A HIGH-RESOLUTION AERIAL SYSTEM OF A NEW TYPE

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Summary

A method of constructing an aerial system of high resolution but small area and low cost is described. Its application to the production of narrow pencil beams at metre wavelengths for investigations in radio astronomy is discussed. A small-scale model has been constructed to test the principle.

I Introduction

Recent studies of cosmic radio-frequency radiation have shown that its brightness distribution over the sky is complex. Sources of an angular size less than about $\frac{1}{4}°$ have been known to exist for some years and, now, extended sources of considerably greater size have been observed (Bolton 1952; Mills 1952), some of which appear to merge with the general background radiation. Interferometric methods, which were so useful in the early days of radio astronomy, have encountered serious difficulties when used for observing such a complex distribution. It therefore appears desirable to rely mainly on the use of pencil beam aerials of high resolving power for future work, and to reserve the use of interferometric methods for special applications.

A study of the available information suggests that a beam width of the order of 1° or less is desirable for such a pencil beam. For an aerial of conventional form at metre wavelengths this beam width would require a prohibitively large and costly structure so that an alternative solution has been sought.

A satisfactory solution is possible because the number of randomly distributed discrete sources which can be individually detected at metre wavelengths with a large aerial is determined by the beam width (or the resolution) rather than the gain of the aerial. This follows from the fact that in these circumstances the number of discrete sources with intensities above the detectable threshold will normally greatly exceed the number which may be separately resolved. Advantage can be taken of this to construct an aerial system of high resolution but relatively low gain, that is, small effective area, which sacrifices very little of the usefulness of a conventional aerial but which can be made at a fraction of the cost.

Such a system can be constructed from two long aerials arranged in the form of a cross. At the wavelengths we are considering, these aerials preferably consist of arrays of dipoles. In Figure 1 this is shown schematically, together with an idealized diagram of the outline of the aerial beam produced when the

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arrays comprising the two arms of the cross are connected together in the same phase. An aerial diagram of this form is unsatisfactory for, although there is an enhanced response in the central region where a source is received by both arrays, the total solid angle over which reception occurs is very large. However, advantage may be taken of the presence of signals in both aerials from the central region and their phase coherence for, if the arrays are now connected in antiphase, there will be no response from this central region, while the " spokes " of the diagram will be unaffected. If, therefore, the connections between the arms of the cross are switched rapidly between the two conditions, a source which is in the solid angle common to both beams will deliver a modulated signal at the switching frequency, while the signal from a source which is received by one aerial alone has no modulation imposed. After amplification and detection the modulated signal may be picked out by a phase-sensitive detector and used to

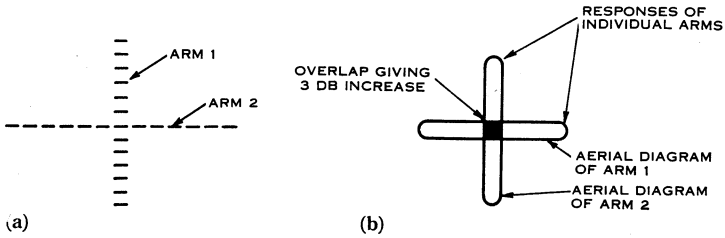

Fig. 1 (*a*).—Plan view of dipoles in cross arrangement.

Fig. 1 (*b*).—Idealized response of the cross arrangement, plan view.

deflect a pen recorder. The recorder then gives the integrated signal from within the central region so that, in effect, a pencil beam is produced which has a size determined by the *maximum* dimension of each array.

A similar method of using the common portion of overlapping beams to produce a narrower effective beam has already been used by one of the authors in an interferometer (Mills 1952).

II. Elementary Theory

In order to appreciate the possibilities of an aerial of this type, it is necessary to examine its operation in more detail. Consider the response of the system to a signal of unit intensity originating in any arbitrary direction and, as a first approximation, assume that there is no interaction between the two arrays. We shall also assume that for each array the response in any direction may be fully represented by the voltage polar diagram, that is, the phase of the response is everywhere either equal or opposite to that in the direction normal to the array. This is true for aerials in which the current distribution is symmetrical about the mid point.

When the arrays are connected together in phase addition the received power is given by $P_1=k(S_1+S_2)^2$, where S_1 and S_2 are the amplitudes of the voltage polar diagrams of each aerial in the selected direction.

When the arrays are connected in phase opposition the received power is given by $P_0=k(S_1-S_2)^2$.

