THE ASTROPHYSICAL JOURNAL, 207:325–328, 1976 July 1

VLBI MEASUREMENTS OF JOVIAN S BURSTS

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Received 1975 November 7

ABSTRACT

VLBI measurements of a series of Jovian S bursts over a 419,000 λ baseline at 18 MHz indicated that all arrived from the same direction to within about 0.″05, except for a relatively slow drift which may have been due to moving solar wind inhomogeneities. The evidence is against a sweeping-beam origin for S bursts.

Subject headings: planets: Jupiter — planets: radio radiation

VLBI measurements of Jovian decametric radio bursts have previously been made over several baselines extending between the University of Florida Radio Observatory and outlying stations in Florida, Kentucky, and Chile, and between the University of Colorado Radio Astronomy Observatory and other stations in Colorado, California, and Puerto Rico. These earlier results have indicated primarily (*a*) that the source cannot be resolved with baselines of 0.″1 incoherent-source resolution capability (Dulk 1970; Lynch *et al.* 1972); (*b*) that individual S bursts (milliseconds duration) display high envelope correlation as well as high fringe visibility, even at long baselines (Block *et al.* 1970); (*c*) that during a period of almost continuous L burst activity, the observed fringe frequency stability implied that the apparent position of the source does not jump about by more than 0.″2 in 10 s (Dulk 1970); and (*d*) that limited measurements indicated that the sweeping of narrow emission beams across the Earth did not appear to be a factor in the formation of burst envelope waveforms (Lynch *et al.* 1972). In this paper we present results on the phase stability of the fringe pattern due to a series of Jovian S bursts obtained with an interferometer having 0.″1 resolution and sufficiently short integrating time that the contributions by individual S bursts to the fringe pattern can be observed. New measurements relating to source size and to possible sweeping emission beams were also performed.

The observations were made at a frequency of 18 MHz at the University of Florida Radio Observatory (UFRO) near Old Town, Florida, and at the Maipu Radioastronomical Observatory (Maipu) near Santiago, Chile. The baseline length was 419,000 λ (6980 km), and its components projected on the $u - v$ plane (Verschuur and Kellermann 1974) were 3630 λ and 416,000 λ, respectively. The antenna used at UFRO was a cross-polarized yagi responding to the right-circularly polarized component, and that at Maipu was a linearly polarized yagi. The 18 MHz Jovian signal at each station was triple-heterodyned down to an audio band 2.1 kHz wide centered on 5 kHz. Local oscillator frequencies and time pulses at each location were derived from a single crystal oscillator with a stability better than five parts in 10^7 s^{-1} and one part in 10^9 day^{-1}. The audio output of the receiver was analog-recorded on one channel of a tape recorder, and the time pulses and a high-frequency synchronization tone were recorded on the other. The tone served to make the digitization of the data on playback (at the time of processing) independent of tape stretch and speed variations. Time pulses were referenced to Universal Time with an accuracy of about 0.1 ms.

The data from which the present results were derived consisted of a train of 68 S bursts that occupied a period of 6 s beginning at $9^{h}35^{m}51^{s}.6$ UT on 1970 April 30. These bursts were part of a Source-B Io-related storm. The average burst duration was 25 ms for 14 of the strongest bursts. The ratio of Jupiter signal plus background noise to background noise alone exceeded 7 db for 50 percent of the bursts, with a maximum of 13 db.

The analog-recorded data were digitized on playback at 45,000 samples s^{-1} using a resolution of 12 bits per sample. The first step in the data reduction was to find the relative time shift, τ_0, which maximized the cross-correlation of the two sets of data. Sine and cosine functions oscillating at the natural fringe frequency (calculated from source-baseline geometry) were multiplied point-by-point with the data from one station. The sine-multiplied data set was cross-correlated with the data from the other station for a range of time shifts τ near the expected delay to form the set of cross-correlation functions, $C_{\sin}(t, \tau)$. Similarly, the cosine-multiplied set was cross-correlated with the other station data to give the set of functions $C_{\cos}(t, \tau)$. The best time shift, τ_0, was found by maximizing the function

$$C(\tau) = [C_{\sin}^2(t, \tau) + C_{\cos}^2(t, \tau)]^{1/2} . \qquad (1)$$

An integration time of 40 ms was used in this step.

