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Measurements of stray antenna capacitance in the STEREO/WAVES instrument: Comparison of the measured voltage spectrum with an antenna electron shot noise model

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[1] One of the most accurate techniques for in situ measuring the electron density and temperature in space plasmas is the quasi-thermal noise spectroscopy, which uses the voltage fluctuation spectrum on an electric antenna. This technique has been used successfully on the WIND and ULYSSES spacecraft; however, on STEREO this technique may only work in high-density filamentary structures, where the Debye length is small, because the STEREO/WAVES antennas have a large surface area, so that the resulting shot noise spectrum in the solar wind dominates the power at lower frequencies. In the unperturbed solar wind, we can use instead the electron shot noise to infer the plasma density. For doing so, we use well calibrated WIND particle data to deduce the stray capacitance of the STEREO/WAVES antenna system in a special configuration when the STEREO-B spacecraft was just downstream of WIND. This stray capacitance is also compared to ground experiments done on the flight spare equipment and independent calibrations performed using the galactic radio background.

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1. Introduction

[2] The WAVES instrument on the STEREO spacecraft [*Bougeret et al.*, 2008], hereafter STEREO/WAVES or S/WAVES, was designed to study solar radio emissions and solar wind plasma waves. An indirect but very accurate technique for measuring in situ the electron density and temperature in space plasmas is the quasi-thermal noise (QTN) spectroscopy [*Meyer-Vernet*, 1979], which is immune to the limitations due to spacecraft charging and photoelectrons [*Salem et al.*, 2001]. When a passive electric antenna is immersed in a stable plasma, the thermal motion of the ambient particles produces electrostatic fluctuations, which can be adequately measured with a sensitive wave receiver connected to a wire dipole antenna. This QTN is primarily determined by the particle velocity distributions in the frame of the antenna. In the absence of a static magnetic field or at frequencies much higher than the electron gyrofrequency (as in the solar wind at 1 AU), the QTN spectrum around the plasma frequency f_p consists of a noise peak just above f_p produced by electron quasi-thermal fluctuations. Since the plasma density n_e is proportional to f_p^2, this allows an accurate measurement of the electron density. In addition, since the shape of the spectrum is determined by the electron velocity distribution, the analysis of the spectrum reveals its properties, such as the temperature and the properties of the suprathermal electrons [*Meyer-Vernet and Perche*, 1989; *Chateau and Meyer-Vernet*, 1991; *Zouganelis*, 2008].

[3] On STEREO, this technique is only meant to work in high-density filamentary structures (when the Debye length is small), because the STEREO/WAVES antennas [*Bale et al.*, 2008] have a large surface area, so that the resulting shot noise spectrum in the solar wind dominates the power at lower frequencies. The shot noise is the

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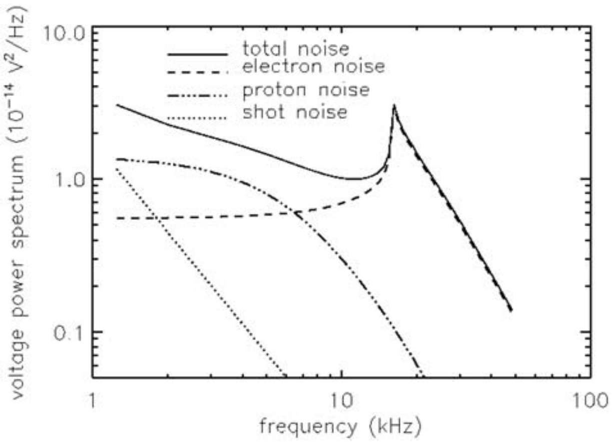

Figure 1. A typical theoretical total noise spectrum for the Ulysses spacecraft (solid line) where we can clearly see the QTN peak at the plasma frequency. There are three main different contributions: the electron quasi-thermal noise (dashed line), the doppler-shifted proton noise (dashed-dotted line), and the shot noise (dotted line). The spectrum has been simulated for typical solar wind parameters at 1 AU: $n_e = 3$ cm^{-3}, $T_e = 10^5$ K, $T_p = 5 \times 10^4$ K, $v_{sw} = 340$ km/s, and $\kappa = 3$. Adapted from *Zouganelis* [2008].

additional noise due to the particles whose trajectory intercepts the antenna and also to the photoelectrons which are emitted by the antenna surface. This noise is proportional to the electron impact rate and therefore an electron density determination can still be made even if on STEREO we cannot see the QTN peak just above the plasma frequency.

