

FIRST RESULTS OF RADIO STAR OBSERVATIONS USING THE METHOD OF APERTURE SYNTHESIS

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Summary

Four surveys, centred on declinations of 52° , 50° , 42° and 05° , have been made at a wave-length of 1.7 m with a large interferometric radio telescope employing the new technique of aperture synthesis. Details of the observational method, calibration, data-reduction and analysis of the computed results are given. An assessment of the performance of the system shows that accurate measurements of the positions and flux densities of radio stars may be extended to limits well beyond those of any previous survey. Lists of sources are given for declinations between 52° and 50° and between 40° and 44° . Observations at 05° were made to study the distribution of radio stars outside the galactic plane; no evidence is found for a population of radio stars in the galactic halo.

1. *Introduction.*—The method of synthesizing a large radio telescope by combining observations made with movable elements in a number of different relative positions has already been described (Ryle and Hewish 1960). It was there shown how both pencil beam instruments and interferometers could be developed and how, in each case, one convenient system employed a long fixed aerial running East/West with a smaller aerial arranged to move on rails running North/South. With this arrangement it is only necessary to provide aerial rotation about the long axis to scan in declination while making use of the Earth's rotation to scan in right ascension.

A large interferometer operating at a frequency of 178 Mc/s which uses this method has been built for the study of radio stars. It was designed to obtain better positional accuracy for weaker sources so that a larger number might be available for optical examination and to obtain more reliable information on the apparent distribution of sources in space. The same radio telescope has already been used in an investigation of the surface brightness of radio stars (Leslie 1961) and for the measurement of the positions of 64 intense ones (Elsmore, Ryle and Leslie 1959).

The present paper is concerned with the use of the instrument with its full resolution. The envelope of the interference pattern then has half-widths of $25'$ and $35'$ in right ascension and declination respectively. The operation of the instrument and the methods of computation and data reduction are described in Section 2. The performance of the system is discussed in Section 3, and in Section 4 preliminary results of the observation of four areas of sky are summarized. The first two areas observed were centred on declinations of 50° and 52° ; the later areas, observed with an improved recording system, were centred on 05° and 42° .

2. The radio telescope.

(a) *The aerial system.*—The aerial system consists of two elements, one of which is fixed and the other mounted on railway lines. Structural details have been discussed elsewhere (Ryle 1960). In the present observations the aerials are used together as a transit interferometer. Both elements are cylindrical reflectors having a parabolic section 65 ft in width and each is aligned on an East/West axis. The fixed element is 1450 ft in length and the movable one, 190 ft in length, traverses a distance of 1000 ft along rails in a North/South direction as shown in Fig. 1.

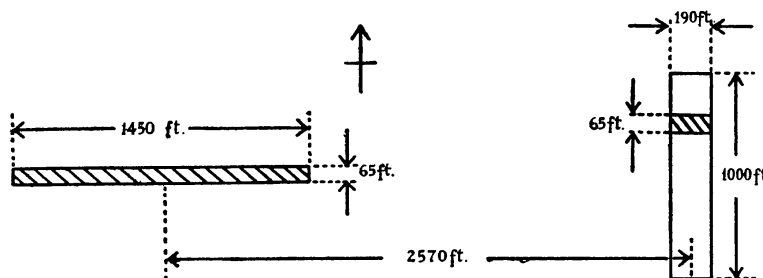


FIG. 1.—Schematic diagram of the aerials.

Both elements may be set to declinations between -05° and 90° . The reception pattern of each has a width of $4^\circ.6$ between half-power points in declination and this determines the area of the strip of sky under observation at a particular setting. In right ascension the reception pattern is related to the product of the reception patterns of the two aerials and to the frequency response of the output filter of the receiver as shown later. Its shape can be regulated either by the distribution of excitation along the fixed aerial or by means of the output filter response to give the narrowest reception pattern consistent with the lowest realizable side-lobe level. Side-lobes in right ascension at angles greater than 5° from the main beam are in any case removed by the lack of coherence between the signals arriving at the widely spaced aerials when using a receiver of bandwidth 4 Mc/s.

Initially, the desired reception pattern in right ascension was achieved by adjusting the excitation of the fixed aerial. Since the spatial frequency spectrum of the reception pattern is derived from the convolution of the aperture distribution of the two aerials it was only necessary to adjust the excitation in steps of length equal to that of the movable aerial. The adjustment was performed by the use of unsymmetrical transformers at the junctions of the branched feeder network. The aperture distribution adopted, the effective spectrum of the combined aerial system and the resulting reception pattern are shown in Fig. 2.

Later it was found more convenient to adopt a uniform excitation along the fixed aerial and to achieve the same reception pattern by using a suitable output filter. This method had the added advantage that the fixed aerial could also be used, independently, as an efficient total power system. In this mode of operation the spectrum of the aperture distribution is uniform, within a band determined by the length of the aerials, and its shape is adjusted to that required by a suitable output filter response. The processes of filtering and convolution are basically equivalent and in this case where the output of the receiver was already recorded in digital form it was convenient to carry out a direct convolution with a time function whose Fourier transform provides the required polar diagram.

The resulting reception pattern is then identical with that shown in Fig. 2. Noise components at frequencies higher than those introduced by the aerial are removed before convolution by a simple CR filter. The spectrum of the original signal, the convolving function and the CR filter are shown in Fig. 3.

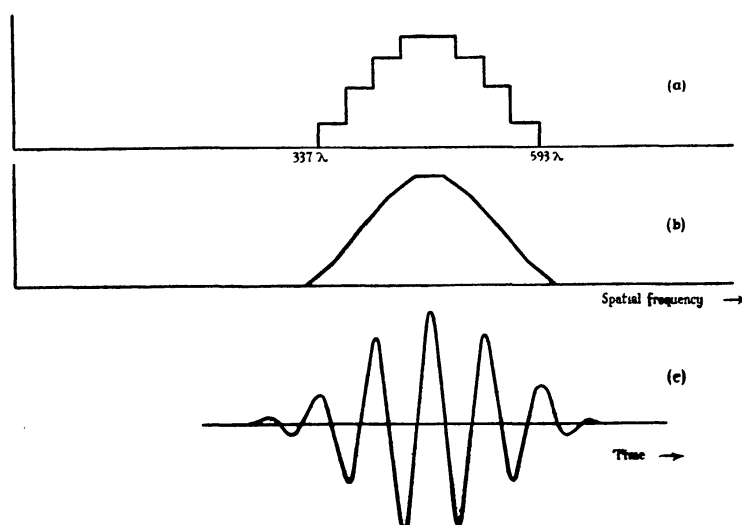


FIG. 2.—(a) *The aperture distribution of the fixed aerial.*
 (b) *The spatial frequency spectrum of the aerial system.*
 (c) *The reception pattern.*

