Estimation of plasma turbulence parameters by observations of radio-source interplanetary scintillations

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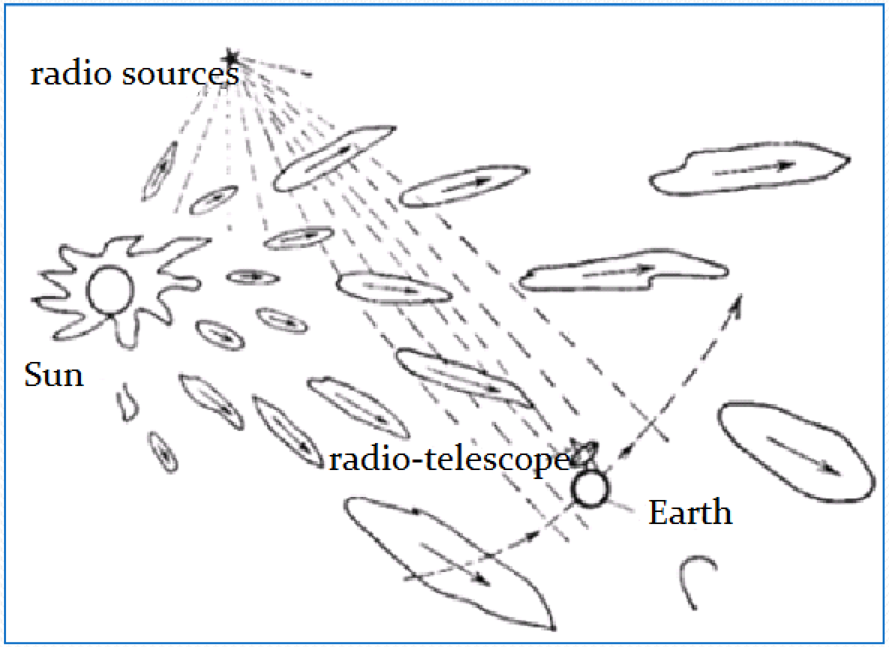
The interplanetary scintillation (IPS)

Solar wind is the plasma flow continuously emanating from the Sun. One of the main properties of the solar wind plasma is turbulence: all the plasma parameters, magnetic field, density, speed etc., are fluctuating at all measurable temporal and spatial scales. Radio waves from space radio sources propagate through interplanetary plasma. The interplanetary scintillation (IPS) is fluctuation of space radio sources flux density, caused by fluctuation of interplanetary plasma density. Scintillation observations allow to derive information on solar wind spatial structure and large scale disturbances.



Compact (<1″) radio sources, such as active galactic nuclei (AGN) are used in IPS observations. The IPS characteristics are dependent only on source/observer geometry relative to the solar wind, and on the level of small scale density turbulence as well as on solar wind speed in the case of the point radio source. Sources angular sizes influence the IPS level and power spectra if sources have finite angular sizes. We presents the method and first results of turbulence spectral index, sources angular sizes and solar wind speed estimations. We shall concentrate below mainly on results concerning spectral index of turbulence spatial spectrum.

LPA FIAN

The scintillation observations are carrying out in monitoring regime by the radio telescope LPA (Large Phased Array) of Lebedev Physical Institute from 2006 to present time. The aim is detection of large scale disturbances in the solar wind.

The observations parameters

- Central frequency: 111 MHz
- Wave bandwidth: 600 kHz
- The effective area of the array in the zenith direction:

  20 000 – 25 000 square meters.
- The array beams system includes 16 beams, covering the sky strip with width about 8 degrees in declination during 24 hours in right ascension.

Strong scintillating radio source

Present work contains IPS data strong scintillating radio source 3C048 near the minimum of solar activity cycle 23 (April-May 2007-2009). During the observation series the angular distance between the line of sight and the direction to the Sun (elongation) was in the limits 20^0 - 40^0. Temporal IPS power spectra were calculated using initial records and then analyzed.

