

Scattering of Interplanetary Radio Waves at Kilometric Wavelengths

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Abstract

We report on measurements of the angular size of Jovian radio sources measured by the URAP instrument on the Ulysses spacecraft. The angular size is found to be substantially larger than that expected from the geometric size of the source, which is essentially a point source when viewed from Ulysses. This increase in size is due to scattering of the radio waves caused by fluctuations in the electron density along the path of the radiation. The angular size varies with wavelength as expected for such scattering, and the magnitude of the scattering is in rough agreement with, though less than, results of previous investigations in the slow solar wind. The magnitude of the scattering is found to vary substantially for different radio events, most likely due to changes in the density and/or fluctuation level along the path of the radiation. These measurements are especially suited to determining scattering parameters as the source is point-like and precisely located. Our results confirm that interplanetary scattering imposes important constraints on low frequency radio observations by new spacecraft missions.

1 Introduction

Radio waves in space are scattered by variations in the refractive index due to electron density inhomogeneities along the path of propagation. This effect can cause information about the spatial and temporal properties of the radio source to become degraded or completely lost. This information is in itself important and is often crucial in determining such things as the generation mechanism of the radio source. Thus, knowledge of scattering effects is important in analyzing data from current experiments and will be even more important for new missions, since many of them propose to perform imaging of radio sources and scattering will cause degradation of the images. Many studies have examined the effects of interstellar scattering on sources such as pulsars and quasars [*Lang*, 1971; *Rickett*, 1990]. In the interplanetary medium, observations of solar type

III radio bursts [Steinberg *et al.*, 1971; 1984; 1985] showed that scattering can affect the angular size, brightness, and arrival time of the radiation. Calculations have been made of scattering effects on 2-3 kHz radiation from sources thought to be located in the outer heliosphere [Cairns, 1995; Armstrong *et al.*, 2000]. Interplanetary scattering has also been studied for its effect on the temporal broadening of Jovian broadband kilometric (bKOM) bursts [Barrow *et al.*, 1998]. We report on one effect of scattering - an increase in the apparent angular size of a radio source beyond that due to its geometric size. Since all radio sources are subject to this effect, it sets a frequency dependent limit on how well the size of a radio source can be measured, and to a lesser extent, its direction. This is analogous to the well-known effect of air turbulence that reduces the resolution of terrestrial optical telescopes. While the scattering may degrade some measurements, it can also act as a probe of certain properties of the interplanetary medium since the amount of scattering that occurs depends on the amplitude and spectrum of density fluctuations along the path of the radio waves.

We studied Jovian narrowband kilometric (nKOM) emissions using data from the Unified Radio and Plasma Wave (URAP) instrument [Stone, 1992] on the Ulysses spacecraft. Although Jupiter emits several types of radiation within the receiving bands of the URAP instrument, nKOM was found to be the most suitable for this study because it is quite smooth temporally and did not vary appreciably during a spacecraft rotation (in contrast to, e.g., bKOM). These measurements are especially suited for the study of interplanetary scattering as the source is point-like and precisely located.

2 Data Analysis

The Radio Astronomy Receiver (RAR), part of the URAP instrument, provided the data for this study. The high frequency band of the RAR has 12 logarithmically spaced frequency channels covering the range from 52 to 940 kHz. Ulysses is a spinning spacecraft with a period of 12 seconds, and signals from the wire dipole antenna located in the spin plane of the spacecraft were used in the following analysis. The radio source, as seen from the spacecraft, was modeled as a circular disk of uniform intensity subtending a half-angle γ . As the spacecraft spins, the signal on the antenna is modulated and the amount of modulation depends on two quantities, γ and θ , where θ is the angle between the center of the source and the direction of the spin axis. The intensity of the signal is found to be [Fainberg *et al.*, 1985] proportional to $1 + m \sin(2(\phi - \phi_s))$ where ϕ is the spacecraft rotation angle, ϕ_s is a phase angle that depends on the source location, and m is the quantity $(3D \sin^2 \theta)/(8 + 2D - 3D \sin^2 \theta)$, where $D = \cos \gamma + \cos^2 \gamma$. We measure the intensity of the signal vs. ϕ , and can determine ϕ_s from the phase of the sine wave. The angles γ and θ cannot be determined independently from these measurements and therefore we fix θ by assuming that the source is located in the direction of Jupiter. We verify that the source is indeed Jovian by ensuring that ϕ_s is the value expected for

a Jovian source. Then, the amount of modulation allows m , and thus γ , to be determined.

