CANADA
DEPARTMENT OF ENERGY, MINES AND RESOURCES
Observatories Branch

PUBLICATIONS
of the
DOMINION OBSERVATORY
OTTAWA

Volume XXV • No. 10

A LARGE 10 MHz ARRAY FOR RADIO ASTRONOMY

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Price 50 cents

ROGER DUHAMEL, F.R.S.C.
QUEEN'S PRINTER AND CONTROLLER OF STATIONERY
OTTAWA, 1967

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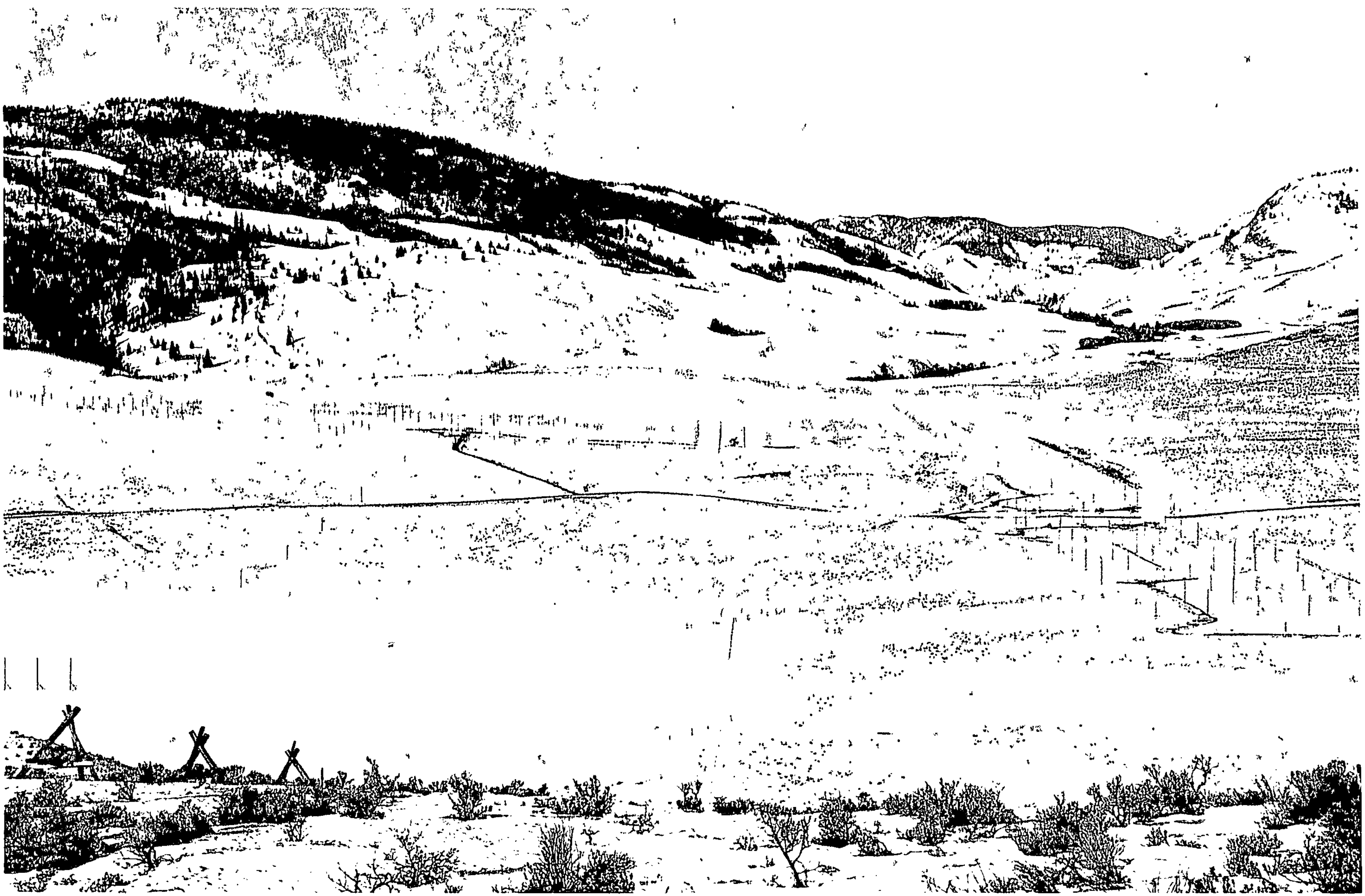

Figure 1. A photograph of the 10 MHz array taken from a hill to the east.

A LARGE 10 MHz ARRAY FOR RADIO ASTRONOMY

J. A. GALT*, C. R. PURTON† AND P. A. G. SCHEUER§

ABSTRACT: A large array-type transit radio telescope for frequencies near 10 MHz is described. It is built in the shape of a horizontal 'T' and consists of 400 half-wave dipoles suspended from wooden poles above a reflecting screen. The voltages from the two arms of the 'T' are multiplied, giving the instrument a pencil beam response. It has a collecting area of 192,000 m², and when used with a bandwidth of 8 KHz, can detect sources to a flux limit of 70×10^{-26} Wm^{-2}Hz^{-1}. The beamwidth is 2°6 × 2°4 at the zenith. An elaborate phasing system is employed which allows observations at many different declinations simultaneously. Fluxes have been measured with this instrument for 166 astronomical sources and a map of the galactic radiation has been prepared.

