce currents in the aerials which will be either additive or will have a zero resultant, depending on the sense of rotation of the waves. If the optical paths to adjacent aerials differ by $\frac{3}{4}$ wavelength, the effect is reversed; the sense of polarization which produced additive currents at a path difference of $\frac{1}{4}$ wavelength now produces zero resultant, while radiation with the opposite sense produces additive currents. The system will now be examined in more detail.

Consider a wave from a distant source, incident on the aerial system, with components of magnitude ε_x parallel to aerials 1, 3, 5, etc., and ε_y parallel to 2, 4, 6, etc. The response v_x of the aerial system to ε_x is given by

$$v_x = \alpha\varepsilon_x \sin(\omega t - 2\pi l_1/\lambda + \delta_1).f(\theta). \quad \ldots\ldots\ldots\ldots (2)$$

Similarly, the response v_y to ε_y is

$$v_y = \alpha\varepsilon_y \sin(\omega t - 2\pi l_2/\lambda + \delta_2).f(\theta), \quad \ldots\ldots\ldots\ldots (3)$$

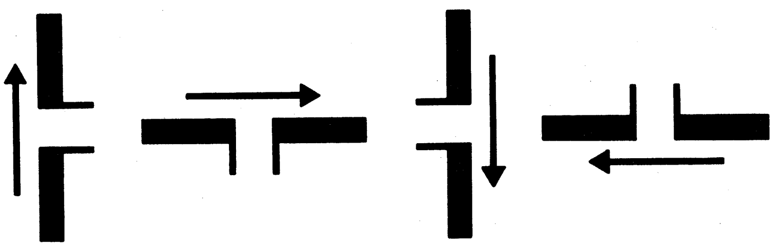

Fig. 4.—Arrangement of four aerials for reception of circularly polarized waves. Eight of these sets make up the complete system.

where α is a constant of proportionality,

$\omega = 2\pi$ times the frequency of the wave,

λ = wavelength,

l_1, l_2 are the optical path lengths from the source to the centres of the two sets of aerials,

δ_1, δ_2 are the initial phases at the source,

$f(\theta)$ represents the directional response of either the x-plane or y-plane system of aerials and is given by

$$f(\theta) = \frac{\sin Np}{\cos 2p}, \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where N and p have the same meaning as in equation (1).

$f(\theta)$ has maxima when

$$2p = (2n+1)\pi/2, \qquad (n = 0,\ 1,\ 2, \ldots)$$

i.e. twice as frequently as the system represented in equation (1).

In order to find the relative phase of v_x and v_y at these values of p, we note that

$$l_1 = l_2 + d \sin\theta,$$

since there is a separation d between the centres of the vertical and horizontal groups of aerials. Hence, at the maxima,

$$2\pi l_1/\lambda = 2\pi l_2/\lambda + 2p = 2\pi l_2/\lambda + (2n+1)\pi/2,$$

therefore

$$v_x = \alpha N/2.\varepsilon_x \sin\{\omega t - 2\pi l_1/\lambda + \delta_1\},$$
$$v_y = \alpha N/2.\varepsilon_y \sin\{\omega t - 2\pi l_1/\lambda + (2n+1)\pi/2 + \delta_2\}.$$

If ε_x and ε_y are equal and the phase difference $(\delta_2-\delta_1)$ between the two components at any point along the path is equal to $\pi/2$, i.e. the wave is right-hand circularly polarized, then the sum

$$\begin{aligned} v_x+v_y &= 2v_x, \text{ if } n \text{ is odd,} \\ &= 0, \text{ if } n \text{ is even.} \end{aligned}$$

If $\delta_1-\delta_2=\pi/2$, i.e. the wave is left-hand circularly polarized, then

$$\begin{aligned} v_x+v_y &= 2v_x, \text{ if } n \text{ is even,} \\ &= 0, \text{ if } n \text{ is odd.} \end{aligned}$$

Hence, for any direction of maximum response for the aerial, one circularly polarized component of the radiation is received, while that of opposite sense is rejected. At adjacent maxima the effect is reversed.

