THE APPARENT SIZES OF THE JOVIAN DECAMETRIC RADIO SOURCES

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Summary

During 1963 and 1964 measurements were made of the angular sizes of the sources of Jovian radio bursts, at a frequency of 19·7 Mc/s, using interferometers with spacings up to 12700 λ. The measured source sizes were mostly in the range 10–15 sec of arc, but it seems likely that these apparent sizes are produced by interplanetary scattering and that the intrinsic size may be much smaller.

It is suggested that many of the "bursts" received from Jupiter are produced by a diffraction or focusing process in interplanetary space and so may be analogous to the interplanetary scintillations recently reported by Hewish, Scott, and Wills (1964). If so, the real angular size of the Jupiter source would probably be less than 1 sec of arc.

I. Introduction

We have previously reported (Slee and Higgins 1963) some interferometer measurements of the Jovian burst sources made during the 1962 apparition and we demonstrated the practicability of resolving them with much longer baselines than the 1940λ spacing used in the preliminary experiment. The present communication describes the positive results obtained at 19·7 Mc/s during 1963 and 1964 by the use of effective spacings in the range 691–12700λ. These observations were made over the baselines listed in Table 1, which also includes the range of effective spacings realized at each separation and the number of storms recorded.

Table 1

OBSERVATIONAL AND BASELINE DATA

Apparition	Baseline*	Baseline Parameters					Range of Effective Spacings (wavelengths)	No. of Storms Recorded
		Spacing (km)	Hour Angle °	′	Dec. °	′		
1963	Fleurs–Jamberoo	85·5	171	31	−55	47	4000–4500	13
1964	Jamberoo–Dapto	17·4	−32	49	52	29	691–778	1
	Jamberoo–Fleurs	85·5	− 8	33	55	47	3480–4730	5
	Jamberoo–Heaton	200·0	−35	01	50	44	7100–12700	20

* The mixing point for each baseline was at the first of the two localities.

The baseline parameters used (Table 1) are those defined by the intersection of the projected baseline, as viewed from the mixing point, with the celestial sphere. Baseline orientations were confined to within 35° of the north–south direction. The

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effective spacing was the projection of the baseline onto the plane perpendicular to the line-of-sight and this quantity depended upon the hour angle of Jupiter relative to the hour angle of the baseline.

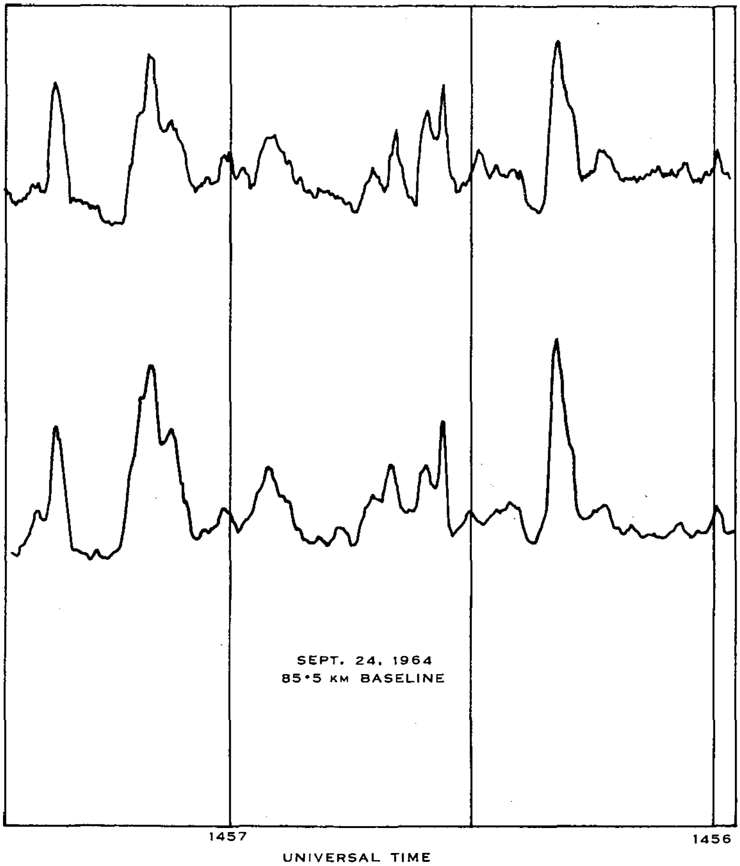

Fig. 1(*a*)

Figs 1(*a*) to 1(*d*).—Examples of 19·7 Mc/s chart recordings obtained during the long-baseline observations. Recordings of the total power from the two ends of the baseline are shown in (*a*), (*b*), and (*c*) and in the two lower traces in (*d*). In each case the upper record of the pair is from the home station. At times of strong activity the A.G.C. produces the depression of the baselevel noticeable in (*b*), (*c*), and (*d*). Recorded time markers are shown by arrowheads in (*b*), (*c*), and (*d*).