3 Predicted Angular Source Size

The amount of scattering along the path of the radiation can be calculated using a statistical approach. Following previous studies [Holweg, 1970; Steinberg *et al.*, 1985; Lacombe, 1997; Lee and Jokipii, 1975; Rickett, 1977; Rickett, 1990], we assume the radio wave is scattered by variations in the index of refraction caused by random fluctuations in the electron density along the propagation path. We further assume that these fluctuations are isotropic and can be described by a distribution function which is the Fourier transform of the two-point correlation function of the density. To determine the scattering, either a geometrical optics method or a parabolic wave equation method can be employed, both methods yielding equivalent results [Cairns, 1998]. The mean square angular deviation of a ray per unit path length in the scattering medium, b , is given by [Holweg, 1970; Lacombe, 1997; Cairns, 1998]:

$$b = \frac{r_e^2 \lambda^4}{\mu^4} \int_0^\infty P(q) q^3 dq \quad (1)$$

where r_e is the classical electron radius, λ is the wavelength of the radiation, μ is the mean index of refraction, q is the wave number of density fluctuations, and P is the spectral density of electron density fluctuations. Since we have assumed that the fluctuations are isotropic, P depends only on the absolute value of the wave number and not its direction. Furthermore, in the situation that we will be analyzing, $f \gg f_p$ (where f is the frequency of the radiation and f_p is the plasma frequency) everywhere along the path of propagation except very near to the source, so that $\mu = 1 - f_p^2/f^2$ can be taken to be 1.

Equation 1 shows the dependence of the scattering on the fluctuation spectral density. The form of P has been the subject of numerous studies. It has been determined by spacecraft measurements [Woo and Armstrong, 1979; Celnikier *et al.*, 1983; Celnikier *et al.*, 1987; Marsch and Tu, 1990; Lacombe *et al.*, 1997] and by scintillation measurement of interstellar sources [Coles and Harmon, 1989; Manoharan *et al.*, 1994]. These measurements have shown that $P(q)$ can usually be approximated by a power law, $P(q) \propto q^{-\beta}$, over an interval determined by two scale lengths, an inner scale ℓ_i and outer scale ℓ_o . The spectrum is approximately flat for $q < 2\pi/\ell_o$ and falls rapidly for $q > 2\pi/\ell_i$. The exponent in the power law is often found to be near the Kolmogorov value (in three dimensions) of 11/3.

The magnitude of the fluctuations can be characterized by the mean square value of the density fluctuations:

$$\langle \delta_N^2 \rangle = 4\pi \int_0^\infty P(q) q^2 dq. \quad (2)$$

Here δ_N is the density fluctuation level. To calculate the mean-square angular source size, $\langle \chi^2 \rangle$, measured by an observer some distance from the source, we integrate along the path of the ray between the source and observer [Williamson, 1972; Blandford and Narayan, 1985; Bastian, 1994]:

$$\langle \chi^2 \rangle = L^{-2} \int_0^L b(z) z^2 dz. \quad (3)$$

Here, $z = 0$ is located at the source, and L is the distance from the source to the observer. This formula is appropriate for a spherical wave emitted by a point source. We have taken b to be a function of z since conditions in the interplanetary medium can vary along the propagation path. We assume for the fluctuation density spectrum the following form (this is the same as that used by Holweg [1970]):

$$P(q) = \left\{ \begin{array}{ll} C_N^2 q_o^{-\beta} & q < q_o \\ C_N^2 q^{-\beta} & q_o < q < q_i \\ 0 & q > q_i \end{array} \right\}. \quad (4)$$

where $q_o = 2\pi/\ell_o$ and $q_i = 2\pi/\ell_i$. C_N^2 is the level of fluctuation and is taken to be independent of q . Using Equation 2, and the fact that $\ell_o \gg \ell_i$, we find that:

$$C_N^2 \approx \frac{3(\beta - 3)}{4\pi\beta} q_o^{\beta-3} \langle \delta_N^2 \rangle. \quad (5)$$

