THE EFFECTS OF INTERPLANETARY SCATTERING ON RADIO OBSERVATIONS OF JUPITER AT VERY LOW FREQUENCIES

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Abstract

Recent feasibility studies, for a Very Low Frequency Radio Telescope Array (VLFA) on the far side of the Moon, have focussed attention on the problems imposed by interplanetary scattering (subsequently referred to simply as 'scattering') and the consequent limitations to measurements of fine temporal and spatial structure. The standard theory, established for higher frequencies, predicts that the temporal broadening τ_b of structured emission will increase with decreasing frequency as $\tau_\mathrm{b} \simeq 0.1\nu^{-4.4}$, where ν is the observing frequency in MHz and τ_b is in seconds. Under these circumstances, the lowest frequency at which a 5 ms structure could be resolved would be about 2 MHz. At 200 and 100 kHz the corresponding values of τ_b are about 2 and 42 minutes, respectively. However, at these low frequencies the small angle approximations used to derive the relation are no longer valid and simple arguments indicate that, at some frequency between 200 and 100 kHz, τ_b should attain a limiting value significantly less than 42 minutes.

We suggest that observations of the Jovian kilometric radiation, by the Unified Radio and Plasma Experiment (URAP) on board ULYSSES, might offer the possibility of establishing some experimental constraints on these ideas. To this end, the durations of structures observed in the Jovian broad-band kilometric radio emission (bKOM), during 1995 when the spacecraft was at distances greater than 5 AU from the planet, are compared with theoretical values of τ_b and with solar wind electron density measurements made by the SWOOPS experiment on Ulysses. A progress report is presented and the results discussed.

1 Introduction

Scattering effects in the interplanetary medium have been reviewed by Woan as part of a recent feasibility study for a radio telescope on the far side of the Moon, operating

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at frequencies below 30 MHz [ESA Report, 1996]. Electron density irregularities in the interplanetary medium (IPM) create refractive index variations, so that rays originating at some distant point travel along a range of paths of different lengths and the received signal is temporally broadened. If we assume a Kolmogorov model for the spectrum of density inhomogeneities in the solar wind and small scattering angles, the temporal broadening, τ_{b}, of structured emission will increase with decreasing frequency as $\tau_{\mathrm{b}} = 0.1\nu^{-4.4}$ seconds as shown in Figure 1a, where ν is in MHz. It can be seen that the lowest frequency at which a 5 ms structure could be resolved would be about 2 MHz. During 1995, a number of Jovian bKOM events were observed which extended to considerably lower frequencies than 2 MHz, when the spacecraft was at distances greater than 5 AU from the planet. The durations of structures within these events are compared with theoretical values of τ_{b} and with solar wind electron density measurements made by the SWOOPS experiment [Bame et al., 1992; Phillips et al., 1995].

2 Interplanetary scattering

The IPM is a turbulent plasma and, as such, it scatters radio waves. At frequencies below a few tens of megahertz, the combined effect of refractive index variations over spatial structures in the IPM is sufficient to introduce random phase variations much greater than one radian across a propagating wavefront. Under these strong scattering conditions we are able to treat the problem geometrically and consider the effect of the medium on the local normal to the wavefront. The simplest analysis originates in the pioneering work of Booker, Ratcliffe and Shinn [1950] applied to the Earth's ionosphere, but the approach is equally applicable to modelling the IPM when scattering is strong.

We begin by considering a thin screen of random plasma density irregularities between the radio source and the receiver. These electron density variations, Δn_{e}, can be taken to be proportional to n_{e} (the total electron density) and correspond to refractive index variations of

$$\Delta\eta = \frac{r_{\mathrm{e}}\Delta n_{\mathrm{e}}}{2\pi}\lambda^2 \ , \tag{1}$$

where r_{e} is the classical radius of the electron (2.82×10^{-15} m) and λ is the wavelength of the radiation.

It is straightforward to show (e.g. Thompson, Moran and Swenson, [1986]; Lyne and Graham-Smith, [1990]) that these variations corrugate an otherwise plane wavefront so that a point source seen through the screen appears scattered to an rms angular size of

$$\theta_{\mathrm{s}} \simeq \sqrt{\frac{D}{a}} r_{\mathrm{e}}\Delta n_{\mathrm{e}}\lambda^2 \ , \tag{2}$$

where the screen is assumed to be thin and of thickness D and a is the scale-size of the irregularities, that is the characteristic width of the distribution, assumed to be Gaussian. The assumption of a scale-size may appear to be overly restrictive but more sophisticated models based on a Kolmogorov power-law spectrum for the density irregularities give