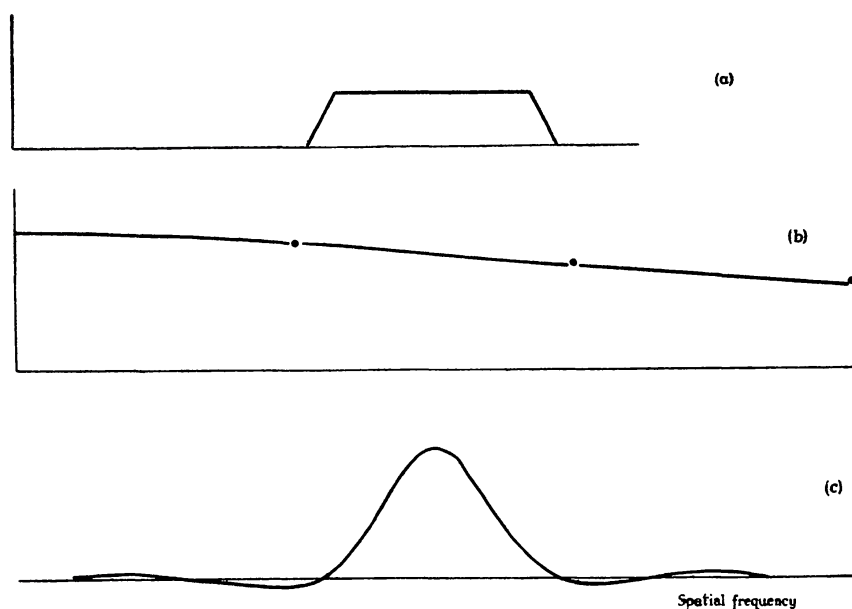


FIG. 3.—*The spectrum of the signal (a), the CR filter (b) and the convolving function (c).*

The resultant reception pattern in declination, after the synthesis is completed, is that of a 500 ft aperture. The required aperture distribution is here achieved by suitably weighting the observations made at the different positions of the movable aerial (Ryle and Hewish 1960).

(b) *The receiver and recorder.*—It is necessary, for synthesis, to record quantities of the form $E_a E_b \cos(\phi_a - \phi_b)$ where E_a , E_b , ϕ_a and ϕ_b represent the amplitudes and phases of the voltage induced in the two aerials. This form of correlation response can be obtained by the use of a phase-switching receiver (Ryle 1952). In the system used here two such receivers were connected to the aerials *via* a hybrid network as shown in Fig. 4 and arranged to provide outputs in antiphase. The difference in output of the two receivers then provides the required quantity and the use of the double system improves the signal/noise ratio by $\sqrt{2}$ (since the combined noise from the two preamplifiers is uncorrelated at the inputs of the two receivers). Furthermore, most types of interference are greatly reduced.

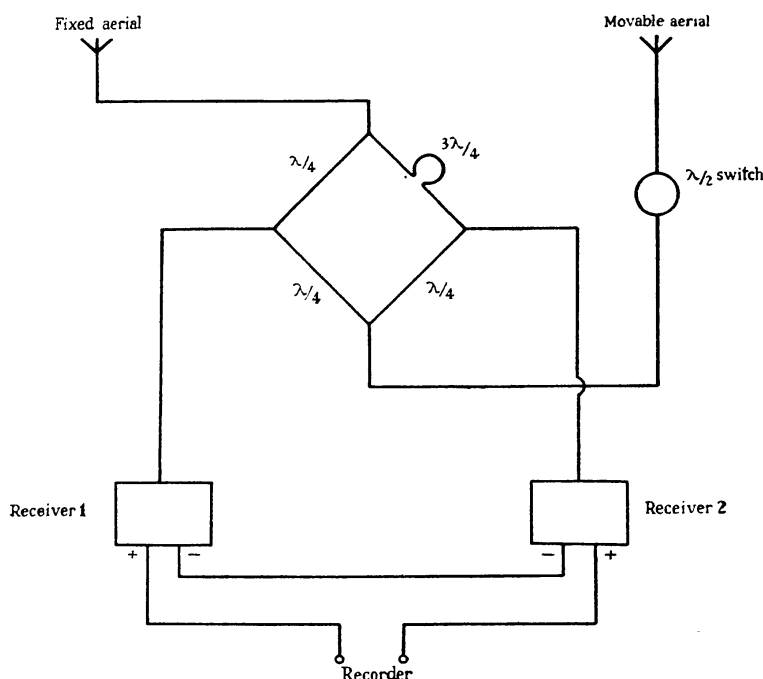


FIG. 4.—Method of connecting two receivers to the aerials.

Few sources of interference are received with appreciable intensity by both aerials, since the reception patterns do not overlap for a distance of about 20 miles. Intense and variable interfering signals containing frequency components near the switching frequency may however cause a small output even when the interference is incident on only one aerial. With the double receiver arrangement such signals appear in phase at the output and may be rejected with a ratio dependent on the gain equality of the receivers. It has been found in practice that ignition and lightning interference are attenuated by a factor of 20 compared with the output of a single phase-switching receiver which is itself very much less susceptible than a simple receiver.

Since large amounts of data must be recorded prior to computation, an automatic device has been developed for continuously digitizing the signal and recording it on punched tape. A normal type of pen recording is also used for immediate checking of performance. In the automatic recorder the signal is used to operate a self-balancing potentiometer on whose shaft is mounted an

optical digitizing disk with a cyclic permuting binary code of 8 digits. To minimize digitizing errors the sensitivity of the receiver is adjusted so that the noise level exceeds the digit interval by a factor of 3 or 4. In order to obtain synchronism between sampling points made at successive positions of the movable aerial the actual sampling rate is chosen to be a sub-multiple of 24 sidereal hours. The instant at which the record is sampled (about once every 8 seconds, depending on declination) is regulated by a gear train driven from a 50 c/s synchronous motor whose power supply is derived from a 100 kc/s sidereal crystal oscillator. An impulse from a control circuit disconnects the servo motor in the self-balancing potentiometer, thus storing the signal as a shaft position. Subsequent impulses cause the outputs of the photo-cells on the digitizer to be read and punched as two successive characters using a modified teleprint punch with standard five-hole tape. The servo drive is then reconnected and the shaft follows the signal until the next sampling time.

The minimum sampling rate which may be employed is determined by the envelope reception pattern (Bracewell 1956) and corresponds to approximately four samples of amplitude and phase of the quasi-periodic response in each beamwidth (to zero power). In this case the lobes of the interference pattern occurred at a frequency slightly greater than twice the minimum sampling rate. The output of the receiver was initially sampled four times in each cycle of the interference pattern. After further smoothing by the correlation process described in Section 2 (*a*) the sampling interval was increased, during computation, to give values of amplitude and phase once per cycle of the interference pattern.

(*c*) *Method of observation.*—With the declination of both aerials set to the required value the movable aerial is driven to the North end of the rails and observations are made for a period of $23\frac{1}{2}$ hours. For computation it is convenient if all tapes commence at exactly the same sidereal time and an interval must therefore be allowed for moving the aerial and for calibration, etc. before each day's observations. After completion of the first run the aerial is moved a distance of 42 ft and the observations are repeated for 24 positions of the movable aerial. The distance moved is somewhat less than the effective width of the aerial in order to eliminate the 'grating' side-lobe which would otherwise appear in the reception pattern at the extreme edge of the $4^{\circ}6'$ strip (Ryle and Hewish 1960). It is necessary to maintain an equal path length to the two aerials so that a wide bandwidth may be used. This is achieved by a set of cables having electrical lengths equal to a whole number of wavelengths and arranged in a scale of two; these cables are altered with each aerial move to equalize the path difference to within 2.5 wavelengths.