Carrying out the integration in Eq. 1 and assuming the Kolmogorov value of 11/3 for β yields:

$$b = \frac{9}{22\pi} r_e^2 \lambda^4 q_o^{2/3} q_i^{1/3} \langle \delta_N^2 \rangle. \quad (6)$$

The quantities q_o , q_i , and δ_N may vary along the propagation path. For simplicity, we assume they vary only with heliocentric distance, R . The ratio δ_N/N has been found to be approximately constant, independent of heliocentric distance [Bastian, 1994], so $\delta_N^2 \propto N^2$, which varies as $1/R^4$.

The values of the fluctuation spectrum that were determined by interstellar scintillation were determined at distances quite close to the sun. Most of the spacecraft values were measured at 1 AU [Celnikier *et al.*, 1983; Celnikier *et al.*, 1987; Marsch and Tu, 1990; Lacombe *et al.*, 1997] or closer to the Sun [Woo and Armstrong, 1979; Marsch and Tu, 1990]. The inner scale of turbulence was found to increase approximately linearly with radial distance from the Sun, so q_i will vary as $1/R$. The outer scale is difficult to determine, and its behavior with R is unknown. Steinberg *et al.* [1985] assumed that q_o also varied as $1/R$, with the result that $b(R)$ varied as R^{-5} . We will assume that q_o is independent of R , so that $C_N^2 \propto R^{-4}$ and $q_i \propto R^{-1}$ giving $b \propto R^{-13/3}$. These values for the variation with R are the same as those used by Armstrong *et al.* [2000]. The values for the fluctuation levels must be extrapolated from where they have been measured. To explicitly show the R dependence of b , we express equation 6 as:

$$b(R) = \frac{9}{22\pi} r_e^2 \lambda^4 q_{o,R_0}^{2/3} q_{i,R_0}^{1/3} \langle \delta_N^2 \rangle_{R_0} (R_0/R)^{13/3}. \quad (7)$$

Here, R_0 is a particular heliocentric distance and q_{i,R_0} , q_{o,R_0} , and $\langle \delta_N^2 \rangle_{R_0}$ are the values of those quantities at R_0 .

Performing the integral in equation 3 along a straight path between the source (Jupiter) and the observation point (Ulysses), and using the above value for b , yields

$$\langle \chi^2 \rangle = \frac{9}{22\pi} r_e^2 \lambda^4 q_{o,R_0}^{2/3} q_{i,R_0}^{1/3} \langle \delta_N^2 \rangle_{R_0} R_0^{13/3} I \quad (8)$$

where L is the path distance and I is given by:

$$I = L^{-2} \int_0^L |(\mathbf{U} - \mathbf{J})(z/L) + \mathbf{J} - \mathbf{S}|^{-13/3} z^2 dz \quad (9)$$

where \mathbf{U} is the position of Ulysses, \mathbf{J} is the position of Jupiter, and \mathbf{S} is the position of the Sun.

We made measurements of the apparent angular size of several nKOM events in 1993, 1994, and 2002 when Jupiter and Ulysses were separated by 4.4 to 5.3 AU. Since nKOM radiation is generated close to the planet, it is effectively a point source at these distances (for example, the angular size of the Io plasma torus is less than one degree) and the measured angular size is completely due to the scattering.

