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A method for reconstructing the solar wind stream structure beyond Earth’s orbit

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Abstract.

The paper describes a new method for reconstructing the solar wind stream structure beyond Earth’s orbit. The method is based on the use of two-station interplanetary scintillation data obtained at decameter wavelengths. Solar wind stream structure is reconstructed by fitting model characteristics to the experimental ones. The model characteristics were obtained by using Feynman path-integral technique. Authors use multiflow model of the solar wind.

Introduction

The solar corona is non-uniform, so it is not surprising that the solar wind also is highly structured. For example the recurrent high-speed streams from coronal holes are clearly seen in in-situ spacecraft data (Figure 1). Ulysses spacecraft measurements show that the solar wind has a "fast" component and a "slow" component [*Lang K.R.*, 1996]. There are some compositional differences in the two wind streams in addition to differences in their speeds [*Ulysses Web page*]. Consequently, the solar wind observed anywhere in the heliosphere is a collection of streams with different parameters.

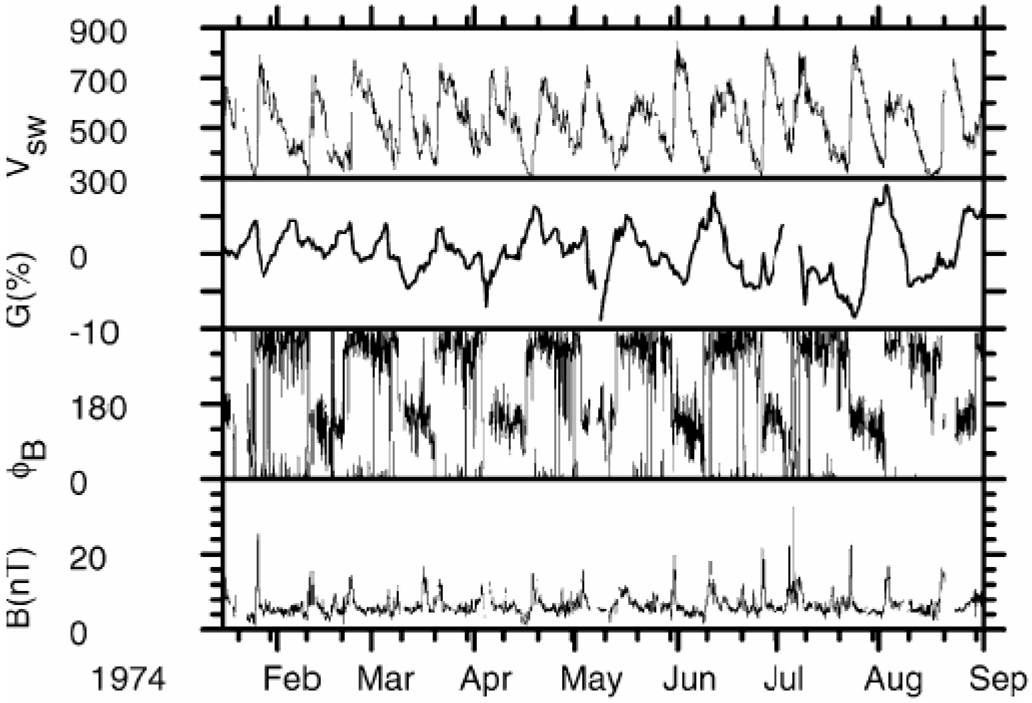

Fig. 1 Solar wind according to IMP-8 space craft observations during January - August, 1974

Also, there is another possibility for the investigations of solar wind stream structure then spacecraft measurements. This is observations of the interplanetary scintillations (IPS) [*Hewish A. et al*, 1964]. Interplanetary scintillations of the radio waves from distant compact cosmic radio sources (such as quasars, pulsars, galaxies) are produced by density irregularities in the solar wind. Observations of IPS phenomenon allow conclusions to be made on the parameters and the stream structure of the solar wind [*Dennison P.A.* and *Hewish A*, 1967; *Coles W.A.*, 1996]. Decameter radio waves provide a possibility to study effectively the solar wind parameters at large distances from the Sun [*Falkovich I.S. et al.*, 2010, *Kalinichenko M.M.*, 2012] where high frequencies are only slightly scattered by the rarefied interplanetary plasma.