The above treatment applies strictly only at the maxima, but the rejection of one circularly polarized component is practically complete over the whole of any beam, because the relative phase of ε_x and ε_y changes slowly with θ. Even at the edge of the beam, i.e. near the first minimum, the phase has been changed only by about 10°, so that the sensitivity of the system to one component is 100 times greater than to the other.

As the Sun passes through one aerial beam after another, the receiver responds to right-hand and left-hand circularly polarized components of the radiation alternately. If the radiation over the whole Sun is linearly or randomly polarized, then successive records are equal in amplitude and similar in shape. If the radiation from a particular part of the Sun is circularly polarized, the response to this appears only on alternate records. With elliptically polarized radiation, or a mixture of circularly and randomly polarized radiation, the amplitude of the response would be different on successive records.

This modified form of the equipment has been used principally in investigating the radiation which originates near sunspots.

V. Design

(*a*) *Aerial System*

The 32 aerials (shown in Plate 1 (*a*)) which form the system are arranged in a straight line at intervals of 23 ft. In setting up the system a maximum error of 1 in., or $\frac{1}{8}$ wavelength in the placement of aerials was allowed. A later survey showed that this had not been exceeded.

Individual aerials, which have a beam width of about 10°, consist of a dipole radiator and reflector placed at the focus of a paraboloidal reflector, 66 in. in diameter. Each is mounted on a polar axis and capable of rapid position change in hour angle. A simple system of pegs and holes in a circular plate allows accurate positioning of each aerial. When in use the positions of the aerials are changed by hand approximately each $\frac{1}{4}$ hr.

Each dipole aerial and reflector is supported on a pair of parallel flat strips of metal attached to the paraboloidal disk as shown in Plate 1 (*b*). These strips serve, in addition, as a balanced open-wire transmission line. At the lower end, $\frac{1}{4}$ wavelength from a shorting strip, a short length of flexible polythene-insulated balanced transmission line connects the aerial to the main transmission line.

(*b*) *Transmission Lines*

The aerials are connected to the receiver through a branching system of transmission lines in the way indicated in Figure 1, so that there are equal lengths of transmission line between each aerial and the receiver. With such an arrangement the system is insensitive to small changes in frequency or to changes in the length of the feeder lines caused by temperature variations, because each aerial is affected equally. This is most important when the length of transmission line is greater than 500 wavelengths.

The transmission lines are of the balanced open-wire type. The reasons for the choice of this type of line, unconventional at such a high frequency, are that it is easily accessible for connections, matching, and testing and can be designed to have low attenuation at small expense.

The pairs of conductors consist of hard-drawn copper wire, 0·16 in. in diameter, with a spacing between centres of 0·37 in. The characteristic impedance of the line is approximately 180 ohms. Each pair is under a tension of about 500 lb. wt. and is supported every 23 ft. on polystyrene insulators. To preserve the correct spacing between the conductors, small polystyrene spacers are placed between the lines at intervals of about 6 ft. Both the supporting insulators and the spacers are arranged in pairs separated by $\frac{1}{4}$ wavelength in order to reduce reflections in the line.

The transmission-line attenuation resulting from resistive losses in the conductors was calculated to be approximately 1·1 db./100 ft. of line. Calculation indicated that the dielectric and radiation losses would be much less than this. Measurements over straight sections of the transmission line showed that the attenuation was approximately 1 db./100 ft. The overall loss in the line was found to be 6 db. The additional loss apparently takes place in the various junctions, matching sections, and short-circuited sections along the line.

Reflections in the line are small. It was found that a standing-wave ratio of 1·1 could be preserved. Small discontinuities in the line have been compensated, usually by a suitably placed single polystyrene insulator.

The branching structure of the transmission line, shown in Figure 1, has been effected by running five pairs of lines one above the other. At a junction a short pair of vertical conductors connects adjacent lines. The unwanted part of the transmission line is effectively disconnected by shorted quarter-wave sections, and matching is effected by use of a quarter-wave matching section formed from two plates of metal. A photograph of such a section is shown in Plate 1 (*c*). A very simple way of adjusting this was adopted. The correct position for the matching section was found by use of a standing-wave indicator, the two metal plates were hung on the line and their spacing varied until a correct match was indicated, and, finally, the plates were soldered in position.