RÉSUMÉ: Les auteurs décrivent une grande antenne, constituée d'éléments alignés, pour les radiotélescopes à transit fonctionnant à des fréquences de près de 10 MHz. Elle a la forme d'un «T» horizontal et consiste en 400 dipôles demi-onde suspendus à des poteaux de bois au-dessus d'un écran réflecteur. Les tensions provenant des deux bras du «T» sont multipliées, ce qui donne à l'instrument une réponse unique. Il a une surface de captation de 192,000 m² et, lorsqu'on l'emploie sur une largeur de bande de 8 KHz, il peut détecter des sources à une limite de flux de 70×10^{-26} Wm^{-2}Hz^{-1}. La largeur du faisceau est de 2°6 × 2°4 au zénith. Un système élaboré de mise en phase permet des observations à plusieurs déclinaisons différentes simultanément. On a mesuré les flux de 166 radiosources à l'aide de cet instrument et on a dressé une carte du rayonnement galactique.

Introduction

Most high-resolution radio astronomical studies have been made at frequencies high enough that ionospheric effects are of little importance. As the frequency is lowered, observations become progressively more difficult because of absorption, refraction and scintillation. There are the further difficulties of the large physical size necessary to achieve a reasonable resolution, and of the very limited bandwidth which can be found free of man-made interference. It has, however, become imperative that the discrete sources and the background radiation be observed over as wide a frequency range as possible in order to detect changes in the slope of their spectra. The slope and curvature of the radio spectra are of great importance in recognizing the type of source being studied and in elucidating the physical processes involved.

The low-frequency surveys which have been published include the 38 MHz synthesis surveys at Cambridge (Costain and Smith, 1960; Williams, Kenderdine and Baldwin, 1966), the 26.3 MHz compound grating surveys at Clark Lake, California (Erickson and Cronyn, 1965; Erickson, 1965), the interferometer survey between 20 and 38 MHz in the Ukrainian S.S.R. (Bazelyan, Braude, Vaisberg, Krymkin, Men' and Sodin, 1965), the 19.7 MHz cross survey of the southern sky in New South Wales (Shain, Komesaroff and Higgins, 1961), the 4.7 MHz survey in Tasmania, (Ellis, Green and Hamilton, 1963) and the 13 MHz synthesis survey at Cambridge (Andrew, 1966).

To extend these measurements both to lower frequencies and to lower flux levels two large arrays have been built at the Dominion Radio Astrophysical Observatory, Penticton, B.C. The 22 MHz array which has a beamwidth of 1° × 1°6 at the zenith and a collecting area of 65,000 m², has been described elsewhere (Galt and Costain, 1965; Costain, Lacey and Roger, 1967). The present paper describes the 10 MHz antenna which was undertaken as a joint project with Cambridge University. Both antennas were put into operation late in 1964 and have been used intensively ever since in an effort to obtain as much data as possible before the next period of solar activity, when it is anticipated that ionospheric conditions will become unfavorable for decametric radio astronomy.

General Description

The array, which is in the form of a 'T' is shown in Figure 1; its dimensions are given in Figure 2. It consists of 400 dipoles supported by wooden poles one-eighth wavelength above a reflecting screen. To obtain the best fit of the antenna to the terrain the plane of the

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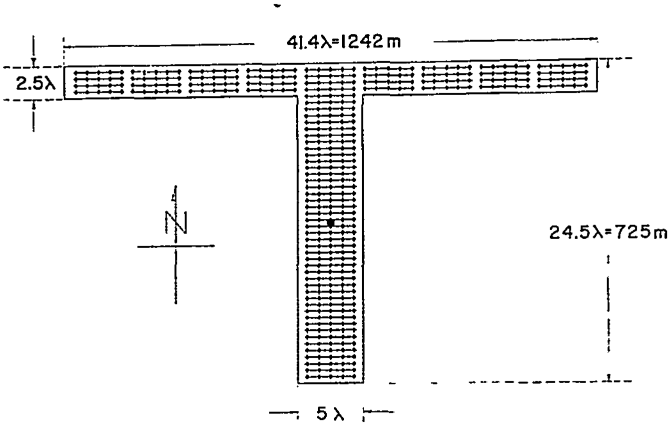

Figure 2. Dimensions of the 10 MHz radio telescope. The dipoles are shown as short vertical lines.

array was tipped down to the north by 2°.8 and down to the east by 1°.6. To have the N-S plane of the instrument pass through the north celestial pole in spite of the E-W tilt, the azimuth of the antenna arms was decreased by $\beta = 1^\circ.8$ where β is given by

$$\tan \beta = \tan \varphi \sin \psi$$

φ is the latitude and ψ is the angle which the plane of the array makes with the horizontal measured along a true E-W line. The over-all effect was to shift the broadside response from the zenith to a higher declination and earlier hour angle. In other words, the antenna behaved as though it were located at latitude 52° 06′ N, longitude 117° 13′ W instead of its geographical position, 49° 19′ N, 119° 37′ W.

The array is supported on 590 wooden poles of various lengths up to 20 m depending on the terrain. The E-W arm consists of four lines of 45 dipoles each, making a total of 180 dipoles. The N-S arm consists of 48 lines of 5 dipoles each, making a total of 240 dipoles. The 20 dipoles in the overlap region are included in both arms.

The receivers and recorders are housed in a trailer situated at the centre of the N-S arm. The receiving system multiplies the voltages from the two arms, using the technique of phase switching (Ryle, 1952), amplifies the product and presents the output on a pen recorder. This system is similar to that used for the Mills cross (Mills and Little, 1953) and for the 22 MHz 'T'. The response of the instrument in any particular direction is then proportional to the product of the voltage responses of the individual arms. Since the voltage response of each arm is a fan beam, and since the two beams are mutually perpendicular, the result for the complete instrument is a pencil beam, 2°.6 E-W by 2°.4 N-S at the zenith.

