DETECTION OF NONLINEAR FEATURES IN PLASMA AND FIELD MEASUREMENTS BY PROGNOZ−8

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1 Introduction

Investigations of plasma processes by spacecraft have shown the importance and necessity of wave measurements for the understanding of the interaction between the solar wind and the magnetosphere. The fine-structure of the magnetopause, the magnetosphere boundary layers and flux transfer events (FTE) were studied by many experiments carried on board of the ISEE (Ref.1), AMPTE (Ref.2), GEOS–2 (Ref.3), PROGNOZ–8 and 10 (Ref.4) spacecraft. It was found that the generation of high amplitude waves plays an important role in the macroscopic and microscopic structures of these regions.

In the present paper an example of high amplitude electric field oscillations is considered, detected by PROGNOZ–8 near the magnetopause at very low frequencies ranging down to fractions of Hz.

On board of this high apogee spacecraft (launched at 25.12.1980, with inclination 65°, apogee 199 000 km and perigee 550 km), a plasma wave diagnostic complex was installed, to study the electric field and plasma flux fluctuations in the frequency band from 30 mHz to 1 kHz. The slow rotation of the spacecraft allowed to investigate, among others, ultra low frequency fluctuations. However, this was not easy, as the frequency characteristics of the device decrease the signal amplitude at low frequencies in a nonlinear way. This is done to maximize the dynamic range in order to overcome telemetry restrictions. Therefore it became necessary to reconstruct accurately the low frequency wave form for the electric field and plasma flux fluctuations.

Besides the plasma wave complex, there was also a plasma spectrometer MONITOR, to study energetic spectra of ions in the 0.16–4.2 keV interval, with a time resolution of 1.29 seconds.

2 Determination of characteristic time-scales or scale lengths

Among the many sessions from PROGNOZ-8 one of them was especially interesting, because of the presence of plasma waves with extremely high amplitude. During the period of about 10 minutes several waves bursts with characteristic time 2-20 sec and amplitude from 10 up to several tens mV/m were found accompanied by more high frequency waves with time scale 0.2 sec. This waves were found both in the electric field and in the plasma flux fluctuations channels.

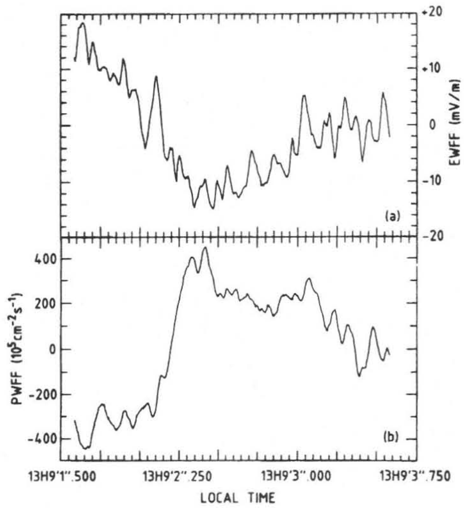

Figure 1: *Plot of EWFF (a) and PWFF (b) as a function of time*

One of the components of the electric field has been measured by a dipole antenna perpendicular to the spin axis of PROGNOZ–8. On the other hand, the plasma flux has been measured in a direction parallel to the spin axis. Both the electric field and the plasma flux were measured every 6.7 ms of time. The raw data have been corrected by two successive Fourier transforms to obtain the actual wave forms of both physical variables. After restitution of these signals, the electric field intensity (EWFF) is given in mV/m and the plasma flux (PWFF) in 10^5 cm^{-2} s^{-1}. It is important to notice that we have measured only fluctuations, not DC components. Figs. 1a and 1b illustrate, respectively, EWFF and PWFF as a function of time in seconds. These two physical quantities are shown