In the setting up of the system, power was fed into the transmission line at the signal frequency, and matching was effected by means of a standing-wave indicator. This consisted of a pair of pick-up probes made from brass rod embedded in a block of polystyrene. The latter was shaped to fit onto the two-wire line, and had a handle by which it could be slid along the line. The probes were connected to a shielded pair of coaxial lines which led, through a balance-to-unbalance transformer, to a single coaxial line terminating at a radio receiver. The D.C. output from the detector of this receiver was taken back through long meter leads to a milliammeter close to the place of measurement.

The aerials were matched individually to the transmission lines. They were then short-circuited and the electrical centre of the transmission line joining each pair of aerials was determined from the positions of voltage minima on the line. This position was checked by length measurements. (In all cases there was negligible difference between the positions of the electrical and physical centres.)

At this central point, a short vertical section of line was used to connect the first transmission line to a second line situated vertically below, as shown in Plate 1 (*c*). The two-to-one mismatch at the junction was corrected by means of a quarter-wave matching section. The same procedure was adopted at each branch.

(*c*) *The Receiver*

A radio receiver is connected to the centre of the transmission-line system through a balance-to-unbalance transformer. The receiver is of conventional superheterodyne design.

At the input is a radio-frequency switch consisting of a rotating condenser and transmission-line sections, which at a frequency of 25 c/s. connects the receiver alternately to the aerial system and to an effectively infinite length of coaxial transmission line. Following the switch is a coaxial cavity tuned to the signal frequency and leading to a crystal detector. A line-tuned heterodyne oscillator is also coupled to the detector, which in turn is connected to a 30 Mc/s. amplifier of 4 Mc/s. bandwidth. The 30 Mc/s. amplifier is followed by a detector, a 25 c/s. amplifier, and a phase-sensitive detector. The output of the latter is connected to a recording milliammeter.

The receiver is calibrated each day by means of a thermal noise generator, which has an output corresponding to a temperature approximately 100 °C. above ambient. This temperature difference produces a change in the receiver output which is approximately equal to that produced by the passage of the Sun through the aerial beam. The noise fluctuations on the receiver record have an r.m.s. value corresponding to a temperature of about 1 °C.

VI. Observational Technique

(*a*) *Daily Recording*

The aerial system has been in operation since February 1952. For most of the time it has been used in its original form, i.e. with all dipole aerials in the same plane of polarization. Records, such as those shown in Figure 3, are obtained each day over a period of about 2 hr. around midday, when the resolving power of the aerial is greatest. Outside this time, two unfavourable effects become significant. The first is the increase in beam width which occurs as the projected length of the system diminishes in a direction normal to the Sun's direction. The second is a distortion which results from the increasing number of wavelengths difference in the optical paths to different unit aerials. This means that frequencies in different parts of the receiver pass-band have their maxima displaced from each other. The second effect may be reduced by decreasing the receiver bandwidth. A bandwidth of 0·5 Mc/s. can be used if records are required outside the normal hours, but this has the adverse effect of causing an increase in the noise fluctuations on the records.

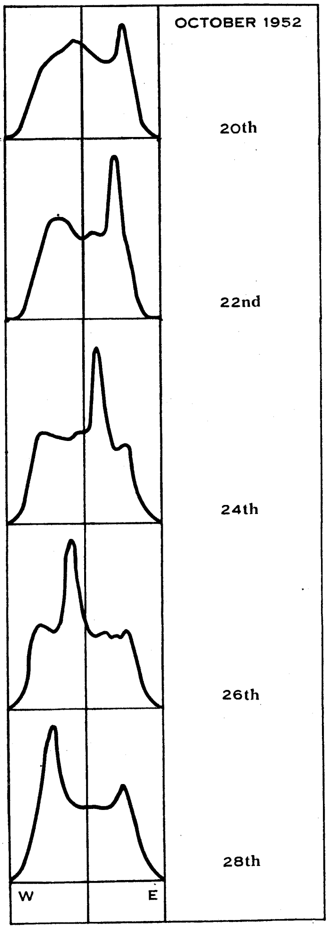

Fig. 5.—A succession of daily records showing the one-dimensional brightness distribution over the solar disk.