3C 048

Type QSO
Z =0.367000
B1950 01h34m49.8287s +32d54m20.161s
J2000 01h37m41.2994s +33d09m35.134s

IPS temporal power spectra

IPS temporal power spectrum $P(f)$ is the Fourier transform of the correlation function $B_I(\tau)$:

$$P(f) = \int B_I(\tau) \exp(2\pi i f \tau)\, d\tau,$$

$$B_I(\tau) = \langle \delta I(t) \delta I(t+\tau) \rangle,$$

where $I(t)$ is the measured flux density and $\delta I(t) = I(t) - \langle I \rangle$ is it's temporal fluctuation.

IPS temporal power spectrum in the weak scintillation regime is defined by the following equation

$$P(f) = 4\lambda^2 \int \frac{A(z)}{v_{\perp(z)}} dz \int dq_\perp \Phi_e(q) \sin^2\left(\frac{q^2 z}{2k}\right) F^2(qz)\Big|_{q_\parallel = \frac{2\pi f}{v_\perp(z)}}$$

where f- the temporal frequency, axis OZ is directed along the line of sight with $z = 0$ at the observation point, $A(z) = \frac{A_0}{(z^2+r_0^2)^2} \sim \frac{1}{r_0^4}$, $A_0 = 5 \cdot 10^{-25} cm^2$, $r_0 = \sin\varepsilon \cdot 1AU$, $v_\perp(z) = v\cos\varphi = v\frac{r_0}{\sqrt{r_0^2+z^2}}$ is the projection of the solar wind speed on the pattern plane at the point z, v is the solar wind speed, q - the spatial frequency, $q_{||}$ - component of the spatial frequency along the projection of the solar wind velocity on the plane, $q_\perp$ - spatial frequency component of the perpendicular projection of the solar wind velocity on the plane, $q = \sqrt{q_\perp^2 + q_{||}^2}$, $\Phi_e(q) = Cq^{-n}$ - spatial spectrum of electron density fluctuations in the interplanetary plasma, n is power exponent of $3D$ turbulence power spectrum, $k = \frac{2\pi}{\lambda}$ -is radio wavenumber, $F(q) = \left(\frac{1}{2\pi}\right)^2 \iint d^2\theta exp[-ikq\theta] I(\theta)$ is spatial spectrum of the radio source and $I(\theta)$ is brightness distribution of the source.

Numerical simulation of the temporal IPS spectra is performed in the following assumptions:

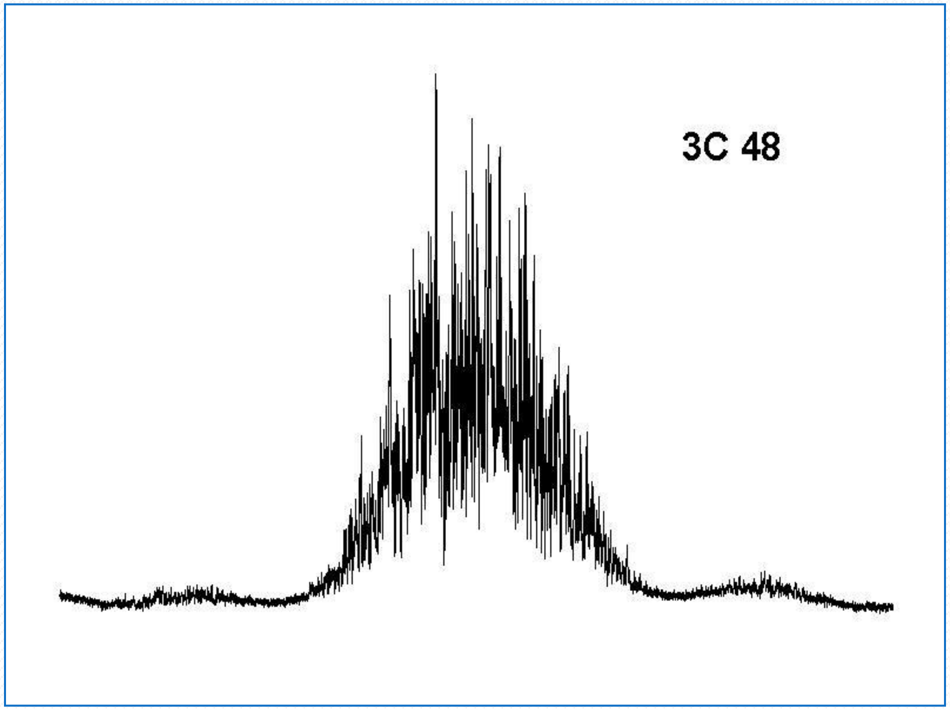
1) $3D$ spatial turbulence spectrum is isotropic power-low, $\Phi_e(q, q_z = 0) = Cq^{-n}$ with structure constant C;

