# The investigations of the outer heliosphere with the large antenna arrays of the low-frequency URAN interferometer.

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# Introduction

The solar wind study is one of priority task of the low frequency radio astronomy and the LOFAR project. Interplanetary scintillation (IPS) method is known to be a powerful tool for studing the interplanetary medium. The experiments at meter wavelengths and shorter ones have allowed the large amount of new data on the structure and the dynamic of the interplanetary plasma in the inner heliosphere to be obtained. Decametric range has been used less actively, but it enables us to study the outer heliosphere at the large distances from the Sun. The outer heliosphere has been investigated by satellites, but deep space missions have been rare enough.

In our talk we discuss the effectivity of the method of the dispersion analysis using observations of the interplanetary scintillation in two spatially separated points. Joint analysis of the dispersion of velocities and scintillation spectra allows the principal parameters of the interplanetary plasma along the line of sight to be determined. Using layered medium model it is possible to evaluate layer widths, their density, velocities, power of spatial spectrum and inner scales of turbulence.

# Special features of dispersion analysis in the decametric range

The method is based on study of the frequency dependence of velocity of the scintillation cross-spectrum harmonics observed at two spatial separated antennas.

Lets present scintillation function $\Delta I_{1,2}(t)$ as transform to Fourier integral form: $$\Delta I_{1,2}(t) = \int P_{1,2}(\Omega) e^{-i\Omega t} d\Omega$$

$$P_{1,2}(\Omega) = \frac{1}{2\pi} \int \Delta I_{1,2}(t) e^{i\Omega t} dt = \left| P_{1,2}(\Omega) \right| \exp\left[ i\varphi_{1,2}(\Omega) \right] \qquad (1)$$

The scintillation cross-correlation function $B(r,\tau)$ is equal to

$$B(r,\tau) = \left\langle \Delta I_1(0,t) \Delta I_2(r,t+\tau) \right\rangle = \int W(\Omega) e^{-i\omega\tau} d\Omega$$

and its cross-spectrum

$$W(\Omega) = \left| P_1(\Omega) \right| \left| P_2(\Omega) \right| \exp\left[ i(\varphi_1(\Omega) - \varphi_2(\Omega)) \right] \qquad (2)$$

It is possible to show that the velocity of harmonics of cross-spectrum (2) is equal to

$$V(\Omega) = \frac{\Omega r}{\Delta\varphi(\Omega)} \qquad \Delta\varphi(\Omega) = \varphi_1(\Omega) - \varphi_2(\Omega) \tag{3}$$

where r – baseline. From the last expression it follows that in order to obtain the dispersion of velocity $V(\Omega)$ it is necessary to know the frequency dependence of phase shift between two points of observation

$$\Delta\varphi(\Omega) = \arctan\frac{\operatorname{Im} W(\Omega)}{\operatorname{Re} W(\Omega)} \tag{4}$$

In the decametric range scattering layer is essentially extended and the most dense plasma layer is situated near an observer. Therefore, the use of phase screen approximation is not correct. More correct way are provided by multiple scattering theory methods.

Using the Feynman's path-integral technique we have obtained the expression for the scintillation cross-spectrum:

$$W(r,f) \approx \pi^2 \frac{L\omega_p^4}{c^2\omega^2} \int_0^1 \frac{d\zeta}{\zeta^{1/2}} \int_A^\infty \kappa_\perp d\kappa_\perp \left[1 - \cos(\kappa_\perp^2 L\zeta / k)\right] \frac{\Phi_N(\kappa_\perp, 0)}{\left[\kappa_\perp^2 v_\perp^2(\zeta) - 4\pi^2 f^2\right]^{1/2}} \times$$

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

Here $f = \frac{\Omega}{2\pi}$, $\kappa_\perp = \{\kappa_x, \kappa_y\}$ -the spatial wave vector, $\zeta = (1 - z/L)$, $v_\perp(\zeta) = v\sin\phi / (R/R_0)$, $R = \left[R_0^2 + L^2\zeta^2 - 2R_0 L\zeta\cos\phi\right]^{1/2}$, $R_0 = 1AU$, $\phi$ - the elongation, $L$ - the layer width, $\theta$ - the source angular size, $\omega_p$ - the plasma frequency, $A = 2\pi f / v_\perp(\zeta)$, $\Phi_N(\kappa_\perp, 0) \propto \sigma_N^2(\zeta)\exp(-\kappa_\perp^2 l_0^2) L_0^{3-n} \kappa_\perp^{-n}$ - the spatial spectrum of the interplanetary turbulence, $l_0$ and $L_0$ - the inner and outer turbulence scales.

