Yale University *New Haven, Connecticut*

23 August 1965

arrived 28/9/65

Observatory
135 Prospect Street

Box 2023, Yale Station
Tel.: 787-3131, Ext. 2814

Mr. Grote Reber
CSIRO
Tasmanian Regional Laboratory
Stowell Avenue
Hobart, Tasmania
Australia

Dear Grote:

I remember with pleasure your visit of several years ago, and we have indeed a working device (at last) which produces 10 simulaneous beams by use of broad operating bandwidth. In brief review, this device takes advantage of the fact that the fringe spacing of an interferometer with, say, a 10% bandwidth changes by 10% across the pass band. Only the fringe maximum corresponding to a zero time delay will occur simultaneously across the panband; others will be more or less displaced. Since the signal from the entire passband is detected, one records the sum of fringe patterns corresponding to each part of the passband. Only the zero-time-delay fringe will have full amplitude, the adjacent ones be washed out increasingly as the time delay increases. In fact, there will be $f/\Delta f$ fringes grouped about the zeroth order fringe having amplitude greater than half the central fringe, others dropping rapidly in amplitude. so $f = 250$ mc

For example, our interferometer is spaced 1500 λ with a bandwidth of $\Delta f =$ 10 Mc/s. This means that there are 25 fringes from half-power point to half-power point. Each fringe is $\frac{1}{1500}$ radian apart; thus our "beamwidth" from this effect is $\frac{25}{1500}$ radian $\approx 1^{o}$.

Multi-beaming is very simple, by using N detectors each of which is preceeded by a different transmission-line delay. The detailed layout of our device is illustrated in the accompanying diagram. Figure 1 shows the geometry: we restrict out attention to the meridian by using E-W linear arrays producing $1^{o}.2$ fan beams. These arrays have very broad beam width in the N-S sense - about 40^{o}. When they are operated as an interferometer, however, the significant fringes are contained in a N-S beam of 1^{o}, as calculated above.

Figure 2 schematically shows the electronic set-up. All amplification occurs before the signals are combined in N detectors producing N different directions of the zero-time-delay fringe. In our case N=10, but it could very easily be 100 or 1000, since the detectors are quite simple. This is the major advantage of the instrument - great ease of multibeaming. A difficulty of course is interference, which can be partially circumvented by proper choice of operating frequency.

The array is currently in operation, with data piling up faster than we can handle it. Not much is available in published form; I'm enclosing a brief article that appeared some time ago, together with a copy of one that will be published in November. I'll send you other material as it becomes available. If you have some questions, I'll be glad to answer them by mail.

missing

After 1 September, I will be at the University of Texas (permanently) where I will start a radio astronomy program to continue this work. My address there is: simply Dept. of Astronomy, Univ. of Texas, Austin, Texas.

How are your hektometric observations proceeding?

Best wishes,

Jim

James N. Douglas

JND/jz
Encl.

SESSION 14: Radio Astronomy II

Chairman: J. Ruze

Radiation Engineering Laboratory, Maynard, Mass.

14.1: A Broad-Band Interferometer for Studies of Discrete Radio Sources

J. N. Douglas

Yale University Observatory

New Haven, Conn.

A RADIO TELESCOPE must possess sufficient sensitivity to permit source detection in the presence of background and system noise, and sufficient angular resolving power to permit the study of one source at a time. Sufficiency in each case depends upon the observational program to be undertaken; in this instance we will be concerned with the requirements of a program for cataloging radio sources having flux greater than some minimum value $S_{min} = s_m(10)^{-26}\ w\ m^{-2}\ cps^{-1}$. The measurements to be made will be flux, angular diameter and precise position. From existing catalogs[1] and statistical experiments[2], we can fix the resolving power requirement at 100 antenna beam-areas per-source, and require sufficient sensitivity for a signal-to-noise ratio of five to one.

The number of sources per steradian outside the galactic plane brighter than a minimum flux s_m is approximately[1,3]

$$N = 1800 \frac{\lambda^{1.6}}{s_m^{\ 2}} \tag{1}$$

where λ is the observing wavelength and s_m is the minimum flux in units of $(10)^{-26}\ w\ m^{-2}\ cps^{-1}$. On the average, then, there will be one source every $1/n$ steradian. The beam area is required to be less than $1/100n$, or the directivity greater than

$$D \geq 2.26\ (10)^6 \frac{\lambda^{1.6}}{s_m^{\ 2}} \tag{2}$$

The sources are seen against a general background of galactic noise which outside the galactic plane produces an antenna temperature of approximately:

$$T_G = 100\ \lambda^{2.5}\ (^oK) \tag{3}$$

when λ is expressed in meters. The antenna temperature of a source of flux $s(10)^{-26}\ w\ m^{-2}\ cps^{-1}$ will be

$$\eta_A T_s = \frac{\eta_A s A}{2360} \tag{4}$$

where A is the antenna aperture in square meters and η_A is the antenna aperture efficiency, which is unity for a lossless antenna. The signal-to-fluctuation ratio at the output of our system is

$$q = \frac{K s A \sqrt{\alpha\tau}}{13.6\lambda^3}\ , \quad \alpha = \frac{\beta}{t} \tag{5}$$

where K is an instrumental constant between zero and one:

$$K = \frac{100\ \eta_A \eta_L \lambda^{2.5}}{T_R + (2 - \eta_A \eta_L)\ 300 + 100\ \lambda^{2.5}} \tag{6}$$

η_A the antenna efficiency, η_L the transmission line efficiency and T_R the receiver noise temperature. It will be noted that K is unity for an ideal system ($\eta_A = \eta_L = 1$, $T_R = O$). The collecting aperture required for a signal-to-fluctuation ratio (q) of five for the weakest source is thus:

$$A = \frac{68\ \lambda^3}{K s_m \sqrt{\alpha\tau}} \tag{7}$$

Equations (2) and (7) permit calculation of antenna directivity and collecting area for a survey down to limiting flux $s_m(10)^{-26}\ w\ m^{-2}\ cps^{-1}$ for a given λ, α, τ, and K. For a conventional, lossless antenna system however, directivity and collecting area are related:

$$A_D = \frac{D\ \lambda^2}{4\pi} \tag{8}$$

where A_D is the aperture required to produce a directivity D at wavelength λ. From (2) we have

$$A_D = 1.8\ (10)^5 \frac{\lambda^{3.6}}{s_m^{\ 2}} \tag{9}$$

The antenna size will thus be given by the larger of (7) or (9), and unless $A = A_D$, either resolution or collecting area is being wasted. For a given λ and s_m, $A = A_D$ for

$$\frac{\lambda^{0.6}}{s_m} = \frac{1}{2460K\sqrt{\alpha\tau}} \tag{10}$$

The observing time constant τ may now be adjusted to insure no wastage, and indeed the ability to observe more rapidly is useful up to a point. For example, with an electronic scanning system, the survey could be carried out at a number of declinations simultaneously on a time-sharing basis. For $\lambda = 1$ meter, $s_m = 1$, $K = 0.5$, we find $\sqrt{\alpha\tau} = 1/1230$, or $\alpha\tau = 1/1.5\,(10)^6$. For $\alpha = .001$, $\tau = 660$ microseconds per measurement, permitting 1600 measurements-per-second on a time-sharing basis.

Although this way to full antenna utilization is possible, it is not usually economical. Alternatively, for a given minimum flux and receiver system, there exists a wavelength of observation at which the antenna will be fully utilized. This optimum wavelength may be inconvenient or undesirable for other reasons. Accordingly, we consider antenna systems which do not obey equation (10). One such system is in general use in astronomy today — the Mills Cross. In this system, a receiver records the cross-correlation of the noise received in two perpendicular fan beams. The beam area of the fan beam is related to collecting area by equation (10), but only that noise appearing in *both* fan beams produces a correlated signal in the receiver. This correlated signal then is received with a pencil beam equal to the area of the junction of the two fan beams, with a collecting aperture proportional to the sum of the fan beam areas. Thus, to a certain extent, equations *(2)* and *(7)* may be satisfied independently, although one still must retain enough area to produce the individual fan beams.

Another radiometer system which does not obey equation *(10)* is the broadband interferometer[3, 4]. Let us consider the case of the multiplicative interferometer, in which the signal received in two antennas is multiplied before detection. In the absence of discrete source radiation, the two signals are uncorrelated, and hence multiplication, which produces an output proportional to the correlation coefficient between the two signals, yields an average result of zero, although small fluctuations will be present. If a point source of noise is present, at angle θ with respect to the perpendicular to the line joining the two antennas, this noise will appear first in one antenna and at a time $\tau = \frac{d \sin \theta}{c}$ seconds later will appear in the second antenna. If we call the point source noise $x(t)$ and assume transmission lines to be of equal length, the interferometer output will be of the form:

$$E_o = \frac{1}{T} \int_t^{t+T} x(t)\,x(t+\tau)\,dt = \rho(\tau) \qquad (11)$$

where $\rho(\tau)$ is the autocorrelation function of $x(t)$. If the source has a flat spectrum across the receiver passband, the spectrum of $x(t)$ is set by the shape of the receiver passband $s(f)$. The autocorrelation function is the *Fourier* transform of the spectral density:

$$\rho(\tau) = \int_{-\infty}^{\infty} s(f) e^{j2\pi f\tau}\, df \qquad (12)$$

If the receiver passband is taken to be that of a single-tuned circuit of bandwidth β

$$s(f) = s_o \left[1 + \frac{4(f-f_o)^2}{\beta^2} \right]^{-1} \qquad (13)$$

then the autocorrelation function will be

$$\rho(\tau) = e^{-\pi\beta\tau} \cos 2\pi f_o \tau \qquad (14)$$

The interference fringes will have maximum amplitude for $\tau = 0$, and for values of τ greater than $0.26/\beta$ second, the fringe amplitude will be below half its maximum value. For the case of equal transmission line lengths, a fan beam perpendicular to the line joining the two antennas is produced; this is of half-power beamwidth $23°/d\lambda\beta$, where $d\lambda\beta$ is the spacing between antennas expressed in wavelengths of the bandwidth. The beam may be steered to other values of θ by suitable changes in transmission line length, producing a fan beam $\frac{23°}{d\lambda\beta}$ to half-power points. By amplifying the signals from each antenna separately but coherently, and combining in a number of detectors after varying time delays, a multichannel system with each channel sensitive to an individual direction may be obtained. By using two systems at right angles to each other, measurement of both right ascension and declination can be made. It must be remembered, however, that this is basically an interferometer, and therefore fringe visibility is also affected by angular diameter of sources, at once permitting a measurement of diameters by the usual techniques, and prohibiting the use of this device on broad sources or the background radiation. The required broad bandwidth may also constitute a problem in some regions of the spectrum, though not an insuperable one. On the other hand, the broadband interferometer appears to offer a number of advantages in this application: *(1)* Directivity and collecting area set independently, permitting the use of antennas only large enough to provide sufficient sensitivity; *(2)* many declinations may be mapped at once without excessive electronic complication; *(3)* the technical problems involved are minimized by having only three antennas to feed; and *(4)* sidelobes of this device are vanishingly small.

A prototype broadband interferometer now under construction at the Yale Observatory has been designed to catalog sources having $s_m = 10$ ($S \geq 10^{-25}\ w\ m^{-2}\ cps^{-1}$) on a 1-2 meter wavelength. From equation *(2)* $D \geq 3.04(10)^4$, 1-2 meter wavelength. From equation *(2)* $D \geq 3.04(10)^4$, corresponding to a 1.° × 1.°2 beam. For the east-west interferometer, this requires a spacing $d\lambda\beta \geq 20$. To maintain the minimum beamwidth to a zenith distance of 60°, the north-south interferometer has $d\lambda\beta \geq 40$. This is achieved by using an 8-*Mc* bandwidth, with the east-west pair spaced 750 meters and the north-south pair spaced 1500 meters. This spacing limits our survey to sources smaller than 3′, and produces a positional accuracy of approximately 20″. From equation *(7)*, we obtain $A = 137\ m^2$ for $K = 0.86$, $\alpha = 1/30$ and $\tau = 3$ *cps*. Each interferometer element is a 32-helix broadside array, adequately fulfilling the aperture condition. Ten declinations will be surveyed simultaneously, and the IBM 709 at the Yale University Computing Center will be programmed for data reduction and error analysis.

It is felt that this prototype system, in addition to providing an independent catalog, will demonstrate the plausibility of this way of approaching the observation of discrete radio sources.

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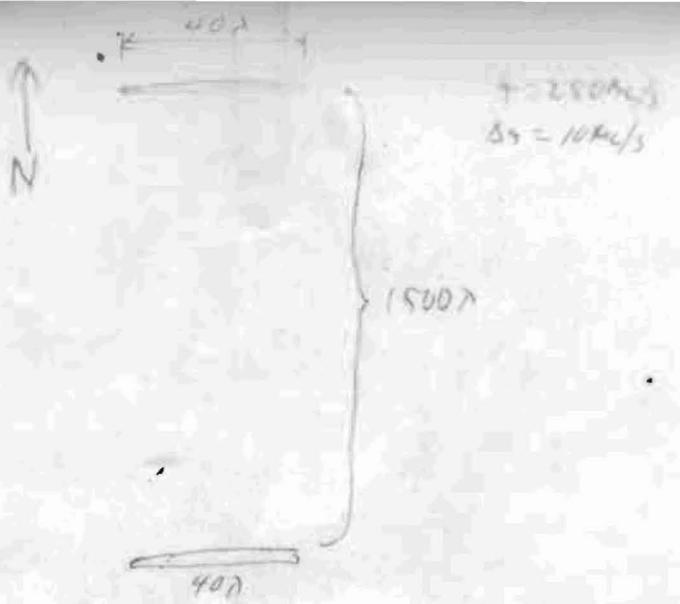
[1] Edge, D. O., Shakeshaft, J. R., McAdam, W. B., Baldwin, J. E., and Archer, S., *Memoirs Royal Astronomical Society;* 68, 37, 1959.