(*a*) Well-correlated bursts over the 85·5 km baseline (Jamberoo–Fleurs).

(*b*) Good correlation between bursts over the 200 km baseline (Jamberoo–Heaton).

(*c*) A more typical example of the correlation seen over the 200 km baseline (Jamberoo–Heaton).

(*d*) The total-power channels (lower) together with the resultant sine and cosine components of the interference pattern (upper) during a noise storm recorded over the 200 km baseline (Jamberoo–Heaton). A section of this record appears as (*b*).

(*a*) *Equipment*

Simple arrays of dipoles phased and oriented to receive radiation from Jupiter over an hour-angle range of ± 4 hr were used at both the home and remote sites. A radio link, which preserved the coherence of the Jupiter signals, was used to transmit

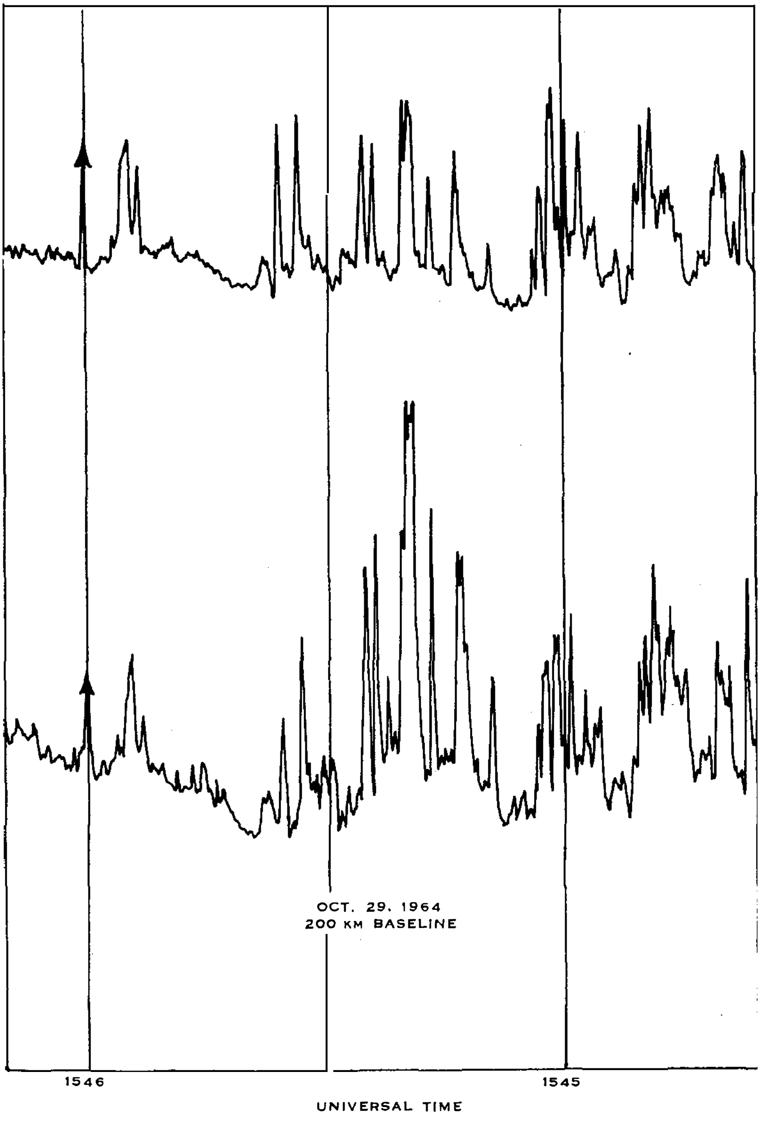

Fig. 1(*b*)

the bursts from the remote station to the home site, where they were multiplied by the appropriately delayed home signals using the conventional phase-switching method. The sine and cosine Fourier components together with the total powers of the two channels were recorded on pen-recorders possessing measured response times of $0^{s}\cdot 5$