At low declinations, where the effective North/South aperture is reduced, it would be possible to increase the distance between successive positions so long as the effective movement in the aperture plane did not exceed about 42 ft. Such a procedure would, however, reduce the signal/noise ratio slightly and so far has not been employed.

Throughout the observations separate records are kept of solar activity and ionospheric scintillations so that runs may be repeated if serious errors are likely to occur in any part of a particular record. Errors due to other sources of interference are either immediately evident on the pen record or are indicated by the data-checking procedure outlined below.

(d) *Calibration and checking.*—Before proceeding with the analysis of the data it is necessary to make a number of preliminary checks. It is particularly important to correct for any systematic variations in the sensitivity or phase of the system since these will introduce side-lobe responses into the synthesized reception pattern in declination. At each of the 24 positions of the movable aerial the phases and amplitudes of a number of intense sources are obtained from the recorded data. Knowing the accurate declination of these sources it is possible to predict the correct value of the phase for each aerial position and so to obtain a phase error for each source; provided the sources have a flux density greater than about $15 \times 10^{-26} \text{ W.m}^{-2} (\text{c/s})^{-1}$ they will not be affected appreciably by noise or confusion. A mean correction for both phase and amplitude can therefore be obtained for each run and used to correct the original data; corrections were seldom found to be necessary.

At the same time as this check is carried out the data are scanned in the computer for wrong values, caused for example by solar or terrestrial interference or by a fault in the digitizing system. This is done by convolving the data with a suitable function and comparing each number on the tape with the 'expected' value obtained by convolution. Errors detected in this way were reported whenever they exceeded five times the r.m.s. noise level. The necessary corrections were then fed into the computer together with the 24 data tapes. The required weighting factor for each position, which determines the reception pattern in declination, was also fed in at this stage.

(e) *The computation.*—It is necessary to carry out the computation in two steps since the data tapes must be fed into the computer serially whereas the calculation requires information, at a given sidereal time, from all the tapes simultaneously. During the first stage the data are sorted into a convenient layout in the store and during this process the convolution mentioned in Section 2 (a) is performed. Two convolving functions are used which yield the sine and cosine components, sampled once per cycle, of the quasi-periodic output from the receiver. These data, corrected for errors as described above, amount to about 100,000 numbers and are stored on magnetic tape in readiness for the main calculation.

At any given sampling time the data for the 24 aerial positions may be represented by the series $C_{12}, S_{12}, \dots, C_{-12}, S_{-12}$. The second stage of computation then gives 16 values of D_m

$$\text{where} \quad D_m = \sum_{n=-12}^{n=+12} (C_n + iS_n) e^{imn\phi} \quad \left(\phi = \frac{2\pi}{24} \right).$$

These values of D represent the output of the full synthesized interferometer, sampled at approximately the optimum interval in declination, within a range of $4^\circ.6$.

On completion of the calculation it is necessary to correct for the known primary reception pattern of the aerials which would otherwise cause the values of D at the edges of the declination strip to be systematically smaller than those at the centre. While 24 values of C_n and S_n are required only 16 values of D are computed since the overlapping of adjacent stations of the movable aerial implies that successive values of C_n and S_n are not entirely independent. The (complex) values of D are next transformed to $|D|$ and $\arg D$ and the printed output then gives the 16 values of $|D|$ across the sheet followed by a second line

giving corresponding values of $\arg D$. $|D|$ is printed as an integer in the range 0–9999 and $\arg D$ as a fraction of a revolution in the range 0–99. The output is thus a two-dimensional map of the sky, sampled at discrete intervals, with declination running across the page and right ascension downwards. The sampling interval is approximately 20' in declination and 7'·5 in right ascension, the precise value of the former depending on the declination of the centre of the strip. An example of the printed output is shown in Fig. 5.

Declination																								
40°								42°								44°								
1																1								
11	45	23	23	09	19	11	10	08	14	24	23	14	54	09	50	1440 12 ^h 02 ^m								
09	06	67	64	81	83	84	13	02	18	27	41	56	37	36	37									
98	43	08	15	04	12	26	04	04	19	36	26	18	38	67	32	1441								
07	08	59	58	32	85	87	21	03	21	27	38	53	41	41	44									
40	15	31	13	14	22	45	03	03	36	51	26	16	22	36	18	1442								
08	93	62	60	22	88	88	76	11	24	28	36	51	57	57	65									
10	31	78	33	17	21	51	10	02	46	67	18	14	20	31	21	1443 12 ^h 04 ^m								
60	73	60	55	20	88	86	73	66	28	30	39	68	70	67	67									
		1														1444								
51	44	20	50	17	14	30	13	05	49	61	04	26	16	12	08									
64	70	60	58	22	98	87	66	63	27	30	45	81	75	64	45									
		1														1445								
72	47	29	48	16	02	07	19	05	37	40	17	34	51	83	04									
69	65	59	58	17	17	78	58	66	26	28	90	89	79	80	47									
		1														1446 12 ^h 06 ^m								
87	66	05	24	19	03	02	19	04	24	23	37	38	66	35	82									
67	53	56	57	11	80	44	54	73	23	25	88	91	82	81	85									
													1	3		1447								
75	70	71	13	22	19	04	13	09	14	24	44	44	03	42	92									
65	52	52	60	05	79	77	66	85	24	27	91	96	82	82	86									
													3	6	1	1448								
68	68	46	10	17	25	12	13	09	15	26	44	38	47	35	23									
68	58	47	40	05	80	90	83	89	20	24	92	97	82	82	85									
													2	5	1	1449 12 ^h 08 ^m								
75	75	17	19	07	25	21	21	14	11	22	42	27	51	34	51									
72	68	45	38	08	82	88	88	96	12	15	96	97	82	81	84									

FIG. 5.—A part of the printed output. Numbers in the upper rows give values of $|D|$ and the lower rows the values of $\arg D$; values of D over 99 are printed thus: $\frac{7}{35} \equiv 735$. $|D| = 71$ corresponds to a flux density of $10^{-26} \text{ w.m}^{-2} (\text{c/s})^{-1}$.

During the progress of the main calculation a record is made of the probability distribution of $|D|$. This is computed in blocks of 20 successive samples in right ascension and the result is obtained on a second output channel. This information is required for statistical investigations of the distribution of radio stars (Scheuer 1957) and the application of the method will be discussed in another paper.

(f) *Analysis and interpretation of the results.*—The position of a given source in right ascension is determined precisely by the value of the phase ($\arg D$) but it is necessary to interpolate, both in declination and right ascension, to find the accurate declination and flux density of a source. Since the reception pattern is known in both coordinates this interpolation is most conveniently carried out by a simple graphical process. In cases where the envelope reception pattern appears to have the wrong shape, it is probable that more than one source is present and values of the phase then give valuable information which may resolve the blend.