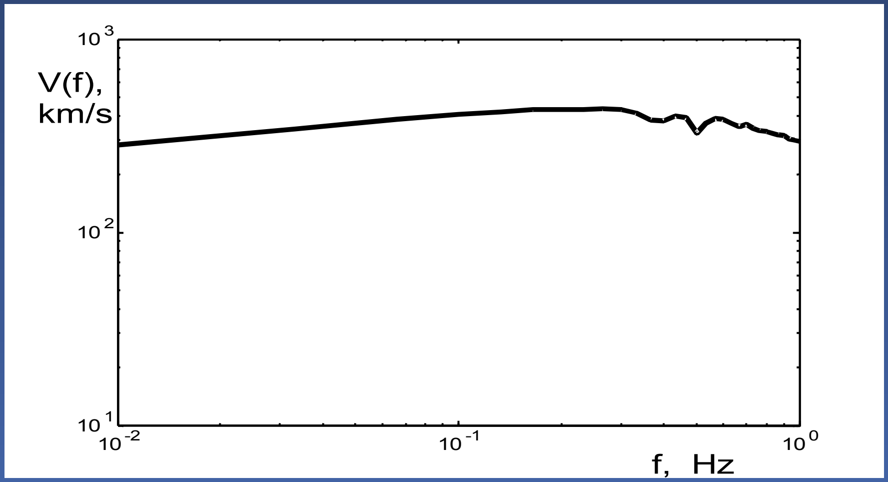


Fig.1 *The dispersion dependence of phase velocity of scintillations at the frequency of 400 MHz at* $\phi = 20^\circ$ *and* $\theta = 0.1''$

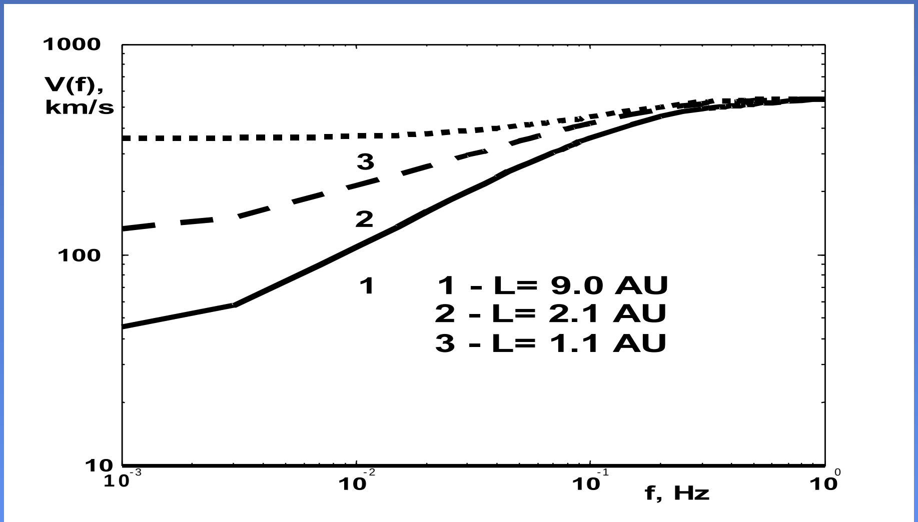


Fig.2 *The calculation of the dispersion dependence at layer widths L=9.0, 2.1, 1.1 AU (curves 1 - 3)*

At the high frequencies scattering layer is thin. In Fig.1 a dispersion dependence which has been calculated using expressions (3-5) for frequency of 400 MHz, spherically symmetric solar wind with velocity of 450 km/s, elongation of 20 degrees, and source size of 0.1 arc sec is presented. In the decametric range at the elongations more than 90 degree the layer which causes scintillations can achieve 9 AU. The tilt of the dispersion curve depends on the velocity diversity, turbulence parameters, and width of streams (see Fig.2).