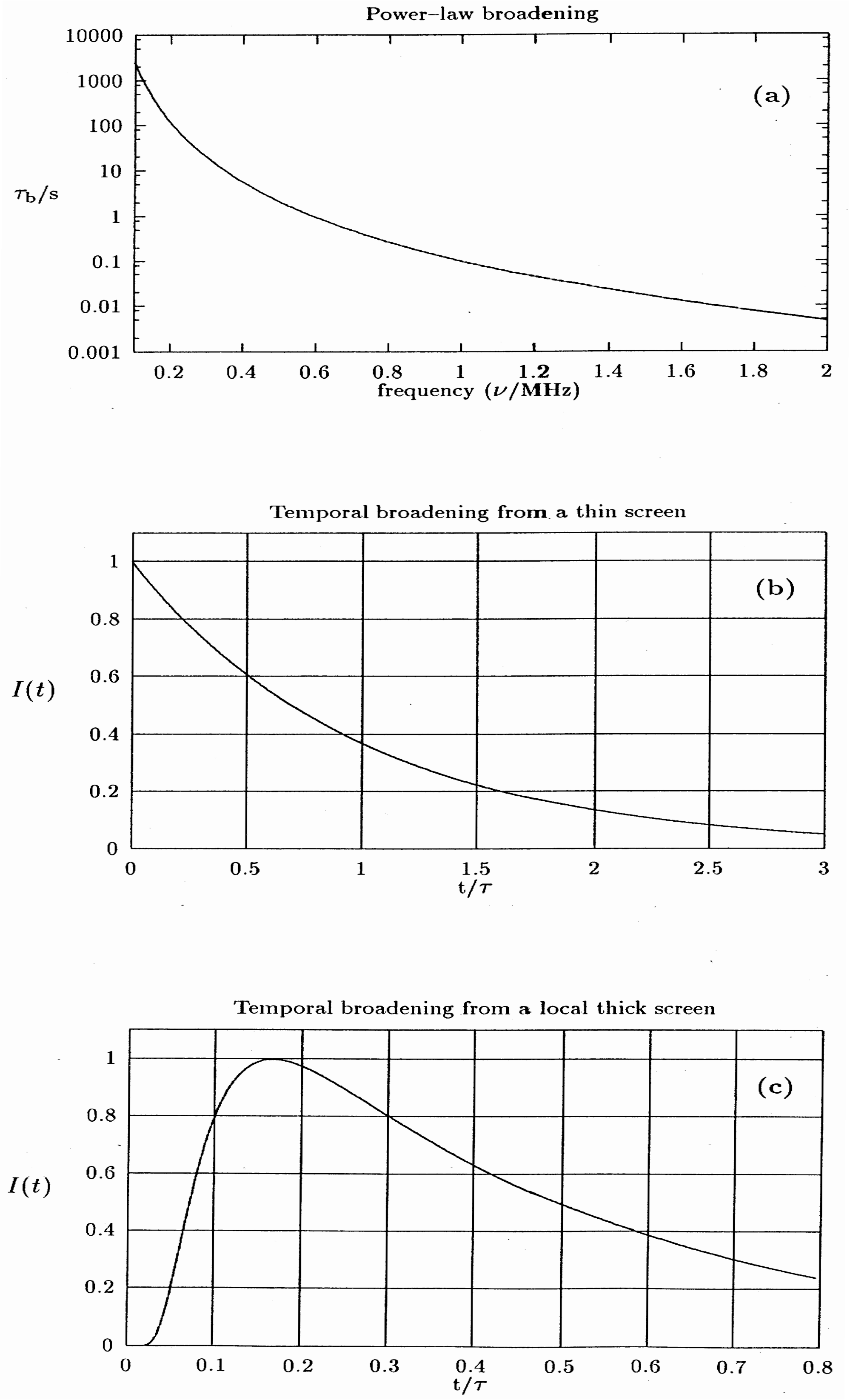

Figure 1: (a) Temporal broadening predicted by scattering theory, (b) Pulse profile predicted by Equation (5), (c) Pulse profile predicted by the Williamson model and a 1 to 2 AU screen.

very similar results down to about 200 kHz, except that $\theta_\mathrm{s} \propto \lambda^{2.2}$ [Rickett, 1977]. The Kolmogorov model leads to the classical $\nu^{-4.4}$ relation stated in the introduction, whereas the Gaussian model gives $\tau_\mathrm{b} \propto \nu^{-4}$ (see below). Both forms of the relation depend upon small angle approximations, which set a lower frequency limit to their validity. In the following analysis, for simplicity, we consider only the Gaussian model.

The effect of the scattering screen on temporal structure in the radiation follows directly from the angular broadening identified above. Rays from a source at infinity, scattered by the screen through an angle θ_s, will take an extra time

$$\tau = \frac{z\theta_\mathrm{s}^2}{2c} \tag{3}$$

to reach the receiver relative to an unscattered ray. Here z is the distance between the receiver and the screen, c is the speed of light and the scattering angle is assumed small, so that $\tan\theta_\mathrm{s} \simeq \theta_\mathrm{s}$. A radio pulse entering the medium will therefore emerge convolved with a function of characteristic width τ and structure on much finer temporal scales will be lost.