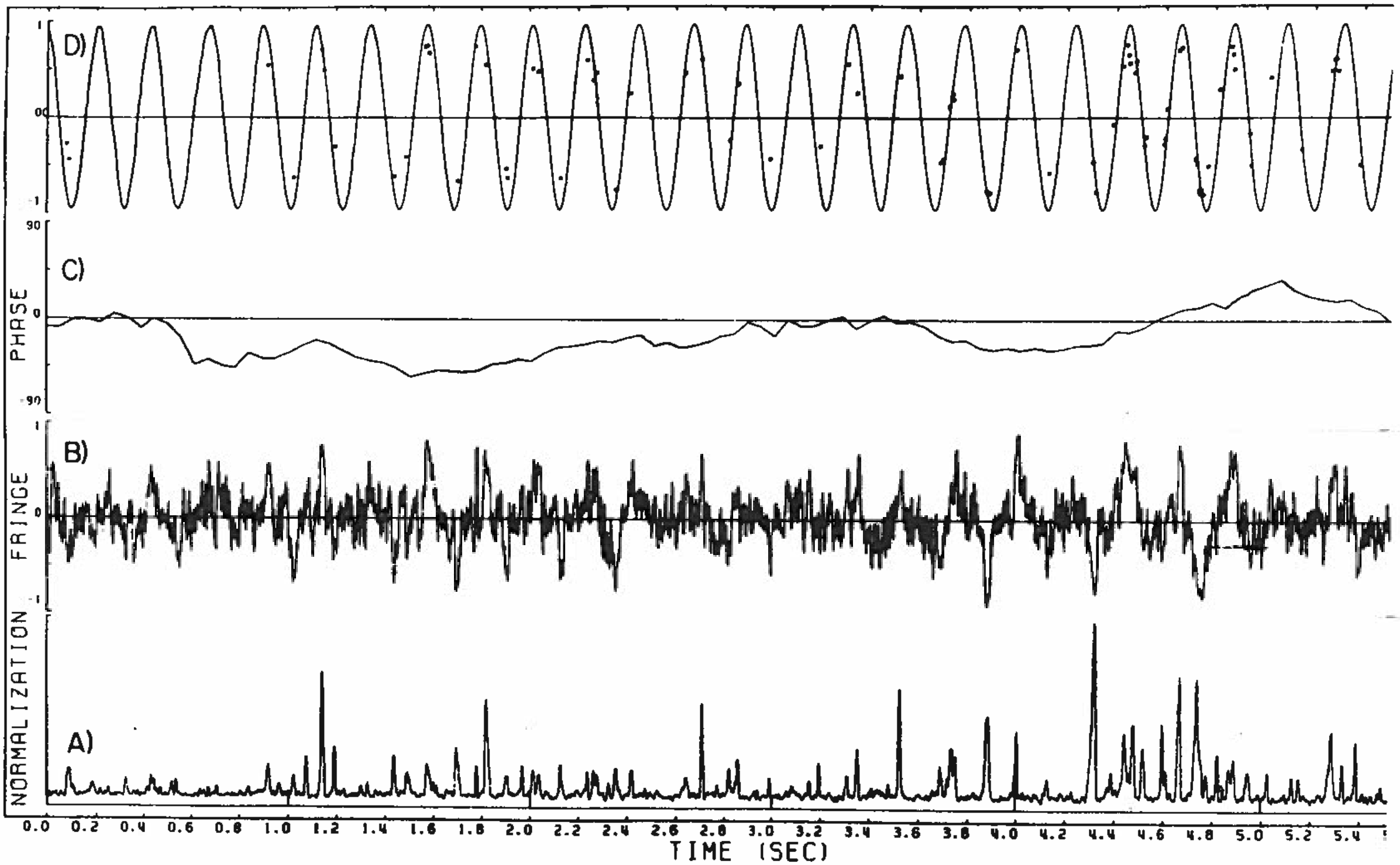

FIG. 1.—(*a*), Geometric mean of the signal voltages from the two stations versus time, showing the S bursts; (*b*), fringe pattern; (*c*), fringe phase versus time; (*d*), phase-modulated function from equation (4); points are from (*b*) at times near S burst maxima.

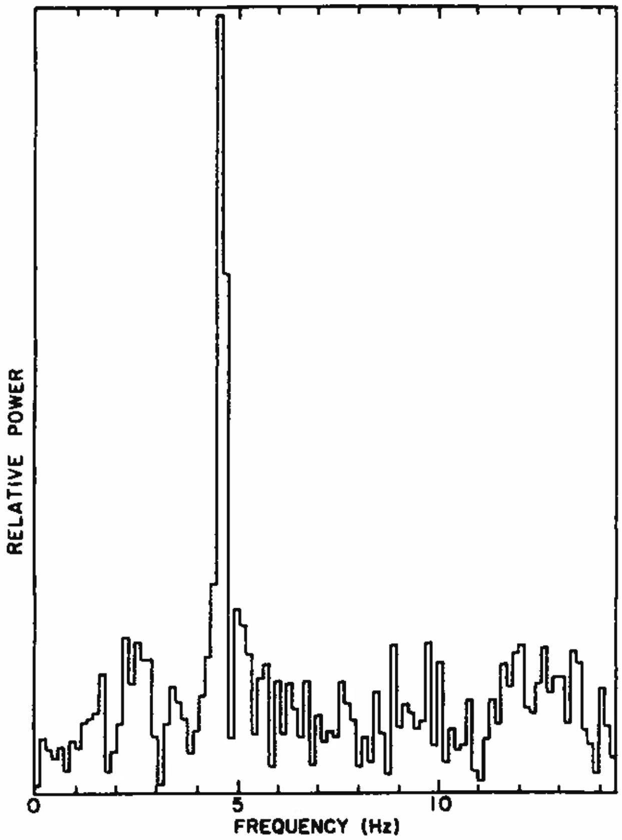

FIG. 2.—Power spectrum of fringe pattern

After τ_0 had been determined, the data from the two stations were cross-correlated directly, using