The modulated power delivered to the receiver is given by the difference of these quantities, that is,

$$P_m=4kS_1S_2.$$

The composite power polar diagram is therefore given by the product of the voltage polar diagrams of each array. One consequence is that the recorder deflection will be negative where the voltage diagrams are of opposite sign. A further consequence is that trouble from side lobes will be accentuated, since in the planes in which one of the arrays has a wide angle of reception, the side lobes of the composite beam will be those appropriate to the voltage rather than the power diagram. For example, if the current distribution is uniform along each array, the first side lobes in the planes of the arrays are 20 per cent. in amplitude instead of the normal 4 per cent. As any complexity in the composite diagram leads to great difficulty in the interpretation of the records, it is therefore imperative to minimize the side lobes.

A well-known method of eliminating side lobes in an aerial is to employ a current distribution across the aperture in the form of a normal error curve which produces a polar diagram of the same shape. Such a distribution has another advantage in the present case, for, consider two idealized polar diagrams

$$S_1=e^{-k_1\theta^2}, \qquad S_2=e^{-k_2\varphi^2},$$

where θ and φ are the two zenith angles in the planes of the arms, then the composite diagram is

$$S_c^2=S_1S_2=e^{-(k_1\theta^2+k_2\varphi^2)}.$$

Thus a beam is produced without side lobes and of simple elliptical section everywhere. When $k_1=k_2$ the beam section will be circular, which is the simplest possible case to deal with.

In practice a beam of exactly this shape cannot be produced because an infinite aperture is required. If, however, the aperture is finite and extended until the current has fallen to about 10 per cent., it is found that a sufficiently close approximation to an error curve is obtained. To obtain the same beam width this requires an aperture some 50 per cent. larger than that for a uniform distribution, but the advantages are obvious.

The above analysis of the operation is approximate only, for in general there will be an interaction between two arrays placed so close together. The effect of such an interaction may be obtained from a thermodynamical argument. Consider such an aerial in a constant temperature enclosure. No modulated output will then be produced, as the power received by the arrays will be a function of the enclosure temperature only and will be independent of any method of connecting them together. If the composite diagram formed from the cross product of the two voltage diagrams were to have an average value of zero this result would be given by the previous analysis. In general, however, the average value will not be zero as can be seen, for example, by integrating the idealized composite diagram above. The neglected interaction between the arrays must then be just sufficient to produce zero output. This point is considered in a practical example later.

From the thermodynamical argument it can be seen that the aerial, as described, measures only *differences* in brightness temperature between the complete reception angle of both arrays and the central solid angle common to both. However, a little consideration will show that the absolute value of the temperature over the central angle may be obtained by adding the temperature calculated from the amplitude of the modulated signal to the average temperature of the two arrays.

When the aerial is used in this way the results are similar to those which would be obtained from a conventional aerial of the same beam width with an attenuator connected between it and the receiver, the attenuation being roughly

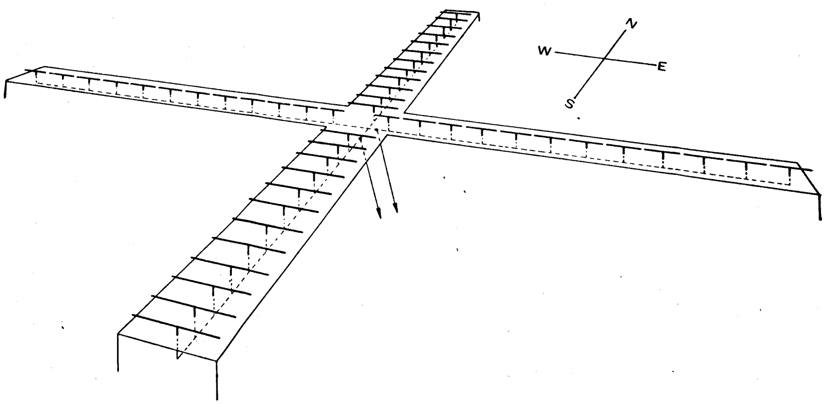

Fig. 2.—The experimental aerial system.

equal to the ratio of the area of the conventional aerial to that of the arrays forming the cross. When using a narrow pencil beam at wavelengths of a few metres for observing discrete sources, this attenuation is not very important because the resolution and not the sensitivity is the limiting factor. It does, however, lead to reduced sensitivity for observing the brightness temperature of extended distributions.

