Solar wind turbulence near Earth bow shock

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Introduction

New technique of solar wind investigations by means of a ground based facility and spacecraft has been proposed. The reciprocal operation was realized in the frame of international cooperation of radio transmitting Russian facility SURA (Belov *et al.*, 1983) and NASA WIND spacecraft (Bougeret *et al.*,1995).

The analysis of scintillations of signal at 9 MHz allows us to study a fine structure of solar wind plasma irregularities with resolution up to 40 km. In this paper the features of this new instrument as well as preliminary results of observations performed during last minimum of solar activity are discussed.

Observation technique

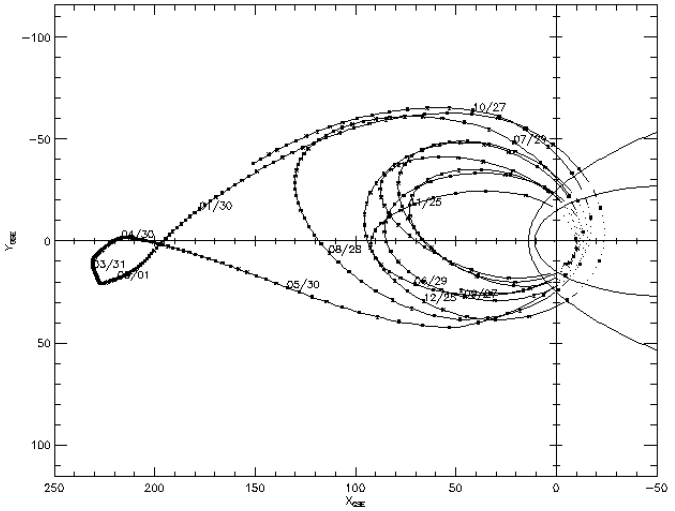

Figure 1: Ecliptic cut of Wind orbit for period from 1996 318^{th} day (November,14) 00:00 UT to 1997 316^{th} day (November, 12) 00:00 UT. X-axis is directed to Sun. Giperbolic curves truck area confined by Earth bow shock and magnetopause (source: http://sscweb.gsfc.nasa.gov)

The study of the propagation of radio signal generated by Vasilsursk facility (operating frequency 4.3 – 9.5 MHz) and detected by the RAD-2 receiver (scanned frequency 1.075 – 13.825 MHz) placed in WIND spacecraft was proposed. This receiver can operate at fixed frequency mode that provides high time resolution with data rate 1 per 63 ms. The spacecraft spins at ecliptic plane with period of about 3 s.

Till October 1998 WIND had been located in the elliptic orbits near to the ecliptic plane with its apogee 80 – 230 Earth's radii in the sunward direction and perigee 10 – 15 Earth's radii. Figure 1 presents WIND orbits for the period discussed in the paper.

The spectral maximum of the interplanetary scintillations $f_s = V/\sqrt{\lambda z}$ is determined by the size of first Fresnel zone $\sqrt{\lambda z}$ where V is the component of solar wind velocity perpendicular to SURA-WIND direction, λ is wavelength, z is the distance to effective scattering screen. The basic scintillation scale (Fresnel zone size) $l_s = 2\pi/f_s$ at 9 MHz radar frequency for spacecraft positions at the distance 1.5 mln km (see Fig. 1) can be found between 40 and 110 km, which is near the upper boundary of inertial interval of the solar wind turbulence. For shorter distances to the Earth l_s becomes smaller that allows to trace a spectral transformation to the range of dissipative scales. For solar wind velocity of about $V = 350$ km/sec the frequency of spectral maximum can be estimated as $f_s \geq 3.5 sin(\epsilon)$ (Hz), where ϵ is angle between solar wind velocity and SURA-WIND direction. For the case when spacecraft is located out of Earth magnetosphere $f_s \approx 0.3 - 6$Hz e.g. the spectral window of RAD-2 receiver always covers frequency of scintillation spectra maximum. The only exclusion is experiment where spacecraft was located near Earth magnetopause and f_s was more then 8 Hz (Nyquist frequency).

The trace geometry in the sunward direction with a distance from the Earth of about 1 500 000 km (0.01 a.u.) allows to study near-Earth solar wind itself without the averaging along a broad range of the heliocentric distances and at the same time to investigate a solar wind evolution at distances from Earth bow shock and up to 1.5 mln km from the Earth. Statistical analisys of signal scintillations for WIND locations inside and outside of Earth magnetopause helps to separate ionospheric and interplanetary scintillations.

Results

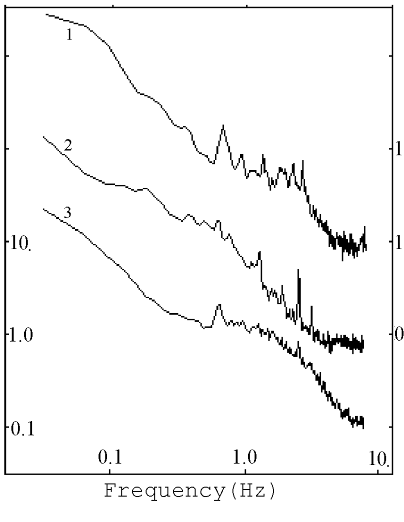

Figure 2: Power spectra shifted vertically, 1) Dec., 29, 1996, $R = 33.4 R_e$, $\epsilon = 82.5°$, $V_{sw} = 320 km/sec$; 2) Apr., 28, 1997, $R = 219 R_e$, $\epsilon = 6.5°$, $V_{sw} = 331 km/sec$; 3) July, 7, 1997 $R = 27 R_e$, $\epsilon = 44.5°$, $V_{sw} = 368 km/sec$

The data of more than 30 radar sounding sessions performed during the last minimum of solar activity (November, 1996 – October, 1997) were registered by Z-antenna of RAD-2 receiver. The normalized ($\int G(f)df = m_4^2$) spectra of scintillation of 9MHz signal were calculated and analysed.