[4] The present paper describes a technique to infer the electron density from the shot noise on the STEREO antennas using the Low Frequency Receiver (LFR) of the STEREO/WAVES instrument. To do so, we first have to estimate the 'base' capacitance, which is any stray, unaccounted capacitance between the antenna element and its enclosure; this determines the final gain of the system. This measurement is useful not only for the shot noise and the density determination described in this paper. It is useful for the QTN spectroscopy that will be applied in CME filamentary material studies, and also for the antenna gain determination at high frequency [*Eastwood et al.*, 2009, and references therein].

2. Shot Noise and Antenna Impedance

[5] When a passive antenna is immersed in a stable plasma, like in the solar wind, a typical LFR voltage spectrum consists of three different contributing noises: the electron quasi thermal noise due to the ambient electrons thermal motion, the proton noise due to the protons thermal motion which is doppler-shifted by the solar wind bulk speed and the shot noise decreasing as $1/f^2$. These different components can be seen in Figure 1 for a typical theoretical spectrum that would be measured by the Ulysses spacecraft. The STEREO/WAVES instrument uses three 6 m monopole antennas; each antenna has average radius of 2.3 cm, which gives a free-space capacitance of $C_A \approx 63$ pF [*Bale et al.*, 2008]. The Low Frequency Receiver (LFR) is a digital spectral analyzer that produces voltage power in three 2-octave bands from 2.5 to 160 kHz with spectral resolution $\Delta f/f \approx 8.7\%$. In the case of STEREO (Figure 2), with the same electron parameters as in Figure 1, but with a shorter antenna and a larger surface, the shot noise dominates so that the peak at the plasma frequency is not detectable with the LFR resolution. The detailed calculation of these three different components and the formulation of the software package used in this study are given by *Zouganelis* [2008].

[6] According to *Meyer-Vernet and Perche* [1989], for $f < f_p$ the shot noise can be approximated as:

$$V_I^2 \approx 2e^2 N_e A |Z|^2 \qquad (1)$$

where N_e is the electron impact rate on one antenna element, the factor $A \approx 1 + e\phi/k_B T_e$ comes from a first-order approximation of the shot noise (the DC spacecraft potential ϕ is roughly estimated to be $\sim$5 V) and $Z = R + 1/iC\omega$ is the antenna impedance where R and C are the antenna resistance and capacitance, respectively.

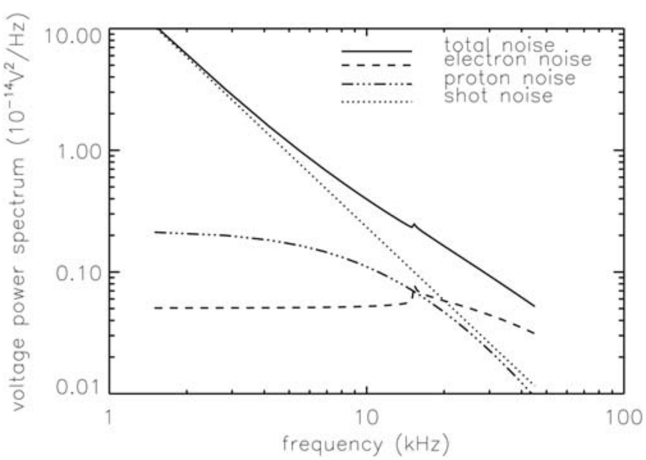

Figure 2. A typical theoretical total noise spectrum for the STEREO spacecraft as in Figure 1 for the same plasma parameters. The shot noise dominates so that the peak at the plasma frequency is not detectable with the STEREO/WAVES LFR resolution.

[7] In practice, however, the antenna of impedance Z is connected to a receiver with a finite impedance Z_R. It is possible to build receivers with an input resistance of the order of 10^9 ohms or larger, but one cannot eliminate, in parallel to this resistance, a 'stray' or 'base' capacitance C_b. This stray capacitance is due to the receiver input capacitance, the capacitance between the antenna and its grounded enclosure, the capacitance in the semirigid coaxial cables that take the signal from the enclosure to the preamplifier, and the input capacitance of the preamplifier itself (see details in the work of *Bale et al.* [2008] and especially their Figures 1 and 2 for the electrical design of the antennas). C_b includes therefore everything other than the antenna and $Z_R \approx 1/iC_b\omega$.