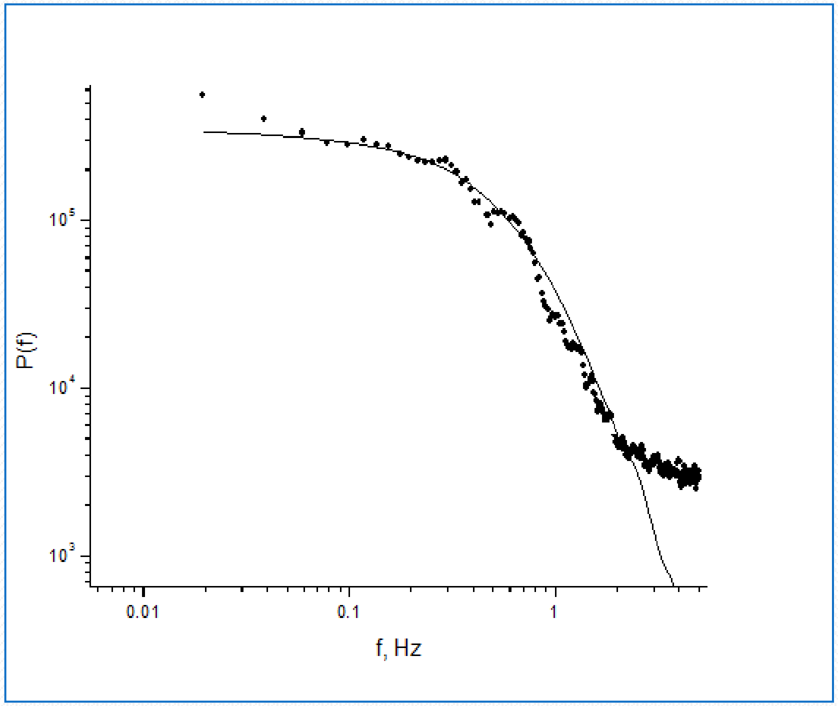
2) the density turbulence level depends on heliocentric distance r as $C \sim r^{-4}$, $C = C_0\left(\frac{1AU}{r}\right)^4$;

3) the solar wind speed v is constant, radial and uniform;

4) the source brightness distribution over the source is a symmetric Gaussian $I(\theta) = exp\left(-\frac{\theta^2}{2\theta_0^2}\right)$ with angular radius θ_0 at the $\frac{1}{e}$ level.

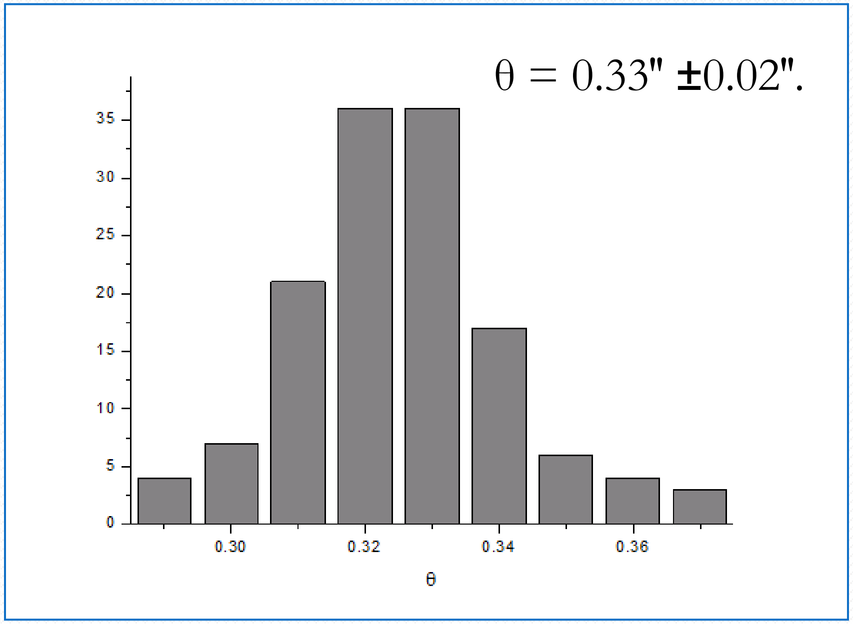
The model used in simulations has four free parameters: absolute turbulence level Co , solar wind speed v, turbulence spectral index n and radio source size θo. First three of them can change from day to day, and last one is assumed to be constant. We define free parameters from the best fitting of calculated spectrum P(f) into spectrum obtained from IPS measurements.