When used with a bandwidth of 8 KHz the antenna is capable of measuring sources to a flux limit of about $70 \times 10^{-26} \mathrm{Wm^{-2}Hz^{-1}}$. This is still well above the confusion limit for reliable identification of individual sources. Greater sensitivity would require the use of larger bandwidths but this is seldom possible because of interference.

Dipoles

The individual elements of the array are 3-wire folded dipoles with a resonant impedance of 365 ohms, and are oriented to accept N-S polarization. The N-S separation of the dipoles is 0.5λ, permitting phasing in that direction. If a larger spacing had been used a grating response would have appeared when the array was phased away from the zenith. The E-W separation is 0.9λ, which was considered to be the maximum spacing consistent with a tolerably low end-fire response. The exact length of the dipole was determined experimentally by erecting a block of 20 dipoles above the reflecting screen, and adjusting the lengths until each dipole was resonant at 10.02 MHz when all the remainder were terminated with resistances approximately equal to their impedances. The dimensions in Figure 3 were so determined and used throughout the array. In order that all dipoles should appear purely resistive the dipoles along the extreme north and south edges of the array were made slightly shorter than the internal dipoles.

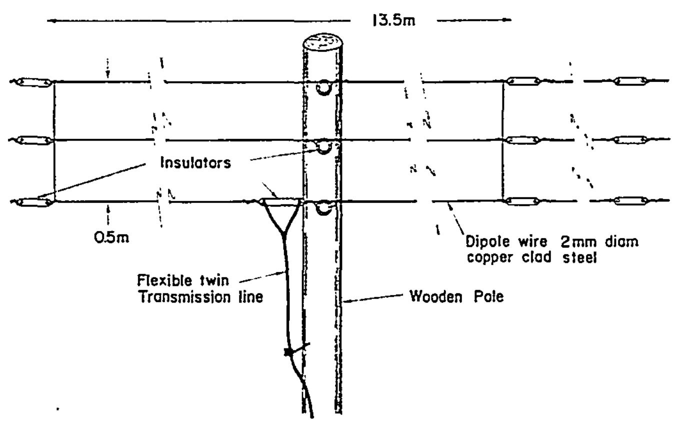

Figure 3. Dimensions of the dipoles.

Reflecting Screen

The ground plane or reflecting screen is placed 3.75 m beneath the centre of the dipoles. It consists of a grid of fine galvanized steel wire 0.7 mm in diameter running north-south, spaced at intervals of 1.2 m. In places where the reflecting screen is closer to the actual ground than 1.2 m the spacing between wire is reduced appropriately. The reflecting screen is supported by taut steel wires which also serve to guy the poles and maintain the correct dipole spacing. The reflecting screen extends 0.5λ beyond the centre of the end dipoles in the N-S direction. In the E-W direction the screen extends beyond the dipoles 0.9λ in the E-W arm and 0.7λ in the N-S arm. The area of the reflecting screen is $213.5\lambda^2 = 192{,}000\ m^2$.

Feeder System, General

Throughout the array, dipoles are fed in parallel in E-W lines of five. The feeder system for a line of five dipoles is shown in Figure 4. An accurately cut 0.5λ length of 225-ohm flexible twin transmission line whose conductors are embedded in polystyrene foam connects each dipole to a horizontal open-wire transmission line ($Z_0 = 370\ \Omega$) running east-west 30 cm above the reflecting screen. The flexible twin lines are soldered to the open wire transmission line at intervals of 1.0λ. Shorting blocks were placed on the open-wire line 0.25λ from the extreme attachment points. The impedance at the centre of this open-wire line resulting from the effective superposition of five dipoles in parallel was 73 ohms. At this point the power was transferred by means of a transformer balun to a 50-ohm coaxial cable (polyfoam equivalent of RG-8/U).

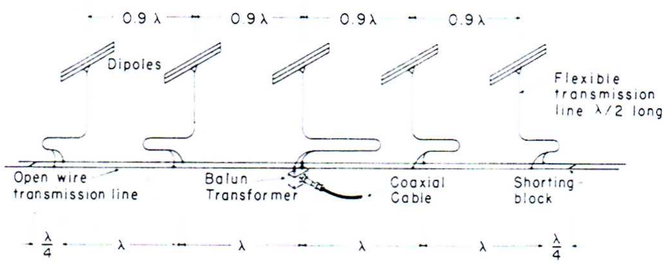

Figure 4. Method of collecting power from a line of five dipoles.

The dipoles in adjacent lines interacted through their mutual impedances, and the impedance at the output was, in general, reactive. This reactance was cancelled by a small adjustment in the position of the shorting block at one end of the open-wire transmission line.

Feeder System, E-W Arm

A diagram of the coaxial cable branching network used for each of the four lines of 45 dipoles in the E-W arm is shown in Figure 5. In the region common to both arms the power from each balun is split in a hybrid ring, half the power going to each arm. To reduce side lobe responses, grading attenuators were inserted between the baluns and the feeder cables as shown; the hybrid ring acted as a 3-db attenuator.

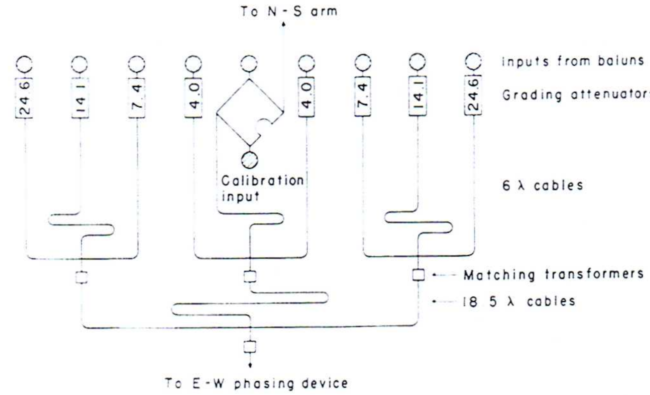

Figure 5. Coaxial cable feeder system for one line of the E-W arm.