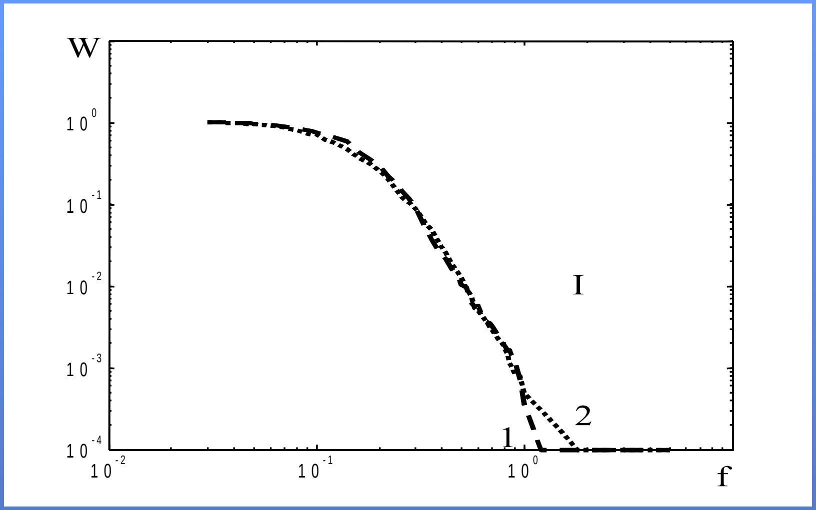


Fig.3 *1 - the scintillation spectrum for spherically symmetric SW at* $\phi = 90^\circ$, $v = 500$ *km/s; 2 -two-stream model at* $v_1 = 350$ *km/s,* $v_2 = 500$*km/s*

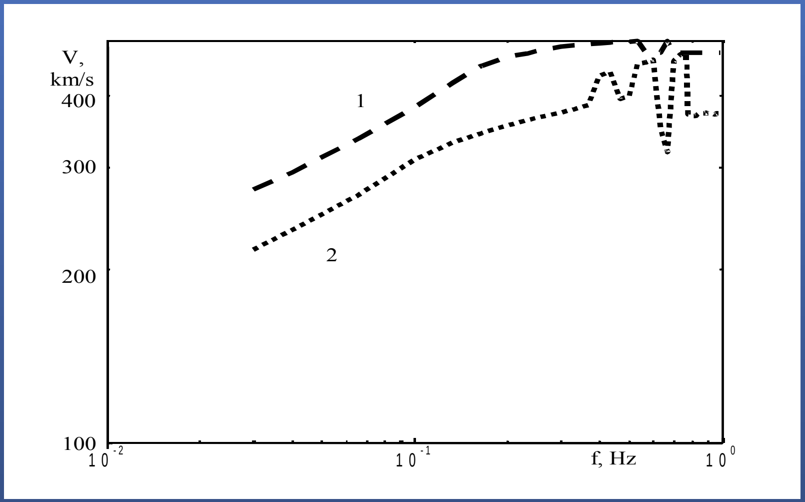


Fig.4 *The dispersion dependences of phase scintillation velocity for spherically symmetric SW (curve1) and for two-stream model (curve 2).*

Joint analyses of the scintillation spectrum and the dispersion dependence allows the model of the solar wind to be determined more correctly. In Fig. 3 and 4 the results of calculations of the scintillation spectra and the dispersion dependences are presented; the frequency is 25 MHz and the baseline is 153 km. Curve 1 corresponds to spherically symmetric solar wind, curve 2 for two-stream model. It is seen that the scintillation spectra are close, but the dispersion curves are different enough.

Thus, the method of dispersion analysis allows the parameters of the streams with different velocities in the outer heliosphere to be determined.