No attempt is made to reduce the collimation errors to zero for each series of observations. Instead, use is made of the accurate positions of 64 intense radio stars which have already been determined in an independent investigation (Elsmore, Ryle and Leslie 1959). Any declination strip will usually contain several of these sources and it is therefore possible to obtain both collimation errors and a flux density normalizing factor for each series of observations.

3. Performance.

(a) *The reception pattern.*—It is only necessary to consider the reception pattern along lines in right ascension and declination which intersect at the centre of the pattern. At other angles the response is given by the product of these patterns and side-lobes will be very small.

The observed reception pattern in right ascension, derived from a uniform excitation of the fixed aerial and the convolution method described in Section 2 (a), is shown in Fig. 6 (a); it is seen that the side-lobes are less than 0.5 per cent at angles greater than 1° .

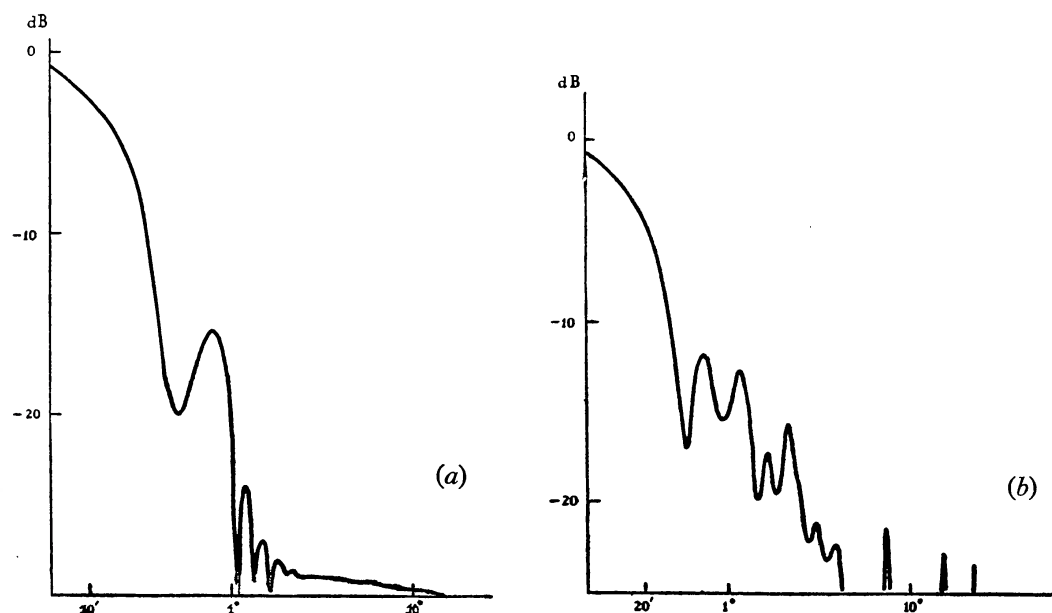


FIG. 6.—The observed reception pattern (a) in right ascension and (b) in declination.

In declination the reception pattern will be affected by errors which may occur in the phase or amplitude of the signal. While systematic errors can be removed as discussed in Section 2 (*d*) there will be random errors due, for example, to refraction in the ionosphere. Variations of amplitude are found to be of negligible importance compared with the phase variations which have an observed r.m.s. value of about 15° , corresponding to a figuring error of about $\lambda/25$ in the synthesized aperture. The latter introduce side-lobes with an r.m.s. level of about 6 per cent confined to the $4^\circ.6$ envelope; beyond this the response is less than 0.5 per cent. The observed reception pattern in declination is shown in Fig. 6 (*b*).

The cause of the random phase variations is not yet known. From existing knowledge of non-uniformity in the ionosphere it seems unlikely that they can be explained simply by ionospheric refraction and it is possible that they may be due in part to temperature variations in coaxial cables.

(*b*) *Sensitivity*.—The noise level for the initial observations at declinations of 50° and 52° was about three times higher than that of the later observations owing to errors introduced by the digitizer. For the surveys at declinations of 42° and 05° an improved digitizer was used and uniform excitation of the long aerial was adopted. To distinguish between true noise and the effect of weak unresolved sources, special records were made with one of the aerials replaced by a resistance at a temperature close to the effective sky temperature. Under these conditions there is no response from radio stars but the noise level due to the combined effects of preamplifier noise and the galactic background emission is the same; additional noise components due to weak terrestrial interference incident on one aerial are also included. The possible incidence of coherent interference in both aerials was investigated in a separate experiment and shown to be unimportant.

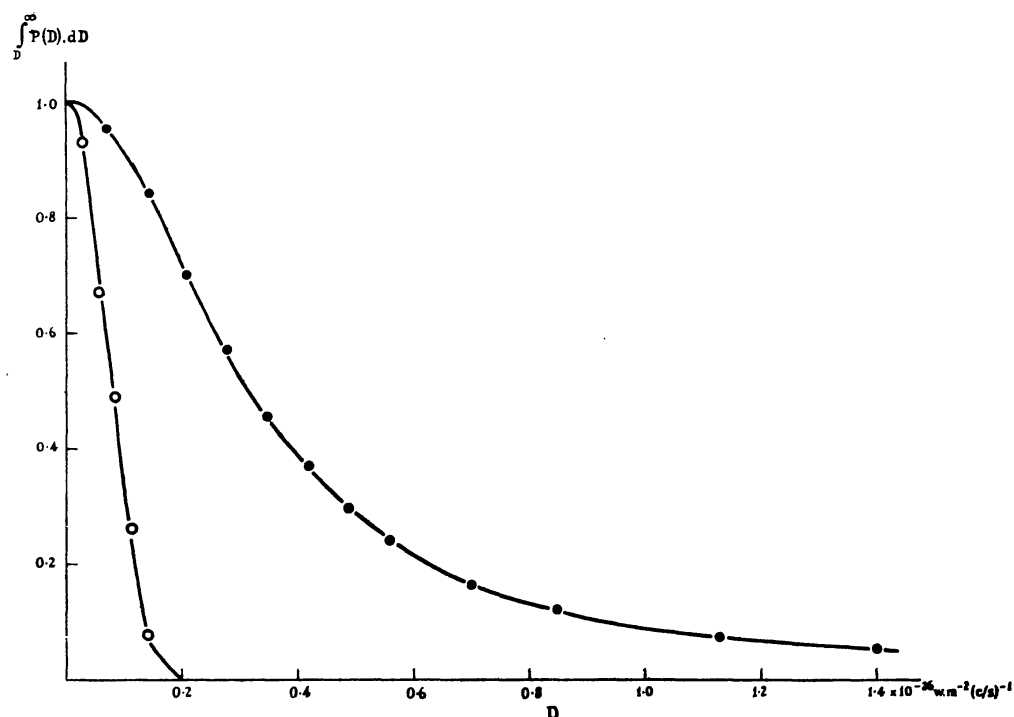


FIG. 7.—The integrated probability distribution of $|D|$ for the 42° survey —•—•—, and that derived —○—○— from the noise measurement.

