AN INTERFEROMETER FOR THE MEASUREMENT OF RADIO SOURCE SIZES

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Summary

Modifications have been made to the 85·5 Mc/s cross-type radio telescope at Sydney to permit the measurement of radio source sizes in the range of 10″ to 1′ arc. The basic modification involves the addition of another aerial at a distant site connected by radio link. A new form of automatic gain control ensures very good stability for the system. The modified instrument is described in general terms and calibration techniques are discussed.

I. Introduction

Knowledge of the angular sizes of discrete radio sources is of the greatest importance as an aid to the identification of the sources, for an understanding of the basic physical processes causing the emission, and in the application of radio-astronomical data to cosmology. However, the measurement of size is usually difficult, and little reliable information is available. Some of the closer and brighter sources, particularly those of galactic origin, are quite large, of the order of a degree or more, and the measurements in this case are relatively easy. Several of these were detected during 1950 and 1951 in an interferometer survey of the sky (Mills 1952*a*). However, it was clear then that the majority of detectable sources were much smaller than this and that special equipment would be needed to resolve them. Such equipment, utilizing very widely spaced interferometer aerials, was constructed in both Australia and England and almost simultaneous measurements made of the strongest unresolved sources (Brown, Jennison, and Das Gupta 1952 ; Mills 1952*b* ; Smith 1952*a*). It was shown that the five sources measured, Cassiopea A and Cygnus A in England and Cygnus A, Taurus A, Virgo A, and Centaurus A in Australia, all had angular sizes of the order of a minute to several minutes of arc, consistent with the identifications which had been made with visible nebulae. These initial measurements were extended and improved (Smith 1952*b* ; Mills 1953 ; Jennison and Das Gupta 1956) and for several years represented the only results available on the small discrete sources. Subsequent measurements extended the number of known sizes to a couple of dozen, all in the range 1′ arc or greater (Carter, personal communication ; Edge *et al.* 1959) and, more important, showed that a few sources appeared to have sizes less than 12″ arc (Morris, Palmer, and Thompson 1957).

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On completion of the survey of the southern sky with the Sydney cross-type radio telescope, it became apparent that to progress in the identification of the radio sources and to apply their statistics in obtaining cosmological information it was necessary to obtain estimates of the sizes of a substantial proportion of the catalogued sources. When the catalogues are complete the total will exceed 2000.

Present results are based on the analysis of the initial catalogue between declinations $+10^\circ$ and -20°, containing nearly 1200 sources ; it appears that the majority are not resolved by the radio telescope, which is a pencil-beam instrument of beamwidth $50'$ arc. The instrument has now been modified, principally by the addition of another aerial at a great distance, to study the sizes of these unresolved sources. In the present paper we describe the modified instrument and its operation ; the principal observational results will be given elsewhere.

The original instrument has been described in detail by Mills *et al.* (1958) ; briefly, it consists of a cruciform arrangement of two arrays of dipoles, each approximately 1500 ft long by effectively 15 ft wide. It operates at a wavelength of $3 \cdot 5$ m ($85 \cdot 5$ Mc/s) and by combining the outputs of the arrays in a switching arrangement, produces a pencil-beam response. Analysis of some unpublished results of A. W. L. Carter, who had performed a relatively low sensitivity survey using an interferometer with spacing between arrays of 1000λ, suggested that the most useful arrangement for the present investigation would be initially an interferometer of about 3000λ spacing. With this spacing, only sources with sizes of the order of $1'$ arc or less would be visible, which would enable the recognition of the very distant and small sources. The relative visibility of the sources at this spacing would also allow crude estimates of angular sizes.

However, estimation of the angular size of a radio source from measurements of its relative visibility using widely spaced interferometer aerials requires some assumption about the distribution of emission across the source. In so far as a good estimate can be made of this distribution the results of a measurement may be quite accurate ; if, however, the distribution is complex or merely elongated, quite erroneous values may be obtained. In fact, some strong radio sources which have been investigated do show complex structure and are not circularly symmetric, so that for accurate results it is necessary to make measurements with base lines of different spacing and azimuths. It is expected that the present instrument will be used in this way at the completion of a sky survey now in progress.