# Results of experiments with interferometer URAN-2

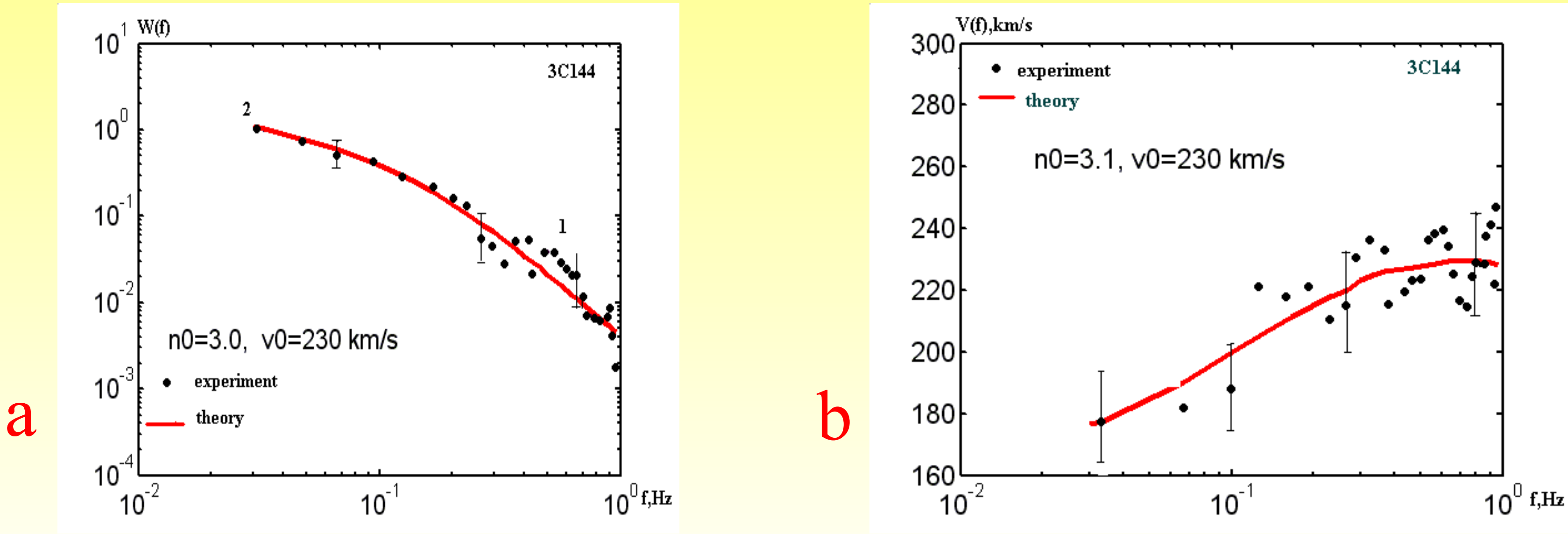


Fig.5 The scintillation spectrum (a) and dispersion curve (b) for radio source 3C144

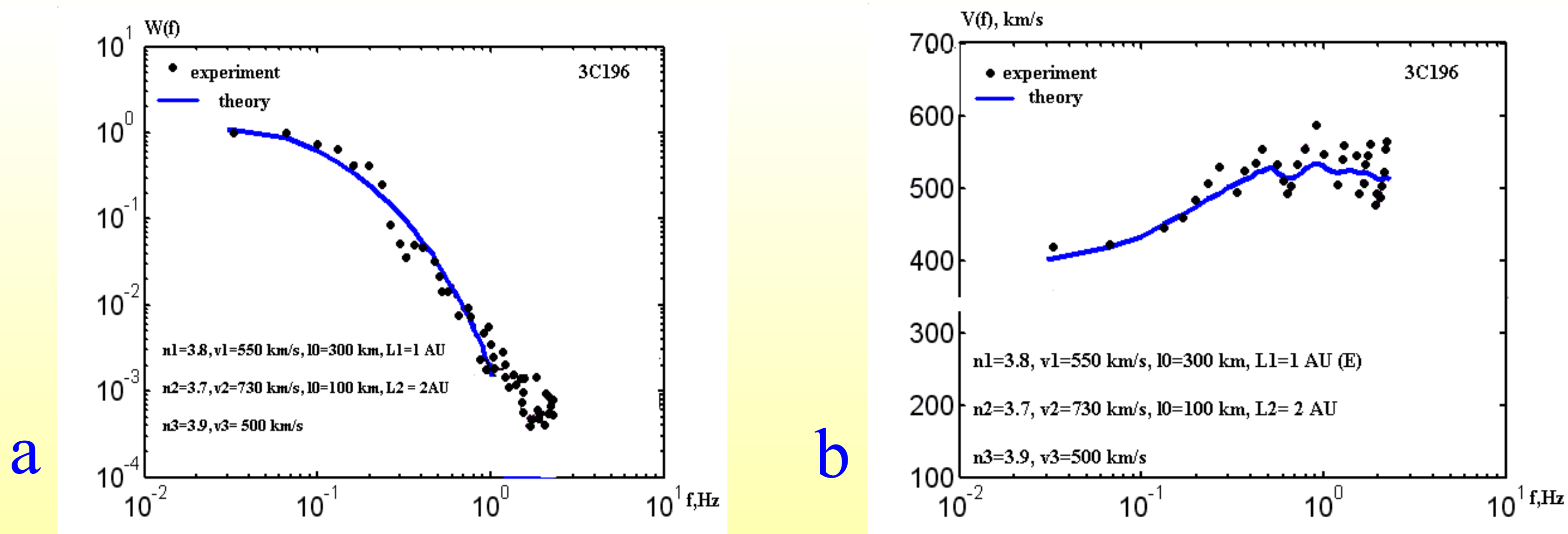


Fig.6 The scintillation spectrum (a) and dispersion curve (b) for radio source 3C196