As originally designed and built the path lengths from each balun to the phasing device were identical. This arrangement provides compensation for changes in the electrical length of the cable with temperature and also preserves the bandwidth of the feeder system. It does, however, introduce more attenuation than is necessary, because of the extra cable length required in the central branch of the network. Since cable attenuation was greater than expected the signal from the E-W arm was not as large as had been intended. To overcome this difficulty the long central cable was shortened from 18.5λ to 0.5λ and the grading attenuators changed appropriately. The observations prior to July 1965 were made with the feeder system as in Figure 5; those made after July 1965 used the modified configuration. An increase in signal from the E-W arm of about 6 db was realized by the change.

Feeder System, N-S Arm

A coaxial cable of length 15.5λ was run from each of the 48 baluns in the N-S arm to the trailer at the centre of the arm. Each cable was connected to a grading attenuator inside the trailer, and these in turn were connected to the input of the N-S phasing device. The attenuation used is indicated in Figure 6.

Feeder System, 10 MHz Personnel

Power for the observer was usually obtained from a small bag containing 'Midnight Lunch'. This was transferred without attenuation while observations were in progress.

Phasing, General

To avoid loss of valuable time, moving the beam in declination had to be a simple and rapid operation.

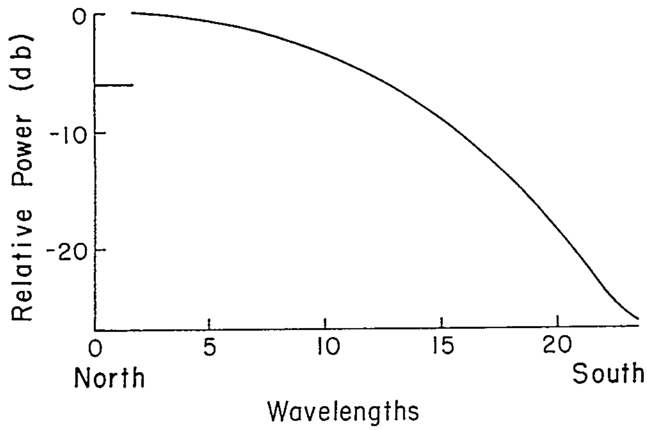

Figure 6. The grading attenuation shown as a function of position in the N-S arm.

Another requirement was the ability to observe several declinations simultaneously. This is a particularly useful feature at a frequency as low as 10 MHz where irregular refraction in the ionosphere is frequently encountered.

To satisfy these requirements two phasing devices were built, one for each arm of the 'T'. In its general form the phasing device used may be considered a 'black box' with n input ports and n output ports, where n is some power of two. The input ports are permanently connected to the elements of the array in a prescribed order. Each output port corresponds to a different phasing configuration of the array, in other words to a different declination for the antenna beam. To observe in a given direction the receiver is connected to the appropriate output port. Similar devices have been used at microwave frequencies (Butler, 1966).

Phasing, E-W Arm

The phasing device which was built for the E-W arm can be understood by reference to Figure 7. The actual circuit diagram of the device is shown in Figure 7 (a) while (b) is a schematic equivalent showing the phase relationships between the four input ports and the four output ports. The effective path lengths between the various ports (less an additive constant or 'zero length') are shown in the circles on each line in 7 (b). This device will be referred to as a nest of hybrid transformers or simply as a 'nest'. When the feeder cables from each of the four E-W lines of dipoles are connected (in order) to the input ports it can be seen that output port 0 will provide a beam phased for reception at the zenith. When output port 1 is used, a progressive phase delay of $\lambda/4$ is introduced between the lines of the array, thus producing a beam tipped 30° to the south of the zenith.