[8] Then the voltage spectral density measured at the receiver input terminals is:

$$V_{obs}^2 = \frac{V_e^2 + V_p^2 + V_I^2}{\Gamma^2} \tag{2}$$

where V_e and V_p are the electron and proton thermal noises, respectively, and

$$\Gamma = \frac{Z_R + Z}{Z_R}. \tag{3}$$

3. Stray Capacitance Determination

[9] For estimating the stray capacitance C_b from equations (1), (2), and (3), we need to use the total observed voltage spectral density V_{obs} and already know the electron density n_e and temperature T_e. We have used LFR data from the STEREO Behind (ST-B) spacecraft on 9 January 2007. The LFR is a direct conversion receiver for spectral processing from 2.5 kHz up to 160 kHz and for this work we use data when the LFR is switched to use the *Ey*/*Ex* pseudodipole combination of the *Ey* and *Ex* 6 m long monopole antennas. The day of 9 January 2007 has been chosen because ST-B was just downstream of the Wind spacecraft so that we can infer the n_e and T_e measured by it. Their positions in GSE coordinates and R_e units are: $\vec{R}_{WIND}$ = (253.27, −37.50, 20.48) and $\vec{R}_{STB}$ = (122.79, −34.18, −9.37). Wind is below the ecliptic, while ST-B is above, but otherwise this was the best conjunction in the early STEREO operation days. This allows us to use Wind particle data, which are well calibrated.

[10] Proton moments are taken from Wind/SWE [*Ogilvie et al.*, 1995], electron moments are calculated from Wind/3DP measurements [*Lin et al.*, 1995] (and corrected for spacecraft potential effects) and magnetic field from Wind/MFI [*Lepping et al.*, 1995]. Since Wind is about $130R_e$ upstream of ST-B, the Wind data are lagged by $\tau \approx 130R_e/v_{sw}$ to the time that they encounter ST-B, where v_{sw} is the solar wind speed. This interval averaged time lag is $\tau \approx 2427s$.

[11] We have selected the interval between 0800 and 2400 UT, an interval over which the solar wind conditions are very steady and during which we had no Langmuir wave bursts like those frequently observed on STEREO/WAVES and no noise produced by impact ionization of nanoparticles striking the spacecraft [*Meyer-Vernet et al.*, 2009]. STEREO and Wind data are shown in Figure 3. There are 1804 individual LFR spectra during this interval. For each LFR spectrum, we first subtract the LFR receiver background as it was measured before the deployment of the antennas on ST-B. We then fit the data to the theoretical total noise given by relation (2) for frequencies up to the plasma frequency f_p which is in all cases larger than 15 kHz. We have excluded all the frequencies above 15 kHz, because the equation (1) only holds for $f < f_p$ [*Meyer-Vernet and Perche*, 1989]. So each spectrum is fitted using 21 points. In the fitting procedure we use the parameters n_e, T_e, T_p and v_{sw} taken by Wind and interpolated onto the time tags of the ST-B data for each spectrum. The plasma density $n_e \approx n_p$ is measured by Wind/SWE and the electron thermal velocity is computed from the electron thermal temperature measured by Wind/3DP. For the protons, we have used the average values of $T_p = 2 \times 10^5$ K and v_{sw} = 340 km/s since the result is not extremely sensitive to these parameters [*Issautier et al.*, 1999]. We also assume that the electron velocity distribution function is a kappa function with $\kappa = 3$ which is the average value observed in the solar wind at 1AU [*Maksimovic et al.*, 2005; *Zouganelis*, 2008] taking into account the suprathermal properties of the distributions.

[12] The only free parameter generated by the fit is then the stray capacitance C_b of the X-Y dipole. The values of C_b are shown in the histogram in Figure 4. The average value is 32 pF and the standard deviation of the distribution is 4 pF. We consider that this statistical width is the minimum uncertainty because of the various assumptions of this technique, but an overall uncertainty cannot be straightforwardly estimated. This result is in agreement with the laboratory stray capacitance measurement done on the S/WAVES deployed flight spare unit by *Bale et al.* [2008] who found 67 pF for the monopole which should be equivalent to twice the capacitance of a dipole. In a separate analysis, *Eastwood et al.* [2009] compared the high-frequency voltage spectrum with the galactic synchrotron continuum and found larger values for the dipole of the order of 40–45 pF. We should, however, note that in our work, contrary to the galactic continuum analysis, the shot noise technique is completely independent of the orientation of the antennas.