II. Description of the Instrument

The modified system comprises, in effect, two interferometers using the existing east-west arm of the Cross as a common aerial. The other aerials consist of (*a*) portion of the existing north-south arm of the cross 300 ft in length centred 30λ south of the centre of the east-west array and (*b*) a new array identical with (*a*) and situated 10 km distant in an east-west direction. The signal from aerial (*b*) is transmitted to the central site by means of a radio link similar to that used in an earlier investigation (Mills 1953).

The general arrangement is shown in Figure 1, together with an indication of the response patterns of the interferometers. In each case the primary pattern is formed from the product of the response of the two arrays in the interferometer, and consists of an ellipse $0^\circ{\cdot}8$ by $3^\circ{\cdot}7$ to the half response points in east-west and north-south directions respectively. This response is broken up into " lobes ", 2° apart in a north-south direction for the close-spaced " local " interferometer, and $1{\cdot}2'$ arc apart in an east-west direction for the wide-spaced " link " interferometer. The overall gains of these interferometers are made equal so that information about the angular size of a source may be derived from the ratio of their responses.

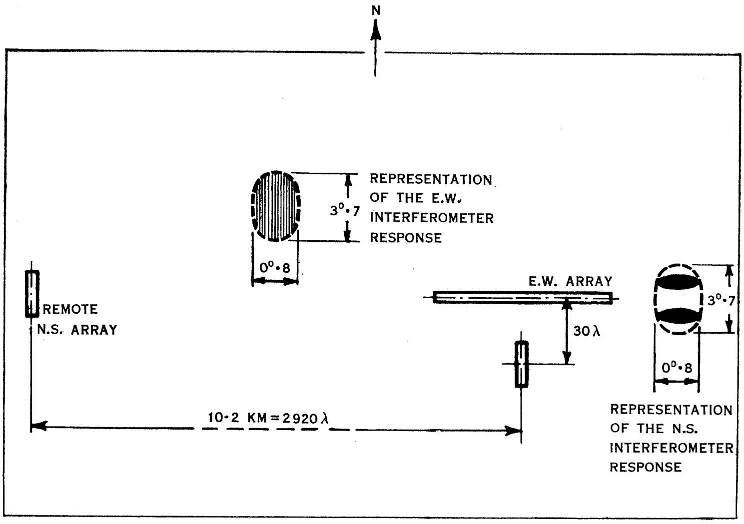

Fig. 1.—Illustrating the layout of the arrays and the form of the resulting response patterns.

The natural period of the interference pattern with the east-west interferometer varies according to the declination of the source, and is given by

$$T=\frac{12}{\pi}\,\frac{\lambda}{d}\sec\delta \text{ hours},$$

where d is the spacing between aerials and δ is the declination. With the operating wavelength $3{\cdot}5$ m and the actual spacing of $10{\cdot}2$ km (2920λ) the fastest period is about 5 sec, occurring when a source is at zero declination. If this interference pattern were recorded directly, it would not be possible to determine the relative visibilities by direct visual observation, since a very short output time constant would be needed, with consequent reduction in visibility. To overcome this, the period is increased by continually sweeping the phase of one half of the interferometer, causing the lobe pattern to follow partially the source's progression (Brown, Palmer, and Thompson 1955). In this way an interference pattern of any desired period can be obtained ; it was decided to use a standard 1 min period for all declinations. To enable direct comparison between the outputs of the long- and short-spaced interferometers, the period of the short-spaced pattern is also made 1 min by continuous phase sweeping. Some such arrangement is necessary, since a north-south interferometer has an