In the thin-screen case considered here, the form of the convolving function can be simply determined. The angular brightness distribution of the screen is taken to be proportional to $\exp(-\theta^2/\theta_\mathrm{s}^2)$. A proportion $2\pi\theta d\theta$ of all rays emerge at an angle θ and with a corresponding delay of $z\theta^2/2c$ as predicted by Equation (3). The intensity profile of a pulse, $I(t)$, can therefore be defined by

$$I(t)dt \propto 2\pi\theta \exp(-\theta^2/\theta_\mathrm{s}^2)d\theta \ . \tag{4}$$

As $t \propto \theta^2$ we can rewrite this as

$$I(t) \propto \exp(-t/\tau) \ . \tag{5}$$

The emerging pulse profile (Figure 1b) is therefore a truncated exponential with $I(t < 0) = 0$ and decay time of τ [Cronyn, 1970].

The more difficult problem of a thick strongly scattering screen has been tackled in a series of papers by Williamson [1972, 1973, 1974] in the context of pulse broadening in pulsars by the interstellar medium (ISM). He found that a pulse travelling through a thick scatterer emerged with a profile having a more gentle rise than in the thin case, but with the same exponential decay. The profile remains asymmetric however, with the rise time significantly shorter than τ.

In the case of Jovian emission, we are concerned with scattering from the IPM rather than the ISM, but the results are entirely applicable. In particular, because the plasma number density of the IPM falls off roughly as R^{-2}, where R is the distance from the Sun, we are concerned with Williamson's solution when the scattering medium is uniform but close to the observer rather than uniformly distributed between observer and source. If we consider the situation in which Jupiter is in the antisolar direction, the amount of temporal broadening of a Jovian signal from material at a distance z from the spacecraft is $\propto z\theta_\mathrm{s}^2 \propto z\Delta n_\mathrm{e}^4 \propto z/(R_0 + z)^4$, where R_0 is the distance of the spacecraft from the Sun.

This function peaks strongly at $z = R_0/3$, so to reflect this distribution we will model the number density of the IPM in the antisolar direction as uniform from 1 to 2 R_0 and zero thereafter. Provided that the Sun, the spacecraft and Jupiter are roughly aligned, the exact geometry is not critical to the general shape of the response function.

The form of a broadened pulse after passing through this model is shown in Figure 1c. Note the time axis scales as λ^4, so that long wavelength signals are strongly affected. Of course the preceding analysis is only correct when the overall scattering angle is reasonably small ($\theta_\mathrm{s} < 30°$) which, in turn, means that τ must be less than about 10 minutes. In the interplanetary medium, this restricts its validity to frequencies greater than 100 or 200 kHz. A suitable analysis for signals scattered over larger angles has not yet been attempted, although it is clear that once we consider back-scattering (and other) effects which occur as the frequency approaches the plasma frequency of the IPM (typically, about 25 kHz at 1 AU) the situation becomes much more complicated. We would not, however, expect to see much structure on timescales *less* than those expected at 200 kHz, so the preceeding analysis provides a lower limit.

3 Ulysses Antennae/Receivers

The URAP experiment has been described in detail by Stone et al. [1992a]. Observations close to Jupiter are reported by Stone et al. [1992b]. ULYSSES approached Jupiter from a Jovicentric declination $D_{\mathrm{s/c}}$ of about 1.5°, passing briefly into an extreme northerly declination before entering a southerly declination close to $-38°$ after encounter. The spacecraft then continued to south solar polar pass in June-October, 1994, and crossed the plane of the ecliptic into a northerly heliographic latitude in March, 1995. During this latter period and afterwards the spacecraft was at distances of 5 AU or more from Jupiter. The receivers cover two bands, from 1.25 to 48.5 kHz (lo-band) and from 52 to 940 kHz (hi-band). Hi-band operates in 12 channels, approximately logarithmically spaced, each frequency being determined by one of twelve crystal local oscillators. The intermediate frequency (IF) amplifier frequency is 10.7 MHz, the dynamic range about 70 dB and the bandwidth 3 kHz. Lo-band operates in 64 channels, arithmetically spaced at 0.75 kHz intervals. The IF amplifier frequency is 432.25 kHz, the dynamic range about 70 dB and the bandwidth 750 Hz. The receivers are connected to a 72 m wire antenna perpendicular to the spacecraft spin axis and to a 7.5 m monopole antenna along the spin axis. The spacecraft and the antenna system spin with a 12 s period. The inputs from the antennas can be combined to synthesize an equivalent dipole tilted with respect to the spin axis. By combining the inputs with suitable phase differences the polarization of the incoming waves can be determined [Manning and Fainberg, 1980; Stone et al., 1992b]. The sensitivity, when used in the separation mode [Stone et al., 1992a], is about $S_{\mathrm{min}} \simeq 10^5$ Jy. In the summation mode the sensitivity is down by about 10 dB.

