THE INVESTIGATIONS OF THE SOLAR WIND BEYOND EARTH'S ORBIT BY IPS OBSERVATIONS AT DECAMETER WAVELENGTHS: PRESENT STATE AND PERSPECTIVES

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Abstract

The present state of solar wind investigations by IPS (interplanetary scintillations) observations at decameter wavelengths is discussed. Radio telescopes, equipment and methods which are used in these experiments are shown. We also describe some interesting results devoted to the long term monitoring of the solar wind beyond Earth's orbit, the detection of the large scale disturbances associated with active processes at the Sun and the reconstructions of the solar wind stream structure. Emphasis is placed on perspectives of low frequency IPS investigations which are particularly connected with the creation of the Giant Ukrainian Radio Telescopes (GURT) and UTR-2 – URAN – GURT – LOFAR collaboration.

1 Introduction

The interplanetary scintillations (IPS) arise when the radiation from compact distant radio sources, such as quasars, pulsars and galaxies, is scattered by density irregularities in the interplanetary plasma [Hewish et al., 1964]. IPS observations are very useful for studying the solar wind. At high frequencies, these observations allow one to obtain the

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solar wind parameters at distances less than 1 AU. At large solar elongations (at distances more than 1 AU from the Sun), the high frequencies are weakly scattered due to the decrease of electron density with radial distance while the decameter wavelengths still show a measurable scintillations index. This fact allows us to carry out the complex investigations of the solar wind beyond Earth's orbit by IPS observations at decameter wavelengths [Falkovich et al., 2010; Kalinichenko et al., 2012; Olyak, 2012]. Our investigations briefly consist of observations, theoretical investigations and fitting models to observed IPS characteristics. This allows us to obtain the main parameters of the solar wind (velocity, spectral index of the interplanetary turbulence spectrum and others), and to find and to track the high–speed solar wind flows at distances more than 1 AU from the sun.

2 Observations

We carry out IPS observations with UTR-2 (8–32 MHz), URAN (8–32 MHz) and GURT (8–80 MHz) radio telescopes [Braude et al., 1978; Megn et al., 2003] (Figure 1).

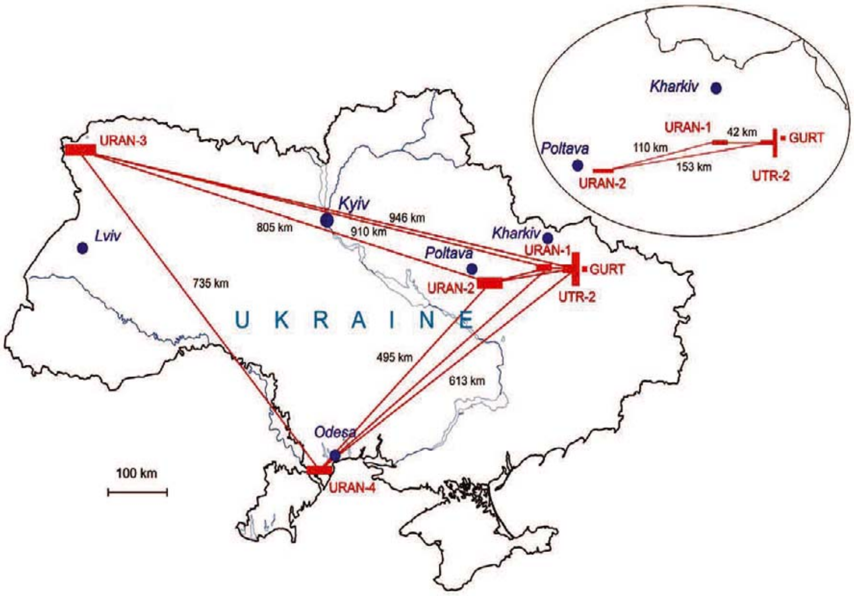


Figure 1: Ukrainian decameter radio telescopes for IPS observations on the map.

Records are obtained by using the digital spectrum analyzers DSP–z and ADR with parameters shown in Table 1.

The use of the high linearity wideband receivers mentioned above 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 a sensitivity that is close to maximal. In particular such receivers enable us to carry out observations even at daytime in presence of strong interference. Figure 2 shows an example of IPS records obtained with the UTR-2 radio telescope.

Table 1: Parameters of DSPz and ADR spectrum analyzers.