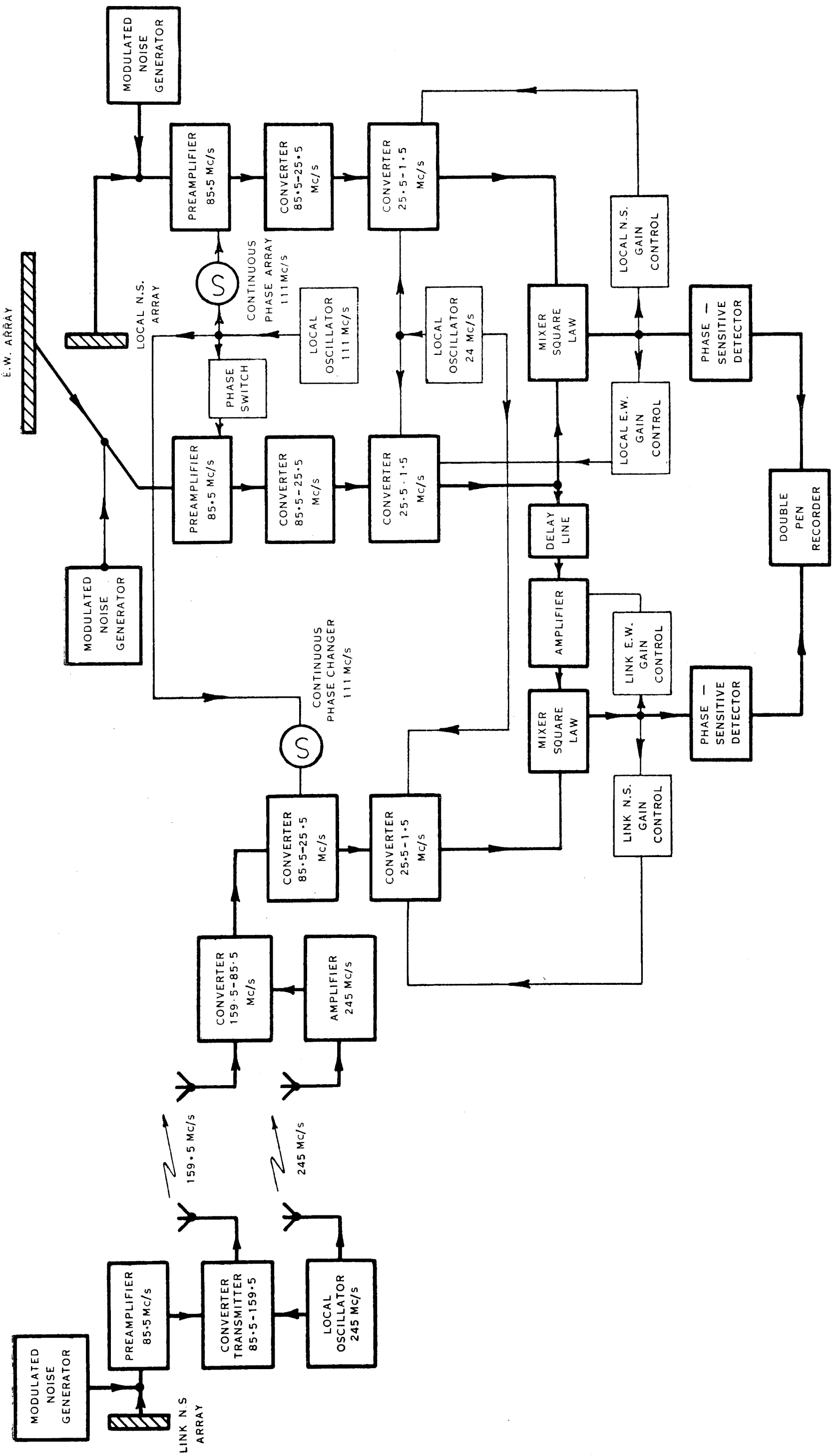

Fig. 2.—A simplified block diagram illustrating the essential functional elements of the system.

infinite period at transit and, with a fixed pattern, the response would depend on the position of the source relative to that of the pattern.

Since the accurate measurement of relative visibilities at the two spacings is required, the amplitude of the interference pattern is of prime importance. It is therefore necessary that the gain should be stable in each part of the system. The degree of stability required necessitated continuous automatic gain control on all receivers. This is achieved by maintaining constant the amplification of a " control " signal injected at the aerial inputs. The gain is then independent of variations in receiver noise factor and interfering signals.

Some of the essential parts of the system will now be discussed in more detail.

(*a*) *The Aerials*

The east-west arm of the Cross is used without alteration as the common element of the two interferometers. The constructional elements and performance of this array have been described elsewhere (Mills *et al.* 1958). Briefly, it consists of two collinear rows of half-wave dipoles separated by approximately half a wavelength and backed by a horizontal wire-mesh reflector. The overall length is approximately 1500 ft.