4 Ulysses URAP Observations

Typical examples of spectra and fixed frequency cuts, relatively close to Jupiter [Barrow and Lecacheux, 1995] and at distances greater than 5 AU are shown in Figures 2 through 6. Figure 2 shows the spectra of a bKOM event, recorded in 1991, when Ulysses was approaching Jupiter at a distance of about 0.59 AU from the planet. Lo-band fixed frequency cuts across these same spectra are shown in Figure 3. The time resolution of both hi- and lo-band data sets is 144 s. Similar plots of a bKOM event, recorded in 1995, are shown in Figures 4 and 5, recorded when the spacecraft was at a distance of about 5.88 AU from Jupiter. Some structuring, which is inherent to the bKOM, can be seen in Figures 2 and 3 but this is less obvious in Figures 4 and 5. Presumably a certain amount of structuring has been smoothed out by the effects of temporal broadening over the greater distance travelled by the radiation through the IPM; of course, the intensity at the spacecraft is lower. Figures 2 through 5 are on a 10-hour time-scale and represent approximately one Jovian rotation. A fixed frequency plot of the same 1995 event is shown in Figure 6 where three adjacent lo-band frequencies (represented by dotted lines) are averaged and the time-scale expanded. Note that, in Figures 3, 5 and 6, the intensity scales are not the same for all frequencies.

The reason for averaging three consecutive lo-band frequencies is to remove most of the signal variation due to spinning of the spacecraft-antenna system; three frequencies are collected in six seconds, which is approximately one-half of the spacecraft spin period. The effectiveness of this can be seen from a comparison of the 47 kHz traces in Figures 5 and 6. In hi-band, the data at a given frequency are collected for 12 seconds; these data are averaged together and so there should not be any spin-modulation in this data. Inbound to Jupiter, close to 0.5 AU, there was little or no spin-modulation because Jupiter was close to the spin-axis of the spacecraft. Thus, most of the structural features shown in Figures 2 and 3 are probably intrinsic to the bKOM.

If we assume that the duration of the main peak of the emission in Figure 6 is the result of temporal broadening of the structured bKOM emission, we can assess the effects of interplanetary scattering over the known distance of Jupiter to Ulysses. Detailed examination of URAP data taken during the period January 1 through August 31, 1995, revealed some 10 bKOM events seven of which were suitable for detailed study. These are summarized in Table 1.

Figure 2: (plate, next page) Typical dynamic spectra of bKOM activity, recorded by URAP on 911126-27, when Ulysses was approaching Jupiter at a distance of about 0.59 AU.