The observed noise level was found to be $0.08 \times 10^{-26} \text{ w.m}^{-2} (\text{c/s})^{-1}$ as compared with an estimated theoretical value of $0.045 \times 10^{-26} \text{ w.m}^{-2} (\text{c/s})^{-1}$.

The integrated probability distribution of $|D|$ for the 42° survey is shown in Fig. 7 together with that derived from the independent noise measurement. It is evident from these curves that the noise on the records is likely to be unimportant, either in the measurement of individual sources, or in the statistical analysis of $|D|$.

4. Observational results

Four surveys have been made centred on declinations of 52° , 50° , 42° and 05° . The first two (52° , 50°) were carried out primarily to test the operation of the whole system. A declination strip 2.5° wide was included in both surveys and a direct comparison of the results has been made. The noise and side-lobe level were both higher than in the later surveys which used an improved digitizer described in Section 2 (b).

The survey at 05° was made primarily to investigate the distribution of sources for different directions in the galaxy. The most recent survey at 42° represents the best series of observations for the study of individual sources and for application of the statistical method of analysis.

(a) *Comparison of surveys at declinations of 52° and 50° .*—The results obtained for the two surveys are entirely independent, both with respect to errors in flux density and position and to those arising from side-lobes. A comparison of results in the overlap region 2.5° wide in declination thus provides an excellent overall test of the operation of the instrument.

In Table I a list is given of all sources in the overlap region having flux densities greater than $3 \times 10^{-26} \text{ w.m}^{-2} (\text{c/s})^{-1}$ and it is seen that there is extremely good agreement. Of the 67 sources listed, the majority show good positional agreement and have flux densities which agree to within 20 per cent. Two sources found on the 50° survey had flux densities of less than $2 \times 10^{-26} \text{ w.m}^{-2} (\text{c/s})^{-1}$ on the 52° survey; in one case the wrong right ascension lobe was chosen.

TABLE I

52° Survey						50° Survey					
R.A.			Dec.		Flux density 10^{-26} MKS	R.A.			Dec.		Flux density 10^{-26} MKS
h	m	s	°	'		h	m	s	°	'	
00	13	21.3	50	22.4	5.7	00	13	21.0	50	19.2	4.0
00	35	43.5	50	17.6	5.0	00	35	42.9	50	16.6	5.6
00	40	21.4	51	46.7	37	00	40	19.9	51	47.5	35
					< 1.5	00	47	47.5	51	42.3	4.1
00	48	06.2	50	56.7	11.4	00	48	05.6	50	56.1	11.1
01	19	44.7	49	51.7	4.3	01	19	45.5	49	49.8	4.1
02	23	38.6	51	06.5	3.5	02	23	38.1	51	03.6	3.8
02	40	17.5	49	51.4	5.0	02	40	19.0	49	53.8	5.5
03	28	20.1	51	25.9	3.3	03	28	19.7	51	22.7	3.1
03	34	04.1	50	37.1	12.0	03	34	04.1	50	35.2	12.5
03	55	47.6	50	48.8	6.1	03	55	46.0	50	49.7	6.5
04	26	01.2	50	09.3	3.9	04	25	58.1	50	10.1	4.3
04	37	36.9	51	25.7	2.4	04	37	31.2	51	25.0	3.2
04	42	56.4	50	32.0	6.9	04	42	56.1	50	33.5	7.3
04	48	55.6	52	00.0	6.5	04	48	53.3	52	02.1	5.1
					< 2.0	04	56	18.5	50	09.2	3.3
05	12	41.6	51	04.4	4.8	05	12	39.0	51	09.7	4.8

TABLE I—*continued*

52° Survey			50° Survey		
R.A.			R.A.		
Dec.			Dec.		
Flux density			Flux density		
10 ⁻²⁶ MKS			10 ⁻²⁶ MKS		
h	m	s	h	m	s
05	15	40.2	05	15	38.1
05	22	11.0	05	22	08.5
05	38	44.6	05	38	42.9
06	15	58.7	06	15	57.0
06	25	54.0	06	25	53.9
06	28	49.9	06	28	50.2
06	35	45.2	06	35	44.8
06	50	15.2	06	50	18.6
07	00	30.1	07	00	31.6
07	03	47.9	07	03	46.5
07	24	17.4	07	24	16.6
07	28	37.9	07	28	35.7
07	29	48.7	07	29	45.5
07	36	30.1	07	36	27.9
08	29	44.6	08	29	40.4
08	35	33.8	08	35	31.0
08	35	58.7	08	35	55.2
08	39	39.4	08	39	34.4
09	00	25.4	09	00	21.7
10	31	20.8	10	31	17.4
10	39	08.9	10	39	07.7
11	30	34.7	11	30	31.3
11	36	13.0	11	36	11.4
11	43	07.8	11	43	05.9
11	50	52.0	11	50	49.8
11	51	12.5	11	51	11.5
12	20	29.6	12	20	27.0
12	49	29.0	12	49	28.5
13	17	44.5	13	17	41.7
13	29	37.1	13	29	39.0
13	43	29.2	13	43	29.2
14	41	24.4	14	41	21.1
14	46	59.5	14	46	59.7
14	52	24.7	14	52	24.8
16	52	40.5	16	52	43.6
17	00	10.2	17	00	13.2
17	23	06.0	17	23	11.8
17	29	51.6	17	29	56.7
18	17	50.5	18	17	56.8
19	40	21.4	19	40	26.7
20	07	49.4	20	07	54.4
20	30	12.5	20	30	17.8
20	37	07.1	20	37	10.4
20	40	36.3	20	40	42.2
20	55	44.6	20	55	49.5
21	22	43.0	21	22	46.9
21	22	53.7	21	23	00.6
21	50	15.4	Region not covered by survey		
23	45	34.8	23	45	36.2
23	46	08.8	23	46	55.0

A precise comparison of the positions yields an r.m.s. differential error of $\sim 3'$ in declination and $\sim 4''$ in right ascension. The declination errors appear to be random but there is a systematic error in right ascension which, when plotted against right ascension, approximates to a sinusoidal variation as shown in Fig. 8.

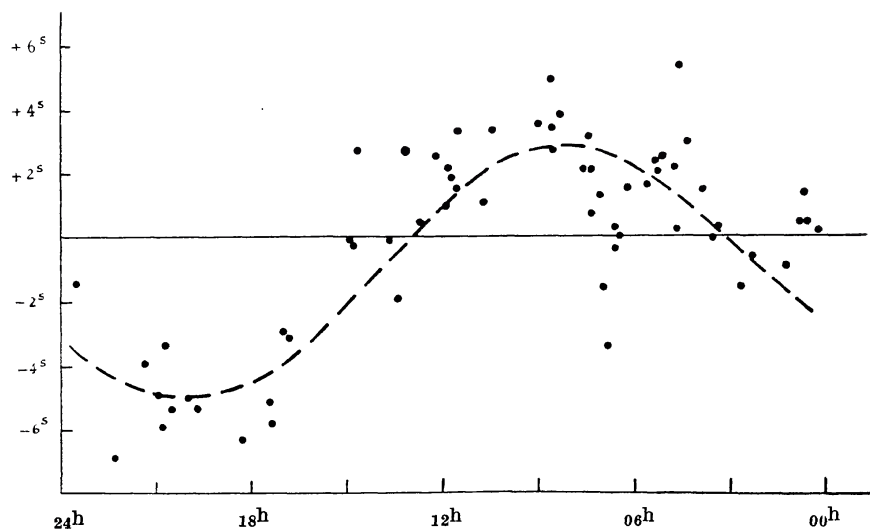


FIG. 8.—A plot showing the systematic error in right ascension between the 50° and 52° surveys.