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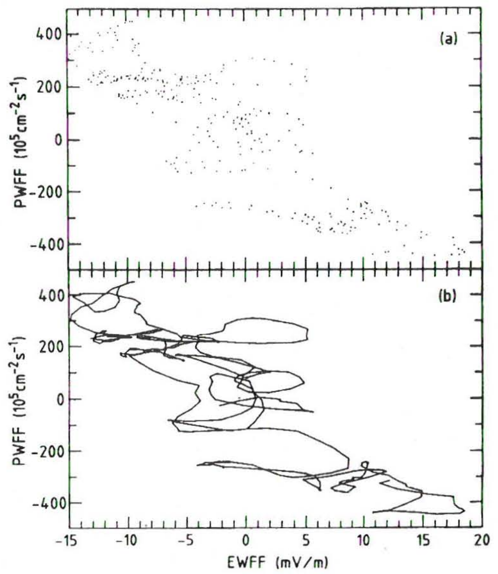

Figure 2: *Plots of PWFF as a function of EWFF*

for a period of 2 seconds, on 14 Jan 1981 between 13:09:01 and 13:09:03 Moscow local time. At that time the satellite was in the magnetosphere, at local time 17H and latitude 40°.

From the measurements shown in figs. 1a and 1b as well as from many similar samples examined in this study, it appears that in addition to these high amplitude variations with characteristic time-scales of 2–20 s there are relatively short time-scales of 0.2 s variations. Figs. 2a and 2b show plots of PWFF as a function of EWFF. In fig. 2a each point corresponds to one measurement. In fig. 2b a continuous line has been drawn between all successive points. Note that this second presentation, which is often used in hodogram representations, is less comprehensive, however, than the former one (fig. 2a) giving the density of points per unit length along the continuous line.

It can be seen from fig. 2a that there are periods of time when 10 or more points are located along a line segment with a constant slope. At other times there is no such linear coherence in the data (*e.g.* see fig. 3): in cases like those illustrated in fig. 3, the plasma is turbulent over smaller time-scales (or shorter scale lengths). The number of points for which the data are well organized along straight-line segments can be used as an indication of the characteristic time (or scale length) over which the plasma is 'coherent', *i.e.* over which some plasma properties are constant in time (or uniform in space). A histogram of such 'number of points forming almost a segment of straight line' can be produced for any set of data. One may envisage that such histograms can be used to identify characteristic time-scales (or scale lengths) in a medium. Depending on the level and type of turbulence of a plasma in a given region of space, the histograms should have different typical shapes. This type of histogram could then become a diagnostic tool for analysing plasmas and their degree of inhomogeneity. Before this method can be used as a tool for plasma diagnostics it has to be studied in more detail from a mathematical and numerical point of view. It could then be complementary to the classical Fast Fourier Transform (FFT) which is now used to determine the characteristic time-scales (or length scales). Indeed power spectra of FFTs are especially suited to study periodic phenomena (waves), whereas the kind of histograms proposed here seems more appropriate to investigate plasma structures within which the properties are piecewise constant.

The comparison of the plasma wave data with the energetic spectra of ions from the MONITOR device has shown that the high amplitude structure discussed above is located at the boundary of a 'plasma island', a plasma structure consisting of magnetosheath plasma which penetrated into the magnetosphere. This plasma structure was investigated elsewhere (Ref.5). In fig. 4 a dynamic spectrogram is shown for ions observed in the sunward direction (top panel). Also shown dynamic spectrograms of the plasma flux (middle panel) and electric field (bottom panel) fluctuations in the frequency range 0.1–70 Hz, obtained by FFT and frequency corrections. The time of observation of the structure considered above is marked by an arrow. Three plasma islands are clearly seen, at 13:08:01, 13:09:00–13:10:00 and 13:11:00, accompanied by bursts of low frequency plasma wave activity. Unfortunately, we do not have full magnetic field measurements and therefore it is impossible to identify the nature of the phenomenon observed. However, such extremely high electric field fluctuations are interesting in themselves. Possible explanations of these phenomena are discussed in the next paragraph.