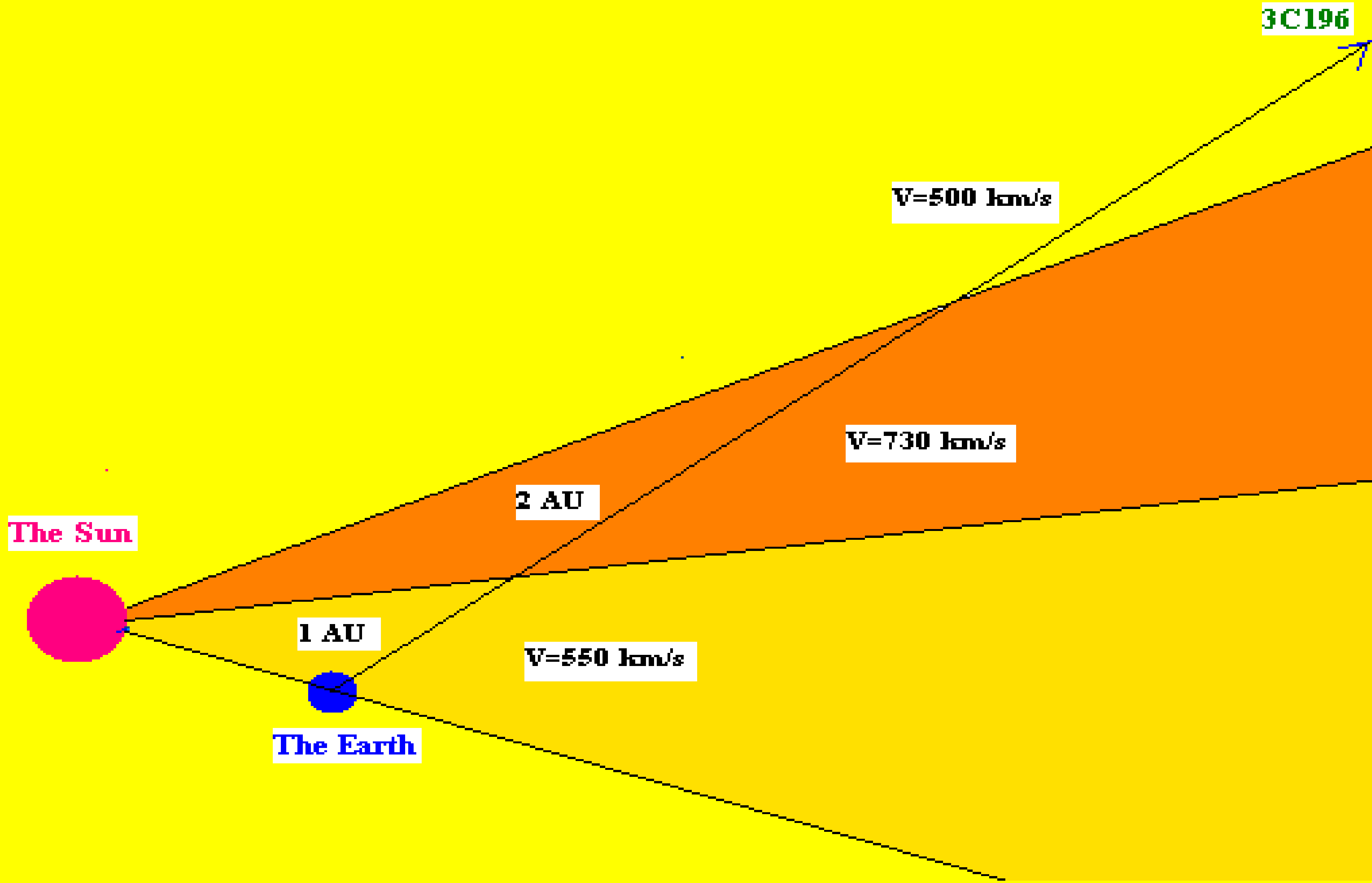


Fig.7 The structure of the solar wind

# Conclusion

- The dispersion analysis method allows us to reconstruct the parameters of the high velocity streams as well as the slow solar wind. The carried out calculations and the experiments show that this method can be successfully used for the three-stream model of the outer heliosphere alone the line of sight. At the present time the biggest effective area of 150 000 square meter has the radio telescope UTR-2 in Ukraine. It allows us to carry out reliable observations of about ten sources, which show scintillations, for a night. Unfortunatelly, the spatial resolution in this case is low enough. LOFAR project will open the opportunity to increase the number of observed sources, at least on an order, and to improve significantly the spatial resolution of the outer heliosphere maps that will be obtained.