The aim of this paper is to describe a new method for reconstructing the solar wind stream structure beyond Earth's orbit by using two-station interplanetary scintillation data obtained at decameter wavelengths.

Observations

We carry out IPS observations with UTR-2 (8÷32 MHz) and URAN system (8÷32 MHz) radio telescopes [*Braude S.Ya et. al*, 1978, *Megn A.V. et. al*, 2003] (Figure 2) since 2006.

Fig.2 Ukrainian decameter radio telescopes for IPS observations UTR-2 and URAN-1-4 on the map

The data used in this investigation were obtained by using UTR-2 (Grakove) and URAN-2 (Poltava) radio telescopes (base 152 km) during the period from January 12 to January 17, 2016. The use of the high linearity wideband receivers and records from several radio telescopes allow us to apply a special technique for selecting data, which are not corrupted by Earth's ionosphere and interferences, and to achieve sensitivity that is close to maximal. Figure 3 shows an example of IPS records obtained with UTR-2 radio telescope.

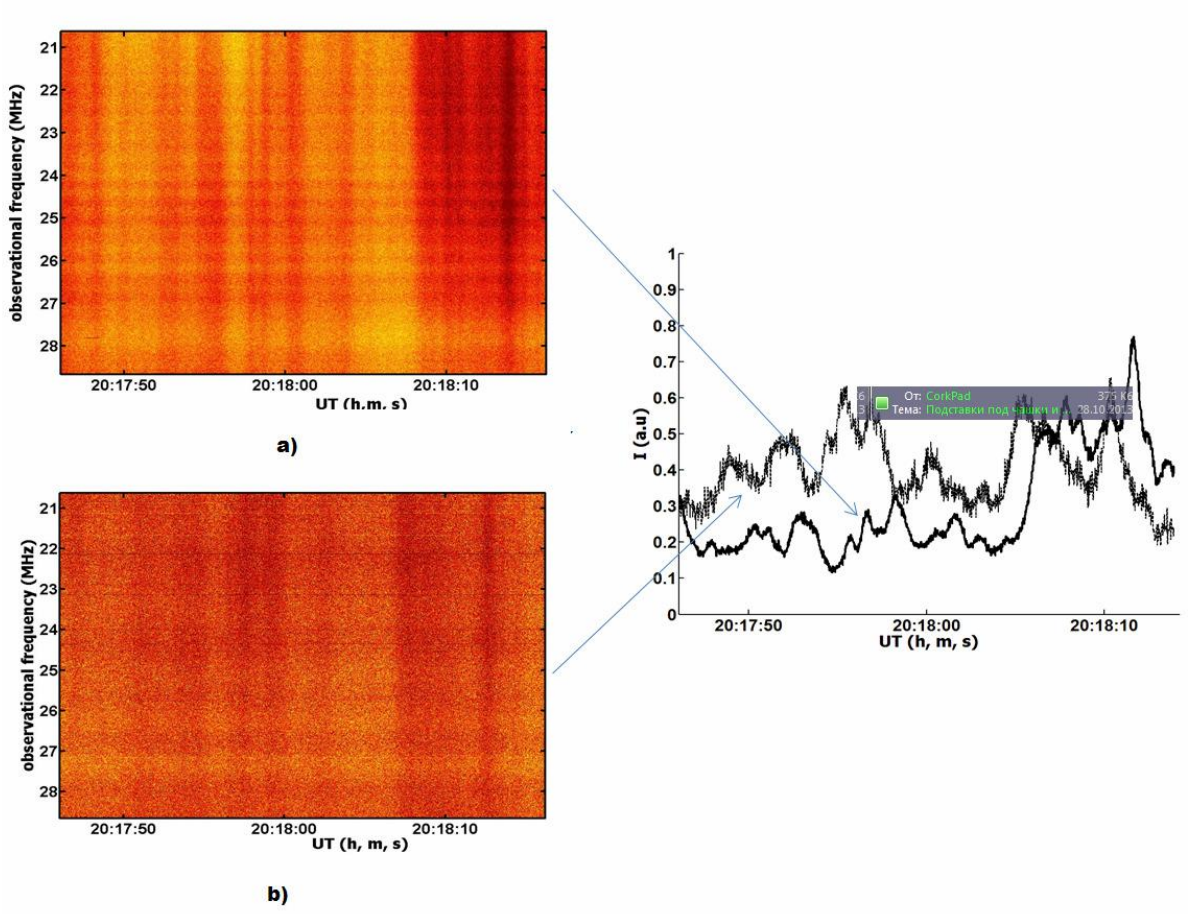

Fig.3 Dynamic spectra which were synchronously obtained by using the radio telescopes UTR-2 (a) and URAN-2 (b). January 12, 2016.

The processing of experimental IPS data consisted in estimation of the experimental spectra and experimental cross-correlation functions between records in two sites. If more than one stream presented on the line of sight to the radio source, the additional knees appeared on experimental spectrum and asymmetric cross-correlation functions were observed.

The model