3 Discussion of high amplitude electric field fluctuations

3.1 Observations by other spacecraft

The velocity and magnetic field shear, density gradient in the regions of magnetosphere boundaries can excite several types of plasma instabilities, such as the tearing mode, Kelvin–Helmholtz and drift instabilities (lower–hybrid, ion–cyclotron) (Ref.6,7,8,9). In the magnetopause region an increased level of wave activity has been observed, of the type of broadband electrostatic bursts, magnetic field fluctuations in the proton gyrofrequency range and lower hybrid waves (Ref.1). Nevertheless, because of the insufficient frequency resolution and the high level of electric field noise in the ISEE measurements, connected with a periodic shadowing of the probes, it was difficult to study the very low frequency range more carefully. The attention was also drawn to investigations of fine structure of such interesting phenomenon like FTE and others, connected with the excitation of high amplitude plasma wave activity.

FTE structures were simultaneously measured by the ISEE and AMPTE UKS spacecraft (Ref.10). Detailed analyses of plasma waves by the AMPTE IRM spacecraft (Ref.11) have shown several important features. In the range from several Hz to several hundred Hz, electric field fluctuations achieve several mV/m, whereas in the range from hundred Hz to 10 kHz one only gets 0.1 mV/m. The principle conclusion of these investigations is that even the maximum wave amplitude (few mV/m) in this

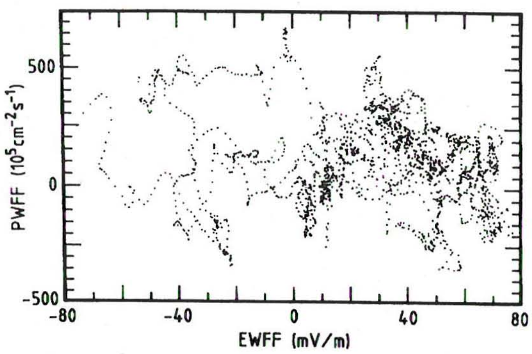

Figure 3: *Plots of PWFF as a function of EWFF in turbulent sessions*

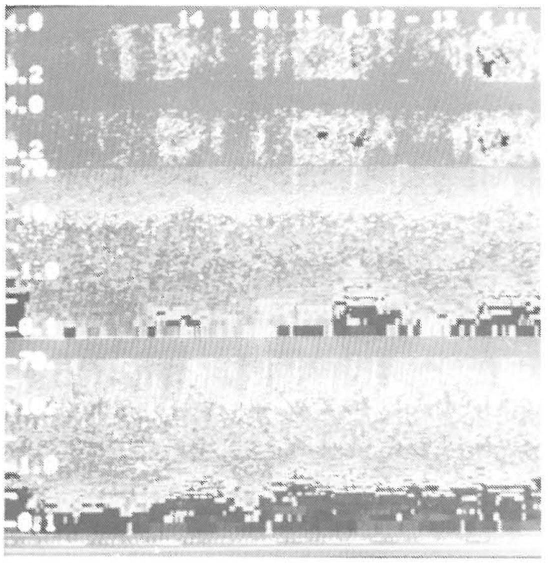

Figure 4: *Dynamic spectrogram of the ions from the MONITOR device, taken in the sunward direction, in the energy range 0.16-4.2 keV (top panel). Dynamic spectrograms of the plasma flux (middle panel) and electric field (bottom panel) fluctuations in the frequency range 0.1-70 Hz.*

frequency range (> 1 Hz) does not correspond to the anomalous resistivity required by the MHD reconnection model of FTE (Ref.12).

Concerning the electric field oscillations in the low frequency range (< 1 Hz), there was the same problem as for ISEE, due to the rapid spin of the spacecraft. Lower frequency electric field measurements by GEOS-2 (Ref.3) have shown the existence of significantly more powerful electric field oscillations, with amplitudes of up to 10 mV/m in the magnetosheath close to the magnetopause. The analysis of these fluctuations, appearing as intensive short duration bursts, has indicated that the best possible explanation is a nonlinear Alfvénic structure traversed by the satellite.