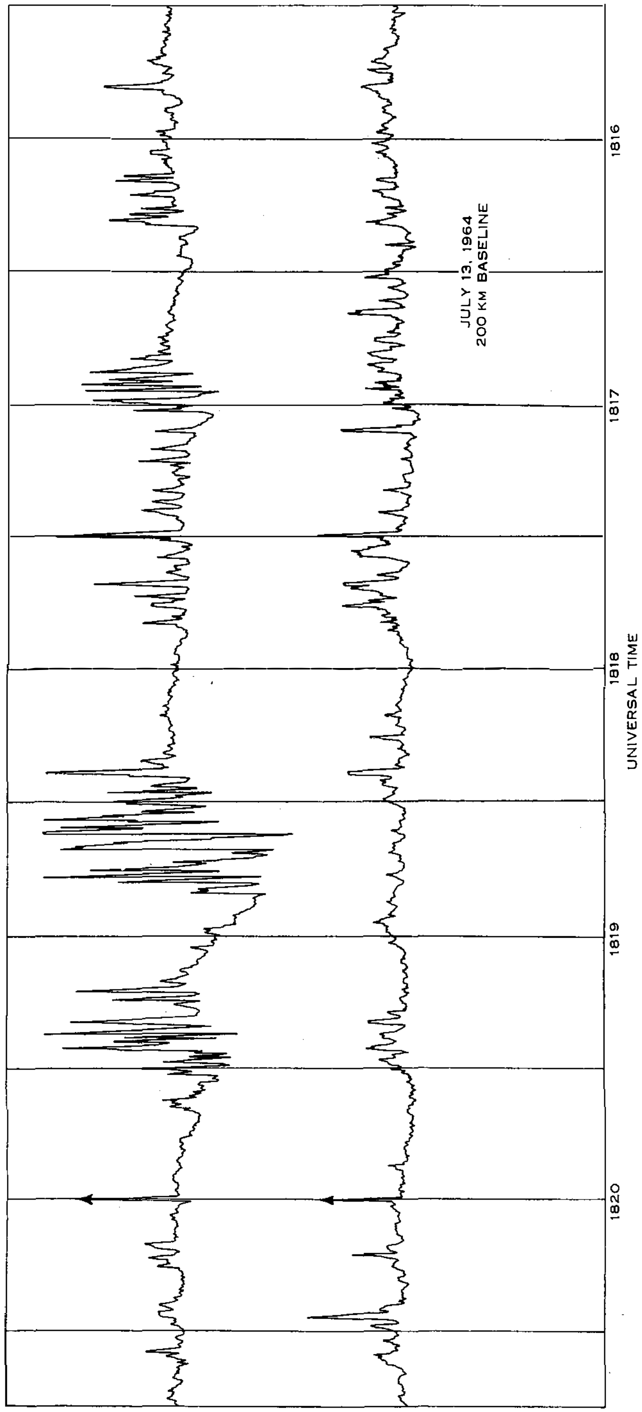
JULY 13, 1964
200 KM BASELINE
1816
1817
1818
1819
1820
UNIVERSAL TIME

Fig. 1(c)

