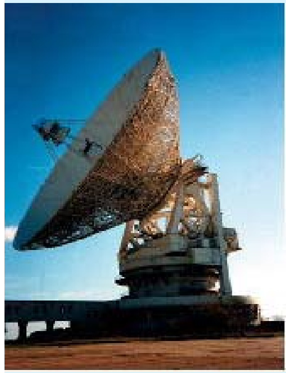
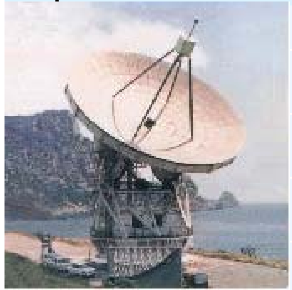

Bear Lakes RT-64


Evpatoria RT-70


Simeiz RT-22


Urumqi RT-25

VLBI-experiments on research of solar wind plasma

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7) Radioastronomy Institute CNR, Noto, Italy

This work devotes to investigations of solar corona and solar wind plasma by the method of radio probing with very long baseline interferometry (VLBI).

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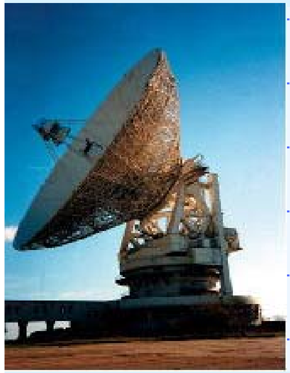
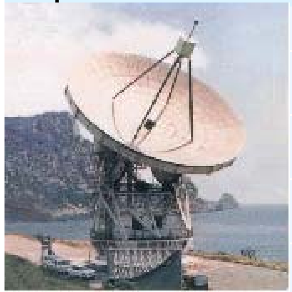


Evpatoria RT-70



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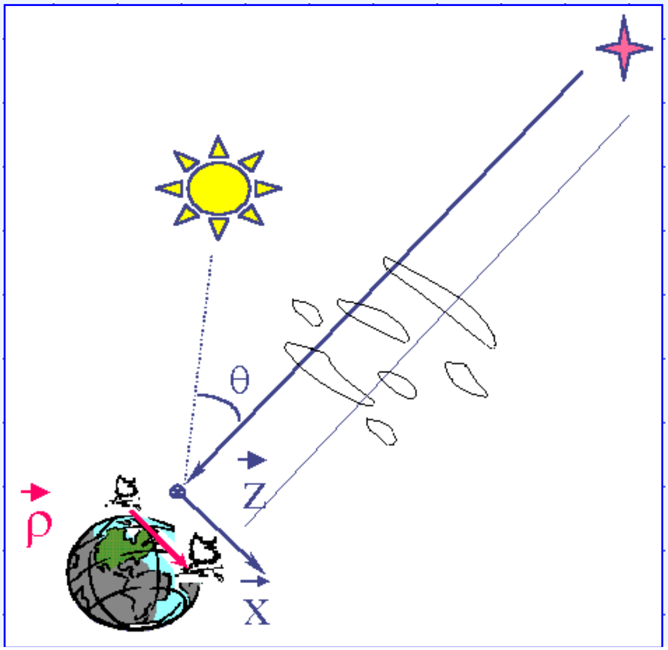
The series of international **VLBI experiments** on investigations of solar wind plasma implemented in 1998, 1999, 2000 at **wavelength 18 cm**.

In 2004 three series of experiment were carried out at **wavelength 6 cm**.

Radio sources were selected to be at different angular distances from the Sun **2-40 degrees**.