$$C(t, \tau_0) = \frac{\sum_i E_1(t_i)E_2(t_i + \tau_0)}{[\sum_i E_1^2(t_i) \sum_i E_2^2(t_i + \tau_0)]^{1/2}}, \qquad (2)$$

where E_1 and E_2 are digitized values of the signal voltage from the two stations, respectively, and the summations extend over an 8 ms interval centered on t. Figure 1(*a*) shows the time variation of the normalizing factor in the denominator of equation (2), and Figure 1(*b*) is the fringe pattern, $C(t, \tau_0)$. Figure 1(*b*) suggests that there is considerable coherence between the contributions of the successive S bursts to the overall fringe pattern, despite the fact that the pattern temporarily loses its identity when the Jupiter signal drops below the background noise between S bursts.

The Fourier transform of the fringe pattern in Figure 1(*b*), with an integration time of 6.9 s, is shown in Figure 2. It indicates a very strong peak at the fringe frequency $\nu_f = 4.49$ Hz. The fringe phase as a function of time was calculated from the equation

$$\tan \Phi(t) = \frac{\sum_i C(t_i) \sin 2\pi\nu_f t_i}{\sum_i C(t_i) \cos 2\pi\nu_f t_i}, \qquad (3)$$

where the summations extend over 445 ms intervals centered on t. The phase function is shown in Figure 1(*c*). Its total excursion is only about 90° in 5.5 s. Figure 1(*d*) is a plot of the function

$$f(t) = 0.9 \sin [2\pi\nu_f t + \Phi(t) + \delta], \qquad (4)$$

consisting of a sine wave oscillating at the natural fringe frequency which is phase-modulated by the calculated phase function (δ being an arbitrary constant). Since a 445 ms summation interval is used in the calculation of $\Phi(t)$ from equation (3), an interval that usually contains several S bursts, any phase fluctuations on a scale much shorter than this would be smoothed out. It is therefore of interest to see how closely the portions of the fringe pattern of Figure 1(*b*) occurring at the times of the peaks of the individual S bursts follow the curve of equation (4). The agreement in Figure 1(*d*) between such points and the smooth curve from equation (4) is excellent. The fringe phase of nearly every S burst agrees with that of the smooth curve within about 0.1 cycle, implying that all of the S bursts appear to come from the same source location. The upper limit on short-term (less than 445 ms) fluctuations in source position is about 0″.05. While the 90° excursion of the curve of Figure 1(*c*) in 5.5 s can be interpreted as a drift in the source position of 0″.13, it is more likely to be caused by phase shifts due to moving solar-wind irregularities (Cronyn 1972). The amplitude of the cross-correlation function, $C(t, \tau_0)$, was at least 0.9, which establishes an upper limit on the size of a noncoherent Gaussian source of 0″.1. This is in agreement with previously published results.

A method described by Lynch *et al.* (1972) was used in an attempt to detect a component of the S burst arrival-time difference at the two stations which might indicate the sweeping of a narrow emission beam past the Earth. The previously described time shift, τ_0, which depends on the wave-front tilt, was compared with the time shift which maximized the cross-correlation function of an S burst *envelope*. This was done for each of four of the most intense S bursts having relatively short durations. In no case did the burst envelope arrival time difference differ from the wave-front arrival time difference by more than 60 μs, the limit of time resolution. This observed degree of simultaneity easily rules out the possibility of sweeping beams carried along with Jupiter's diurnal rotation and Io's orbital motion, as well as a beam fixed to the foot of the Io flux tube which has a component of motion due to the rapid change of ionospheric drag from night to daytime conditions (Goldreich and Lynden-Bell 1969). The dawn conditions favorable for the latter effect must have prevailed, since Jupiter was near opposition and Io was at 90° from superior geocentric conjunction at the time.

Another possible beam-sweeping mechanism resulting in a much greater angular velocity consists of a narrow beam emitted by a group of radiating electrons traveling upward along a curved flux tube toward Io. The beam produced by a group of electrons moving with a longitudinal velocity of 0.1c from the north polar region along a flux tube with a curvature of 5 Jovian radii would rotate southward with an angular velocity of about $5^\circ\ \mathrm{s}^{-1}$. An S burst of 10 ms duration could be produced by a beam of 3′ width sweeping past the Earth with this angular velocity. The north-south component of our baseline subtended an angle of about $0\overset{\circ}{.}0005$ at Jupiter; therefore the estimated time resolution of the system (50 μs) would imply that an angular velocity of $10^\circ\ \mathrm{s}^{-1}$ or less could have been detected. No evidence of any sweeping effect was observed. However, this marginally negative result should not be a deterrent to further searches for a north-south sweeping of S burst beams.

Further analyses of the variations in fringe phase are being made using Jovian L bursts instead of S bursts. Since L bursts are of much longer duration and are far more abundant than are S bursts, they are better suited for investigations of the phase stability of the Jovian source, and of the effects caused by inhomogeneities in the interplanetary medium.

We thank Dr. Will Cronyn for a most helpful discussion on the measurement of the fringe phase of Jovian bursts. This work was supported in part by the National Science Foundation.

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