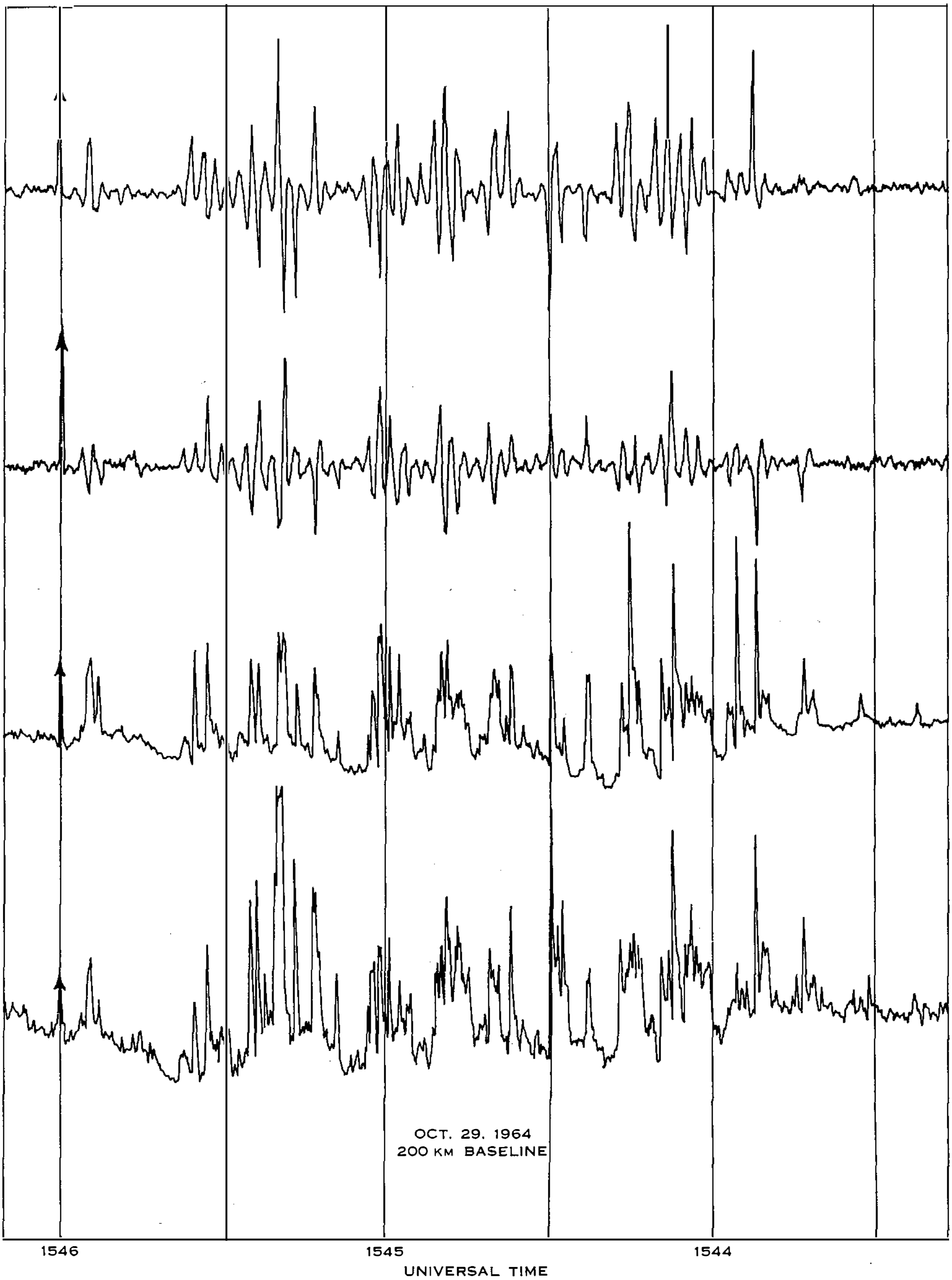

Fig. 1(d)

for full-scale deflection. Each channel possessed a bandwidth of 4 kc/s accurately centred on the second intermediate frequency of 250 kc/s. Variations in gain over the radio link path were controlled at the home site by means of an automatic gain control (A.G.C.) system with a time constant much longer than the durations of the majority of Jovian bursts. In order to keep the characteristics of the two channels as closely alike as possible, a similar A.G.C. system was used to control the home receiver. No attempt was made to artificially retard the natural fringe frequency, which, at the highest resolutions, was about 0·5 fringes/sec. In order to reproduce the occasional noise storms containing bursts of duration less than $0^s \cdot 5$, an additional four channel pen recorder with a response time of $0^s \cdot 02$ was used.

(b) *Appearance of Records*

Some examples of the recordings obtained are shown in Figure 1. Here, Figures 1(*a*) and 1(*b*) are tracings of the home (upper trace) and remote (lower trace) total-power signals for baselines of 85·5 and 200·0 km respectively, on nights during which almost complete burst-for-burst correlation was present. Figure 1(*c*) shows a more typical degree of total-power correlation over the 200 km baseline; it also shows the comparatively long-period modulation effects that were often observed on all baselines and that are probably attributable to the well-known ionospheric scintillations. However, not all differences between the records can be due to a modulation with a period of $30–60^s$, since there is here firm evidence of changes taking place within a few seconds, an interval much shorter than the usual time scale of ionospheric scintillation. Records exhibiting the degree of correlation shown in Figure 1(*a*) were obtained probably on half the nights for which noise storms were observed on the 85·5 km baseline, although this high degree of correlation was not always maintained for the duration of the storm. Over the 200 km baseline, records such as Figure 1(*b*) were rarely obtained and Figure 1(*c*) is a much more typical record.

In Figure 1(*d*), in addition to the total-power deflections, the sine and cosine components of the resultant interference pattern are shown for portion of a long storm recorded over the 200 km baseline. The regularity of the fringes seen in this record is typical of the behaviour noted during all storms for which a reasonable degree of correlation exists between the bursts at each end of the baseline. For poorly correlated records, such as shown in Figure 1(*c*), fringes of regular appearance were obtained whenever bursts were simultaneously present at each site, even though the individual bursts varied widely in shape and amplitude.

II. Calibration and Record Reduction

The zero baseline reference point was provided by feeding Jupiter signals into the two receiving channels (without the radio link on the remote channel) from independent arrays situated a few metres apart at the home site. Such a measurement was made at approximately fortnightly intervals in order to guard against changes in the interferometer fringe visibilities due to instrumental factors. In addition, the home and remote total-power channels were calibrated nightly by injecting noise signals from similar noise diodes at the two sites. By modulating the injected noise at the phase-switching frequency, it was also possible to calibrate the gains of the mixing and phase detector circuits.

During the initial analysis of a noise storm, the total-power traces were inspected and bursts for which there was some evidence at both sites were marked and numbered (see Fig. 1), their amplitudes t_1 and t_2 being measured. The phase-sensitive traces