Experiment / source

NTAS 98.5
- OR-140
- NRAO530
- OT111
- 1643-223
- 1741-038

INTAS 99.4
- OR-140
- 1555-140
- 1741-038
- NRAO530
- OT111
- 1643-223

INTAS 00.3
- 3C279
- 1622-253
- 1643-223
- 1524-136
- 1555-140
- 1504-167
- NRAO530
- 1741-038


Bear Lakes RT-64


Svetloe, RT-32


Ussuriysk, RT-70


Ventspils RT-32


Zimenki RT15


St. Pustyn RT-14

These observations were realized with participation of radio telescopes, included at **Low Frequency VLBI Network (LFVN)**:

Bear Lakes (RT-64, Russia),
Puschino (RT-22, Russia),
Hartebeesthoeck (RT-25, South Africa),
Urumqi (RT-25, China),
Noto (RT-25, Italy),
Shanghai (RT-25, China),
Svetloe (RT-32, Russia)
and others

10-20 minutes scans were recorded using **S2 system**.

Preprocessing of VLBI-data was carried out at the **S2-correlator at Penticton** (Canada) in 2003.

Post processing was performed at **RRI (Russia)**.

Output signal of an interferometer under conditions of heterogeneous medium

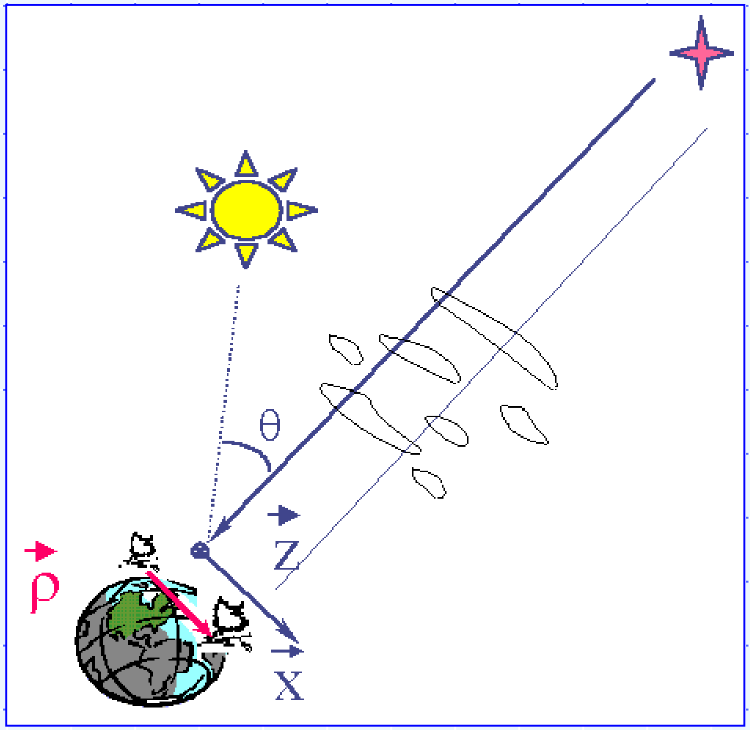
The purpose of this work was to carry out theoretical analysis of power spectrum of output interferometer signal and to determine the connection between the results of experiment and physical characteristics of propagation medium.

The signals received at separated antennas:

$$*\left[\begin{array}{l} E_1\left(\vec{r},t\right)=E_0 e^{\Phi_1\left(\vec{r},t\right)} \\ E_2\left(\vec{r},t\right)=E_0 e^{\Phi_2\left(\vec{r}+\vec{\rho},t\right)} \end{array}\right.$$

$$e^{\Phi\left(\vec{r},t\right)}=e^{\chi+i\phi}$$

$\vec{\rho}$ - the baseline of the interferometer, Φ – complex function of amplitude and phase fluctuations caused by the turbulence; E_0 – undisturbed component of field



Multiplication of signals without time shift: this procedure allows to study turbulent medium, when it is sounded by wideband emission from natural radio source.

$$*\left[\, r(\vec{\rho})=\left\langle E(\vec{r},t)E^*(\vec{r}+\vec{\rho},t)\right\rangle\right.$$

The autocorrelation function of multiplication result:

*
$$R(\tau)=\left\langle E(\vec{r},t)E^{*}(\vec{r}+\vec{\rho},t)E(\vec{r},t+\tau)E^{*}(\vec{r}+\vec{\rho},t+\tau)\right\rangle \sim e^{-\frac{D^{2}}{2}}$$

D – structure function of phase difference

The power spectrum of the interferometer field signal:

*
$$Y\left(\Omega_{0}\right)\approx\frac{1}{2\pi}\int_{-\infty}^{\infty}R(\tau)e^{-i\Omega_{0}\tau}d\tau$$

Ω_0 - the frequency of Fourier-analysis.

