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Solar wind velocity measurements near the sun using *Ulysses* radio amplitude correlations at two frequencies

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Abstract

Measurements of solar wind velocity have been derived from simultaneous coronal sounding observations of radio amplitude scintillations at both S-band and X-band during the solar conjunction of the *Ulysses* spacecraft in August 1991. The signal amplitude was recorded with an averaging time of 1 s. A cross-correlation analysis between S- and X-band amplitude fluctuations shows that the fluctuation signature at S-band appears to be shifted to earlier times with respect to the X-band recording. The time difference is proportional to the coronal separation of the ray paths and inversely proportional to the apparent velocity of plasma inhomogeneities across the ray paths. Preliminary estimates of solar wind speed obtained using model calculations of the differential refraction are found to lie near the expected transition from subsonic to supersonic velocities at solar offset distances of the order of 6–8 $R_{\odot}$. As a byproduct of the investigation, we find that the transition from weak to saturated scintillation occurs at about 16 $R_{\odot}$ for S-band and 7 $R_{\odot}$ for X-band.

Keywords: Solar corona; Radio sounding; Solar wind velocity; *Ulysses* spacecraft

1. Introduction

Studies of the solar wind motion in its initial acceleration (formation) region (roughly, at heliocentric distances less than 10 $R_{\odot}$) suffer from a lack of applicable diagnostic techniques. Many of the conventional radio scattering methods lose their validity under the near-Sun conditions. In general, scintillation observations require the use of very short wavelengths to retain validity of the weak scattering approximation (Scott et al., 1983). The strong anisotropy of the irregularities, however, creates significant uncertainty in the determination of the apparent velocity from intensity fluctuation spectra (Efimov et al., 2000). Another technique is the simultaneous recording of intensity fluctuations at two ground stations spaced at distances of the order of the Fresnel zone. At present, only a single series of such observations was carried out close to the Sun using the NRAO-VLA, which utilizes 27 antennas in a

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suitably-arranged baseline configuration for operation in L-, C- and U-band (Armstrong et al., 1986). Two-station observations of frequency fluctuations, which are not subject to the Fresnel zone limitation of the ray path separation, have other difficulties. In particular, since the spectral index of the spatial inhomogeneity spectrum tends to the value $p = 3$ at small solar distance, the cross-correlation of the frequency fluctuations becomes negligibly small (Armand et al., 2003).

This paper presents dual-frequency amplitude scintillation data acquired during the 1991 *Ulysses* solar conjunction (referred to as C1 in the following). Preliminary estimates of solar wind velocities in its formation region ($R < 10\ R_\odot$) are obtained from dual-frequency amplitude cross-correlations recorded at a single ground station. The technique exploits the differential refraction and resulting ray path separation of the radio signals at S- and X-band.

2. Amplitude measurement data processing

The amplitudes of the S- and X-band signals of the *Ulysses* spacecraft were recorded during solar conjunction at an averaging time of 1 s. The values of the signal amplitude are recorded in the form

$$x_i = 20\log(A_i/A_{\rm ref}), \tag{1}$$

where A_i is the ith measurement of signal amplitude, and $A_{\rm ref}$ is some reference level (typically -140 dBm at X-band and -155 dBm at S-band, where the unit dBm gives the power in decibles referred to 1 mW). In accordance with scintillation theory, it is preferable to convert this quantity to a parameter of the form

$$y_i = \ln(A_i/A_0), \tag{2}$$

where A_0 is the average value of the signal amplitude for a given segment of the recording, containing a total of N points. It may be shown that

$$A_i/A_{\rm ref} = \exp\left[\frac{\ln 10}{20}x_i\right], \tag{3}$$

$$A_0 = \frac{1}{N}A_{\rm ref}\sum_{j=1}^{N}\exp\left[\frac{\ln 10}{20}x_j\right]. \tag{4}$$

From which it follows that

$$y_i = \frac{\ln 10}{20}[x_i - x_0] - \ln\left\{\frac{1}{N}\sum_{j=1}^{N}\exp\left[\frac{\ln 10}{20}(x_j - x_0)\right]\right\}, \tag{5}$$

where

$$x_0 = \frac{1}{N}\sum_{j=1}^{N}x_j, \tag{6}$$

is the average signal amplitude over the data record of question. The initial amplitude measurements recorded in the form of Eq. (1) are thus converted to the parameter defined in Eq. (5) for subsequent analysis.

If the fluctuations are weak, such that $A_i \simeq A_0 + \delta A_i$ and $y_i = \ln(A_i/A_0) \simeq \delta A_i/A_0 = \delta I/2I$, where I is the signal intensity, then the second term in Eq. (5) can be neglected and we obtain

$$y_i = \frac{\ln 10}{20}[x_i - x_0]. \tag{7}$$

In this case the rms value of the fluctuations $2y_i$ over a given time interval is essentially the well-known scintillation index.

3. Amplitude fluctuation study results: *Ulysses* C1

3.1. Spectral analysis and radial dependence

As an example, simultaneous measurements of *Ulysses* S- and X-band signal amplitude fluctuations, recorded at the Goldstone (DSS 14) and Canberra (DSS 43) ground stations on 24 August 1991, are presented in Fig. 1. The radio ray path was located on the west solar limb (egress) at a mean solar offset of $\langle R\rangle = 11.4\ R_\odot$ and heliolatitude $\langle\theta\rangle = 24°$.

The curves in Fig. 1 are one second averages of y_i converted from the initial measurement data x_i. Noting that the ordinate scale for each panel is the same, the S-band fluctuations are clearly stronger than at X-band. It may be seen that these data, which were processed according to the method outlined in the previous section, do not display the large deviations of signal intensity encountered in earlier work (Efimov et al., 2003).

Temporal spectra of the signal amplitude fluctuations, calculated with a standard FFT-1024 algorithm, are shown in Fig. 2. As seen in all cases, the spectral density $G_{yf}(\nu)$, with $f = s,\ x$, is roughly constant, i.e., $G_{yf}(\nu) \simeq G_{y0f}$, where G_{y0f} is defined as the mean level for fluctuation frequencies in the range $0.02\ \text{Hz} < \nu < 0.3$ Hz. This is consistent with the theoretical behavior of amplitude scintillation spectra at low frequencies, which predicts a power-law falloff at both S- and X-band only at temporal frequencies $\nu > \nu_{\rm F}$, where $\nu_{\rm F} = V_{\rm app}/d_{\rm F} \gtrsim 1$ Hz is the Fresnel frequency for an apparent pattern velocity $V_{\rm app}$ and a Fresnel scale size $d_{\rm F} \simeq 773\sqrt{\lambda}$ km (with λ in meters). Fig. 3 shows the radial dependence of this characteristic amplitude fluctuation level, $G_{y0f}, f = s,\ x$, on a log–log scale. The measurements for S-band are presented as filled circles; X-band data are plotted as open triangles. The change of scintillation regime from weak to saturated is clearly seen in Fig. 3. The heliocentric distance of this transition is about 16 $R_\odot$ at S-band and 7 $R_\odot$ at X-band. Both sets