The effect of noise fluctuations in the records is diminished by averaging a number of records for each day. A series of " averaged " daily records is shown in Figure 5. No convenient way of measuring the beam width of the aerial system has yet been found. However, on several occasions when there have been small areas of great radio brightness on the disk, an upper limit to the beam width could be determined. This is approximately 3·4′ of arc, which is a little greater than the calculated value for a point source.

(*b*) *Intensity Calibration*

The calibration of the receiver in terms of the effective temperature at the input, in the way described earlier, is not completely adequate to detect changes in gain of the system, because it does not indicate any changes that may occur in the aerial system. A comparison is made each day, therefore, between the total amount of energy received from the Sun as indicated, on the one hand, by the integral of the recorded curve of solar disk brightness obtained with this equipment, and on the other hand, that indicated by different equipment which measures daily the energy received from the whole solar disk. (The comparison equipment operated at 25 cm. instead of 21 cm., but results indicate that no significant error is introduced by this.) Occasional changes in aerial gain have been found, these usually being associated with faults at junctions of the transmission line. When such changes have occurred, a check is usually possible through a comparison of the heights of certain parts of the records obtained on adjacent days.

(*c*) *Determination of Position*

In order to make a comparison between optical and radio features of the solar disk it is necessary to know the position of a particular aerial beam with respect to the solar disk at any time. The direction of the line along which the aerial system lies is known, hence the directions in space of the various aerial beams may be calculated and compared with the known direction of the Sun at any particular time. Time marks are placed on the daily radio records, and thus the position of the Sun with respect to an aerial beam can be calculated for any part of the radio record.

Analysis over a period of many weeks showed that bright areas near the limb do not markedly increase the apparent diameter of the radio Sun. It follows that the radio Sun and optical Sun are centred on the same line in space. This fact was used to eliminate much tedious calculation, because the centre of the radio record could be taken to correspond to the centre of the solar disk, and the position of any features of the radio record determined with respect to this line.

VII. Analysis of Observations

It is not intended to analyse results in this paper, but merely to show how the observations can be used to elucidate certain solar phenomena. The daily records show characteristic peaks which change in position from day to day, moving at approximately the same rate as sunspots, i.e. they indicate local areas of enhanced brightness which rotate with the Sun. In addition, the records appear to show a lower level below which the brightness does not fall, and this presumably represents the radiation from the quiet Sun. In order to study the two components it is necessary to separate them. The first step is to deduce the contribution of the quiet Sun, i.e. to determine the one-dimensional brightness distribution for the thermal component. When this is done, the contributions of the areas of enhanced brightness are represented by projections above the quiet-Sun level.