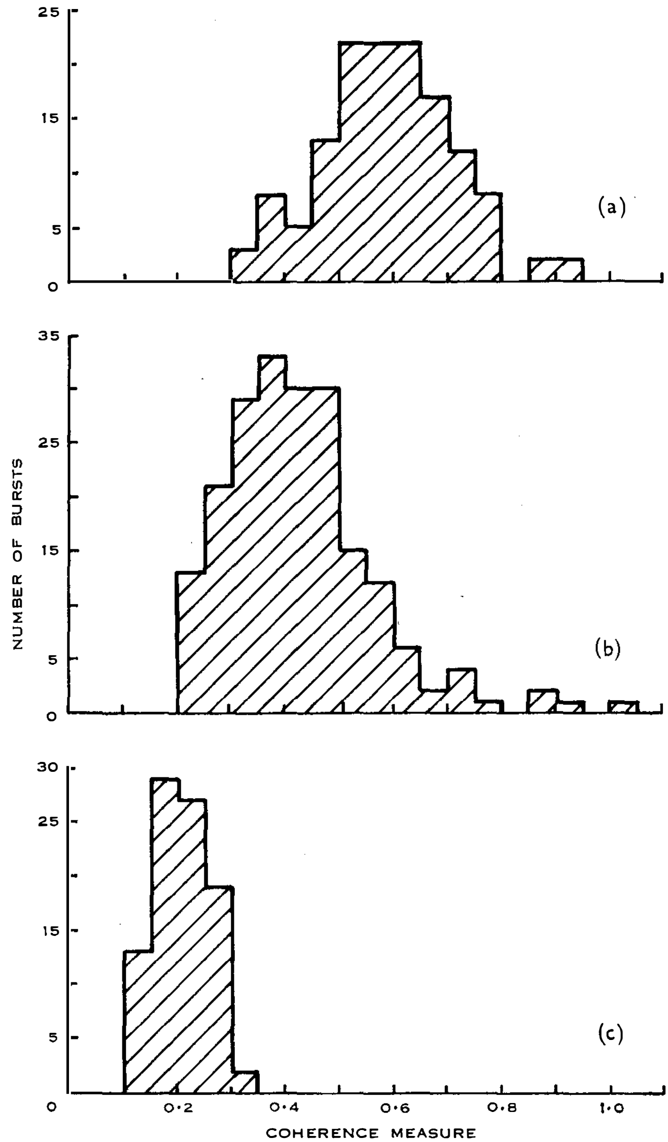

Fig. 2.—Histograms of the distribution of coherence measure for three noise storms in 1964. (*a*) October 1, spacing 734 λ; (*b*) September 24, spacing 3705 λ; (*c*) August 4, spacing 7550 λ.

were then inspected at the times corresponding to the total-power deflections and the amplitudes of the sine and cosine components, p_1 and p_2, were noted down.

Then for each burst a coherence measure

$$C(S) = \{(p_1/P_1)^2+(p_2/P_2)^2\}^{\frac{1}{2}}(t_1\, t_2/T_1\, T_2)^{-\frac{1}{2}}$$

was adopted, where T_1 and T_2 are factors obtained from the total-power noise calibrations, P_1 and P_2 from the modulated noise calibrations, and $C(S)$ refers to the coherence measure at effective spacing S wavelengths. Running averages $\overline{C(S)}$

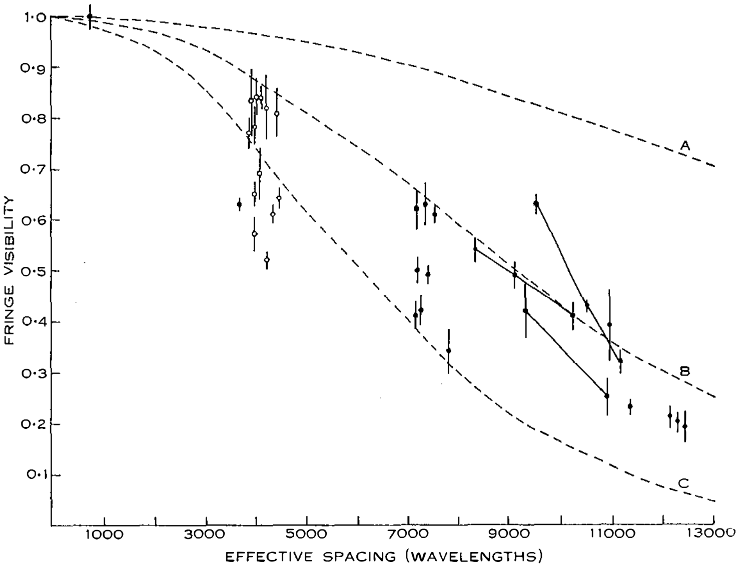

Fig. 3.—Nightly mean values of Jovian fringe visibility plotted against effective interferometer spacing. Open and full circles refer respectively to the 1963 and 1964 noise storms. The vertical bar at each point has a half length equal to the standard error of the mean. On the three occasions for which there were significant changes in angular resolution during the course of the storm, the means have been computed separately for the burst pairs in each 1000 λ interval of effective baseline and the points have been joined by straight lines. The broken-line curves represent the fringe visibilities for Gaussian sources of half-brightness widths (A) 5, (B) 10, and (C) 15 sec of arc.

of groups of about 10 bursts were then taken, in order to minimize the effects of noise fluctuations and differential timing errors between the four records. Similar coherence measures $\overline{C(0)}$ were computed for the zero baseline observations, except that the averages were taken over many more bursts. The fringe visibility

$$\gamma = \overline{C(S)}/\overline{C(0)}$$

was then computed for each sample of bursts, and, if there were no systematic temporal changes in sample fringe visibility, for the complete noise storm. However, on the three occasions in 1964 for which there were significant changes in angular resolution during the storm, separate averages were taken over the bursts in each 1000λ interval of effective baseline.