Noto RT-32

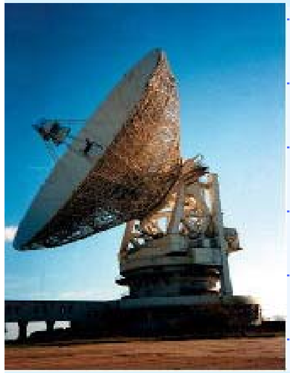
Puschino, RT-22

Ventspils RT-32

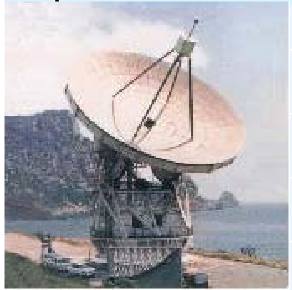
Zimenki RT-15

St. Pustyn RT-14

Bear Lakes RT-64



Evpatoria RT-70



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Urumqi RT-25

The general form of autocorrelation function:

$$R(\tau)=\exp\left\{-4\pi A^2 Z\int_{-\infty}^{\infty}F(\boldsymbol{\kappa}_\perp)[1-\cos(\boldsymbol{\kappa}_\perp\mathbf{V}_\perp\tau)]\cdot[1-\cos(\boldsymbol{\kappa}_\perp\boldsymbol{\rho}_\perp)]d\boldsymbol{\kappa}_\perp\right\}$$

- geometrical-optical approach

- "frozen-in" hypothesis:

$$\Phi_p(\boldsymbol{\kappa}_\perp,\mathbf{V}_\perp)=F(\boldsymbol{\kappa}_\perp)\delta(\Omega-\boldsymbol{\kappa}_\perp\mathbf{V}_\perp)$$

- spatial spectrum of electron-density fluctuations :

$$F(\kappa)=0.033\cdot C_N^2\left(\kappa_0^2+\kappa^2\right)^{-\frac{p}{2}}e^{-\frac{\kappa_\perp^2}{\kappa_m^2}}$$

$A=-\omega_p^2/(2N\omega_0 c)$; ω_p - plasma frequency, c – speed of light, ω_0 - the receiving frequency, N – **electron density**, Z – thickness of inhomogeneous layer; Φ_p – spatial-temporary spectrum of electron density fluctuations, C_N^2- structural coefficient, $\kappa_0=2\pi/\Lambda$, $\kappa_m=2\pi/l_m$, Λ_0 и l_m – outer and inner scale of turbulence, $\boldsymbol{\kappa}_\perp$, $\boldsymbol{\rho}_\perp$, $\mathbf{V}_\perp$ -projections of wavenumber, baseline and velocity of solar wind on the sky plane.

The baseline projection onto the wavefront (100-10000km) determines the maximal heterogeneities' scale, to which the interferometer is sensitive.

Strong phase fluctuations:

$$\left\langle D_{\rho}^{2}\right\rangle >> 1$$

-the structure function of phase fluctuations

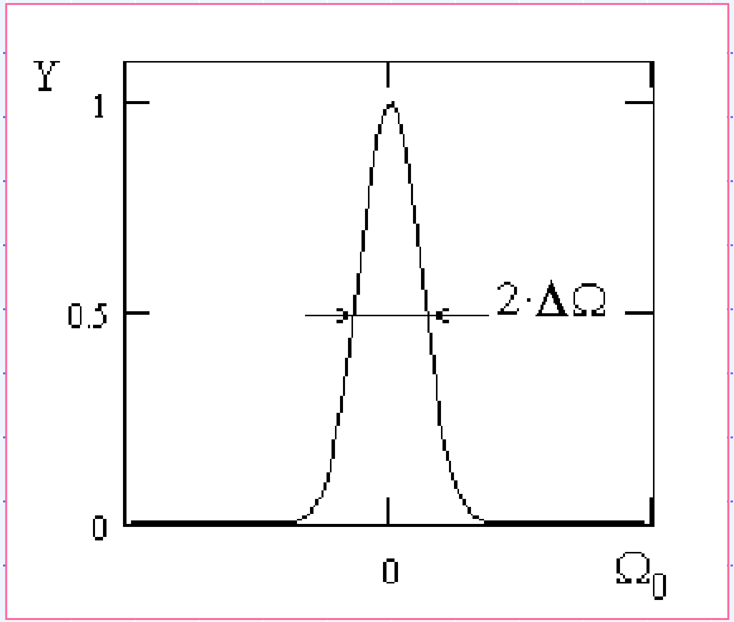
$$Y(\Omega_0) = \frac{1}{\sqrt{2\pi}\cdot\Delta\Omega}\exp\left\{-\frac{\Omega_0^2}{2\cdot\Delta\Omega^2}\right\}$$

$$\Delta\Omega = 2\frac{V_{\perp}}{l_E}$$ -halfwidth of spectrum

$$(\Delta\Omega)^2$$ -intensity of phase fluctuations

l_E – effective scale of phase fluctuations of emission in inhomogeneous layer.

The power spectrum of the output signal $Y(\Omega_0)$ has the form of Gaussian function, independently of the spatial spectrum's type $F(\kappa)$

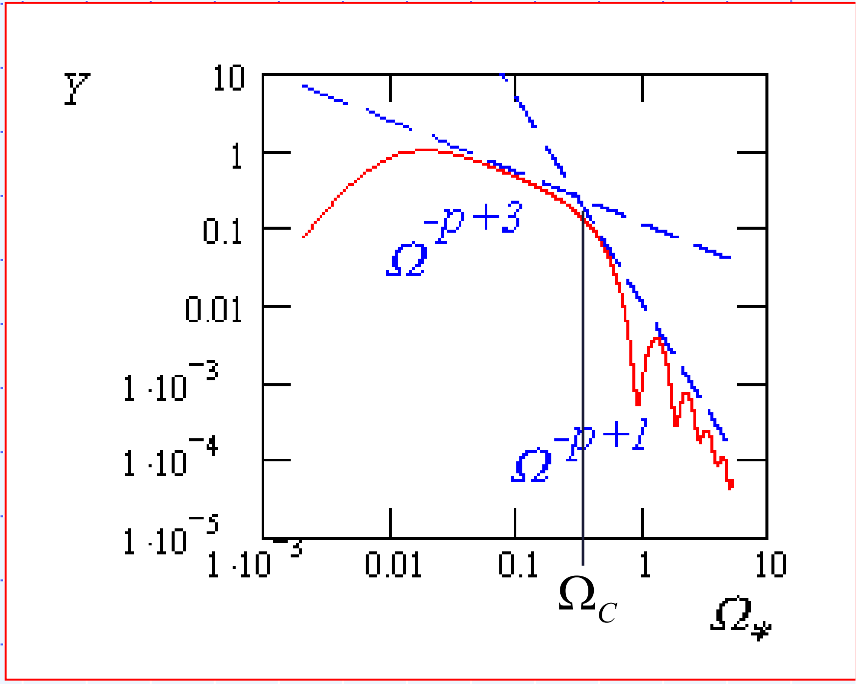


Weak phase fluctuations:

$\left\langle D_\rho^2 \right\rangle << 1$ -the structure function of phase fluctuations