Parameters	**DSPZ – UTR-2**	**ADR – GURT**
Frequency band [MHz]	8 – 32	8 – 80
Number of freq. channels	8 192	16 384
Frequency resolution [kHz]	4	5.450
Time resolution [ms]	0.5	0.183
ADC resolution [bits]	16	16
Dynamic range [dB]	90	90
Input channels	2	2

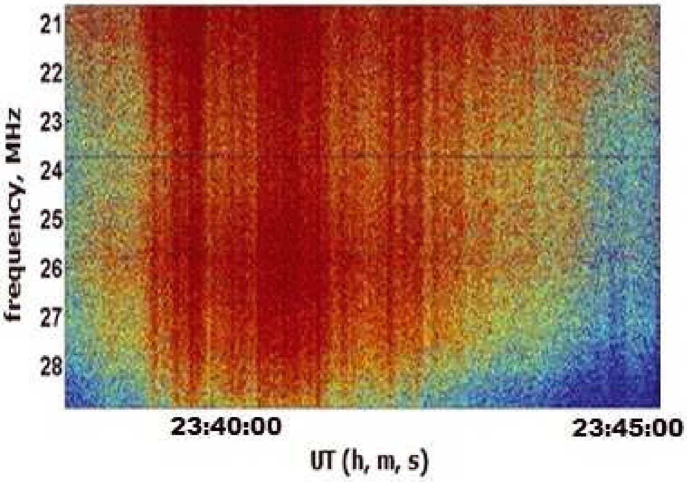


Figure 2: Dynamic spectrum of IPS at an elongation of 170 degrees. Radio telescope UTR-2. Radio sources 3C196. December 11, 2010.

3 Data processing

The data processing consists of estimations of the power spectrum $P(\nu)$(Equation (1)), the scintillation index m (Equation (2)), and the velocity of harmonics of the spatial cross-spectrum $V(\Omega)$(Equation (3)):

$$P(\nu) = |F(\nu)|^2 / T, \tag{1}$$

where $F(\nu)$ is Fourier transform of $I(t)$ process, ν is the fluctuation frequency, and T is the duration of the time series.

$$m = \frac{\sigma_{IPS}}{\overline{I(t)}} = \frac{\sqrt{\sigma^2_{(IPS+n)} - \sigma^2_n}}{\overline{I(t)}} \quad , \tag{2}$$

where $\overline{I(t)}$ is the mean intensity of the radio source, σ^2_{IPS}, σ^2_n, $\sigma^2_{(IPS+n)}$ – are the dispersions of the interplanetary scintillations, noise and their sum estimated from the power spectrum.

$$V(\Omega) = \frac{\Omega r}{\Delta\varphi(\Omega)} \tag{3}$$

where $\Delta\varphi(\Omega)$ is the phase of the spatial cross-correlation function $W(\Omega)$, $\Omega = 2\pi f$, r – base.

Solar wind parameters are usually obtained by fitting theoretical characteristics to the observed ones and using a multi–flow model of the solar wind. At high frequencies the phase screen model is usually used [see e.g. Cronyn, 1970] for the calculations of the theoretical characteristics. However, at large elongations and at low frequencies the scattering medium is essentially expanded and the most scattering layer is situated near the observer, so the use of the phase screen model is not correct. For our case we obtained equations for the power spectrum (Equation (4)) and the spatial cross-correlation function (Equation (5)) using the Feynman path–integral technique [Frehlich, 1987].

$$W(f) \approx 2\pi^2 \frac{L\omega_p^4}{(c\omega)^2} \int\limits_0^1 d\zeta \int\limits_a^\infty \kappa_\perp d\kappa_\perp \left[1 - \cos\left(\kappa_\perp^2 L\zeta^2/k\right)\right] \times$$

$$\exp\left[-\frac{1}{2}\left(\kappa_\perp L\zeta\theta\right)^2\right] \frac{\Phi_N(\kappa_\perp, 0)}{\left[\kappa_\perp^2 V_\perp^2 - 4\pi^2 f^2\right]^{1/2}}, \tag{4}$$

where ω_p is the plasma frequency, $a = 2\pi f/V_\perp$, $\zeta = z/L$, L is the stream thickness, $V_\perp \equiv V_\perp(\zeta) = V \sin\varepsilon/\left(R(\zeta)/R_0\right)$, $R_0 = 1\,AU$, θ – angular size of radio source, $\kappa_\perp = |\vec{\kappa}_\perp|$, $\kappa_\perp = \{\kappa_x, \kappa_y\}$ – spatial wave vector, $\sigma_N^2(\zeta)$ – dispersion of electron density fluctuations $\delta N^2/\langle N\rangle^2$, L_0, l_0 are the outer and inner turbulence scales, n – spectral index of the interplanetary turbulence spectrum.