The frequency distributions of coherence measures for three of the longer storms recorded in 1964 are shown in Figure 2. The numbers of burst pairs are large enough to show that the distributions are unimodal and probably of the type expected for samples taken from approximately normal populations. Under these circumstances, the application to our results of the statistical theory of sampling from normal populations is probably justified.

The random errors in the determination of fringe visibility were found by computing the standard errors for 13 noise storms recorded over the 2 year interval. Since the standard errors of these distributions lay in the range 20–30% of the means and were not influenced significantly by the degree of resolution, we have adopted a standard error of 25% for a single observation of γ. The standard errors of the mean fringe visibilities will be diminished,of course, by the square root of the number of burst pairs included in the mean.

Systematic errors are difficult to estimate, since they are usually due to unknown factors. However, all known sources of systematic error were reduced, we believe, to negligible proportions by the imposition of suitable precautionary measures. For instance, changes in the equipment at the mixing (home) site were virtually eliminated as a source of error by frequent zero baseline observations of the Jupiter coherence measure. Again, the same transportable receiver and radio link transmitters operating under controlled conditions, were used at all remote sites and were calibrated nightly on a total-power basis; an overall check on the sensitivity and linearity of the remote receiver and radio link system was obtained by recording this calibration at the mixing site.

III. Observational Results

(a) *Angular Sizes*

Both the 1963 and the 1964 measurements have been summarized in Figure 3, in which the mean fringe visibility for each storm has been plotted against the average effective spacing. On the three occasions for which there were significant changes in angular resolution during the course of the storm, the means have been computed separately for the burst pairs in each 1000λ interval of effective baseline and the points have been joined by straight lines. Also drawn on Figure 3 are the theoretical visibility curves for sources having Gaussian brightness distributions of half-brightness widths 5, 10, and 15 sec of arc respectively.

Before discussing the conclusions we have drawn from these results, we ought to point out that, with one major exception, all of these storms occurred in the main peak of the Jupiter activity profile, i.e. when the system III longitude of the central meridian on Jupiter lay in the range $180° < \lambda_{III} < 330°$. In our case, the naturally occurring preference for Jupiter storms to be observed in this longitude range was accentuated by operating the interferometer only near the times of expected peak activity. The one major noise storm ($109° < \lambda_{III} < 171°$) that was observed away from the main activity peak occurred on October 29, 1964 (see also Figs 1(*b*) and 1(*d*)) and is recorded on Figure 3 by the three points joined by the steepest line. It may be a coincidence that, at the commencement of the storm, the apparent angular size of the source was unusually small but that as the activity progressed (and $\lambda_{III} \rightarrow 180°$) the fringe visibility decreased at a much faster rate than can be accounted for by the increase in resolution alone. We are thus led to the conclusion that a systematic increase in apparent angular size took place during the course of the storm; whether this is due to a change in intrinsic source size (which could be conceivably dependent upon the longitude of Jupiter's C.M.P.) or to temporal and/or spatial changes in the scattering properties of the interplanetary medium, is a question we cannot at present answer.

It can be seen from Figure 3 that the 19·7 Mc/s Jupiter sources have apparently been largely resolved at effective spacings of about 12500 λ. One interesting feature of the results is the large dispersion in fringe visibility from one storm to the next at a

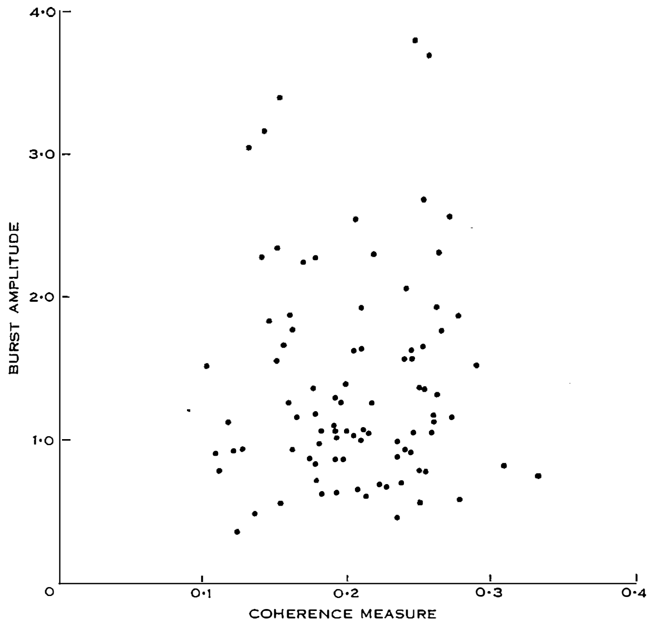

Fig. 4.—A plot of burst amplitude $(t_1 t_2/T_1 T_2)^{\frac{1}{2}}$ against coherence measure for all bursts measured during the storm of August 4, 1964. Mean effective spacing is 7550 λ.

given effective spacing. The differences between many pairs of measurements greatly exceed their individual standard errors so that, in the absence of any known systematic error, we conclude that the apparent source size is variable. It appears from the narrowness of the fringe visibility distributions, such as those shown in Figure 2, that there are not usually significant changes in angular size over the duration of a typical storm; indeed, in Figure 3 we show two long storms for which the changes in fringe visibility are consistent with those expected for a source of sensibly constant angular size. On the other hand, we have already remarked on the atypical result for a third occasion on which there was a very marked change in angular size during a storm of 2 hr duration.