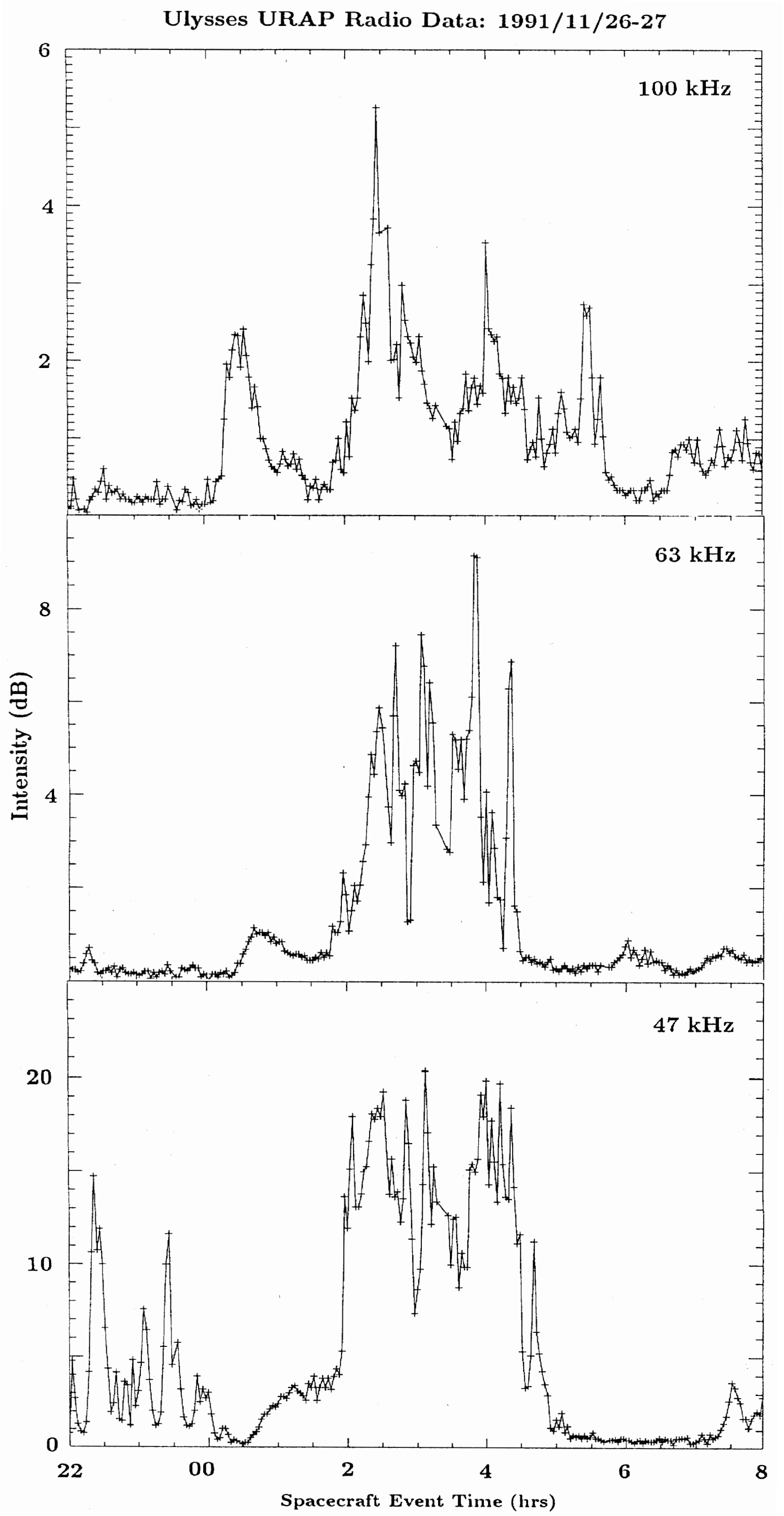

Figure 3: Fixed frequency plots of the event shown in Figure 2.

Figure 4: (plate, next page) Dynamic spectra of bKOM activity, recorded by URAP on 950707, when Ulysses was at a distance of about 5.88 AU from Jupiter.