The remaining element in each interferometer is a north-south array of full-wave dipoles similar in arrangement to the original north-south arm of the Cross. The spacing between dipoles is $\frac{1}{2}\lambda$ and the phasing is arranged so as to produce a fan-beam response at right angles to the meridian plane. The position of this fan beam (i.e. its angle of elevation) is altered by a rearrangement of the phasing of each dipole by changing the point at which the coupling transformer is connected into the feed line, as in the original north-south arm of the Cross. However, the north-south arrays in this case have only 51, instead of 251, dipoles. With coupling and current distribution set as in the original north-south array, the aerial efficiency would be greatly reduced. To offset this, the coupling has been increased and the current distribution adjusted for rather less taper, resulting once again in an efficiency approaching 50 per cent. These alterations have caused an increase in the side-lobe responses, but they are only of the order of a few per cent. in the meridian plane and much less elsewhere: in view of the reduced sensitivity of the instrument compared with the original Cross, these are not serious.

(*b*) *The Receivers*

The overall receiving system consists of three separate receivers interconnected as shown in Figure 2. The three receivers are identical except for the inclusion of a radio link in the remote receiver and a compensating delay line in one of the local receivers. Two signals are transmitted over the radio link, one is the original 85·5 Mc/s cosmic noise signal converted to 159·5 Mc/s and re-radiated, the other is a 245 Mc/s c.w. signal derived from the local oscillator. When these are combined at the local site the original 85·5 Mc/s signal is reconstructed with phase information unaffected by the conversion processes. The 245 Mc/s signal also carries a pulse modulation for synchronizing the automatic gain control system as described later. The level of transmitted power is about $\frac{1}{2}$ W in each case.

The 85·5 Mc/s receivers use double frequency conversion, first to 25·5 Mc/s and then to 1·5 Mc/s, the delay line being inserted at the latter frequency. The system bandwidth of 250 kc/s is determined at 1·5 Mc/s after combining the signals from each aerial; the bandwidth up to that point is greater than 1 Mc/s in all receivers. Phase switching and phase-sensitive detection is used in both interferometer systems, the phase-reversing switch being inserted in the local oscillator feed to the common east-west converter (85·5 Mc/s→25·5 Mc/s). This corresponds exactly to the original Cross receivers (Mills *et al.* 1958).

The lobe sweeping of each interferometer is accomplished by continuous phase rotation of the local oscillator signal fed to each north-south receiver. The phase changer consists of a pick-up loop rotating in crossed magnetic fields excited in quadrature. The loop is driven by a small synchronous motor fed from a variable frequency oscillator, to enable the period of the interference pattern to be kept at 1 min for all declinations.

Square-law detection is achieved by an electronic multiplier at 1·5 Mc/s. This multiplier is a balanced type to improve the square law and eliminate unwanted components (Coates 1957).

(*c*) *Automatic Gain Control*

The automatic gain controls operate by keeping constant at the outputs of the receivers a standard modulated noise signal injected at the input to each preamplifier. The " control " signal is derived from a square-wave-modulated noise generator. The average noise diode current is maintained constant by a feedback control system operating on the output of the oscillator supplying power to the diode filament. The fundamental component of the control signal in the receiver output is extracted from the remaining noise by a filter and phase-sensitive detector, and a feedback control system maintains the amplitude of this component at a preset level. This action, in conjunction with the control of the injected noise, maintains a constant overall gain which can be set to any desired value by altering the comparator voltage. Since it is the fundamental Fourier component which is measured at the output and not the average value of the " square " wave, which is controlled at the input, it is important that the on-off ratio of the square wave be accurately maintained. For best performance, this ratio should be unity and to achieve this a bistable multivibrator is used, triggered by a free-running pulse generator at double the frequency.

In order that the input to the phase-sensitive detector be proportional to the gain of the system, regardless of the total level of the noise, it is necessary to extract the control signal after square-law detection.

Referring to Figure 2, it can be seen that the output of each detector contains components of:

(i) Control signal of the east-west receiver
(ii) Control signal of the north-south receiver
(iii) Coherent noise due to 429 c/s phase switching.

To avoid interaction, a modulation frequency of 1080 c/s was chosen for the east-west receiver and 632 c/s for the north-south receiver.

The phase-sensitive detector used is a gating type switched by a square wave which must be identical to the one which modulates the noise diode. In the systems located wholly at the local site this is achieved by connecting the phase-sensitive detector and the noise modulator to the same square-wave generator. In the case of the remote system it is necessary to generate another square wave at the local site, which must be coincident with the square wave modulating the noise diode at the remote site.