The interpretation of the observed fringe visibilities in terms of equivalent angular sizes rests upon certain simplifying assumptions concerning the brightness distributions under observation. We have assumed that they are simple circular

Gaussian distributions so that the measurement of the amplitude of one Fourier component provides all the required angular size information. We can, however, imagine much more complex brightness distributions for which the measurement of only one Fourier component would provide little useful information. Nevertheless, in the absence of more detailed measurements, it seems legitimate for the present to regard the brightness distributions as having simple forms. On this basis, most of the angular sizes fall in the range 10–15 sec of arc to half-brightness points, i.e. about one-quarter of the Jovian diameter, or between 31×10^3 and 46×10^3 km. For one group of five storms in 1963 and one storm in 1964, in the range of effective spacings 3700–4500 λ, the equivalent angular sizes were significantly larger.

If the angular sizes measured are intrinsic to the Jupiter source and the radiation is emitted as bursts, a relationship may exist between burst amplitude and source size; for example, we could imagine that the burst amplitude depends upon the volume in the planet's atmosphere over which an initiating disturbance is distributed. In Figure 4 is plotted the burst amplitude, as measured by the factor $(t_1 t_2/T_1 T_2)^{\frac{1}{2}}$, against the coherence measure for a storm recorded over the 200 km baseline in 1964. There is apparently no significant relationship between burst amplitude and angular size; similar negative results were obtained for several other storms. Thus, if the bursts and angular sizes are intrinsic to Jupiter, it would appear that, during a storm, the brightness of the source fluctuates by a factor of up to 10. This may imply that the intensity of the initiating disturbance determines the burst amplitude rather than the volume over which it is distributed. Alternatively, the same behaviour may be expected if either the bursts or angular sizes (or both) are imposed upon an essentially steady signal by scattering in the interplanetary medium.

(b) *The Distribution of Burst Sources*

It is not possible with a long-baseline interferometer at decametric wavelengths to make meaningful measurements of the absolute phase of an interferometer pattern and hence to deduce the positions of the sources with respect to the optical disk of the planet. However, the frequent presence of a regular interference pattern with fringe period agreeing closely with that calculated from the baseline parameters suggests that differential phase changes in the ionosphere above the widely separated sites and across the radio link can often not be detected for time intervals of up to several minutes. Under these conditions, an upper limit can be placed on the movement of the Jovian source during that time interval; alternatively, an upper limit can be placed on the angular area over which independently radiating sources could be distributed. The mere existence of a regular fringe pattern allows the conclusion to be drawn that the successive bursts are generated in a region near the planet, which is small compared with the fringe separation; if this were not so, a succession of bursts would give rise to an interference pattern with irregular intervals between crossover points on the phase-sensitive pattern. If one attributes the Jupiter bursts to scintillation in the intervening medium, then the associated angular position scintillations must be small compared with the fringe spacing.

On the record reproduced in Figure 1(d), for example, the systematic shift in the pattern over 42 continuous fringes is $0\cdot2$ fringes or 4 sec of arc when compared with the theoretical pattern. The maximum deviation of the crossovers from the average position is $\pm 0 \cdot 15$ fringes or $\pm$ 3 sec of arc. Hence, for a steady Jupiter source there was no shift in the centroid of emission greater than 4 sec of arc or one-eleventh of the planet's diameter during the 2 min time interval, while the angular scintillations did not exceed 3 sec of arc. For a bursty Jupiter source, the variation in angular position from burst to burst did not exceed 6 sec of arc (or one-seventh of the planet's diameter), while the centroid of the assembly of radio emitters did not shift by more than 4 sec of arc. The behaviour just described is typical of the results obtained on most occasions when the total-power deflections at the ends of the baseline were reasonably well correlated, resulting in a continuous fringe pattern. Occasionally, however, there were significant differences between observed and theoretical fringe periods, with systematic angular shifts as great as 45 sec of arc over a time interval of about 1 min. On these occasions, there was generally some evidence on the total-power traces of a slow amplitude modulation consistent with the presence of ordinary local ionospheric scintillations.