4 Results and Discussion

Figure 1 contains dynamic spectrum plots of four nKOM events showing the intensity of the radio signal received by URAP as a function of frequency and time. The nKOM events are in the frequency range 50–200 kHz and usually last for 1–2 hours. Figure 2 is an example of the raw data from one nKOM event on 2002-05-23 at six different frequencies. Both solar and Jovian radiation is present. The sun was only a few degrees from the spin axis so the signal from solar events is modulated very little by the spacecraft rotation, while Jupiter was 75 degrees from the spin axis, producing large amounts of modulation. The nKOM event occurs between 1900 and 2030 hours at 196 kHz and extends from 1600 to 2100 hours at 52 kHz. The solar events peak at 1615 and 1815 hours in the 196 kHz plot. Equation (8) shows that the scattering angle is proportional to the square of the wavelength, and this effect can be clearly seen in the plots of the nKOM event. At the highest frequency, the modulation is close to 100%, the signal dropping to the background level when the antenna is aligned most nearly in the direction of Jupiter. As the frequency decreases, the percentage modulation also decreases, indicating a larger source size. At the lowest frequency, the modulation is significantly smaller and the signal does not reach the background level.

Table 1 is a summary of the results of analyzing a number of nKOM events. We have chosen events that occurred while the URAP instrument was in a mode of operation that allowed the analysis described in section 2 to be performed most accurately. That mode was used infrequently during the mission and not at all during the in-ecliptic phase before February 1992. For each event and

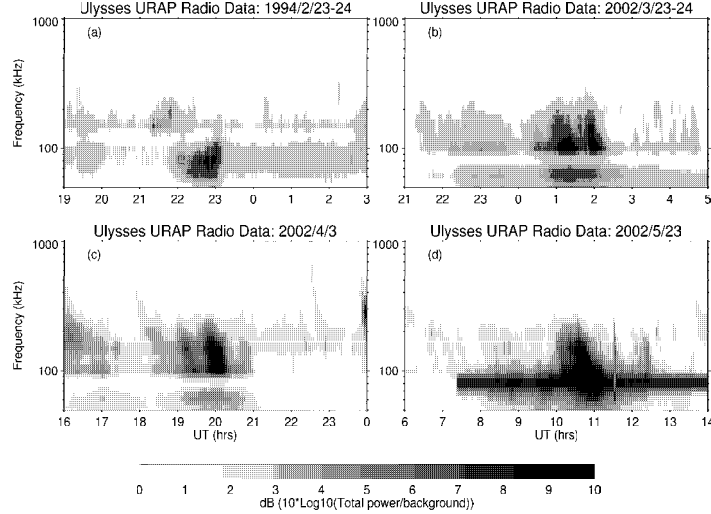


Figure 1: Dynamic spectrum of four nKOM events. The color indicates the intensity of the radio signal relative to the background level. The abscissa in each plot is the time of day in hours. The events analyzed are centered at: (a) 22:30, (b) 01:30, (c) 20:00, and (d) 10:45. The URAP instrument has only 12 frequency channels in the range shown, so the data have been interpolated in frequency. There is intermittent interference from other instruments at 80 and 100 kHz, which has been subtracted out in (a), (b), and (c).

frequency an estimate of the source size and its error is given. A blank entry indicates that the nKOM signal was absent or too weak to analyze. These data were taken when Ulysses was out of the plane of the ecliptic. Figure 3 shows the trajectory of Ulysses and the location of Ulysses during the analyzed nKOM events. In 1994 Ulysses was approximately 2.5 AU below the ecliptic at a heliolatitude of -50 to -74 deg., and in 2002 it was about 2.5 AU above the ecliptic at a heliolatitude of about 44 to 50 deg. Thus the path of the radio signals passed from a point in the ecliptic (Jupiter) to regions far above or below it. Therefore, estimates of the fluctuation spectrum must take into account the possible effects of heliolatitude.

Because of the $R^{-13/3}$ dependence of the scattering coefficient, the amount of scattering will be weighted strongly at points nearest the Sun. Table 1 also shows the radial distance to the Sun at the point along the signal path that is closest to the Sun. All of these distances are greater than 2.5 AU so that our knowledge of the fluctuation spectrum must be extrapolated substantially beyond where nearly all of the measurements of it have been made - at or within 1 AU of the Sun.