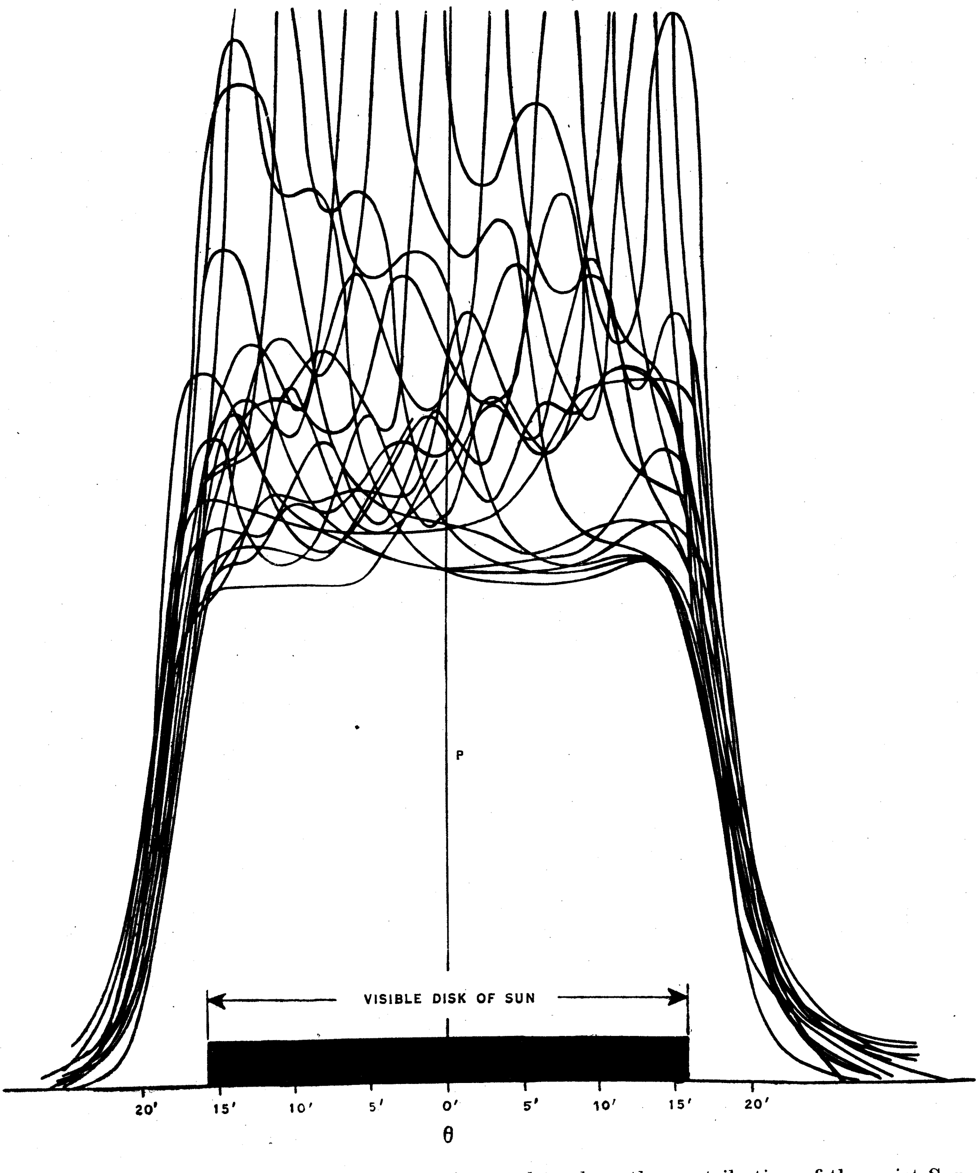

Fig. 6.—A succession of daily records superimposed to show the contribution of the quiet Sun. P is the power received, in arbitrary units. θ is the angular separation between the centre of the aerial beam and the centre of the optical disk of the Sun.

(a) *Determination of the One-Dimensional Brightness Distribution of the Quiet Sun*

One way in which this might be done would be to compare records in which no peaks are apparent. If these have the same shape and amplitude, one would be justified in saying that the curves represent the quiet-Sun brightness distribution. Unfortunately cases of complete absence of areas of enhanced brightness were very rare during 1952. (The absence of sunspots is not sufficient.)

An alternative way to determine the distribution is to plot a series of daily records on one diagram and to investigate the existence and shape of a lower envelope to the curves. In Figure 6 a typical set of 20 superimposed records is shown. The existence of a lower envelope to the curves is clearly seen. The shape of this envelope will be discussed in a following paper.

(*b*) *Study of Areas of Enhanced Radio Brightness*

The positions on the disk of these areas indicated by peaks on the records change with the solar rotation. This can be demonstrated by drawing on a Mercator's projection of the Sun for each day an arc which represents the position of an aerial beam with respect to the heliographic coordinates of the Sun when a particular peak appears on the record. The approximate position of the area of enhanced brightness on the Sun can be found from the place of intersection of the arcs. If this is done with different assumed values for the effective solar radius, i.e. the distance of the radio source from the centre of the Sun, then the best intersection represents the probable position in the solar atmosphere in height as well as latitude and longitude. A comparison may then be made with optical features of the solar disk.

The energy being received from each area of enhanced radio brightness may be deduced once the quiet-Sun level has been found. The changes in received energy from such a source depend both on real changes in total emission from the source, and on apparent changes of emission related to the position of the source in the solar atmosphere. The possibility of separating these two effects will be discussed in a later paper.