The double frequency triggering pulses previously referred to are used to modulate the 245 Mc/s local oscillator of the link, and these pulses are then extracted at the local site and used to trigger a similar bistable multivibrator. A sensing device in the output of the phase-sensitive detector is used to ensure that the second square wave is generated in phase with the one at the remote site. This is necessary because the bistable multivibrator has an inherent 180° ambiguity of phase.

In normal operation the automatic gain controls appear to have a stability of better than 2 or 3 per cent. over periods of 24 hours, with a long period stability over weeks of better than 10 per cent. With frequent calibration, as described in the next section, the relative sensitivities of the two interferometer receiving systems have an uncertainty of about 2 per cent.

III. Calibration

Since the measurement of angular size involves the ratio of the responses of the two interferometers, only a knowledge of relative sensitivities is required. It is convenient to consider the two main parts of the system, the aerials and the receivers, separately.

The two north-south aerials are made as nearly as possible identical. The methods of setting up have been described in detail elsewhere (Mills *et al.* 1958); briefly, the current distribution is adjusted by feeding power from a crystal-controlled oscillator into the aerial via its normal output connection, which is situated at the centre of the array. The current in each dipole is sampled in turn by a pick-up loop and fed to a detector. A reference signal is obtained by inserting a directional coupler into the feed line at a point close to the centre of the array, i.e. near the feed point. This reference signal is passed through a variable attenuator and a variable phase shift to the same detector. The magnitude and phase of the current in any dipole relative to the current at the reference point can then be determined by adjusting the attenuator and phase shift for a null. Using this technique, the individual currents are adjusted to conform with the required law and, if the corresponding reference point is used when setting up each array, the dipole currents can be adjusted for approximate equality in the two arrays; any remaining differences may be included in the overall calibration. Similar measurements made at different times have indicated an uncertainty of about 5 per cent. in the relative gains of the arrays.

To check the receivers, a standard signal of a special type is injected into each preamplifier in turn and the output is measured on the recorder. The ratios of the deflections on the recorders then give directly the ratios of the gains.

In order to include correctly the effects of the output time constant on the responses, the calibration signal is arranged to simulate the standard 1 min interferometer pattern. The standard signal is an accurately controlled noise signal, square-wave-modulated at a frequency differing from the phase-switching frequency by 1 c/min, obtained by the use of a continuously rotating goniometer. Thus, the rectified receiver output has a component at a frequency which differs from the gating frequency of the phase-sensitive detector by 1 c/min, producing the required sine-wave output on the recorder. This calibrating signal, which except for the frequency chosen is similar to the A.G.C. control signal, is injected

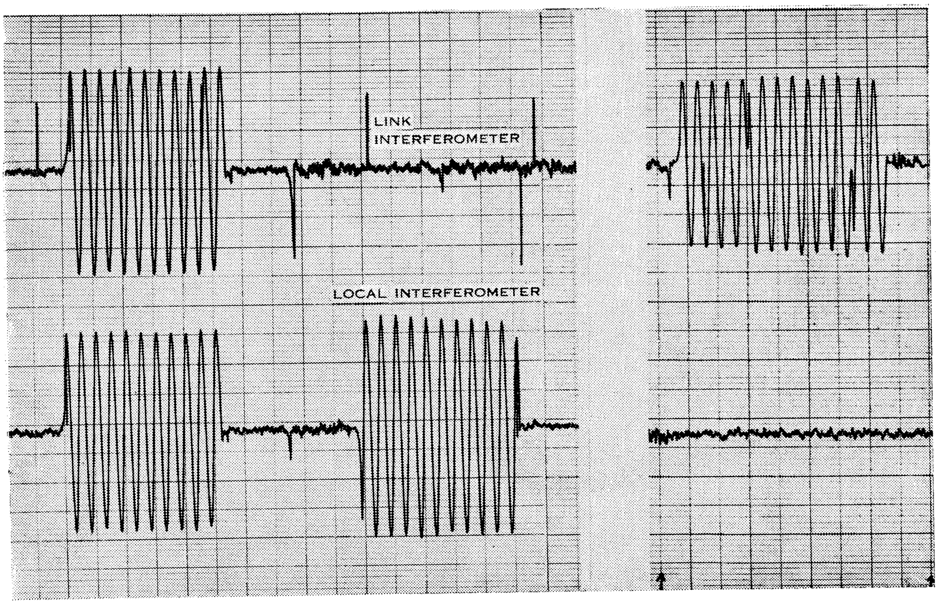

Fig. 3.—Some calibration records—on the left is shown the two east-west calibrations performed by injection of the signal into the common preamplifiers and beside them the calibration of the local north-south system. On the right is shown the corresponding calibration of the remote preamplifier transmitted over the radio link.