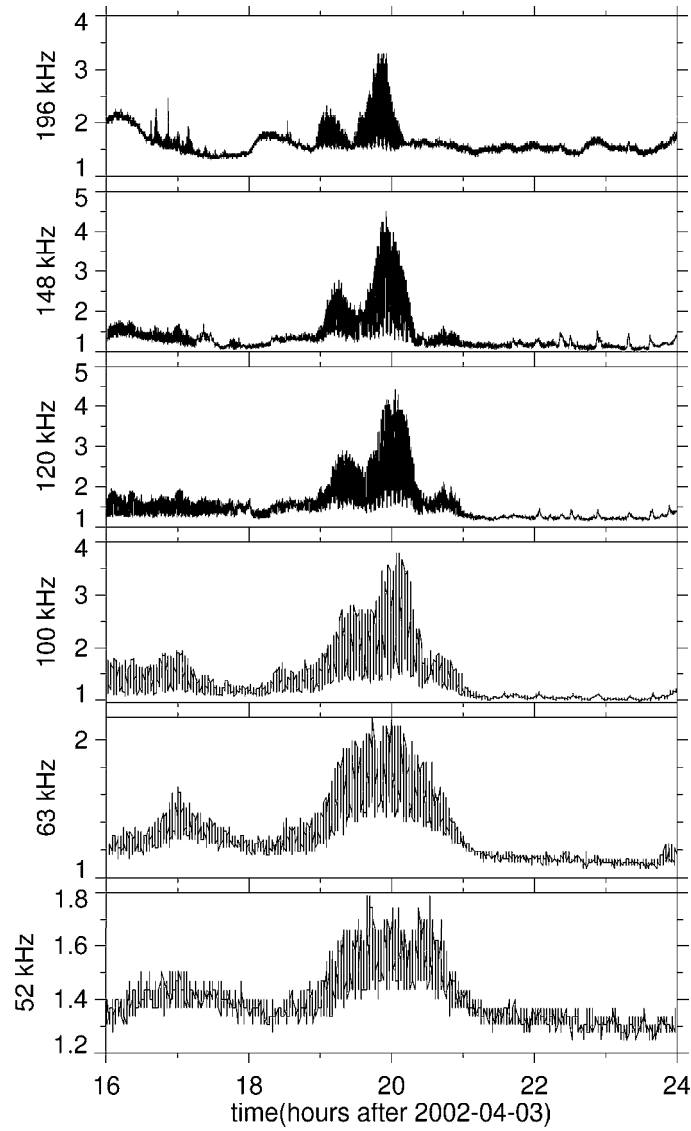


Figure 2: Radio wave signal intensity for an nKOM event. Data at six frequencies are shown. The plots are labeled on the left with the frequency in kHz. The Y axis is the signal intensity (on a linear scale) in relative units. The X axis is spacecraft event time. Note that the signal is sampled more often at higher frequencies, explaining the “denser” look of the signal.