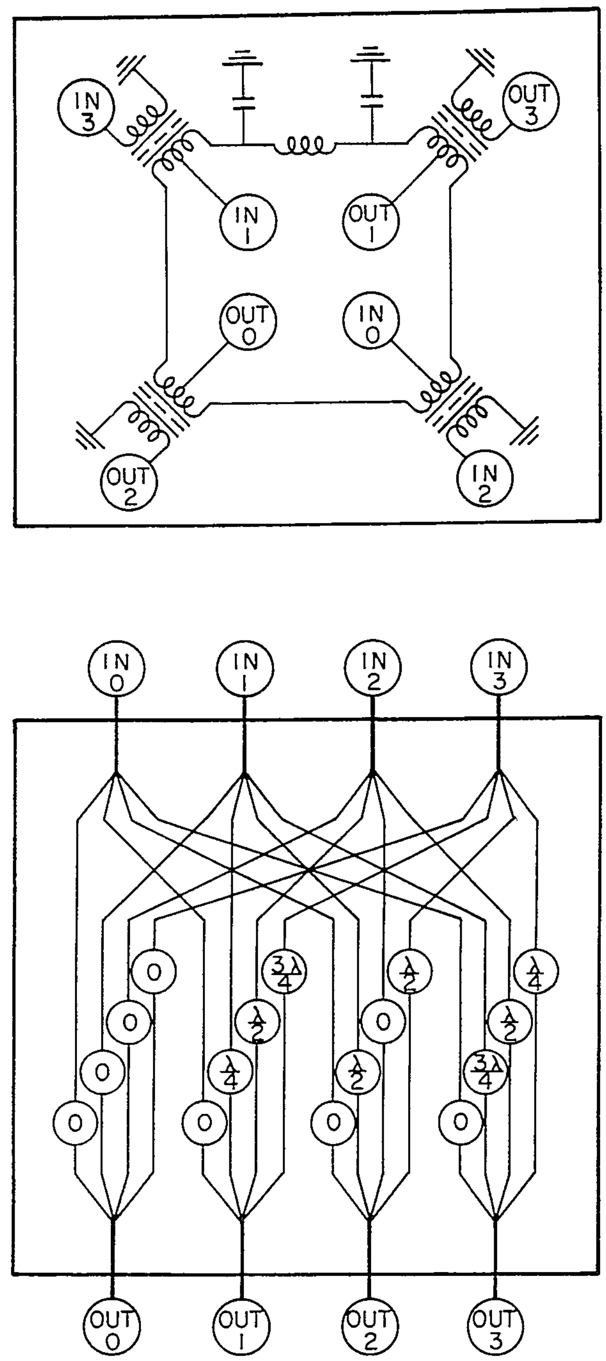

Figure 7. Nest of hybrid transformers which accept four input signals and produce four separately phased combinations of these as outputs. (a) Actual circuit diagram. (b) Equivalent schematic showing path lengths between ports.

Similarly output port 3 produces a beam 30° to the north. Output port 2 provides a phase delay of λ/2 between lines, producing end-fire beams both north and south. To obtain beams at intermediate elevations a set of cables of lengths λ/8, 2λ/8 and 3λ/8 can be switched in ahead of the nest. The complete circuit diagram of the E-W phasing device is shown in Figure 8. All unused output ports are terminated in 50-ohm loads.

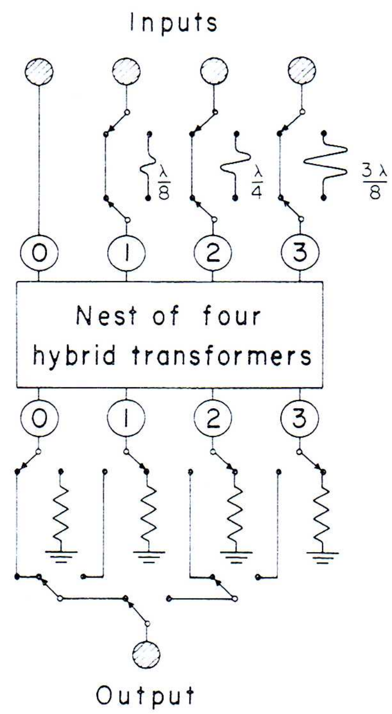

Figure 8.
Complete phasing network of E-W arm. All switches are remotely controlled coaxial relays.

Although the circuit shown selects only one beam at a time it is possible to bypass parts of the output relay system and observe as many as four beams simultaneously.

Phasing, N-S Arm

The N-S phasing system involves an extension of the principle described for phasing the four lines of the E-W arm. It is made up of 48 nests interconnected with cables of various lengths as shown in Figure 9. The input lines from the antenna are connected to the ports at the top of the diagram, and the output ports provide the various phasings, or beams, from the southern horizon through the zenith to the northern horizon. Each beam corresponds to a unique declination, the angular separation between adjacent beams at zenith angles θ_i and θ_j being given by

$$(\sin\,\theta_i - \sin\,\theta_j) = \frac{1}{32}$$

In general, a device of this sort will have 2^n input ports and 2^n output ports, where n is an integer. The present device for which $n = 6$, would accommodate 64 lines of dipoles. As only 48 lines could be built in the land available, the remaining 16 inputs were terminated with 50-ohm resistors and treated as antennas graded to zero. All 64 output ports were available simultaneously, and the number which could be used for observing was limited only by the number of receivers available.

The transformers used in the construction of the N-S phasing device were 50-ohm unbalanced to 100-0-100-ohm balanced. The π section was designed to give a 90° phase shift with a terminating impedance of 100 ohms. Because the transformers differed somewhat in their characteristics, it was necessary to match each port to 50 + j0 ohms by the insertion of a capacitor and a resistor between the connector and the transformer winding. Measurements were then made to determine the small departure from the ideal of Figure 7 (b). The difference appeared in the form of phase and attenuation errors which were associated with the individual ports of the nest. Errors in phase were corrected by appropriate changes in the lengths of the interconnecting cables. To compensate for the errors in the attenuation of the ports three sets of attenuators were inserted as shown in Figure 9. The two sets of inter-level attenuators insure that equal powers are transferred between each pair of nests. They also compensate for the differences in loss of the various interconnecting cables (RG-58C/U) due to the differences in length required for phasing. The input attenuators compensate for the differences in attenuation of the various input ports. A set of output compensating attenuators was not made because the attenuation associated with an output port affected one beam only and could be treated as a simple factor applied to observations with that beam. Compensating attenuators were typically a few tenths of a decibel, and were made to an accuracy of a few millibels. Interconnecting cables were made to an accuracy of a few centimetres.