The solar wind stream structure is obtained by fitting the model theoretical characteristics to the experimental ones as you see in Figure 4. For model fitting we obtain equations for theoretical spectrum (1) and cross-spectrum (2) by using Feinman path integral technique [*Frehlich R.G.*, 1987]. These equations give better results than equations obtained by using phase screen model and allow us to estimate the width of the solar wind stream. We consider spectrum and cross-correlation function as a sum of contribution from each flow.

$$
W(f)=\sum_{m=1}^{M}W_m(v_m,f)
$$

$$
W_m(v_m,f)\approx 2\pi I_0^2 l_m\left(\frac{4\pi r_e^2}{k}\right)^2\int_0^1 d\zeta\int_{2\pi f/v_{m\perp}(\zeta)}^{\infty}\sin^2\left(\frac{\kappa_{m\perp}^2 l_m\zeta}{2k}\right)\times \tag{1}
$$

$$
\times\frac{\kappa_{m\perp}\Phi_{Nm}(\kappa_{m\perp},0,\zeta)}{\sqrt{\zeta\left(\kappa_{m\perp}^2 v_{m\perp}^2(\zeta)-4\pi^2 f^2\right)}}\exp\left(-\frac{1}{2}\kappa_{m\perp}^2 L^2\zeta^2\theta_0^2\right)d\kappa_{m\perp}
$$

$$
W(b,f)=\sum_{m=1}^{M}W_m(b,v_m,f) \tag{2}
$$

$$
W_m(b,v_m,f)\approx
$$

$$
\approx 2\pi I_0^2 l_m\left(\frac{4\pi r_e^2}{k}\right)^2\int_0^1 d\zeta\int_{2\pi f/v_{m\perp}(\zeta)}^{\infty}\mathbf{sin}^2\left(\frac{\kappa_{m\perp}^2 l_m\zeta}{2k}\right)\mathbf{exp}\left(\frac{2\pi i f b\,\mathbf{cos}\,\beta_m}{v_{m\perp}(\zeta)}\right)\times
$$

$$
\times\frac{\kappa_{m\perp}\Phi_{Nm}(\kappa_{m\perp},0,\zeta)}{\sqrt{\zeta\left(\kappa_{m\perp}^2 v_{m\perp}^2(\zeta)-4\pi^2 f^2\right)}}\mathbf{exp}\left(-\frac{1}{2}\kappa_{m\perp}^2 L^2\zeta^2\theta_0^2\right)d\kappa_{m\perp}
$$

Dispersion dependence can be written as:

$V_f(f)=2\pi f b\cos\beta/\Delta\Psi$, where $\Delta\Psi=\arccos\left(\mathrm{Re}\,W(b,f)/\left|W(b,f)\right|\right)$