The r.m.s. error of the individual surveys thus amounts to $\sim 1'$ in right ascension and $\sim 2'$ in declination. When the systematic error is more fully understood the error in right ascension should be reduced to ~ 0.3 .

(b) *Survey at 05° .*—Previous observations have indicated that while most radio stars remote from the galactic plane are probably of extra-galactic origin there is a possibility that they can be accounted for by a class of objects in the galactic halo (Ryle 1958). This possibility may be eliminated by studying the isotropy of the distribution of sufficiently weak radio stars. A survey has therefore been made at a declination of 05° which includes longitudes towards the centre and anti-centre at galactic latitudes near 50° where the greatest anisotropy might be expected to occur.

Application of the statistical method enables deductions to be made about the number-intensity relationship of radio stars at a flux density considerably lower than that at which the sources can be reliably distinguished individually. The probability distribution of $|D|$ was computed for two areas towards the centre and anti-centre (right ascensions $22^h 40^m - 02^h 40^m$ and $10^h 40^m - 14^h 40^m$). The results are shown in Fig. 9. It is seen that any differences in these distributions are less than the statistical uncertainty and hence there is no evidence for a reduction in the density of radio sources in the longitude of the anti-centre. It will be shown in another paper (Hewish 1961) that this observation implies an isotropy which extends to at least 10,000 sources steradian.

(c) *The 42° survey.*—Positions and intensities were derived for sources having flux densities $> 2 \times 10^{-26} \text{ W.m}^{-2} (\text{c/s})^{-1}$. 175 sources were found in an area of 0.3 steradians ($\alpha = 20^h 40^m - 19^h 15^m$, $\delta = 40^\circ - 44^\circ$); this number corresponds to an average of 1 source per 30 beam areas so that errors due to confusion should be small. A complete list of these sources is given in Table II. The quoted error for each source includes a confusion error derived from the probability distribution of $|D|$, a reading error and the residual collimation error; it does not include the systematic error in right ascension, discussed in Section 4 (a), for the $50^\circ - 52^\circ$ strip, which has an upper limit of $\pm 4^s$.

The radio sources M31 and NGC 1275 came within the region of the survey. A number of weak sources were found within the boundaries of M31 but, as discussed elsewhere (Baldwin and Costain 1960), there is no significant excess as compared with a neighbouring area of sky and hence no reason to associate them with the nebula. NGC 1275, a member of the Perseus cluster, has been resolved into two distinct components separated by 32', together with a weak extended component which may be associated with the cluster as a whole. The new information about NGC 1275 will be discussed fully in another paper (Leslie and Elsmore 1961).

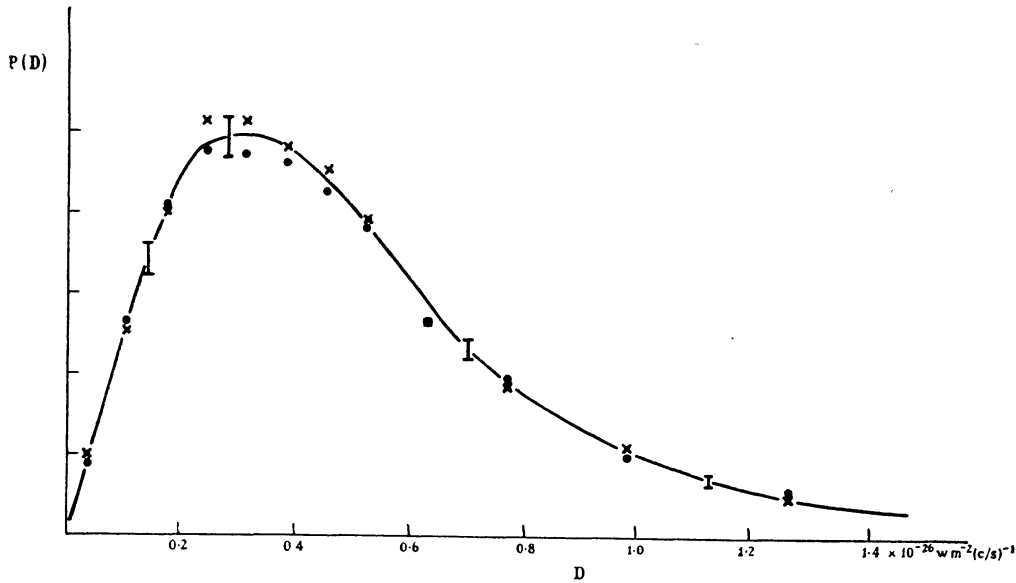


FIG. 9.—The probability distribution of $|D|$ for areas at galactic latitudes near 50° and longitudes towards the centre and the anti-centre.
● R.A. $22^h 40^m$ to $02^h 40^m$
× R.A. $10^h 40^m$ to $14^h 40^m$

TABLE II

R.A.			Error	Dec.		Error	Flux density	Error	
h	m	s	± s	°	'	±'	10^{-26} MKS	±	
00	10	54.7	3.0	40	34.6	3.0	5.0	0.6	
00	19	09.6	2.0	43	10.7	3.0	3.5	0.6	
00	20	50.0	2.5	43	48.0	3.0	2.5	0.5	
00	28	06.7	2.5	40	53.2	3.0	2.5	0.5	
00	41	54.1	2.5	42	30.5	3.0	2.0	0.4	
00	45	25.6	2.0	40	06.0	3.0	3.2	0.5	Possibly complex
00	51	38.4	2.0	40	26.1	2.5	3.2	0.5	
00	53	58.1	2.5	43	58.0	3.0	2.4	0.5	
01	03	51.6	2.0	42	12.8	2.0	3.7	0.5	
01	09	22.7	2.0	41	37.0	2.5	3.6	0.5	
01	13	33.8	3.0	40	03.3	3.0	2.3	0.4	Possibly complex
01	20	32.0	2.5	40	34.8	4.0	2.8	0.5	Complex
01	44	55.3	2.5	43	09.3	3.0	2.5	0.5	
01	52	26.3	1.5	43	32.5	2.0	9.6	1.0	
01	53	17.3	2.0	41	48.9	2.5	3.1	0.5	
01	57	03.3	2.5	40	34.1	3.0	2.7	0.5	
02	16	00.6	2.0	42	24.4	2.5	3.9	0.6	