Even though the individual nests, cables and attenuators were carefully tested as they were built, it was necessary to perform over-all tests. One such test, which checked every path in the system at least once, involved measuring the phases and losses of a selected set of 64 paths from input connectors to output connectors. These phases and losses were compared with the nominal values worked out with the help of the diagrams of Figures 7 (b) and 8. Another test made use of a 1:48 resistively matched power divider. The antenna input cables were removed and the 48 cables from the power

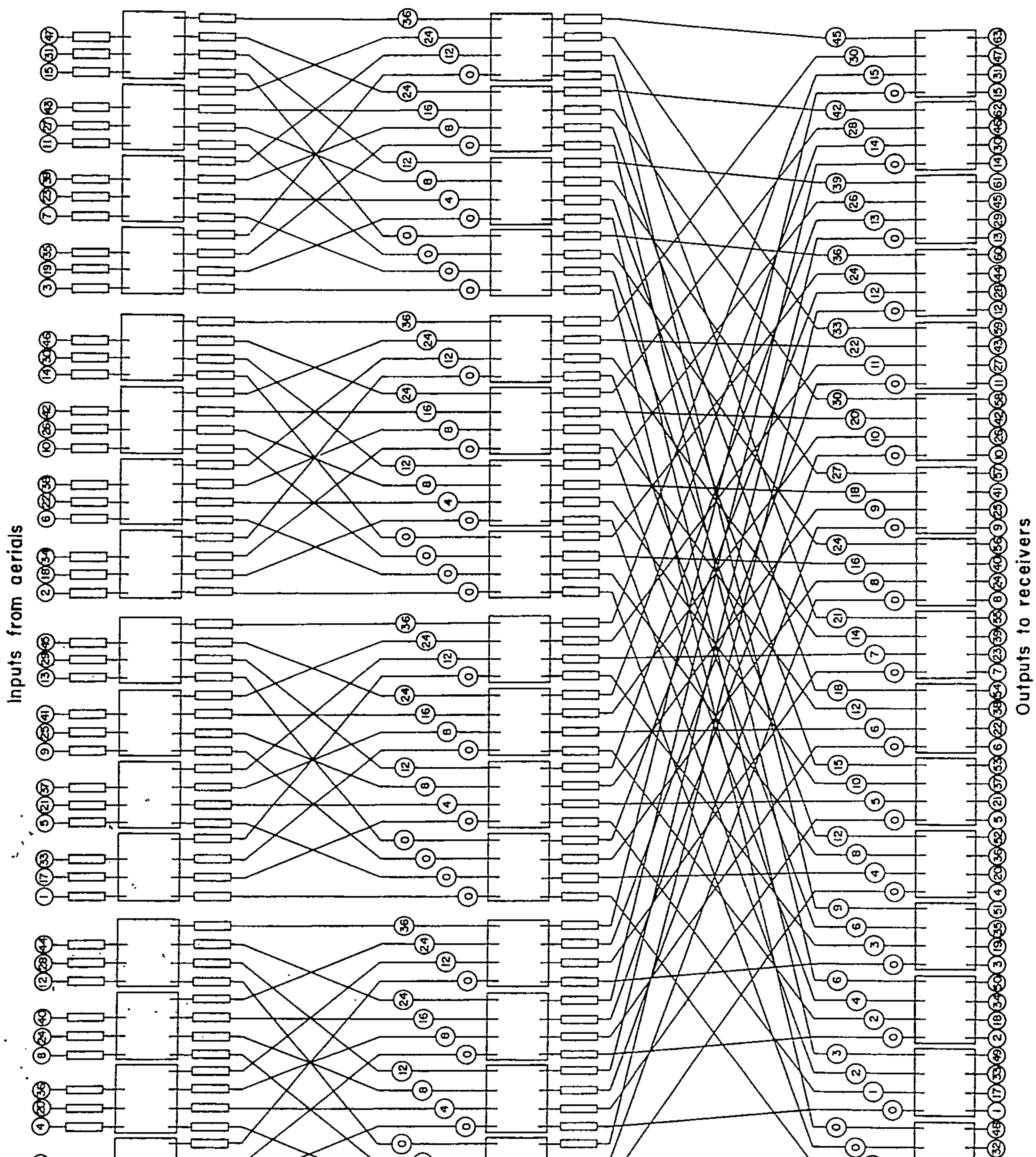

Figure 9. The large blocks represent nests of the type shown in Figure 7. The circled numbers on the interconnecting cables indicate extra lengths in units of $\lambda/64$. The small rectangles are compensating attenuators.

divider inserted in their place. A signal at 10.02 MHz was inserted into the input of the 1:48 divider and output power was measured at each of the 64 output ports. Figure 10 shows the result of such a test. Every fourth output is low corresponding to a zero in an ideal network. Near the 'main beam' measurements agree with theoretical calculations to 0.5 db while the agreement for the 'sidelobes' is usually ± 2 db.

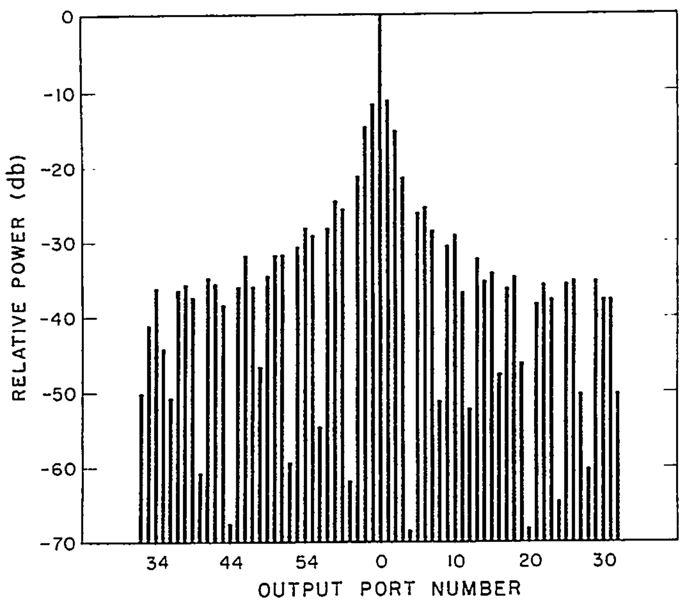

Figure 10. Relative power output from the N-S phasing device when 48 inputs are excited with equal phase and amplitude.