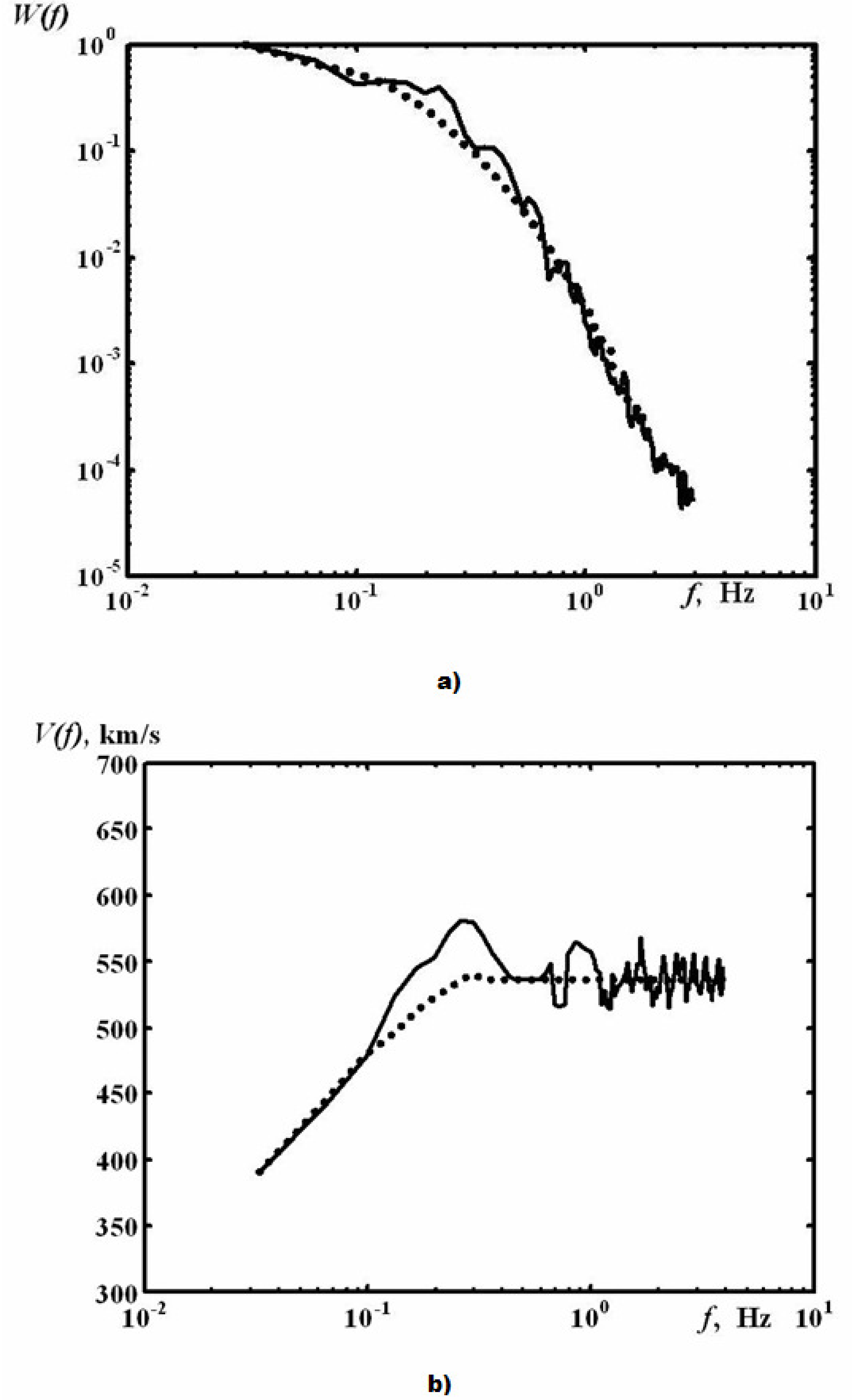

Fig. 4 Model fitting procedure. Experimental (solid lines) and model (dotted lines) spectra (a) and dispersion dependences (b)

Reconstructed stream structure of solar wind

Figure 5 shows an example of the reconstruction of the solar wind stream structure for January 13, 2016. The different streams are marked by the different colors - the higher velocity, the deeper red color is used. There are two streams of the solar wind on the line of sight to the radio source 3C144: the fast flow with parameters: speed v_1=530 км/с, spectral index of the interplanetary turbulence spectrum n_1=3.9, the width l_1=0.4 а.е., and the slow flow with v_2=400 км/с, n_2=3.9, a_2=2.2, l_2=2 а.е. The estimated solar wind speed on the line of sight to the radio source 3C144 is in agreement with one measured by spacecraft (during 12÷15 we see speed about 500 km/s and then it becomes lower).