3.2 Convection of plasma structures

The most natural source of the very low frequency bursts with a duration of $\tau \approx 2 \div 20$ s is the motion over the spacecraft with a convection velocity V_{conv} perpendicular to the magnetic field of a plasma magnetic structure with characteristic transverse dimension $\lambda \approx \tau V_{conv}$. In this case one should register a convection electric field of the order of $E \approx BV_{conv}$. Using the characteristic time of the magnetospheric convection ($\approx$ 15 min), one can evaluate this convection velocity $V_{conv} \approx 15 R_E/15$ min ≈ 100 km/s and for $\tau = 5 \div 20$ sec estimate the dimensions as $\lambda \approx (0.5 \div 2)10^3$ km, which is of the order of typical spatial scale of the MHD turbulence in the magnetosheath plasma flow. Assuming a geomagnetic field value close to the magnetopause of $B \approx 60$–80 nT, we find the associated convective electric field $E \approx 6$–8 mV/m. Such relatively 'weak' (≤ 10 mV/m) events are observed rather often. In the case shown on Fig. 1 very low frequency bursts was detected in the magnetosphere (under the magnetopause) simultaneously with plasma islands. Localized penetration through the magnetopause of structures consisting of magnetosheath plasma suggests something similar to FTE events (Refs. 13-15) and impulsive penetration events (Refs. 16,17). FTE are thought to be generated during spontaneous or driven reconnection processes of the interplanetary and geomagnetic fields and are convected to the night side by the solar wind. On the contrary, solar wind plasmoids with an excess momentum density with respect to the background can penetrate impulsively inside the geomagnetic field.

In certain cases more intense impulses with $\delta E \geq 20-40$ mV/m are much more rarely observed. Observation probabilities of such impulses correspond most likely to the probability that diamagnetic plasma irregularities with characteristic dimensions of the order of $1\,R_E$ originate in the solar wind. Their densities and velocities can substantially exceed average values. Such 'plasmoids' have been observed in laboratory experiments long ago (Ref.16). Plasma blobs, moving with relative velocities of 400–600 km/s, can penetrate through the magnetopause and will be observed in the magnetosphere as plasma islands. This event is called impulsive penetration and can be observed as an increase of the convection electric field up to $E = V_{conv}B/c \approx$ (400–600 km/s) $\times$(60−−80nT)$/c \approx 24 - - 48$ mV/m. Such a type of interaction of plasmoids with the magnetosphere has been simulated in terms of currents and magnetic fields (Ref.17,18).

The above described high amplitude fluctuations are connected with the convection of plasmas in transverse electro-magnetic fields. In this sense it is natural to suppose that one sees high amplitude nonlinear waves moving over the satellite. This is supported by the observed correlation or anticorrelation of the electric field and ion flux fluctuations (fig. 1). A nonlinear Alfvén wave description was used by Rezeau *et al.* (Ref.3) to explain low frequency electric field fluctuations in the magnetosheath. But even an overestimated value of the Alfvén velocity only gives electric field fluctuation amplitudes of at most 20 mV/m, with dimensions of the structure of the order of the ion gyroradius. The investigations of nonlinear evolution of ion–cyclotron wave have been carried out analytically and numerically in (Ref.8,9). The estimates of characteristic wavelength and nonlinear wave amplitudes indicate that structures with dimensions of interest have electric field amplitudes of the order of few mV/m.

3.3 Solitary nonlinear structures

An alternative explanation of the observed phenomenon is a solitary nonlinear structure. Among several types of nonlinear motions in magnetized plasmas, namely the above mentioned Alfvén waves, the potential drift and the drift vortices (Ref.19), we will only consider the last one. This is a negative energy structure and so under certain conditions it can grow, due to some kind of dissipation leading to highly nonlinear quasistationary structures in a plasma flow with magnetic field and plasma density gradients.