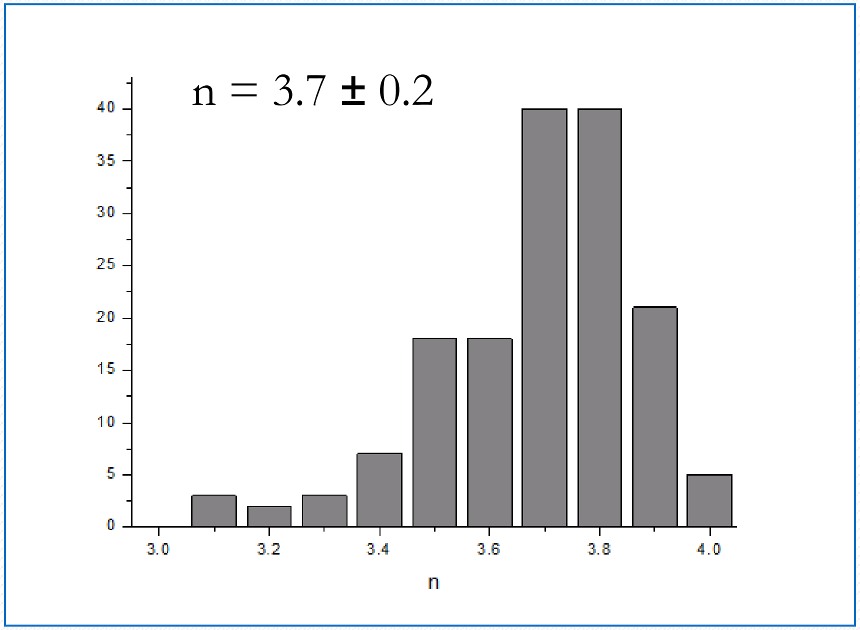




The example of IPS record for the source 3C 48.	A sample of the power spectrum of the source 3C 48 (dots) and inscribed the theoretical power spectrum (full line).n=3.74, v=520 km/s).

Simulation results





The histogram for distribution of angular sizes of 3C 48.	The histogram for distribution of values of index of turbulent plasma.

- The problem of physical processes responsible for formation of wide power-law spectrum in inertial spectral range and energy cascading from turbulence outer scale to dissipation spectral range is still unsolved. Three possible mechanisms were considered.
- Suggested firstly by Kolmogorov strong turbulence of noncompressible neutral fluid and later modified for magnetized plasma has spectral index $n = 11/3$.
- Second possibility is strongly anisotropic power spectrum which was suggested by Goldreich and Sridhar for magnetic field turbulence . If the same spectrum takes place for density turbulence then the measured spectral index would be $n = 3$, that is in contradiction with our observations.
- Third turbulence model considers the formation of turbulence spectra in inertial range by weak decay non-linear interactions. The value of power spectral index is $n = 7/2$ for Iroshnikov/Kraichnan model .

Conclusions

- The estimates of the density turbulence spectral index $n = 3.7 \pm 0.2$ found from IPS data are in a good agreement with similar estimates at much greater turbulence scales found from both, local, in situ, measurements on spacecraft and solar wind radio sounding by coherent signals of spacecraft . This coincidence confirms the hypothesis that large scale and small scale density irregularities belong to single power-law spectrum in the very wide range of scales.
- Our data do not allow distinguishing between Kolmogorov ($n = 11/3$) and Iroshnikov/Kraichnan ($n = 7/2$) spectra because both models are in agreement with measurements within the error limits.
- Future studies based on more rich statistics with large scale and small scale data comprehensive comparison are needed for convincing conclusions.

Thank you!