TABLE II—continued

R.A.			Error	Dec.		Error	Flux density	Error
h	m	s	±s	°	'	±'	10^{-26} MKS	±
02	20	08.3	1.5	42	49.6	2.0	16.6	1.5
02	22	37.0	2.0	40	19.2	2.5	3.1	0.5
02	32	45.6	1.8	41	11.1	2.0	4.5	0.5
02	46	15.0	1.5	42	56.2	1.8	6.6	0.6
02	54	33.9	2.5	40	40.4	3.0	2.0	0.4
03	00	16.1	2.5	43	35.5	3.0	2.1	0.4
03	02	30.1	2.5	43	55.5	3.0	2.8	0.5
03	09	42.6	2.5	41	24.7	3.0	2.1	0.4
03	11	23.6	1.5	43	06.0	1.8	8.5	0.8
03	14	54.2	2.0	41	44.7	3.0	14.5	2.0
03	16	28.6	1.5	41	21.0	1.5	41.0	4.0
03	23	18.3	1.8	41	44.6	2.0	5.2	0.5
03	27	07.1	1.8	40	53.4	2.0	5.5	0.6
03	30	50.7	2.5	43	24.4	3.0	3.0	0.6
03	44	37.8	3.0	40	39.1	3.0	2.8	0.5
03	51	06.8	2.5	41	47.2	3.0	2.5	0.5
03	54	19.6	2.5	41	42.4	3.0	2.4	0.5
04	04	35.7	1.5	42	54.1	1.5	25.1	1.5
04	16	49.1	2.5	43	37.2	3.0	2.8	0.5
04	19	52.6	1.8	40	47.7	2.0	5.1	0.6
04	22	37.8	2.5	41	21.2	3.0	2.8	0.5
04	25	47.2	1.8	42	27.7	2.0	4.2	0.5
04	29	08.0	1.5	41	33.7	1.5	14.9	1.0
04	41	17.7	2.5	43	54.0	3.0	2.1	0.4
04	46	04.4	2.5	42	13.0	3.0	2.1	0.4
05	11	12.1	2.0	42	37.5	2.5	3.0	0.5
05	25	15.5	1.8	41	40.5	2.0	4.0	0.6
05	28	10.1	2.5	43	46.1	3.0	2.3	0.4
06	02	43.0	2.0	41	37.9	3.0	4.1	0.6
06	11	24.0	2.0	42	53.1	2.5	3.0	0.5
06	12	52.5	2.5	41	31.4	3.0	2.3	0.4
06	13	32.5	2.5	40	41.4	3.0	2.5	0.5
06	14	47.3	2.5	43	33.5	3.0	2.5	0.5
06	21	36.5	2.0	40	01.3	2.0	6.6	0.7
06	21	50.1	2.5	40	30.6	2.5	3.8	0.6
06	27	13.3	2.5	42	31.4	3.0	2.0	0.4
06	28	46.1	3.0	42	20.3	3.0	2.6	0.5
06	42	51.8	2.5	40	49.7	2.5	2.8	0.5
06	44	12.1	2.5	42	22.9	3.0	2.8	0.5
06	47	22.4	2.5	41	33.5	3.0	2.6	0.5
06	49	29.1	3.0	42	39.6	3.0	2.2	0.4
06	52	37.4	3.0	42	42.2	4.0	2.2	0.4
07	03	10.4	2.0	42	35.3	3.0	3.5	0.6
07	09	02.6	2.5	40	55.3	3.0	2.2	0.4
07	26	19.0	2.5	43	08.0	3.0	2.0	0.4
07	31	51.7	1.8	43	49.2	2.0	5.0	0.7
08	05	42.7	2.5	40	44.5	3.0	2.4	0.5
08	06	39.5	1.5	42	36.8	1.8	9.6	1.0
08	09	33.4	2.5	40	26.4	3.0	2.9	0.5
08	20	05.1	1.8	43	07.6	2.0	5.4	0.7
08	36	39.0	2.5	42	37.9	3.0	2.4	0.5
08	36	56.0	2.0	40	13.0	2.5	3.3	0.6
08	49	17.7	2.0	42	30.2	2.5	3.1	0.6
08	56	47.5	3.0	40	34.6	4.0	2.3	0.5
09	01	00.2	2.0	42	50.0	2.5	3.7	0.6

Possibly complex

Complex

TABLE II—*continued*

R.A.			Error	Dec.		Error	Flux density	Error
h	m	s	±s	°	'	±'	10 ⁻²⁶ MKS	±
09	02	50.0	2.5	41	30.2	3.0	3.0	0.6
09	03	50.2	4.0	42	55.4	5.0	2.7	0.5
09	04	22.2	2.0	41	49.4	2.5	5.2	0.7
09	06	19.5	1.5	43	05.0	2.0	19.5	1.5
09	06	34.8	5.0	40	46.2	5.0	4.5	1.0
09	06	46.6	5.0	41	19.7	5.0	4.0	0.8
09	22	14.1	3.5	42	31.6	5.0	2.4	0.5
09	22	52.2	3.5	42	17.3	5.0	2.0	0.5
09	35	06.7	2.5	42	53.8	3.0	2.5	0.4
09	36	14.0	2.0	40	30.2	2.0	3.4	0.5
09	45	25.2	1.8	41	53.6	2.0	4.1	0.6
09	45	53.0	2.5	40	47.6	3.0	2.3	0.4
09	47	13.1	2.5	42	28.0	3.0	2.0	0.4
10	07	27.4	1.5	41	49.9	1.8	6.0	0.8
10	09	08.7	2.5	43	30.8	3.0	2.1	0.4
10	13	00.8	2.0	40	59.6	2.5	3.8	0.6
10	20	14.6	2.5	40	05.4	3.0	2.3	0.4
10	22	33.0	2.0	43	15.2	2.5	4.5	0.7
10	33	27.0	3.0	40	48.7	5.0	2.0	0.4
10	34	20.4	2.5	40	27.7	3.5	3.1	0.5
10	55	10.2	3.0	40	27.8	4.0	2.3	0.4
10	56	10.0	1.5	43	17.8	1.5	11.2	1.4
11	08	53.1	2.0	41	08.4	2.0	5.1	0.7
11	09	53.4	2.0	43	43.1	2.0	6.3	0.8
11	11	54.0	1.5	40	52.0	1.5	21.2	1.5
11	28	07.4	2.5	43	42.2	4.0	3.2	0.6
11	31	58.5	1.5	43	47.4	1.8	6.6	0.8
11	32	06.2	3.0	40	56.6	3.5	2.8	0.5
12	06	45.0	1.5	43	56.6	1.5	10.7	1.0
12	20	08.8	2.5	40	50.9	3.5	2.0	0.4
12	22	03.0	1.5	42	22.7	1.8	7.2	0.8
12	31	55.0	2.5	43	10.7	3.0	2.5	0.5
12	32	04.6	2.5	41	26.5	3.0	2.4	0.4
12	49	44.7	2.5	43	18.6	3.0	2.3	0.4
12	53	28.7	2.0	43	13.6	2.5	2.5	0.5
12	58	14.6	1.5	40	23.0	1.8	8.6	1.0
13	19	08.1	2.0	42	51.6	2.0	6.0	0.8
13	19	41.7	4.0	43	27.7	5.0	2.4	0.5
13	21	12.5	3.0	41	30.0	3.5	2.9	0.5
13	24	54.1	2.5	43	08.1	3.0	2.1	0.4
13	33	10.7	1.8	41	14.8	2.0	5.0	0.7
13	40	27.3	3.0	43	51.5	3.0	2.2	0.4
13	43	28.7	2.0	43	04.6	2.0	3.4	0.6
13	50	26.5	3.0	43	14.9	3.5	2.6	0.5
13	58	30.7	2.5	43	21.9	3.0	2.3	0.4
14	10	21.5	2.0	43	51.3	2.5	2.7	0.5
14	18	47.1	2.5	40	17.8	3.0	2.1	0.4
14	18	50.3	2.5	43	51.8	3.0	2.7	0.5
14	19	08.0	1.5	41	59.4	1.5	11.6	1.0
14	35	03.8	2.5	42	57.1	3.0	2.5	0.5
14	37	53.8	2.0	42	45.8	2.0	3.9	0.6
14	44	35.0	2.0	41	44.5	2.5	2.3	0.4
14	49	16.9	3.0	41	55.1	4.0	2.1	0.4
14	55	51.0	2.5	42	11.3	3.0	2.3	0.4
15	21	24.2	2.0	42	07.6	2.5	2.4	0.4