into the preamplifiers of each of the three systems in turn, i.e. the local and remote north-south systems and the east-west system. Typical calibrations are shown in Figure 3. When injecting into the north-south systems a pattern is produced only on the corresponding side of the record, but the common east-west system gives a response on both sides.

IV. Size Measurement

As indicated above, the chief use of the instrument in its present form is to recognize radio sources of small angular size. A further aim is to obtain estimates of the actual sizes of the sources, but, because of the expected diversity of shapes and orientations, estimates obtained with two spacings only must necessarily be very crude. However, they have proved of some use in identification work and a study of their statistics should yield information of cosmological interest.

In order to represent the measured visibility ratios by the size of an equivalent model, we assume that all sources have circularly symmetric Gaussian brightness distributions, i.e. possibilities of fine structure, elongation, and asymmetry are ignored.

This distribution is defined by

$$B(r)=B_0 \exp(1\cdot 67r/\theta_0)^2, \quad \dots\dots\dots\dots\dots\dots \quad (1)$$

where r is the angular distance to the centre and θ_0 is the angle between half brightness points.

It is well known (e.g. Mills 1953) that the relative visibility of a circularly symmetric distribution $B(r)$, is given by

$$A_n=\int_0^\infty I(\theta)\cos(2\pi n\theta)\mathrm{d}\theta, \quad \dots\dots\dots\dots\dots \quad (2)$$

$$I(\theta)=2\int_\theta^\infty \frac{rB(r)}{(r^2-\theta^2)^{\frac{1}{2}}}\mathrm{d}r, \quad \dots\dots\dots\dots\dots\dots \quad (3)$$

where A_n is the relative visibility at a spacing of n wavelengths.

Inserting (**1**) in (**2**) and (**3**), it is readily shown that the equivalent size of the model source is given by

$$\theta_0=37\cdot 4\,(\log_e X)^{\frac{1}{2}} \text{ seconds of arc}, \quad \dots\dots\dots\dots \quad (4)$$

where X is the ratio of visibilities at the two aerial spacings, i.e. $X=A_{30}/A_{2920}$. This expression is plotted in Figure 4.

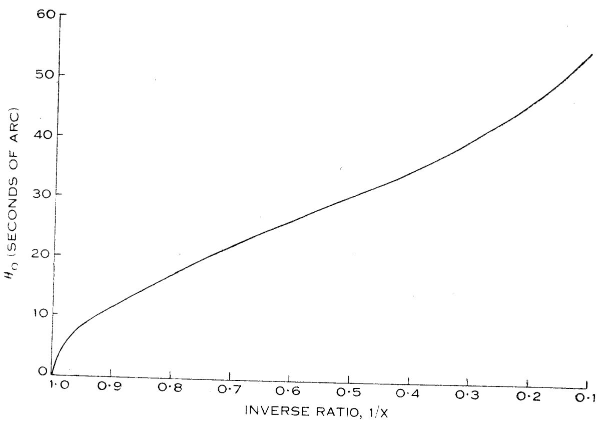

Fig. 4.—A plot of the equivalent source size against the ratio of responses on the two systems.

For large values of X the model source becomes meaningless, as fine structure in the distribution will dominate the picture: the indicated size then will be usually smaller than the actual. Below values of $X\approx 3$, however, the value of θ_0 represents approximately the half brightness angle in an east-west direction of quite a variety of distributions. As X approaches unity, the errors in measurement become important and, if the accuracy is about 10 per cent., as expected, a lower limit to the resolution is set at about 10″ arc. For the weakest sources, statistical fluctuations reduce the accuracy considerably and, hence, also the effective resolution: for these sources the resolution limit is of the order of 30″. A substantial number of relatively strong sources have already been observed with apparently equal amplitudes at both spacings, i.e. $X \approx 1 \pm 10$ per cent.: for these we have $\theta_0 < 10''$.