The spatial spectrum of the interplanetary turbulence can be written as:

$$\Phi_N(\kappa_\perp, 0) \propto \sigma_N^2(\zeta) \exp\left(-\kappa_\perp^2 l_0^2\right) L_0^{3-n} \kappa_\perp^{-n}.$$

$$W(r,f) \approx \pi^2 \frac{L\omega_p^4}{c^2(2\pi f)^2} \int\limits_0^1 \frac{d\zeta}{\zeta^{1/2}} \int\limits_a^\infty \kappa_\perp d\kappa_\perp \left[1 - \cos\left(\kappa_\perp^2 L\zeta/k\right)\right] \frac{\Phi_N(\kappa_\perp, 0)}{\left[\kappa_\perp^2 V_\perp^2(\zeta) - 4\pi^2 f^2\right]^{1/2}} \times$$

$$\times \exp\left[-\frac{1}{2}\left(\kappa_\perp L\zeta\theta\right)^2 + i\frac{2\pi f r}{V_\perp(\zeta)}\right]. \tag{5}$$

For more details see Olyak [2012].

4 Results of observations

4.1 Stream structure of the solar wind

Analysis of data from spacecraft near Earth's orbit shows the presence of the solar wind streams with different velocities [Burlaga and Lazarus, 2000]. Does the stream structure remain at distances more than 1 AU from the Sun? Figure 3 answers this question. Sometimes at least three streams with different parameters can be seen at large distances from the sun by IPS observations at large elongations.

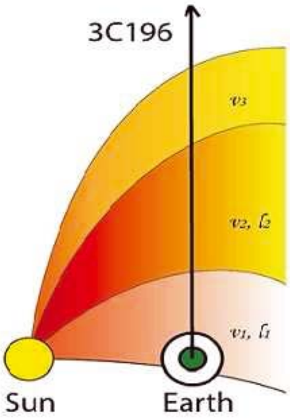


Figure 3: The stream structure of the solar wind on the line of sight to the radio source 3C196 ($v_1 = 550$ *km/s*, $n_1 = 3.8$, $l_1 = 1$ *AU*, $v_2 = 700$ *km/s*, $n_2 = 3.7$, $l_2 = 2$ *AU*, $v_3 = 500$ *km/s*, $n_3 = 3.9$)*. The data was obtained with UTR-2 and URAN-2 radio telescopes.*

4.2 ICME beyond Earth's orbit

Interplanetary Coronal Mass Ejection (ICME) reveals itself in IPS data at decameter wavelengths as sharp increases of the scintillation index and the width of power spectrum (Figures 4 and 5 correspondingly). Why are ICME observations beyond Earth's orbit important? As ICMEs continue slowing at the distances of several a.u. from the Sun, the investigations of ICME dynamic beyond Earth's orbit will allow us to construct a reliable model of ICME propagation in the heliosphere. For instance such model allows precise prediction of the arrival time of ICME at Earth.

4.3 Annual statistics of solar wind parameters

A large enough volume of experimental data allows us to obtain the annual statistic of the solar wind parameters. Figure 6 compares the solar wind velocity for two years in a declining period of solar activity, and the difference is seen in histograms for two years (2003 and 2004).

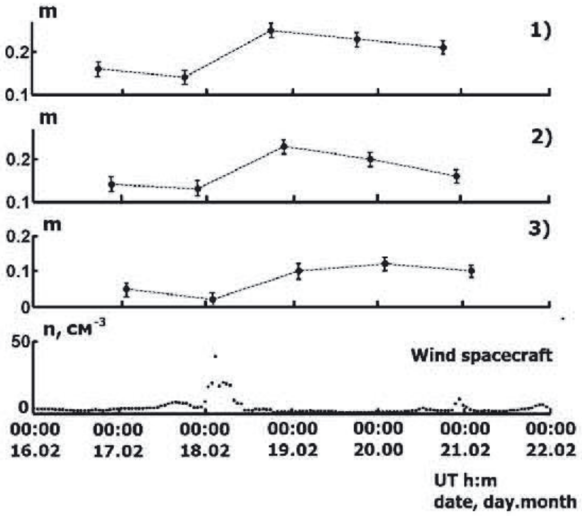


Figure 4: The behavior of the scintillation index during 5 days for observed radio sources (1 – 3C144, 2 – 3C196, 3 – 3C273) and the proton density in the solar wind measured by the NASA spacecraft Wind (the bottommost panel of the figure). Valentine's Day CME (February 15, 2011).