$\vec{V_\perp} \parallel \vec{\rho_\perp}$: $(\kappa_0 V_\perp << \Omega_0 << \kappa_m V_\perp)$

$$\boxed{Y(\Omega) \sim \left(1-\cos\left(\frac{\Omega\rho_x}{V_x}\right)\right)\left[\left(\frac{\Omega}{V_x}\right)^2+\kappa_0^2\right]^{\frac{(-p+1)}{2}}}$$



p – the index of the spatial spectrum **of electron density fluctuations – is determined by the slopes of experimental spectra:**

$$Y_1(\Omega) \approx [\Omega]^{-p+3}, 0 < \Omega_0 < \pi V_x / \rho_x,$$

$$Y_2(\Omega) \approx [\Omega]^{-p+1}, \Omega_0 > \pi V_x / \rho_x$$

$\Omega_C = \pi V_x/\rho_x$ $\quad \Omega_* = \frac{\Omega_0}{2\pi}\frac{\rho_x}{V_x}$

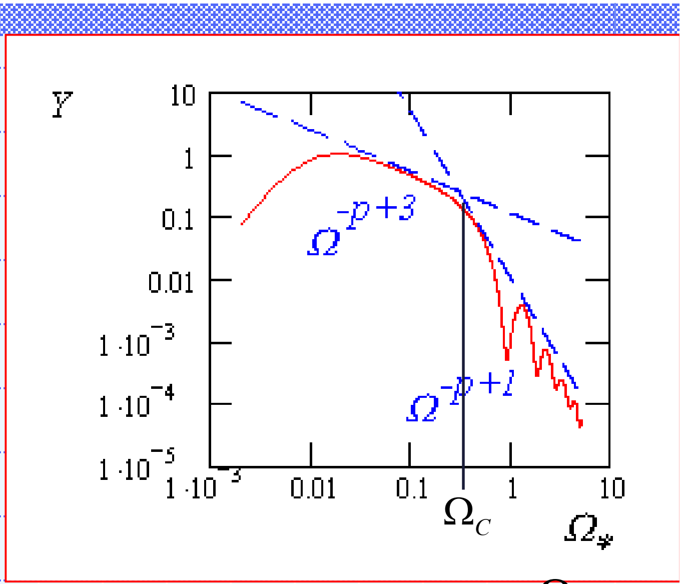
During observations spectral index took on a value p=3.2-4.5 depending on the angular distances of radio sources from the Sun.

$\vec{V}_\perp \parallel \vec{\rho}_\perp$: $(\kappa_0 V_\perp << \Omega_0 << \kappa_m V_\perp)$

$$Y(\Omega) \sim \left(1 - \cos\left(\frac{\Omega \rho_x}{V_x}\right)\right)\left[\left(\frac{\Omega}{V_x}\right)^2 + \kappa_0^2\right]^{\frac{(-p+1)}{2}}$$

$$Y_1(\Omega) \approx [\Omega]^{-p+3}, 0 < \Omega_0 < \pi V_x / \rho_x,$$

$$Y_2(\Omega) \approx [\Omega]^{-p+1}, \Omega_0 > \pi V_x / \rho_x$$



$\Omega_C = \pi V_x / \rho_x$ $\Omega_* = \frac{\Omega_0}{2\pi} \frac{\rho_x}{V_x}$

V_x - solar wind velocity

The expression shows, that must be *oscillations* on spectrum wings, depending on relation of velocity and baseline:

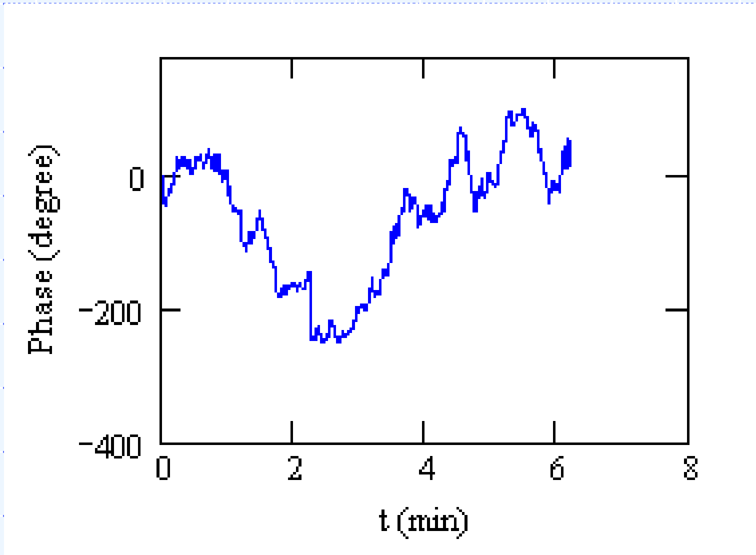
$$\Omega_{\min} = 2\pi \frac{V_x}{\rho_x} n, n = 0, 1, 2..$$