III. An Experimental Model

The construction of an aerial at metre wavelengths to produce a 1° beam, even when using the above method, is a large undertaking. It was decided, therefore, to construct first a small-scale model to test the principle and to allow experiments with possible designs. A sketch of this model is shown in Figure 2. It operates at a frequency of 97 Mc/s and the arms of the cross are 120 ft in length. They are arranged in the north-south and east-west directions. The beam width is 8°.

The east-west arm consists of a line of folded dipoles, end to end, backed by a wire-mesh reflecting screen. The dipoles are fed from a twin-wire transmission line stretching the length of the arm which is itself fed in the centre and terminated at each end by matching resistors. Quarter-wave resonant stubs are used to couple the dipoles to the feed line, the currents in the dipoles being adjusted by changing the point at which they are connected to the stub as shown in Figure 3. Standing waves on the feed line are kept low by adding capacity at appropriate places. The north-south arm consists of an array of full-wave dipoles similarly fed. The beam is swung in declination by changing the phases of the currents in the dipoles of this arm. Phase changing is performed by changing the points of connection of the stubs to the feed line.

The currents are adjusted in each arm to coincide with the normal error curve which has a value at the ends of the arrays of about 10 per cent. of that at the centre. Only about one-half of the power collected by an array is fed to the receiver, the remainder being dissipated in the matching resistors at the end of each feed line. Each arm is connected to its own preamplifier, the outputs of which are combined through a phase switching arrangement as described above. Further amplification, detection, and recording are accomplished in a conventional manner (Mills 1952).

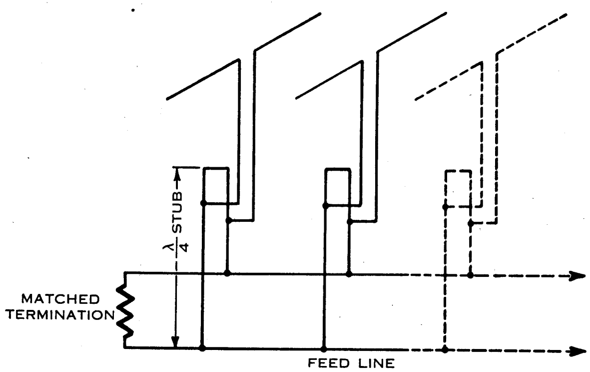

Fig. 3.—Arrangement of dipole feeds in experimental aerial.

The factors involved in observing uniform temperature distributions can be seen very clearly with this aerial. In order to reduce complications due to cross coupling between the arrays the central dipoles of each were omitted. This results in relatively large distances between the closest dipoles so that cross coupling is small. An attenuation of more than 40 db was measured between arrays. The effect of omitting the central dipole, however, is to subtract its radiation field from the total, so that the voltage polar diagrams of each array, which would normally be zero outside the central beam, are now negative in that region. Sources in the spokes of the diagram of Figure 1 therefore produce a negative deflexion. It is easily shown that the average value of the composite diagram is now zero so that, if the aerial is pointed at a uniform temperature distribution, the positive deflexion over the central beam is counterbalanced by the negative deflexion produced over the much larger solid angle of the spokes of the diagram, and the net deflexion is zero. If a different construction were utilized to eliminate this depression of the polar diagram, then, as was shown before, the cross coupling between aerials which is introduced produces a similar effect.

Sample records obtained with this experimental model are shown in Figures 4 and 5. Two quantities are recorded in each case, the output from the phase-sensitive detector in the upper graph and the receiver output level in the lower. The latter is a measure of the average temperature of the two arrays The addition of the two temperatures derived from these graphs gives the actual temperature averaged over the central beam. Calibration marks are shown every 20 min when the preamplifiers are connected to cold resistors for a period of 1 min.