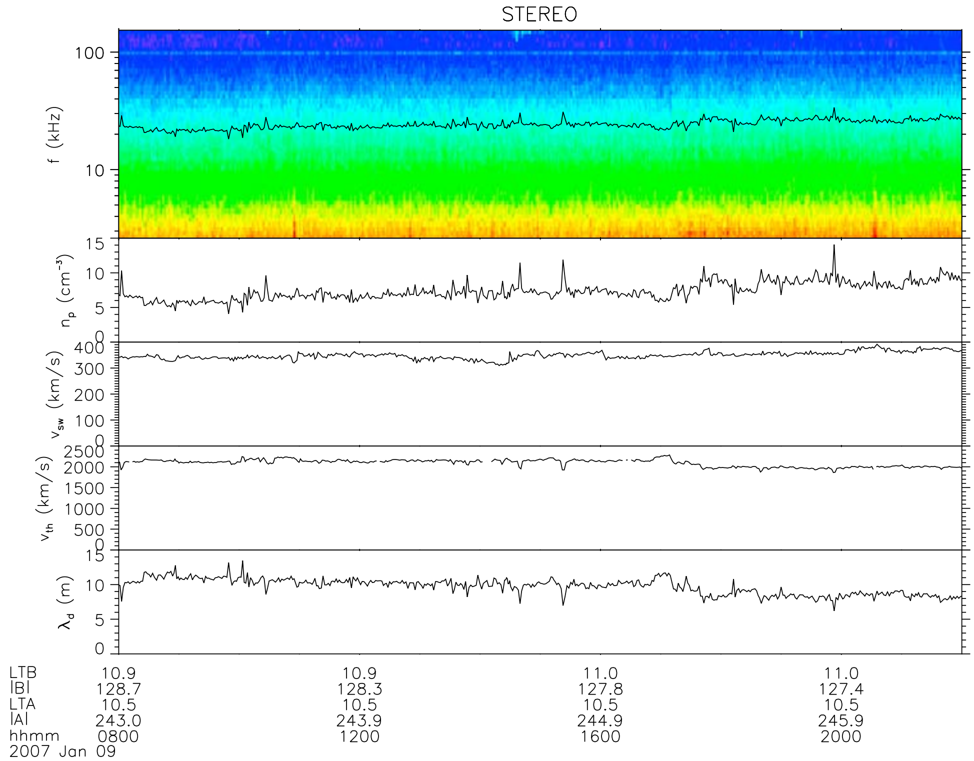

Figure 3. Overview of the data: The first panel is the STEREO/WAVES LFR spectrum, with the WIND/SWE plasma frequency overlaid. The second panel is the WIND/SWE proton density. The third panel is WIND/SWE solar wind speed. The fourth panel is WIND/3DP electron thermal speed. The fifth panel is the electron Debye length. All WIND data represented here are lagged as explained in the text.

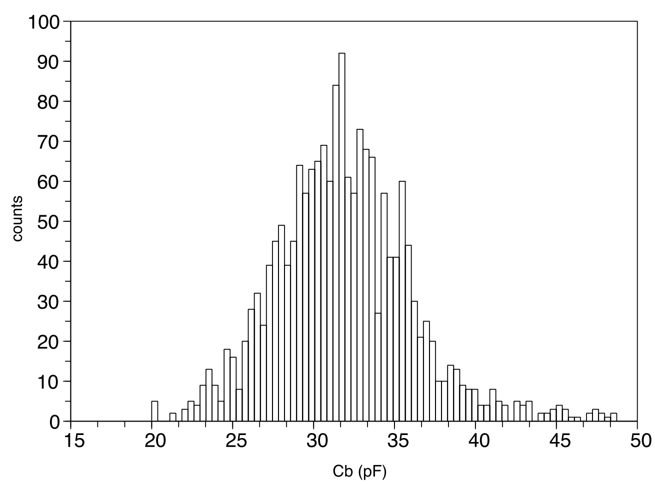

Figure 4. Histogram of the inferred values of the total stray capacitance from the X-Y dipole. The average value is 32 pF, and the distribution has a standard deviation of 4 pF.

[13] To summarize, in this work, in order to provide an absolute calibration of the STEREO/WAVES instrument, we have used the electron shot noise measured with the LFR receiver due to the electrons whose trajectory intercepts the antenna and also to the photoelectrons which are emitted by the antenna surface. The other components of the quasi-thermal electron noise and of the Doppler shifted proton noise have been as well taken into account even if their contribution at low frequencies is small in the studied cases. We then deduced the stray capacitance including all unaccounted capacitance of the antenna-receiver system except the antenna itself. This absolute calibration will be important for any future solar and space science research done with the STEREO/WAVES instrument. It will particularly make possible to determine routinely, on all the available data, a rough estimate of the electron density using the shot noise measurement. This rough estimate with an uncertainty of the order of $\approx$10–20% may then be useful for finalizing the STEREO/SWEA electron data [*Sauvaud et al.*, 2008].

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