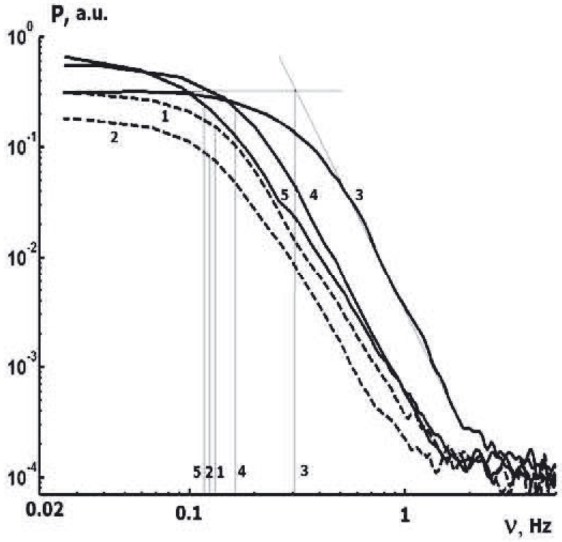
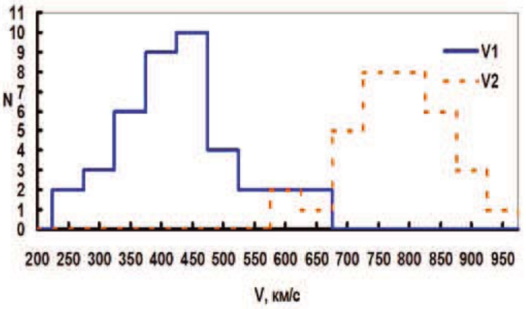


Figure 5: The power spectra for the radio source 3C144: 1 – 16.02.2011, 2 – 17.02.2011, 3 – 18.02.2011, 4 – 19.02.2011, 5 – 20.02.2011. Valentine's Day CME (February 15, 2011).

5 Perspectives

Further progress in IPS investigations at low frequencies is linked, among others things, to the creation of the Giant Ukrainian Radio Telescopes (GURT) (frequency range 10–80 MHz) in Gracove, Ukraine. The new radio telescope GURT has been built near the radio telescope UTR-2 (Figure 7). It consists of 25-element sub-arrays. It is planned that GURT will include about 100 sub-arrays. At present 3 sub-arrays are fully equipped and



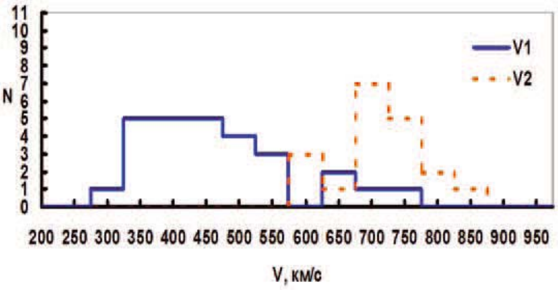


Figure 6: The histograms of the solar wind velocity for two years (2003 and 2004)in a declining period of solar activity. $V1$ and $V2$ are the velocities of the slow and high speed streams correspondingly.

Figure 7: North–south arm of the radio telescope UTR-2 (foreground) and the radio telescope GURT behind it (white color).

9 sub-arrays are partially equipped. GURT allows us to carry out more effective observations at small elongations (less than or about 70 degrees) in the frequency range 40 to 80 MHz with a lower level of interference at day time. It also enables us to use more effectively our method of separation of the interplanetary and ionospheric scintillations. Joint synchronous nightside observations of the same radio sources with UTR-2 (8–32 MHz) – URAN (8–32 MHz) – GURT (10–80 MHz) and LOFAR – KAIRA (10–80 MHz) radio telescopes also arouse considerable interest. Such observations allow us to answer several important questions connected with the interplanetary and ionospheric scintillations.

Firstly, in what measure does the ionosphere's impact in radio source scintillation depend on the geographic latitude? Secondly, in what measure do the characteristics of the ionospheric scintillations depend on the geographic latitude of the observation? What is the usefulness of such very long base (about 2000 km) IPS observations for diagnostics of the interplanetary plasma, finding ICME, or corotating streams etc?

6 Conclusions

IPS observations at decameter wavelengths allow us to obtain the solar wind parameters, reconstruct the stream structure of the solar wind and to find and study ICMEs. The new radio telescope GURT (10–80 MHz) enables us to rise the efficiency of such investigations especially at small solar elongations (less than 70–80 degrees).

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