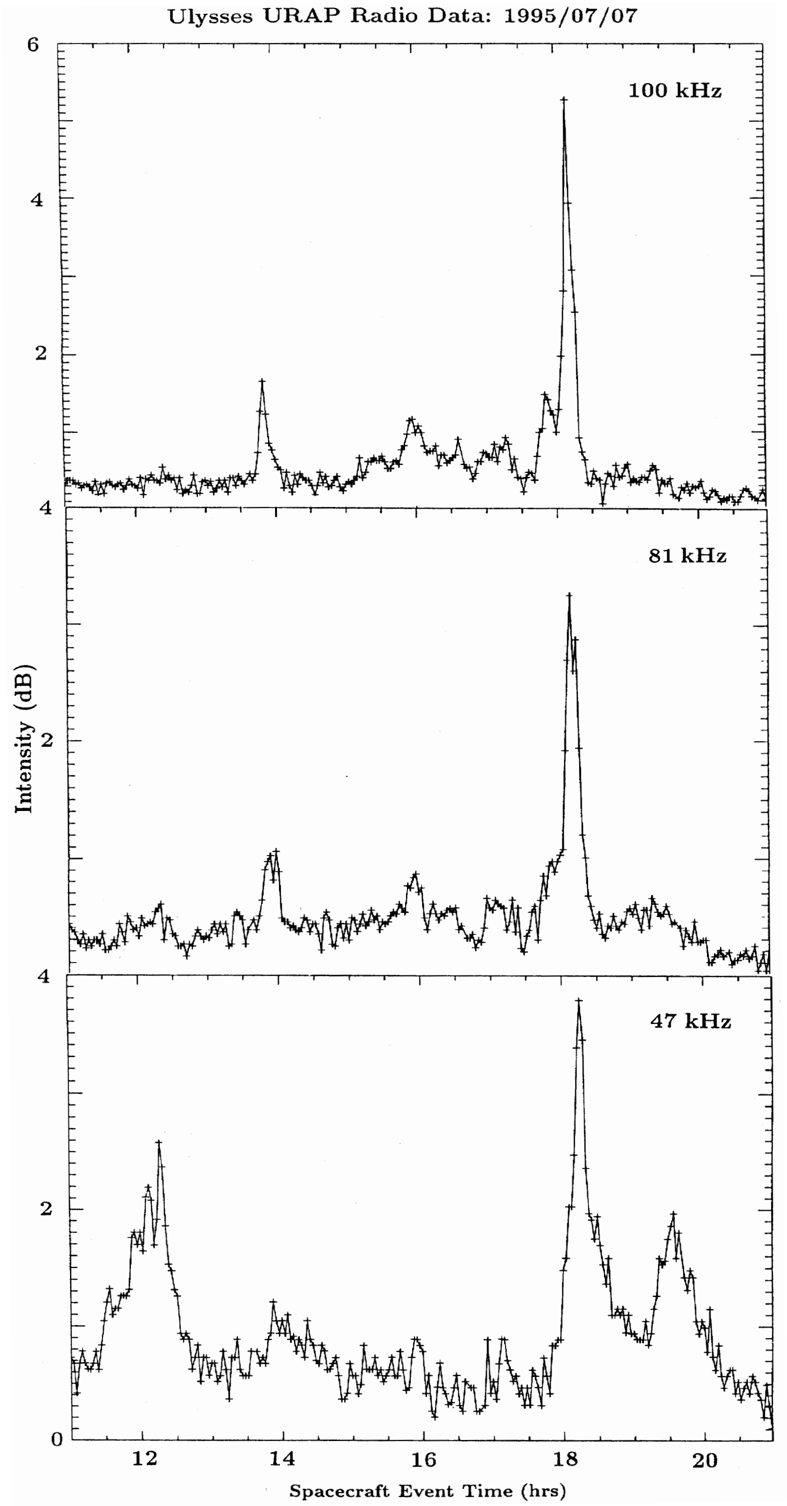

Figure 5: Fixed frequency plots of the event shown in Figure 4.

bKOM EVENTS OBSERVED BY ULYSSES

DATE YMD	APPROX SCET HHMM	HELC DIST (AU)	HELC LAT (Deg)	JUPITER DIST (AU)	JOVIC LAT (Deg)	NUMBER FREQS MEAS	STRUCTURE DURATION (min)					ELEC DENS (cm^{-3})
							47 (kHz)	63 (kHz)	100 (kHz)	148 (kHz)	196 (kHz)	
910928	1000-1030	4.28	1.4	1.08	5.4	12	14.1	8.5	-	-	-	0.3
911126	2215-2245	4.79	1.3	0.59	10.3	15	12.4	5.1	-	-	-	0.1
950102	1930-2030	1.55	-50.9	5.55	-12.6	20	24.3	15.8	8.5	2.8	-	1.0
950107	1300-1500	1.53	-48.0	5.55	-11.8	14	22.6	11.9	4.5	-	-	1.0
950123	1330-1430	1.45	-38.0	5.57	-9.2	17	36.2	20.3	10.7	5.7	4.0	1.2
950706	1930-2100	1.83	69.5	5.88	16.9	15	63.2	33.9	27.7	18.1	-	0.8
950707	1800-1830	1.84	69.6	5.88	17.1	17	16.4	11.3	7.9	8.5	4.5	0.8
950708	0230-0300	1.85	69.9	5.89	17.2	22	42.9	31.1	18.1	8.5	6.8	0.7
950802	1900-2000	2.02	77.6	5.99	19.2	19	19.2	17.5	8.5	7.9	8.5	0.6

Table 1: Characteristics of the bKOM events recorded in 1995. Two events from 1991, when Ulysses was closer to Jupiter, are also listed for comparison.

5 Measurements

The duration of the main peak can be measured at various frequencies from fixed frequency plots, of the type shown in Figure 6, with an expanded time-scale. In principle this seems simple enough but several problems arise as follows:

1. The main peak of activity often has ragged edges. Are these the remnants of some characteristic of the bKOM or, in the lo-band data, are they the remnants of spin-modulation?
2. How much of the outburst is Jovian and how much is background noise?
3. How is the actual duration of the outburst best assessed?