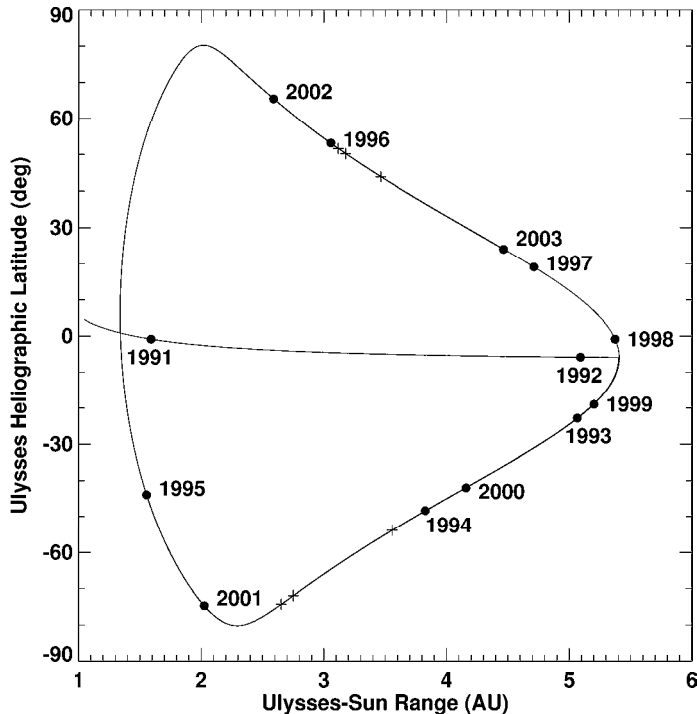


Figure 3: Trajectory of Ulysses spacecraft. The filled dots indicate the location of Ulysses on January 1 of the specified year. The crosses indicate the location of Ulysses on the dates of the nKOM events given in Table 1. The abrupt change in the trajectory in February 1992 was due to a Jovian gravity-assist maneuver.

Date	Freq(kHz)							$R_{min}(AU)$	$C_N^2(10^6 \text{ m}^{-20/3})$ at 1AU
	52	63	81	100	120	148	196		
1994-02-23	5 ± 5	5 ± 5	8 ± 7					3.48	<0.04
1994-07-08	22 ± 5							2.69	0.05
1994-07-23			30 ± 3	20 ± 9				2.59	0.55
2002-03-24	44 ± 7	38 ± 5		16 ± 4	12 ± 3	14 ± 4		3.07	0.70
2002-04-03	50 ± 5	43 ± 3		19 ± 3	14 ± 2	6 ± 6	5 ± 5	3.13	0.97
2002-05-23	26 ± 4	19 ± 3	14 ± 6	11 ± 3	11 ± 3	10 ± 3	15 ± 8	3.42	0.25

Table 1: Source size (angular half-width in degrees) for nKOM events at different frequencies. The next to last column is the minimum distance of the signal path from the Sun. The last column is the density fluctuation spectrum coefficient at a heliocentric distance of 1 AU.

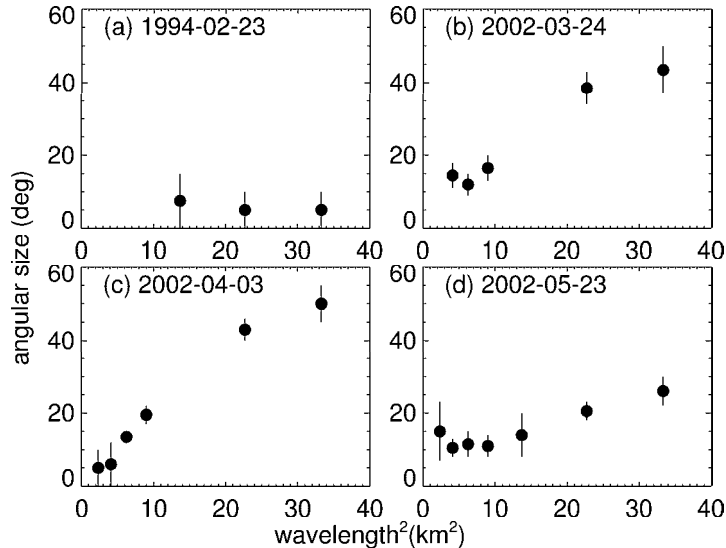


Figure 4: Plot of angular half-width source size vs. square of radio wavelength for four nKOM events. The vertical lines represent the measured values, and indicate estimates of the error in the measurements. Each plot contains the date of the event.

Figure 4 shows plots of scattering angle versus wavelength squared for the four events shown in Figure 1. If the theory is correct, the data points should fall on a straight line that passes through the origin. The data values are consistent with such an interpretation, although the values at both short and long wavelengths don't fit very well for some events. These discrepancies may be explained by the fact that at small angular sizes the results are more sensitive to errors in the background value chosen, and at the largest sizes a saturation effect may be responsible as the radiation covers a significant fraction of the sky. The events in Table 1 for the dates 1994-07-08 and 1994-07-23 have too few data points to provide any information in regards to the dependence of the scattering angle on wavelength, so our conclusions are based upon the last three events in Table 1.