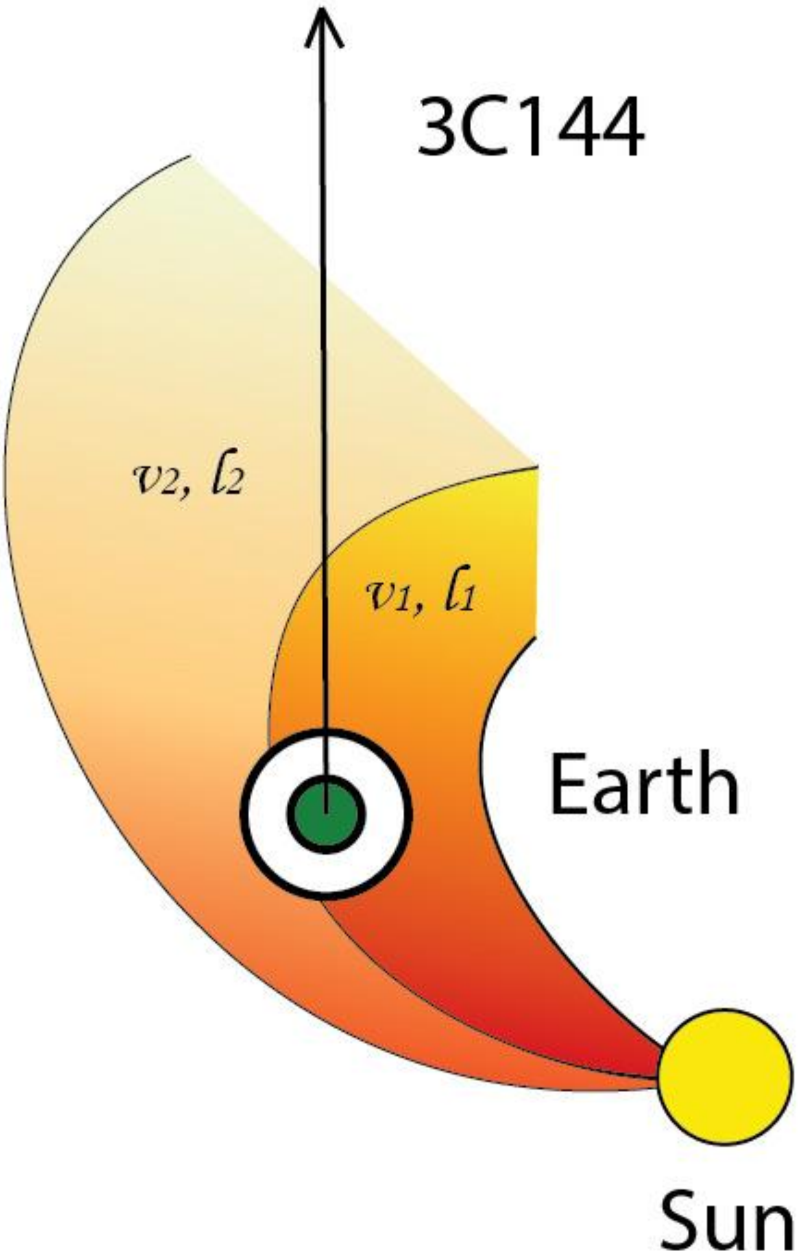

Fig. 5 The reconstructed stream structure of the solar wind for January 13, 2016

Conclusions

IPS observations at decameter wavelengths allow us to obtain the solar wind parameters and to reconstruct the stream structure of the solar wind beyond Earth's orbit. The future progress in this investigation is connected with using more scintillating radio sources. As the resolving ability of the IPS observations is improved due to the much larger baselines, the use of other European radio telescopes for synchronic observations of the same radio sources is desirable. Such approach is good from the standpoint of the different ionospheric effect and interference immunity.

Acknowledgment

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