To describe such large scale magnetized plasma motions one can use the kinetic description given by Khabibrakhmanov and Verheest (Ref.20), in which the solution of the Vlasov equation is expanded up to third order, using as small parameters the ratios of characteristic temporal and spatial scales to respectively the ion gyroperiod and gyroradius. In this approximation the flux of plasma particles of species α is expressed as:

$$\begin{aligned} n_\alpha u_{\alpha x} &= n_\alpha V_{Ex} + \frac{1}{\Omega_\alpha}\left(-\frac{1}{m_\alpha}\frac{\partial P_\alpha}{\partial y} + n_\alpha \hat{T} g\right) \qquad (1) \\ &- \frac{1}{\Omega_\alpha^2}\hat{T}\frac{1}{m_\alpha}\frac{\partial P_\alpha}{\partial x}, \\ n_\alpha u_{\alpha y} &= n_\alpha V_{Ey} + \frac{1}{\Omega_\alpha}\left(\frac{1}{m_\alpha}\frac{\partial P_\alpha}{\partial x} + n_\alpha \hat{T} f\right) \qquad (2) \\ &- \frac{1}{\Omega_\alpha^2}\hat{T}\frac{1}{m_\alpha}\frac{\partial P_\alpha}{\partial y}, \end{aligned}$$

where $\mathbf{V}_E = (f = cE_y/B, g = -cE_x/B)$ is the convective drift velocity, n_α the density, P_α the pressure and Ω_α the gyrofrequency of particles of species α with mass m_α. Furthermore, $\hat{T} = \partial/\partial t + \mathbf{V}_E \cdot \nabla$.

The continuity equation for the ions, $\partial n_i/\partial t + \nabla \cdot (n_i \mathbf{u}_i) = 0$, and the ion pressure equation, $\hat{T}P_i = 0$, constitute the set of equations describing drift vortex type motions:

$$\hat{T}P = 0, \quad (3)$$

$$\frac{n}{\Omega}\hat{T}\Delta\Psi = \hat{T}n - \frac{1}{\Omega^2 m}\nabla \cdot \{P, \nabla\Psi\} + \frac{1}{\Omega m B}\frac{\partial B}{\partial x}\frac{\partial P}{\partial y}. \quad (4)$$

Here we have dropped subscripts on the ion parameters and used the drift velocity potential $\mathbf{V}_E = (-\partial\Psi/\partial y, \partial\Psi/\partial x)$, together with the standard notation for Poisson brackets

$$\{\alpha, \beta\} = \frac{\partial\alpha}{\partial x}\frac{\partial\beta}{\partial y} - \frac{\partial\alpha}{\partial y}\frac{\partial\beta}{\partial x}. \quad (5)$$

In dimensionless variables, $\Omega t \to t$, $r/r_{ci} \to r$, $n/n_0 \to 1 + N$ and $\Delta\Psi/\Omega \to \Delta\Psi$, we have the set of equations:

$$\hat{T}N = 0, \quad (6)$$

$$\hat{T}\Delta\Psi = \hat{T}N - \nabla \cdot \{N, \nabla\Psi\} - 2g\frac{\partial N}{\partial y}, \quad (7)$$

where $2g = -\partial \ln B/\partial x$. There is an energy integral:

$$W = \int \left[(\nabla\Psi)^2 - 4xgN + 4x^2 k_n g\right] d^2x, \quad (8)$$

with $k_n = d \ln n_0/dn_0$, so that $N \to k_n x$ far from a disturbance. There are well known solutions of this Larichev–Reznik type equation. The detailed discussion of this solution for the case of a cometary coma is given in a companion paper (Ref.21).