[2] Goldstein, S. J., *Astrophysical Journal;* 130, 393, 1959.

[3] von Hoerner, S., *National Radio Astronomy Observatory;* vol. 1, no. 2, 1961.

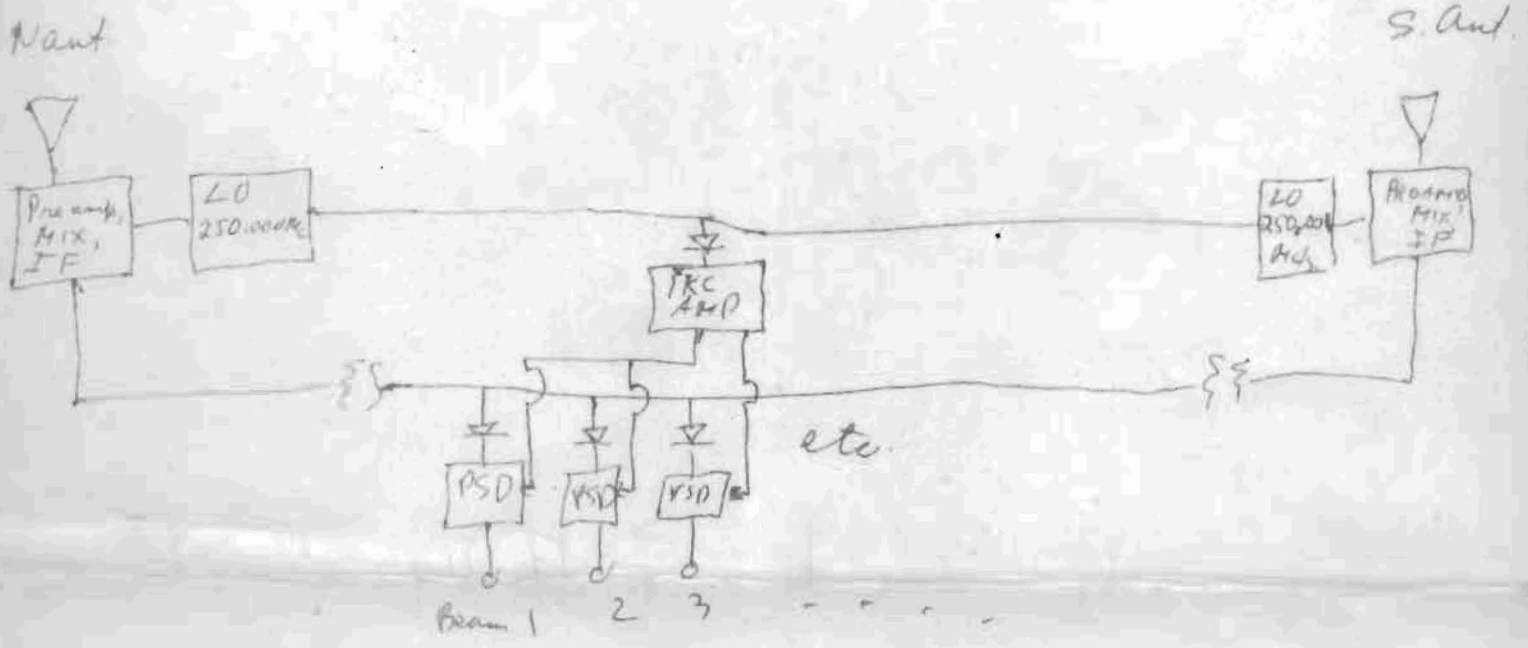
[4] Vitkevitch, V. V., *Proceedings of the Academy of Sciences of the USSR (Dokladi Adademii Nauk SSSR Hovaya Seria 91)*, 1301-1303, 1953.

[5] Whitfield, G. R., *Paris Symposium on Radio Astronomy*, Stanford Univ. Press, p. 297-304; 1959.



40λ
N
f = 250 Mc/s
Δf = 10 Kc/s
1500λ
40λ

Fig. 1



N ant
S. Ant.
Preamp, MIX, IF
LO 250.000 Kc
LO
Mc/s
Mix IF
1 KC AMP
PSD
PSD
PSD
etc.
Beam 1
2
3

Fig 2.