} Confused region

TABLE II—*continued*

R.A.			Error	Dec.		Error	Flux density	Error	
h	m	s	± s	°	'	±'	10 ⁻²⁶ MKS	±	
15	24	55.7	2.0	43	18.0	2.5	2.6	0.5	
15	55	02.0	1.5	43	07.7	1.8	7.3	0.8	
15	57	57.5	2.0	43	58.8	2.5	2.8	0.5	
16	10	10.4	2.5	40	47.2	3.0	2.3	0.4	
16	18	49.0	3.0	43	24.0	3.5	3.0	0.6	
16	19	45.7	3.0	43	56.6	4.0	2.0	0.4	
16	24	24.3	3.0	41	35.9	3.0	2.1	0.4	
16	37	15.5	3.0	42	38.8	4.0	2.3	0.4	
16	47	25.1	4.0	42	58.8	3.5	3.5	0.6	Complex
17	10	36.0	2.5	43	21.4	3.0	2.5	0.5	
17	14	31.3	4.0	43	42.4	5.0	2.9	0.5	Complex
17	23	43.4	1.8	40	36.9	2.0	5.4	0.7	
17	29	05.0	2.5	43	33.0	3.0	2.1	0.4	
17	29	14.0	2.5	40	56.6	3.0	2.0	0.4	
17	31	33.4	1.8	43	45.3	2.0	4.8	0.7	
17	37	24.0	2.0	42	48.6	2.5	4.9	0.7	
17	38	38.3	2.5	41	34.8	3.0	2.6	0.5	
17	49	09.4	3.0	43	53.4	3.5	2.3	0.4	
18	09	23.0	2.5	40	43.2	3.0	5.6	0.7	
18	11	48.0	1.8	43	01.4	2.0	4.1	0.6	
18	12	14.7	2.5	41	08.3	3.0	2.8	0.5	
18	14	17.2	2.5	42	56.2	2.5	2.5	0.5	
18	19	17.4	3.0	40	48.2	3.0	2.5	0.5	Complex
18	34	13.2	2.0	41	59.9	2.5	2.9	0.5	
18	39	12.7	2.5	40	36.1	2.5	3.0	0.6	
18	54	47.0	2.5	42	44.2	3.0	2.8	0.5	
19	10	41.7	3.0	40	14.0	3.5	3.5	0.6	
19	13	35.5	3.0	43	36.0	3.0	3.1	0.6	Possibly complex
20	42	54.1	3.0	40	20.7	4.0	2.0	0.4	
20	43	23.4	2.5	43	31.6	2.5	2.8	0.6	
20	47	09.8	2.0	42	58.3	2.0	6.1	0.7	
20	49	06.1	2.5	41	51.1	3.0	2.2	0.4	
20	56	15.6	2.5	42	40.2	3.0	2.5	0.5	
21	04	24.4	2.5	42	24.7	3.0	2.5	0.5	
21	19	26.1	2.0	43	32.9	2.0	3.8	0.6	
21	38	26.4	2.5	43	57.2	3.5	2.0	0.4	
21	56	55.4	2.5	43	30.4	3.0	2.3	0.5	
21	59	41.4	2.0	40	49.8	2.5	2.7	0.5	
22	09	01.3	2.5	42	52.9	3.0	2.2	0.4	
22	19	45.6	3.0	41	19.0	3.0	2.5	0.5	
22	21	12.3	1.8	43	19.4	2.0	3.2	0.6	
22	22	35.6	3.0	40	39.7	3.0	2.0	0.4	
22	24	35.2	2.5	41	27.6	3.0	2.5	0.5	
22	33	39.1	1.8	40	52.5	2.0	3.4	0.6	
22	37	58.1	2.0	43	16.4	2.5	2.0	0.4	
22	41	08.6	1.5	43	46.5	2.0	4.5	0.7	
22	49	46.7	2.0	43	47.0	2.5	2.8	0.5	
22	55	05.9	2.0	41	33.4	2.5	2.7	0.5	
23	02	36.2	2.0	40	11.4	2.5	2.8	0.5	
23	24	30.6	1.5	40	28.4	1.8	8.5	1.0	
23	30	58.0	2.5	43	26.6	3.0	2.3	0.4	
23	49	22.6	2.5	41	03.2	3.0	2.2	0.4	
23	51	23.8	3.0	40	01.7	2.5	3.1	0.6	
23	56	03.3	1.5	43	48.9	1.8	9.9	1.0	
23	58	46.1	2.0	41	35.5	2.0	3.9	0.6	

5. *Conclusion.*—The first surveys carried out at a wavelength of 1.7 m using the new principle of aperture synthesis have shown that the theoretical possibilities of the technique may be fully realized in practice.

A primary resolving power of $25' \times 35'$ has been achieved with a noise level of $0.08 \times 10^{-26} \text{ W.m}^{-2} (\text{c/s})^{-1}$. The side-lobes in right ascension are negligible beyond $\pm 1^\circ$ from the centre of the beam; in declination the side-lobe level is ~ 5 per cent within $\pm 2\frac{1}{2}^\circ$ and less than 0.5 per cent at greater angles. Radio stars may be reliably detected to a flux level of $2.0 \times 10^{-26} \text{ W.m}^{-2} (\text{c/s})^{-1}$, corresponding to one source/20 beam areas, with positional accuracies of $\pm 2'$ in declination and $\pm 1'$ in right ascension; at this limit the noise is still only 5 per cent so that statistical investigations may be used to study the distribution of radio stars at smaller flux densities.

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