The most significant feature of this solution is that for a configuration in which the magnetic field and plasma density gradients are aligned, their energy

$$W = \int \left[(\nabla\Psi)^2 + \frac{4k_n g}{u} k\Psi\right] d^2x, \quad (9)$$

is negative ($k_n g < 0$), and the whole structure can be amplified due to some kind of dissipation. The three dimensional structure of electric field in such a vortex is shown on Fig. 5. Hence

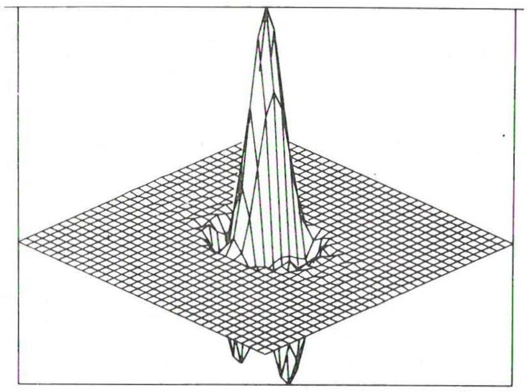

Figure 5: *Three dimensional image of the electric field in vortex.*

fluctuations can reach high amplitudes $E = E_{conv}\alpha$ ($\alpha \gg 1$, $E_{conv} \approx V_{conv}B/c$) and sufficiently large dimensions of the order $a = 1/k$, where $k^2 = 2gk_n/u(k_n - u)$.

The dependencies of amplification coefficient α on vortex size normalized on the ion gyroradius are shown on Fig. 6.

Assuming the magnetic field value in magnetosheath $B \geq 5$ nT, $k_n \approx 0.01$ (curve 1 on Fig. 6) and $V_{conv} \approx 100$ km/sec we find

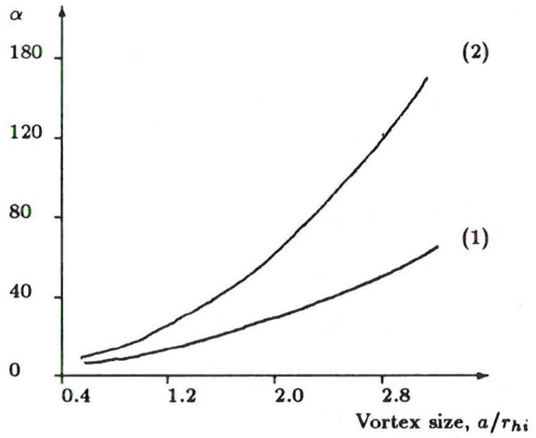

Figure 6: *The dependencies of the amplification factor α on normalized vortex size. Curve 1: $k_n = -g = 0.01$, $u = 0.01001$. Curve 2: $k_n = -g = 0.25$, $u = 0.2501$*

$\rho_i \approx 500$ km and $E_{conv} \approx 0,5$ mV/m. For vortex size $a \approx 3\rho_i$ the amplified value of electic field $E \approx 30$ mV/m. In the vicinity of the magnetopause the values of B and k_n become much large $B \approx 50$ nT and $k_n \approx 0.1 \div 0.25$ (curve 2 on Fig. 6) the apmlified electric field value in principle can become larger by the order of magnitude. Such vortices may penetrate through the magnetopause along the FTE's open field lines frozen in magnetosheath plasma flow and detected in magnetosphere as plasma islands.

However, without additional observational data it is difficult to choose between different types of nonlinear wave disturbances. We hope to have this information from future projects.

4 Detection of charged dust grains

It has also been envisaged to examine the whole set of PROGNOZ–8 high time resolution waveforms to determine if there is any evidence for electric field spikes produced
(1) either by the impact of interplanetary dust grains on the surface of the spacecraft, or
(2) by the passage of a charged micrometeoroid within a distance of one Debye length (10–20 m) from the electric antenna.

Indeed, it has been shown by Lesceux *et al.* (Ref.22) that dust grains, at a potential of 5 V with respect to the ambient plasma, can produce large electric potential differences, provided they pass close enough to the dipole antenna.

