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QUASI-THERMAL NOISE SPECTROSCOPY IN EARTH'S MAGNETOSHEATH: THEORY AND APPLICATION TO PLASMA DIAGNOSTIC ON WIND SPACECRAFT

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Abstract. 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 immersed into plasma. This method has been used since the last three decades in different space plasma environments, since it is immune to spacecraft limitations. The method is based on the analysis of the electrostatic field spectrum produced by the quasi-thermal fluctuations of the electrons, and Doppler-shifted thermal fluctuations of the ions. Here, the method has been adjusted for plasma in magnetosheath of Earth, just behind the Earths bow-shock, where flat-top velocity distribution function of electrons has been measured. Theory has been applied to measurements performed by WIND satellite.

1. INTRODUCTION

Although the conventional use of electric antennas is for remote sensing by detection of electromagnetic waves, they can also be used for in situ measurements, by detecting electrostatic waves produced by the random motion of the ambient plasma particles. 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 quasi-thermal noise (QTN) is completely determined by the particle velocity distributions in the frame of the antenna. The problem is simplest in the absence of a static magnetic field or at frequencies much higher than the electron gyrofrequency, since in this case the plasma can be considered to be an assembly of "dressed" "test" particles moving in straight lines.

The QTN spectrum around the plasma frequency f_p, consists of a noise peak just above f_p, produced by electron thermal fluctuations. Since plasma density n_e

is proportional to f_p^2, this allows an accurate measurement of the electron density. In addition, the electrons passing within Debye length L_D from the antenna induce voltage pulses on it, producing in the spectrum a plateau just below f_p, and above f_p, a noise level which decreases as the observing frequency increases. The analysis of these spectrum regions gives the electron core temperature T_c (Meyer-Vernet and Perche, 1989). One of the main advantages of the QTN spectroscopy is its relative immunity to the spacecraft potential and photoelectron perturbations which, in general affect particle analyzers. This method, based on the electron contribution of the QTN, was first introduced for studies of the solar wind by (Meyer-Vernet, 1979).

QTN spectrum is determined by plasma properties, which are contained in particle velocity distribution function (VDF) in the frame of the antenna. Technique is independent of antenna orientation if VDF of plasma particles is considered to be isotropic.

In this work, technique has been adopted for usage in region of magnetosheath of Earth, just behind bow-shock. Location of bow-shock is easily detectable in QTN spectrum since plasma density increases for approximately factor of 4 as spacecraft passes from free solar wind to magnetosheath. As a consequence, frequency of 'plasma peak' in the spectrum is increased approximately twice. Some preliminary testings on WIND spacecraft Thermal Noise Receiver (TNR) instrument data have been performed, and some predictions for future research are given.

2. QTN SPECTRUM FOR FLAT-TOP DISTRIBUTIONS

2. 1. BASICS OF THE METHOD

Spectrum which is measured by radio antenna 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 f^{-2}. As protons pass through the bow-shock, their motion gets thermalized so no bulk motion and no Doppler shift is present. For this reason, proton contribution to the spectrum can be completely neglected in the magnetosheath.

The voltage spectral density of QTN measured at the terminals of an electric antenna immersed in a plasma with drifting velocity $\vec{V}$ is (Meyer-Vernet, 1979)

$$V_\omega^2 = \frac{2}{(2\pi)^3} \int \left| \frac{\vec{k} \cdot \vec{J}}{k} \right| E^2(\vec{k}, \omega - \vec{k} \cdot \vec{V}) \mathrm{d}^3 k \tag{1}$$

The first term in the integral involves the antenna response to electrostatic waves, which depends on the Fourier transform $\vec{J}(\vec{k})$ of the current distribution along the antenna. The second term is the autocorrelation function of the electrostatic field fluctuations in the antenna frame. At frequencies much higher than the gyrofrequency, we have for electrons

$$E^2(\vec{k}, \omega) = 2\pi \frac{e^2 \int f(\vec{v}) \delta(\omega - \vec{k} \cdot \vec{v}) \mathrm{d}^3 v}{k^2 \epsilon_0^2 \left| \epsilon_L(\vec{k}, \omega) \right|^2} \tag{2}$$

where $f(\vec{v})$ stands for VDF of electrons and ϵ_L for the plasma longitudinal dielectric permittivity.