Figure 2 demonstrates the examples of typical spectra obtained for positions of spacecraft with different distances from the Earth and different elongation angles (angle between directions to the Sun and to the spacecraft).

It has been found that almost each of scintillation spectra calculated for SURA signals contains a high frequency singularity in the 0.4-6 Hz range.

Note, that sharp rises in scintillation spectra rests from slight circular motion of Z-antenna (with inclination about 1°) while the high frequency plato is caused by sampling noises.

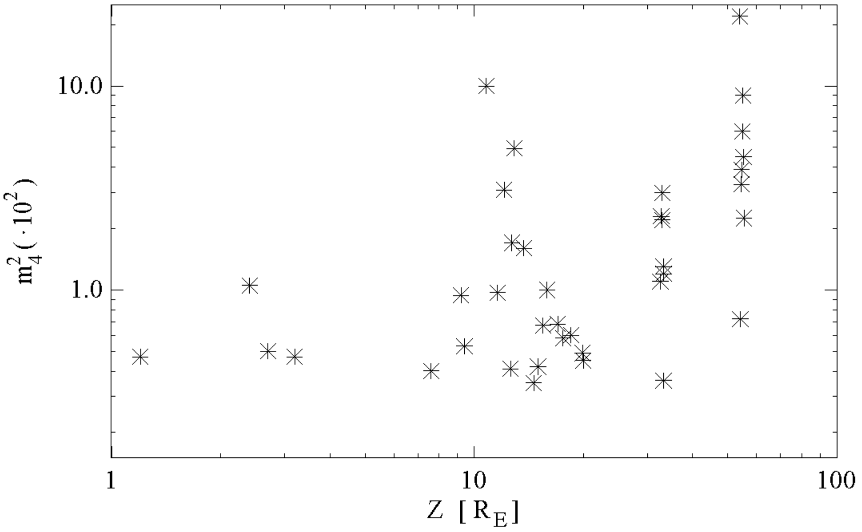

Figure 3: Scintillation Index (m_4^2)

The scintillation method allows also to calculate the scintillation index $m_4^2 = \frac{<I>^2 - <I^2>}{<I>^2}$, as well as to estimate the spectral power index, which are used for the calculation of the electron density fluctuations $< \delta N >$ and its distribution in the scales at the solar wind clouds. Figure 3 demonstrate a plot of m_4^2 for different distances Z to effective scatering layer which is suggested to be located between spacecraft and magnetopause. The both spacecraft and magnetopause positions were defined from orbital data, value of solar wind velosity was taken from WIND *in situ* mesurements (gopher://proton.sec.nasa.gov).

Discussion and Conclusion

The spectral behavior at low frequencies reflects ionospheric scintillations with Fresnel frequency ≤ 0.03 Hz. This low frequency spectral component was extrapolated to high frequency range as $G_f \sim f^{-3}$ and taken into account while analyzing an interplanetary scintillations. As it is seen from Figure 2 the contribution of ionospheric scintillations into observed spectra is negligible small for the frequency range $f \geq 0.3$ Hz of interested.

Appearance of high frequency singularity could be referred to the radio wave scattering by the interplanetary plasma irregularities. The singularity appears when the spacecraft take the position out of bow shock region and disappears when spacecraft crosses magnetopause boundary toward the Earth as it can be seen from Figure 4. Thus, observed spectral

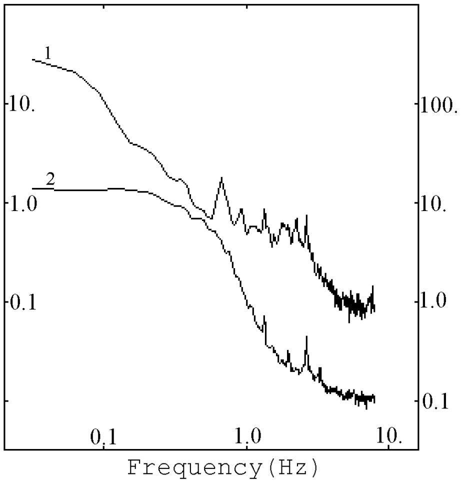

Figure 4: Power spectra shifted vertically, 1996, 1 - Dec.,29, $R = 33.4R_e$ (WIND is outsite bow shock), $\epsilon = 82.5°$, $V_{sw} = 320km/sec$; 2 - Dec.,30, $R = 24.2R_e$ (WIND is insite bow shock), $\epsilon = 127.5°$

feature of SURA signal transmitted through near-Earth ingomogeneous plasma can be assosiated with spatial spectral structure of geoeffective region of the solar wind.

The form of m_4^2 dependence on distance shows that markable contribution into interplanetary scintillation along SURA-WIND trace could be done by a turbulent region with depth about 10 Earth radii in the vicinity of Earth's bow shock. More detailed analysis of available data as well as future observations for spacecraft located near Earth magnetopause are desirable.

Main feature of our experiments is that for the first time the signal frequencies less then 10 MHz has been used for interplanetary investigations by means of radio scintillation technique. These frequencies are most effectively scattered by plasma irregularities, and we were able to detect even weeker variations of solar wind electron density than it has been done before with shorter wavelength.

It is resumed that the decameter radar with ground-based transmitter and space-borne receiver can be successfully used for study the geo-disturbed solar wind and related magnetospheric and ionospheric phenomena.

Acknowledgements

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