Therefore, solar wind velocity can be determined from the characteristic frequency at the *break point* of measured spectrum $\Omega_C = \pi V_x / \rho_x$.

For evaluation of V_x power spectrum should be calculated at wide frequency band (df>1-2 Hz), i.e. short integration time is need (t<0.2 sec)

INTAS98.5 - t=2 s ☹
INTAS99.4 - t=2 s ☹
INTAS00.3 - t=0.1s ☺

Weak phase fluctuations

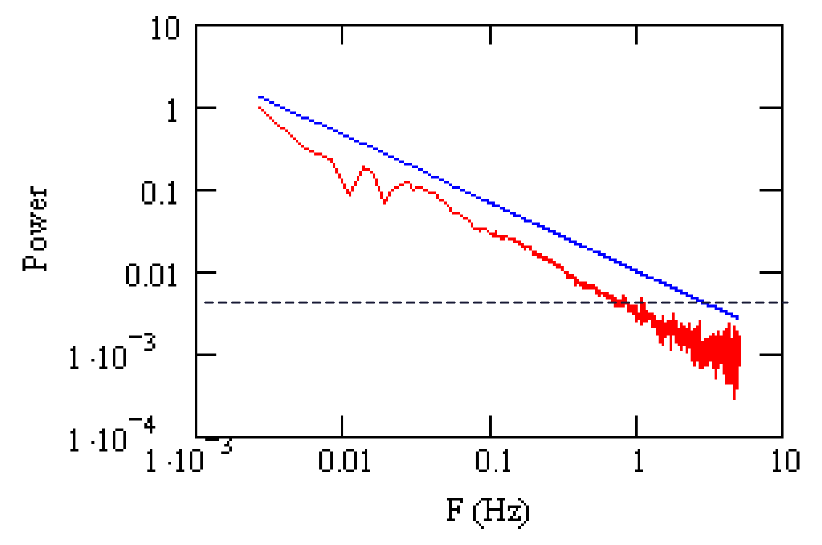


experiment name: **INTAS99.4**
04 December, 1999,
source **NRAO530**,
elongation $\theta=16^0$,
λ=18 cm, baseline
Bear Lakes (Russia) – **Noto** (Italy),
Integration time **t=0.1** sec.

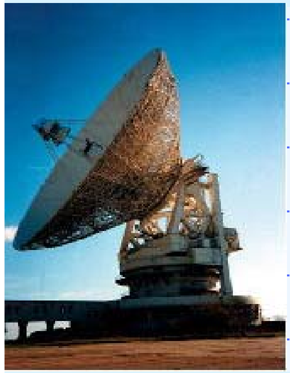
Spectral width *df=0.0034 Hz,*
Spectral index *p=3.8*

Experimental spectrums do not demonstrate distinct oscillations. Supposed, velocity fluctuations at solar wind were significant, that provokes the smoothing of minimums and rendered impossible the evaluation of velocity.