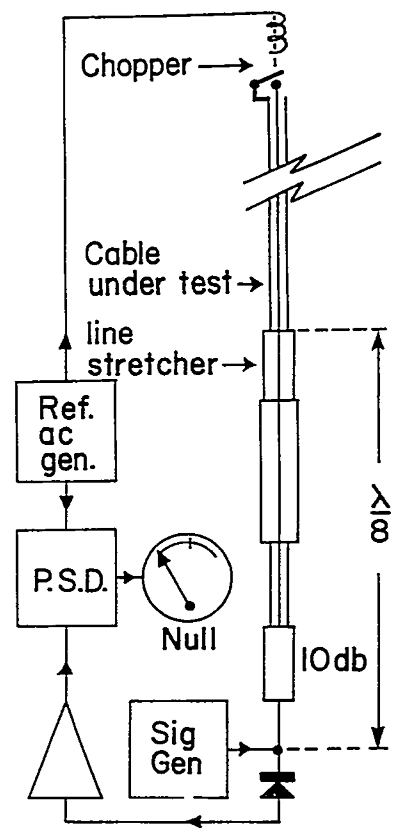

Figure 11. Apparatus used for measuring the electrical lengths of cables in the feeder systems.

Measurement of Cable Lengths

Conventional methods were used to cut the cables in the feeder systems to the nearest quarter wavelength but it was found that normal impedance bridge methods were not accurate enough for final trimming because of reflections from discontinuities in the foamed dielectric of the cable. To overcome this difficulty a system for measuring cable lengths was devised which senses only the wave travelling in one direction. The system is shown in Figure 11 and is similar to that used by Swarup and Yang (1961) at much higher frequencies. When a signal is fed into a cable $(2n+1)\lambda/8$ long which is terminated in either an open or a short circuit, it will return to the driving point in quadrature with the input signal. With this phase relationship the resultant voltage at the driving point is unchanged whether there is an open or a short circuit at the far end of the cable. An AC-driven chopper alternately shorts and opens the far end of the cable and the detected voltage at the chopper frequency is measured. By adjusting the line stretcher for a null, a very sensitive electrical length measurement can be obtained. Reflections from cable discontinuities no longer contribute to the measurement because they are not modulated at the chopper frequency. The estimated accuracy of this method was $.0015\lambda$ for a relative measurement, and $.005\lambda$ for an absolute measurement.

Receivers

At a frequency of 10 MHz the receiver should not present great problems because the sky brightness temperature is many times greater than receiver noise temperature. In the present case, however, because of the large losses in the coaxial cable feeder system, low noise preamplifiers were built, to use with slightly modified communication receivers. The method of phase switching described by Ryle (1952) and by Mills and Little (1953) is used to multiply the voltages from the N-S and E-W arms to produce a pencil beam from the two fan beams. A diagram of the apparatus is shown in Figure 12.

Narrow band (8 khz–6 db) crystal filters were inserted immediately after the phasing networks to delineate the reception band and to prevent very strong out-of-band signals from causing cross modulation in

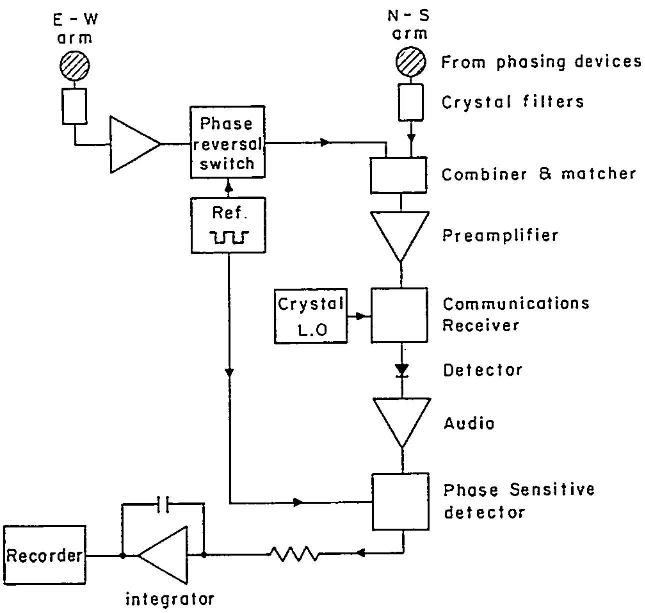

Figure 12. Receiving apparatus for observing one declination.

subsequent nonlinear circuits. So that these filters shall not degrade the system, their phase vs. frequency characteristics must be well matched.

The receiver employs conventional circuits (Bracewell, 1962). Output time constants from 8 to 100 seconds were used.

Observing Techniques

When preparing to observe an astronomical source whose declination is known the appropriate beam is chosen for each arm of the 'T'. A single beam of the E-W arm was broad enough in the N-S direction to cover the same range of declination as eight adjacent beams of the N-S arm.

Four or five receivers were in operation most of the time during the winters of 1964–65 and 1965–66, observing several declinations simultaneously. They were used to observe adjacent beams of the N-S arm within one beam of the E-W arm. However, the flexibility of the system made it unnecessary for the beams to be adjacent, or even confined to one beam of the E-W arm.