In Figure 5 a record of two sources is reproduced, showing, in one case, a strong source Hydra A (09–1*4*, Mills, Slee, and Hill 1958), which has an appreciable angular size ($X = 4 \cdot 0$ and $\theta_0 = 45''$) and a weaker source (11−1*8*), which is unresolved by the equipment ($X \approx 1$, $\theta_0 < 10''$).

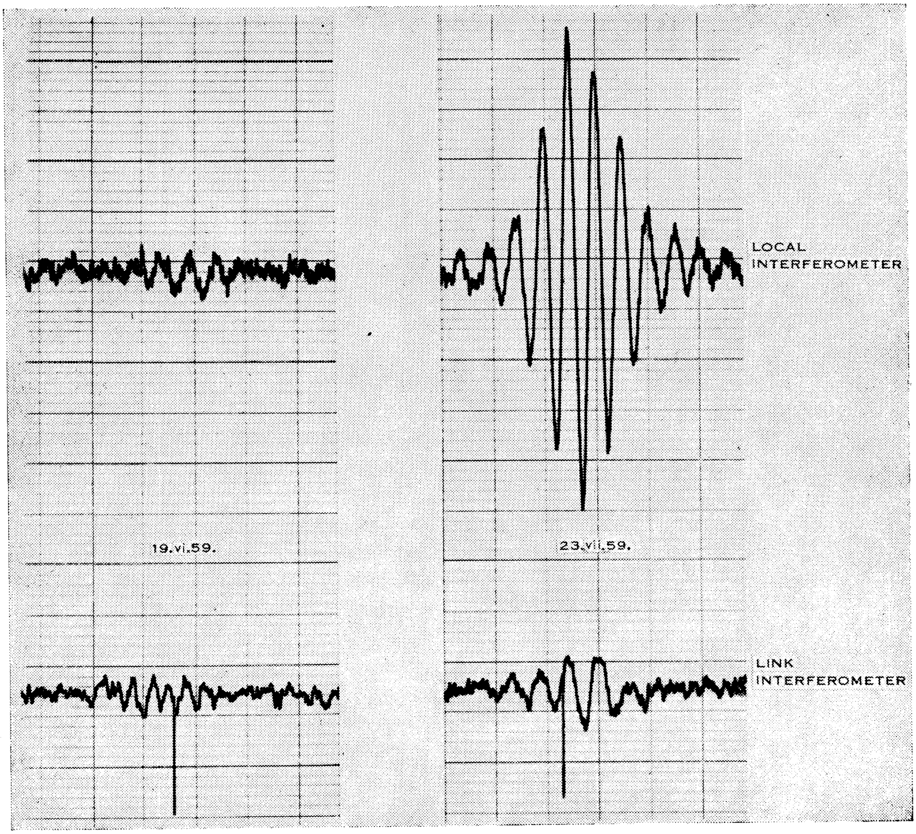

Fig. 5.—Some sample records showing, on the left, a strong source resolved by the instrument and, on the right, a weaker unresolved source.

Finally, one should mention the effects of the ionosphere on the measurement of size, since irregularities of electron density which cause the scintillation of radio sources might be expected to cause difficulties. If the ionosphere were sufficiently irregular to scatter coherent radiation into each of the widely separated aerials simultaneously, the whole basis of the method would be undermined: it is easily shown, however, from the known size of the irregularities that the scattering angle is too small by several orders of magnitude for this to occur.

Another possible cause of drastic error is the *differential* Faraday rotation at each aerial, but in this case, too, the known amounts of ionospheric refraction suggest that the effects would normally be negligible. One is therefore left with the usual effects of amplitude and phase variation, which, because of the great separation, are largely uncorrelated at the remote and local aerials. The latter variation is the more serious of the two: it can cause substantial changes in the period of the observed interference pattern and, occasionally, can be sufficiently rapid to destroy the pattern entirely, leaving it indistinguishable from random noise. To guard against the latter possibility it has been found desirable to take several observations at each declination and this has led to a considerable lengthening of the observational programme. Some of the results of this programme have already been described (Mills 1960) and others will be reported in subsequent papers.

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