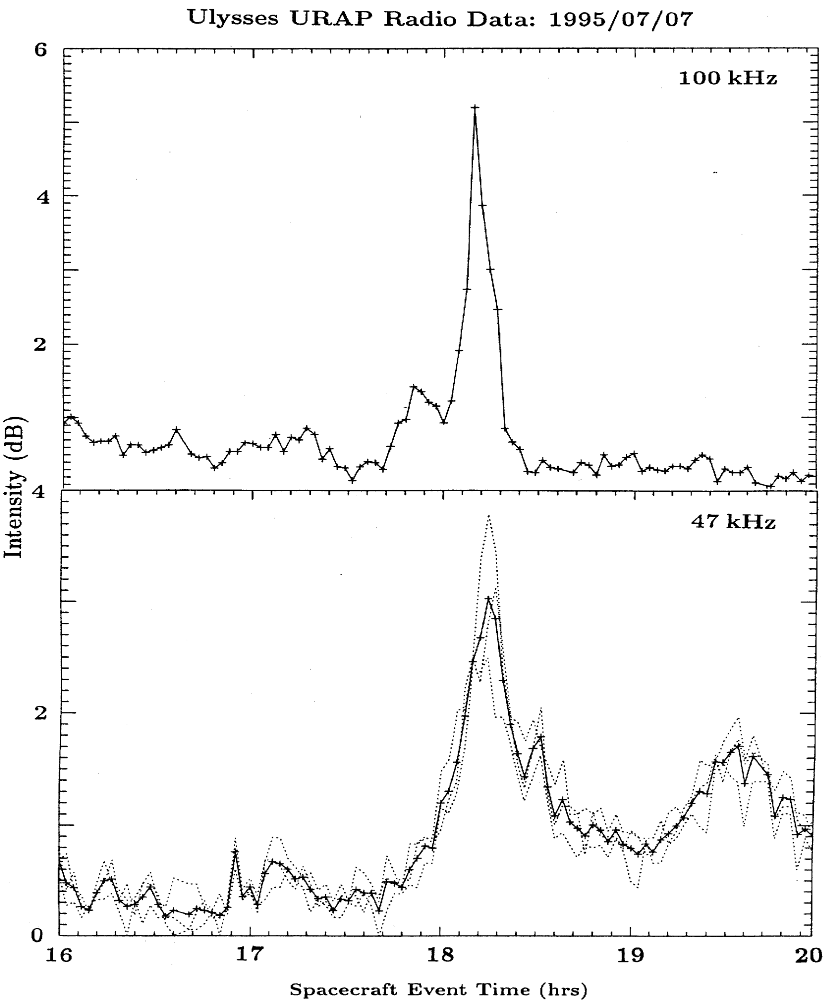

Figure 6: Expanded time-scale fixed frequency plots of the event shown in Figure 4. The half-height durations of the main peak are about 16 minutes at 47 kHz and 8 minutes at 100 kHz. The 47 kHz plot is average of three adjacent frequencies represented by dotted lines.

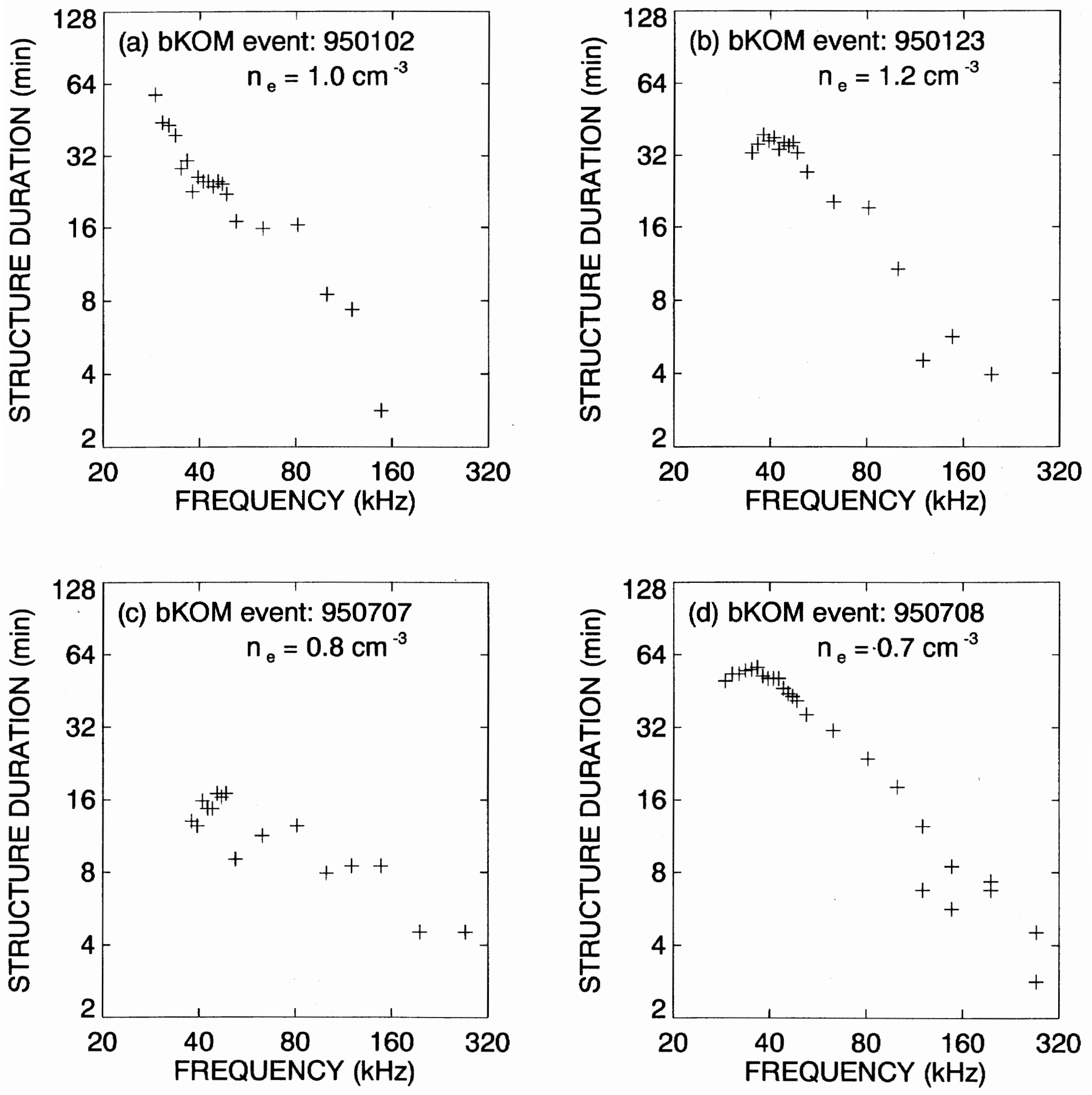

Figure 7: Frequency-structure duration statistics of four bKOM events recorded in 1995, when Ulysses was more than 5 AU from Jupiter.