These equations can be simplified using few approximations. First, electron thermal velocity is higher than the plasma velocity ($\vec{v} >> \vec{V}$) and second, $f(\vec{v})$ is considered to be isotropic. In this case, we obtain (Chateau and Meyer-Vernet, 1989)

$$V^2(\omega) = \frac{16 m_e \omega_p^2}{\pi \epsilon_0} \int_0^{+\infty} \frac{F(kL_{ant})B(k)}{k^2 |\epsilon_L|^2} \mathrm{d}k \tag{3}$$

where L_{ant} is antenna length and $F(kL_{ant})$ is antenna response function for wire dipole antenna, given as

$$F(x) = x^{-1} \left[Si(x) - \frac{1}{2} Si(2x) - \frac{2}{x} \sin^2 \frac{x}{2} \right] \tag{4}$$

($Si(x)$ stands for sine integral). Function $B(k)$ is, by definition

$$B(k) = \frac{2\pi}{k} \int_{\omega/k}^{+\infty} v f(v) \mathrm{d}v \tag{5}$$

and longitudinal dielectric permittivity is given as

$$\epsilon_L = 1 + \frac{2\pi\omega_p^2}{k} \int_{-\infty}^{+\infty} \frac{v_{||} f(v_{||})}{k v_{||} - \omega - i_0} \mathrm{d}v_{||} \tag{6}$$

where $v_{||}$ s the component of $\vec{v}$ parallel to $\vec{k}$.

2. 2. CHOICE OF THE DISTRIBUTION FUNCTION

We choose the following electron velocity distribution function

$$f(v) = \frac{A}{1 + \left(v/v_0\right)^8} \tag{7}$$

which is normalized by a factor

$$A = \frac{\sqrt{2 + (2)^{1/2}}}{\pi^2 v_0^3} \tag{8}$$

This function is reasonably simple and represents rather well the flat-topped shape of actual distribution functions measured in the Earth magnetosheath. This function has characteristic flat part at small velocities and power-low decrease to high velocities (approximately v^{-8}). This feature indicts larger portion of very fast, 'supra-thermal' electrons, compared to classic Maxwellian, with characteristic exponential velocity decrease.

Shape of QTN spectrum is obtained by replacing Equation 7 into Equations 5 and 6 and then into Equation 3. Details of the calculation are given elsewhere (Chateau and Meyer-Vernet, 1989), and we finally obtain

$$V^2(\omega) = \frac{4}{\pi^2 \epsilon_0} \frac{T^{1/2}}{r^2} \sqrt{6\left(2 + 2^{1/2}\right) k_b m_e} \int_0^{+\infty} \frac{z b(z) F[ru/z\sqrt{1 + 2^{1/2}}]}{\left|\epsilon_L(z)\right|^2} \mathrm{d}z \tag{9}$$

where we use following substitutes: $r = f/f_p$, $u = L_{ant}/L_D$, $z = \omega/kv_0$ and

$$b(z) = \pi - arctan(\sqrt{2}z^2 - 1) - arctan(\sqrt{2}z^2 + 1) + \frac{1}{2} ln\left(\frac{z^4 - \sqrt{2}z^2 + 1}{z^4 + \sqrt{2}z^2 + 1}\right) \quad (10)$$

As the analytic calculation of Equation 9 cannot be done in general, so it must be numerically computed.

2. 3. SHOT NOISE AND ANTENNA IMPEDANCE

Since the antenna is a physical object which disturbs the trajectories of the particles (they cannot pass through its surface) and furthermore the antenna surface can eject photoelectrons, there is an additional noise, which is called shot noise (Meyer-Vernet and Perche, 1989). For a thin antenna ($a_{ant} << L_{ant}$) and antenna potential ϕ which satisfies $e\phi/k_b T_e << 1$ shot noise can be well approximated by expression

$$V_{sn}^2 = 2e^2 N_{impact} |Z^2| \quad (11)$$

with $N_{impact} = n_e v_{the} S_{ant} (4\pi)^{-1}$ being electron impact rate on the antenna. Here, Z stands for antenna impedance, given by

$$Z(\omega) = \frac{4i}{\pi^2 \epsilon_0 \omega} \int_0^{+\infty} \frac{F(kL_{ant})}{\epsilon_L} \mathrm{d}k \quad (12)$$

Final step taking the receiver gain into account. Namely, antenna of impedance Z is connected to a receiver with a finite impedance Z_R containing 'stray' or 'base' capacitance $C_b \approx 33pF$. Relation between spectrum given in Equation 9 and spectrum measured by the receiver is

$$V_{obs}^2 = \frac{V^2 + V_{sn}^2}{\Gamma^2} \quad (13)$$

with

$$\Gamma = \frac{C_{ant}}{C_{ant} + C_b} = \frac{Z + Z_b}{Z} \approx 0.49 \quad (14)$$

Example of QTN spectrum in the magnetosheath is given on Figure 1.

3. APPLICATION TO WIND MEASUREMENTS

In this section, presented QTN method is applied to measurements from TNR instrument of WIND spacecraft. TNR consists of two multi-channel receivers that cover frequency range from 4kHz to 256kHz with 5 logarithmically-spaced frequency bands (Bougeret et al, 1995). Each band covers 2 octaves with 1 octave overlap, each containing 32 frequency channels. This leads, in total, to obtaining spectrum of 96 different frequencies.