VIII. Conclusions

The multiple-aerial interferometer principle provides a very economical means for a detailed study of the radio-emitting surface of the Sun. The system described in this paper has been found simple to adjust and will remain in adjustment over periods of months. The main factor in producing these desirable characteristics is undoubtedly the branching system of transmission lines which is non-critical to changes of frequency or atmospheric conditions. The construction of such a system would have been difficult if open-wire transmission lines had not been used.

The records obtained with this equipment allow the quiet-Sun and slowly varying components of the solar radiation to be separated. In later papers the brightness distribution over the solar disk of the first of these components and the characteristics of the second component will be discussed.

IX. Acknowledgments

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X. References

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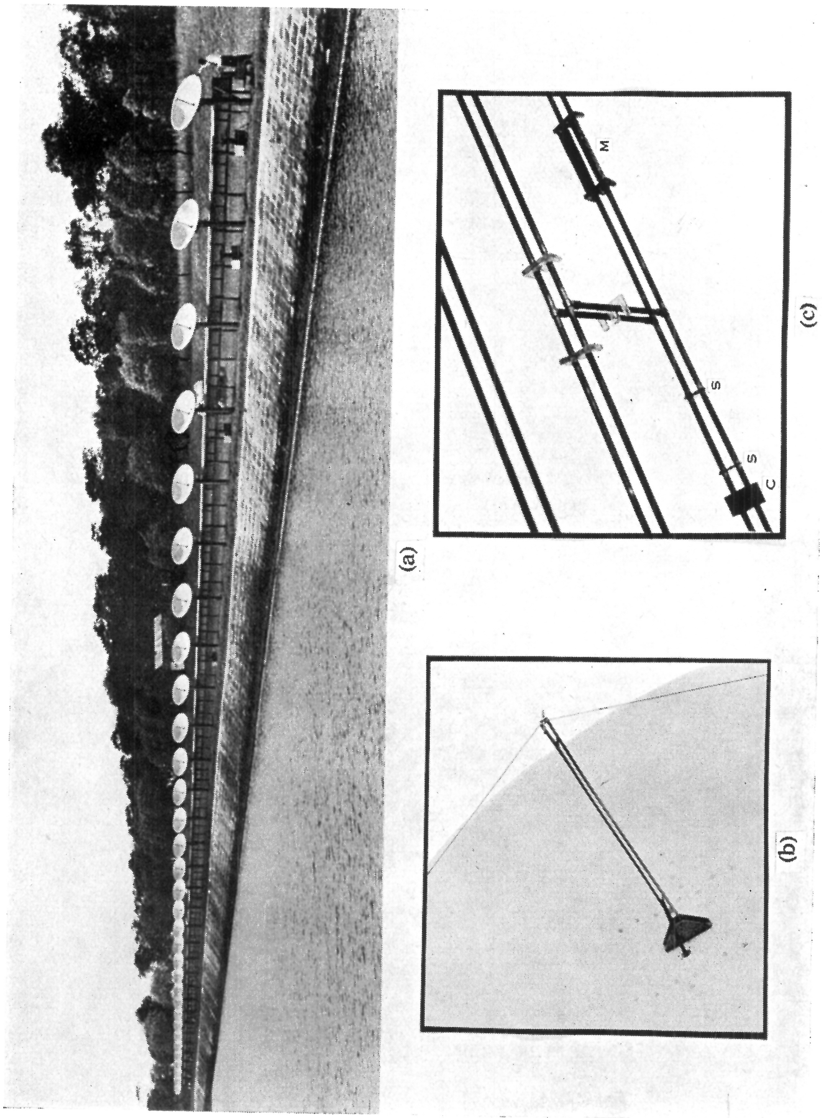
RADIO BRIGHTNESS OVER THE SOLAR DISK. I



(*a*) The 32-aerial interferometer.

(*b*) Dipole-aerial and reflector.

(*c*) A typical junction of two transmission lines. *C*, a clamp; *S*, short circuits; *M*, a quarter-wave matching section consisting of two flat plates, each bent to fit on to wire conductor.