Evidently some criteria are needed to establish a consistent method of measuring each event.

The first problem can be overcome, to some extent in lo-band, by plotting the average of three adjacent frequencies rather than an individual frequency, as described in the previous section. This can be seen in the 47 kHz plot, shown in Figure 6.

Some, but not all, of the ragged edges are smoothed out and possible effects of the spinning spacecraft and antenna are reduced. We have seen that this is not necessary in hi-band.

The background level is determined by inspection of the fixed frequency plots and the spectra. Adjustment of the colour scale for the spectra can indicate the beginning and the end of the main activity and this is compared with fixed frequency traces of the event. The background level is not necessarily the same for each frequency and it is usually different for hi-band and lo-band. The structure duration is measured at half-height above the background level from fixed frequency plots of the type shown in Figure 6. In hi-band, this is for all frequencies where the structure is clearly defined; in low band, alternate frequencies are measured. Structure durations are plotted against frequency in Figure 7.

6 Electron density measurements

The SWOOPS experiment on board Ulysses [Bame et al., 1992; Phillips et al., 1995] measured electron density in the vicinity of the spacecraft. Provided the spacecraft is on the Jupiter side of the Sun and not too far from the Sun-Jupiter line, the inverse square density gradient in the IPM will usually mean that it is this local material that dominates in the scattering process. The hourly-average value, at the time of the main bKOM event, is shown in each section of Figure 7 for comparison. These values represent the total electron density at the spacecraft.

All of the 1995 bKOM events were recorded when Ulysses was out of the plane of the ecliptic and so the electron densities and corresponding plasma frequencies will be lower than those characteristic of measurements made in the plane of the ecliptic. For the events of 950102 and 950707, the plasma frequencies were about 9 kHz and 8 kHz when the spacecraft was about 1.55 and 1.84 AU from the Sun and at heliocentric latitudes of -50.9° and 69.6°, respectively. The corresponding Jovicentric latitudes were about -12.6° and 17.1° at distances of about 5.55 and 5.88 AU, respectively, from Jupiter. The bKOM is beamed quite sharply [Leblanc, 1988] and the electron density at the spacecraft will be an indication of the close-to-observer density in the direction of Jupiter.

7 Discussion

Several points of interest arise out of the foregoing, as follows:

1. There seem to be two types of plot: (i) those like 950102 (Figures 7a,b and d), where the measured durations show a fairly clear increase with decreasing frequency, and (ii) those like 950707 (Figure 7c), where the decrease is much less pronounced. In both cases, however, the power law index appears to be considerably less than either 4.4 or 4.0.

2. As predicted, the 4.4-law has clearly broken down below 100 kHz, and there are structures with durations well below 42 minutes. We regard this as an indication of the limit to temporal broadening implied in Section 2.

3. There are indications (Figures 1b,c) that temporal broadening should impose a steeper leading edge than trailing edge on a structure, similar in fact to any unresolved radio burst. Most of the fixed frequency plots used for measuring structure duration show little or no indication of this asymmetry so far, suggesting that, even at distances greater than 5 AU, we may still be seeing bKOM structure durations intrinsic to the emission mechanism rather than temporal broadening in the IPM.

On the other hand, it is possible that at the hi-band kHz frequencies the asymmetry may not be detectable with the time resolution of 144 s, mentioned in Section 4. At lo-band frequencies, close to 47 kHz, the longer trailing edge may be obscured by the background.

4. It can be seen in Figure 7 that the measured durations may decrease towards the lowest frequencies. This is probably an intensity effect and a characteristic of the bKOM emission which can often be seen in the spectra (Figures 2 and 4, for example).

8 Conclusion

The existence of relatively rapid intensity fluctuations in the data below 100 kHz confirms the prediction that the power-law relationship between frequency and temporal broadening should break down at these low frequencies. The frequency range 200 kHz down to about 50 kHz is of particular interest and will be the subject of further study. To date, there has been no formal investigation of the intrinsic temporal characteristics of bKOM, observed sufficiently close to Jupiter for scattering effects to be negligible. Thus we have only been able to consider the apparent durations of the bKOM structures rather than infer possible increases in the durations observed at distances greater than 5 AU. The absence of asymmetry in the bKOM structures may be an effect of the temporal resolution available. On the other hand, it is possible that, so far, we may have seen mostly the intrinsic durations of the bKOM structures rather than any increase in these durations due to scattering in the IPM. We hope to investigate the intrinsic durations of the bKOM structures and to address this problem in the future.

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