Peak values of 5×10^{-4} V can be obtained this way, at the time of closest approach of the charged grain. From the shape of the electric signal, and from its duration Lesceux *et al.* (Ref.22) have shown that the velocity of a micrometeoroid relative to a spacecraft can be determined.

For micrometeoroids moving with a velocity of 10 km/s nearby an antenna 10 m long, the whole duration of the characteristic double-spike signature is less than 10 ms. Since the time resolution of the PROGNOZ–8 electric wave experiment is at best 20/3 ms, the chance to detect such short duration signals in the data is marginal; except perhaps for the rare dust grains whose relative velocity with respect to the spacecraft would be less than 1 km/s. Indeed, for such slowly moving micrometeoroids the duration of the signal would be comparable to the actual time resolution of PROGNOZ–8 E–field measurements.

Except for the many spikes attributed, by IKI's spacecraft engineers and scientists, to electronic upsets, there seems to be no characteristic E–field signature which can be attributed to the passage of micrometeoroids in the close vicinity of the dipole antennae of PROGNOZ–8. The data sets that we have examined cover only a period of 2 hours. From the interplanetary micrometeoroid flux model of Grün *et al.* (Ref.23), it can be calculated that circa one micrometeoroid could come close enough to be detected by this method. Therefore, on top of the question of the too low time resolution of the electric field measurements, the amount of data available is rather small to catch such rare events in the interplanetary medium.

This would of course not be the case in dusty cometary plasmas or in the upper atmosphere of Earth and other planets or of their natural satellites where such a method could be quite appropriate.

5 Search for solar wind Alfvén waves

One additional aim of our investigation was to look for low-frequency phenomena, such as Alfvén waves, in the sessions when PROGNOZ–8 was in the solar wind outside the magnetosphere. Such Alfvén waves have periods which are typically of the order of the spin period of the spacecraft (about 2 minutes). This spin period, however, is known only approximately and a programs was developed to remove the rotational effects when the satellite was in the solar wind outside the bow shock. This was done by minimizing $\frac{1}{N}\sum_{i=1}^{N}[(B_y(t_i)-\overline{B}_y)^2+(B_z(t_i)-\overline{B}_z)^2]$, where the x–axis has been taken along the spin axis of the spacecraft, N is the number of measurements in a session, $\overline{B}_{y,z}$ are the average values of the components of the solar wind magnetic field and

$$\begin{aligned} B_y(t_i) &= B_y'(t_i)\cos\Omega t_i - B_z'(t_i)\sin\Omega t_i, \\ B_z(t_i) &= B_y'(t_i)\sin\Omega t_i + B_z'(t_i)\cos\Omega t_i. \end{aligned} \tag{10}$$

The primed variables are the measurements in a reference frame, co-rotating with the spacecraft at angular frequency Ω. In an inertial frame, the smoothed data showed no clear evidence of any solar wind Alfvén waves of sizeable amplitude, but we did not dispose of enough periods when PROGNOZ–8 was in the solar wind to draw meaningful conclusions.

6 Identification of discontinuities

The data, demodulated or not for the rotation effects of the satellite, did show the occurrence of several discontinuities in the solar wind, as shown in the demodulated fig. 7.

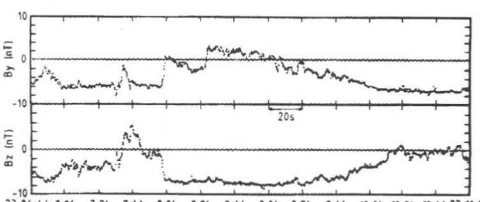

Figure 7: *Plot of the demodulated magnetic field components*

However, as obvious already from the notations and remarks in the preceding paragraph, PROGNOZ–8 measured the magnetic field only in the two dimensions perpendicular to the spin axis. Hence the precise nature of discontinuities or shocks (tangential or rotational), nonlinear waves and vortices could not be inferred. Three-dimensional information is needed to elucidate these nonlinear phenomena or structures.

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