Sets of crystal filters were available for 10.01, 10.02, 10.03, 10.04 and 10.05 MHz, but 10.03 MHz appeared to be more often clear of interference than the other frequencies, hence most of the observations were conducted at this frequency. The bandwidth of the antenna, feeder systems and phasing devices was great enough that no difficulties arose in using these nearby frequencies even though the design frequency was 10.02 MHz.

An attempt was made to use the standard frequency guard bands assigned to the Radio Astronomy Service by the ITU. These bands were seldom free from interference. Also the bandwidth available outside the region occupied by the standard frequency transmissions themselves was so small that only the strongest sources could be detected even with the large antenna collecting area available.

It was generally necessary to insert an extra length of phasing cable into either the line from the N-S arm or the line from the E-W arm whose length depended on the beam and frequency in use. This compensated for three effects: (a) the change of electrical length with frequency of the cable, since a greater length of cable was used in the E-W arm than in the N-S arm; (b) a slight difference in effective phase centres of the arms and the phasing devices; and (c) small differences between the individual crystal filters. Although the lengths of cable required for (a) and (b) are calculable, (c) can only be determined experimentally. It was therefore convenient to determine the length of this extra phasing cable empirically, as follows. A large noise signal was introduced into the calibration port of the most northerly hybrid ring (see Figure 5). This signal passes through the entire system in a manner similar to that of a signal from the sky. The cable length needed to produce a maximum deflection was then determined by substitution. This length is the same as required for correct phasing of the 'T'.

Because the array could only be phased along the meridian, all observing was done by drift scans. A calibrating signal was introduced before or after the transit of each source.

Corrections must be applied for refraction and absorption in the ionosphere. In order to estimate the the ionospheric absorption, a Riometer was operated continuously using the 2°.9 × 11° beam (to half power) of the N-S arm at the zenith. To estimate refraction, two adjacent beams of the N-S arm are used to observe one source, since the beams overlap considerably. The relative amplitudes obtained with the two beams give a unique value for the apparent declination of the source.

Calibration

The absolute calibration of a large array of this sort is a formidable task. One method is to use a separate dipole whose gain is readily calculated as the common element of two interferometers. One interferometer consists of the dipole and the N-S arm, the other consists of the dipole and the E-W arm. This method has been described by Little (1956) and used successfully with the Mills Cross at 85 MHz. The calibration dipole used with the 10 MHz array was erected over a dry lake bottom and is seen at the extreme left of Figure 1. This method of calibration has, so far, proved less accurate than other methods.

A second approach is the direct measurement of the absolute flux density of Cass A and Cyg A at 10 MHz using a completely independent simple interferometer. Flux measurements were made with an accuracy of ± 10 per cent by Bridle (1967). This method is reliable but restricts the calibration to declinations near the zenith.

A third method is the detailed calculation of the gain of the antenna, treating each arm independently. The beam of the arm was integrated to find the forward gain and the losses in cable, phasing devices, etc., were measured. The total loss for each arm could be checked by measuring the intensity of the background radiation with measurements made using the calibration dipole alone. Because of the different beam shapes involved, these comparisons must be treated with caution. The calculated value of the gain could be checked near the zenith using the results of the absolute flux density measurement. A severe complication entering these calculations was the effect of mutual interactions in the array. These interactions have two effects, both of which are a function of zenith angle. The change in impedance of the antenna causes, first, a power loss by reflection at the mismatch, and second, a redistribution of current near the edges of the array resulting in a slight distortion of the beam. Both these effects are present at the zenith, since the conditions under which the antenna was matched (one line driven, the remainder terminated in load impedances and having parasitic currents only) were different from the conditions under which it was used (all lines driven).

A fourth method used was purely empirical, and as such avoids many of the above complications. It relies on linear extrapolation from higher frequencies of the spectra of radio sources to provide flux densities at 10 MHz, then the use of these sources to calibrate the array. This was done using only elliptical galaxies away from the galactic plane which had straight spectra down to 26 MHz. The selection of sources provided a gain measurement over a wide range of zenith angles.

The final calibration used is based on the most reliable features of the latter three methods.

Results

The observations, which are continuing at the time of writing, include 132 sources whose fluxes have been well determined, 34 sources observed under difficult conditions and a map of the background radiation for a large part of the northern sky. These results have been reported elsewhere (Galt and Costain, 1965; Roger, Costain and Purton, 1965; Purton, 1966; and Bridle, 1967). Figure 13 (a) shows an exceptionally good record of the radio source Hercules A.

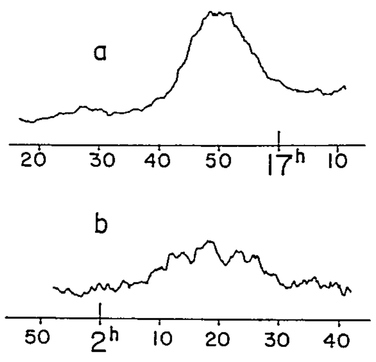

Figure 13.
(a) A record of the radio source Hercules A made under exceptionally good observing conditions. This source is at declination +5°.0 and has a flux at 10 MHz of 5390 $\times 10^{-26}$Wm^{-2}Hz^{-1}. (b) A record of a fainter radio source observed under scintillation conditions. 3C 66, flux = 735 $\times 10^{-26}$Wm^{-2}Hz^{-1}.

Figure 13 (b) shows a more typical record of a transit of 3C 66 showing strong ionospheric scintillation.

Acknowledgments

The authors wish to thank Dr. C. H. Costain, Dr. P. E. Argyle, Dr. J. L. Locke and Mr. J. D. Lacey for discussions and assistance at various stages in the design and construction of the array. Observations during 1965–66 were made by Mr. A. H. Bridle.

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