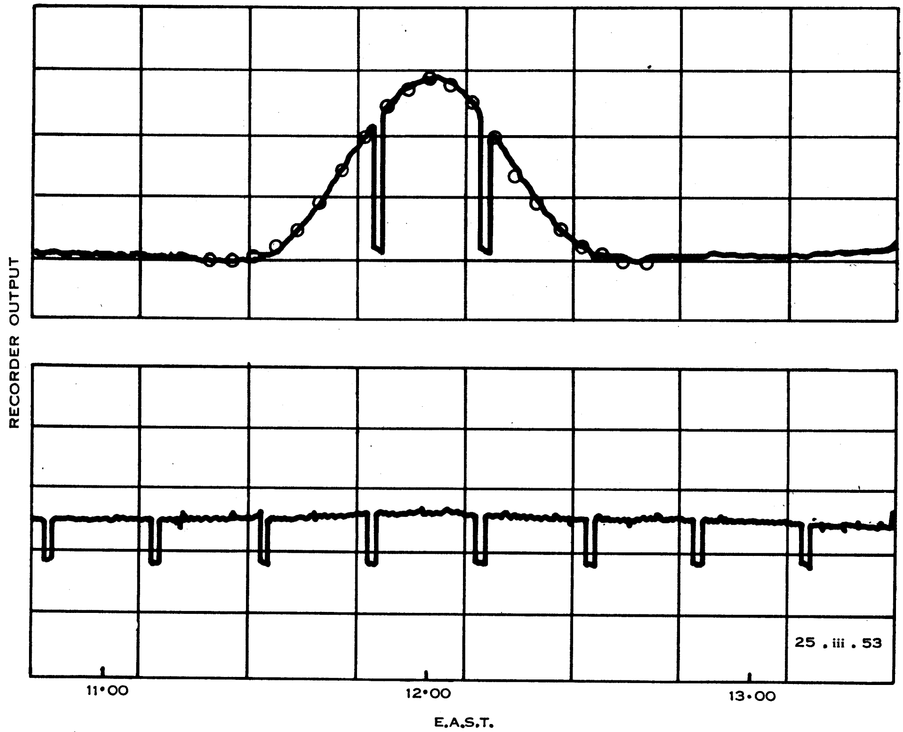

Fig. 4.—A record of the Sun showing the agreement between the observed and computed polar diagrams.

A record obtained on the Sun at a declination of $+1°$ is shown in Figure 4. The sensitivity was much reduced for observing such a strong source. Points derived from the computed polar diagram are shown superimposed on the record for comparison; the agreement is excellent. The lower graph shows only a slight increase as the Sun passes through the aerial beams, the major part of the deflexion being due to the galactic background. The declination of $+1°$ represents an inclination of the beam of 35° from the vertical.

Figure 5 shows portion of a record obtained at a declination of $-34°$, that is, with the beam pointing vertically upwards. The comparatively strong " point " source 03–3 (Mills 1952) is shown first, then the weaker source 04–3. The effect of an " extended " source is illustrated when the Galaxy at about galactic longitude 220° crosses the beam. The record illustrates one advantage of this system, for the sky temperature is divided into a slowly varying background which is recorded at relatively low sensitivity on the bottom graph and a detailed structure which is recorded at high sensitivity on the upper. A conventional aerial operating at the same sensitivity would require some system of backing off the output to keep the deflexion within the range of the recorder.

A survey of the southern sky is now in progress and an analysis of this and similar records will be given in a subsequent paper. It is interesting to note, however, that the resolution of the model aerial has been sufficient to detect radiation from the large Magellan Cloud and to show that the centre of the Galaxy is narrower than previously suspected from earlier low-resolution surveys.

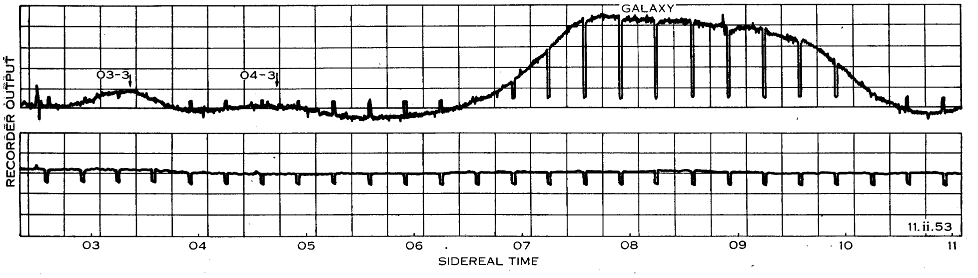

Fig. 5.—A record centred on declination —34°, showing two discrete sources and the Galaxy at longitude 220°.

The experimental work which has been performed with the small-scale model has shown that the principle of operation is sound and has demonstrated the feasibility of a full-size aerial. Work is in progress on the design and construction of an aerial which will operate at a frequency of about 80 Mc/s and have a beam width of less than 1°. It will be capable of surveying approximately one-half of the celestial sphere.

IV. Acknowledgments

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V. References

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