IV. Time Delays between Bursts at Spaced Sites

Following the spaced receiver results recently reported by Douglas (1964), who found time displacements of up to 1^{s} between well-correlated bursts at sites 100 km apart, we decided to examine our records for similar effects. We were faced with two main difficulties, the first and major one being the comparatively small number of records that showed sufficiently good correlation in the fine-burst structure to permit certain identification of the same bursts at the two sites. The second difficulty concerned the relatively poor time resolution of the records, which were not originally taken with the object of measuring relative time displacements as small as $0^{s} \cdot 1$.

Although we have not yet analysed all our records for these effects,* we have selected two records (Figs 1(*a*) and 1(*b*)) that showed the required high degree of correlation. By making use of photographic enlargements of portions of these

* *Note added in Proof.*—A more complete examination of our 1963 and 1964 recordings has confirmed the time delays tentatively reported in this section. The relative arrival times of the longer ($> 0^{s} \cdot 5$) bursts were measured during 11 Jovian noise storms for which the total-power correlation was good enough to identify the same bursts at the ends of the baseline; on 8 of these occasions, all of which occurred within 4 months before opposition, significant systematic time differences were detected. When interpreted in terms of a diffraction pattern sweeping across the Earth, the sense of the movement was always from north to south with a value of between 250 and 4500 km/sec, although six of the derived values were less than 1300 km/sec. The low accuracy of these determinations (r.m.s. error in the mean value for each storm was as high as 30%) did not allow us to find a systematic relationship between the velocity of the pattern and the distance of Jupiter from opposition.

On the two occasions when the very short duration millisecond Jupiter pulses (*S*-pulses) were recorded with the interferometer, no time shifts were detected; the appearance of these pulses at good strength on the phase-sensitive recordings implied that the time shifts, if any, were less than the pulse durations. For pulse durations < 20 msec and a baseline of 200 km, the speed of a diffraction pattern would need to be $> 10^{4}$ km/sec.

A more complete account of these burst arrival time measurements will be published in a later paper.

records, we found an average time displacement of $0^s \cdot 29 \pm 0^s \cdot 06$ for 16 bursts of Figure 1(*a*) and $0^s \cdot 22 \pm 0^s \cdot 02$ for 14 bursts of Figure 1(*b*). The limits quoted here are the standard errors of the means. In both cases, the bursts at the northern site were advanced relative to those at the southern station.

The result suggests that the Jupiter noise storm is the manifestation of an interplanetary diffraction pattern sweeping across the Earth. If this is so, then the observed average time shifts, when combined with the spacings of the sites, yield for these two samples resolved velocities of 295 and 910 km/sec respectively. Such values are far higher than the velocities that can be associated with the Earth's or Jupiter's rotational motions or their orbital velocities about the Sun; they are, however, consistent with Mariner II measurements (Neugebauer and Snyder 1962) of the velocity of the interplanetary plasma.

Since the burst correlation was often reasonably good at our 85·5 km spacing and occasionally also over the 200 km baseline, we assume that the terrestrial scale of the diffraction patterns would also reach these proportions.

V. Discussion

We have shown in the previous section that a simple interpretation of the fringe visibility measurements indicates that the apparent source sizes were usually in the range 10–15 sec of arc during the 1963 and 1964 observations. It was also suggested that the relative time shift between bursts recorded at separated sites, first announced by Douglas (1964) and now tentatively verified by us, indicates that the bursts may be produced by a diffraction or focusing process in interplanetary space. In this respect, the Jupiter bursts may be analogous to the interplanetary scintillations recently reported by Hewish, Scott, and Wills (1964) from observations of those quasi-stellar radio sources nearest to the Sun.

Pisareva (1957) and others have shown that if the diffracted or focused patterns are not to be smeared out at the observation point, then the angular size of the source should be considerably less than the angle subtended by an irregularity. For an intrinsic source size of, say, 10 sec of arc and a maximum irregularity scale of 5×10^3 km, as suggested by Hewish and Wyndham (1963), the diffracting irregularities would need to be located well within a distance of 1 A.U. of the Earth in order to satisfy the angular size conditions. However, Pisareva (1957) has also shown that under these conditions, the diffracted radiation would not be focused at the Earth and deep scintillations of the type observed could not occur.

Accordingly, we are led to suggest that the source sizes measured may not be intrinsic, but may be yet another manifestation of the diffraction or focusing process; this would imply that, in effect, the interferometer measures the angle subtended at the Earth by the assembly of irregularities responsible for the observed patterns. Such an interpretation would allow the irregularities responsible for the scintillations to be placed at greater distances from the Earth, where effective focusing could take place. However, the angular size condition would now dictate a small intrinsic angular size for the Jupiter source, probably considerably less than 1 sec of arc to half-brightness points.

Future work on the problem of deciding between intrinsic source size and interplanetary scattering will probably again rely upon long-baseline interferometry. A repetition of the present experiment at a different observing frequency, say 30 Mc/s, should clarify the role played by interplanetary scattering. If, as seems possible, scattering is a major contributor to the apparent source size, then it is unlikely that the intrinsic source size will be measured by interferometric methods.

VI. Acknowledgments

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