Plot (a) in Figure 4 is of special interest. The scattering of the radiation for this event is very small. An important question is why little or no scattering was observed for this event while substantial scattering was seen for other events when the Jupiter-Ulysses distance and geometry was quite similar. From (8), it can be seen that $\chi \propto \langle \delta_N^2 \rangle^{1/2}$, so a substantial drop (by a factor of 4-5) in the fluctuation level could explain the absence of significant scattering in this case. Since we have assumed that $\delta_N \propto N$, a drop in δ_N could be due to a drop in either the magnitude of N or a drop in the relative level of fluctuations.

Either of these are a possibility. The density in the interplanetary medium varies substantially with time, and occasionally drops to very low values. Also fluctuation levels are undoubtedly affected by various phenomena occurring in the interplanetary medium such as shock waves, and coronal mass ejections. The presence of the heliospheric current sheet should also have an effect on the fluctuation level. If the radiation happens to follow a path where these disturbances are absent, or of low level, weak relative fluctuations are also to be expected.

Table 1 also shows calculated values for C_N^2 at 1AU using the measured values for the scattering angle, an inner scale length of 160 km at 1AU, and Equations 5 and 8. These values have a large variation and are all smaller than the value of 1.8×10^6 given by *Armstrong et al.* [2002] for fluctuations measured by interplanetary scintillations in the ecliptic plane. A likely explanation for these results is the low level of fluctuations in the high speed solar wind from coronal holes. *Coles et al.* [1995], using interplanetary scintillations, found a density variance 15 times lower in polar streams than near equatorial regions. *Huddleston et al.* [1995], using data from IEEE 3, measured electron density variance in interaction regions that were ~ 13 times higher than solar wind from coronal holes. The lower electron density in the high speed wind will also tend to decrease the amount of scattering through its effect on the inner scale. The physical processes believed to be the source of damping of the density fluctuations lead to an inner scale that is proportional to $N^{-1/2}$ [*Coles and Harmon*, 1989]. This causes an increase in the inner scale length, and hence less scattering, at lower densities.

The quantitative effect of these phenomena on the scattering angle is difficult to determine without a detailed knowledge of plasma conditions along the entire path from Ulysses to Jupiter. During 1994 Ulysses was continuously embedded in the high speed polar wind. The situation in 2002 was more complex as Ulysses was passing alternately through regions of fast and slow wind. Therefore, the path of the path of the radio signal probably passed through a longer region of slow solar wind during 2002 than in 1994, and this may account for the generally higher values of C_N^2 during 2002. The value of C_N^2 is also affected by the radial dependence of q_i and C_N^2 . For instance, if $b \propto R^{-5}$ rather than $R^{-13/3}$, the values of C_N^2 in Table 1 would be raised by a factor of ~ 2 .

5 Conclusions

We have measured the effects of interplanetary scattering on the angular size of Jovian nKOM radio events. The measurements show the size to be proportional to the square of the wavelength, as predicted by theory. The fluctuation level, determined from the angular size of the radio events, is highly variable, most likely due to the path of the radio signal passing through regions of different densities and speeds of solar wind. The level of fluctuations is consistent with other measurements made when account is taken of uncertainties due to extrapolation of parameters from inside 1AU to 5AU, and the varying solar wind

conditions along the propagation path of the radio signals.

Scattering of this type could lead to considerable constraints on spacecraft missions designed to produce radio images at low frequencies, or ones that use multiple spacecraft to obtain three dimensional information about radio sources. Any substantial scattering would cause points on an extended source to appear as a disk. This would degrade an image or three dimensional structure under observation.

The data presented here show that the magnitude of scattering can vary with time, most likely due to changes in electron density or fluctuation levels along the propagation path. Thus the impact that scattering will have on observations may also vary with time. Further studies of this variability will be needed to clarify its cause and its dependence on the presence of solar wind structures, such as the heliographic current sheet or CMEs, and variations due to differences in scattering strength for fast and slow solar wind.

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