Fitting procedure is a standard Levenberg-Marquardt χ^2 algorithm adopted for fitting the sum of expressions from Equations 9 and 11, with free parameters of electron density and temperature, defined as moments of flat-top VDF (defined in Equation 7), with taking receiver gain into account (Equation 14). Example of typical spectrum obtained in magnetosheath of Earth is given on Figure 2. It is important to

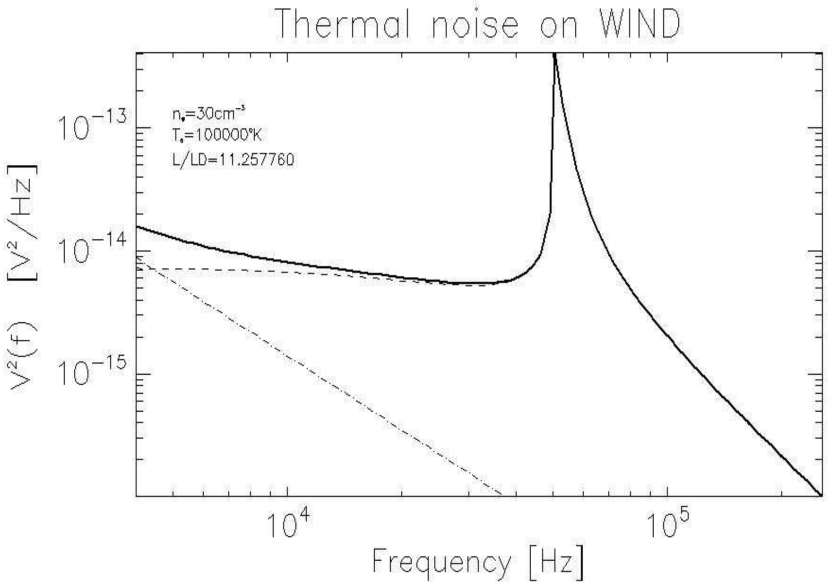

Figure 1: Example of theoretical spectrum of quasi-thermal noise in the magnetosheath of Earth. Spectrum is adopted for parameters of WIND spacecraft ($a_{ant} = 0.7mm$, $L_{ant} = 50m$). QTN spectrum is given by dashed line and shot noise contribution by dash-dotted line.

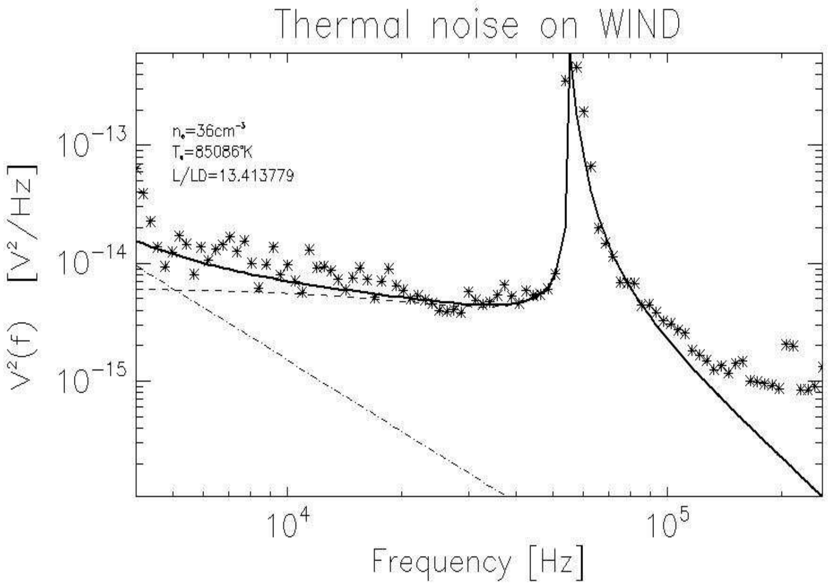

Figure 2: Spectrum from magnetosheath of Earth measured on 2.12.1996.

note that TNR spectrum is affected, on higher frequencies, by other factors, especially terrestrial and galactic background radiation. Consequently, measured high-frequency values are higher that intended. To avoid this problem influencing fitting procedure 'points' in the spectrum above 90kHz are not taken into account.

4. CONCLUSIONS AND PERSPECTIVES

In this work, QTN fitting technique has been adopted for usage in magnetosheath of Earth. This implies use of 'flat-top' VDF measured in these particular conditions. Method has been successfully applied to measurements of WIND spacecraft TNR instrument.

Procedure developed here can, in the future, be applied to comprehensive study of magnetosheath and bow-shock of Earth. Since this method is very well understood and applied in free solar wind (see, for example, Le Chat et al, 2009 and references therein) it is now possible to study in detail the radio spectra development as spacecraft passes the bow-shock, and how is it affected by the position with respect to Earth and Parker spiral.

Acknowledgments

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