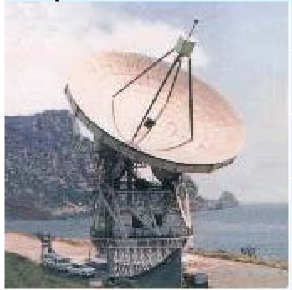
$$\frac{V_x}{2\rho_x} = 0.14Hz$$



Bear Lakes RT-64



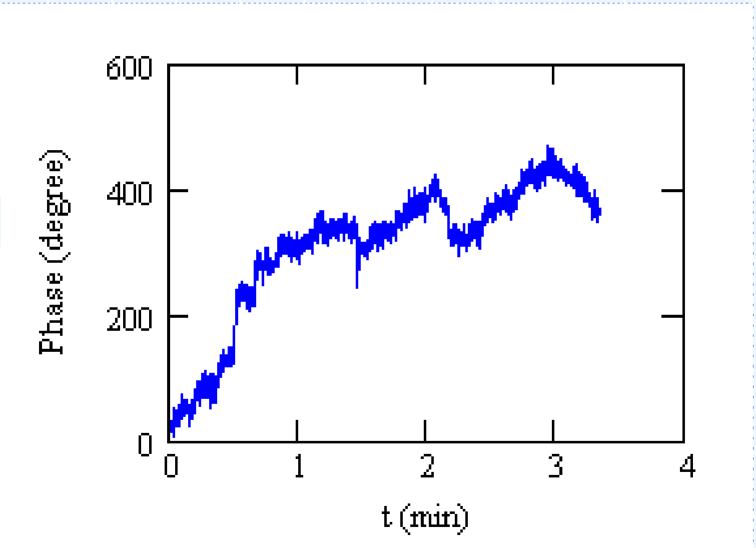
Evpatoria RT-70



Simeiz RT-22

Urumqi RT-25

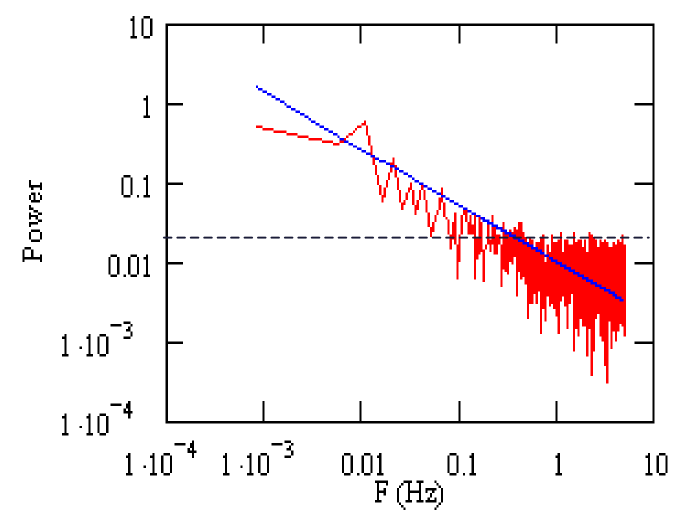
Weak phase fluctuations



experiment name:
INTAS99.4
04 December, 1999,
source **NRAO530**, elongation
$\theta=16^0$,
λ=18 cm, baseline
Bearn Lakes (Russia)–**Svetloe**
(Russia),
Integration time **t=0.1** sec.

Spectral width
df=0.006 Hz,
Spectral index
p=3.7

$$\frac{V_x}{2\rho_x} = 0.43Hz$$



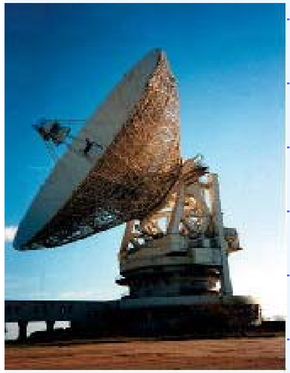
Solar wind observation in 2004 at λ=6 cm

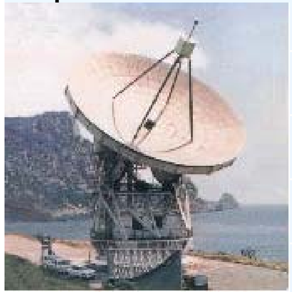
LFVN: *Evpatoria (RT-70, Ukraine), Bear Lakes (RT-64, Russia), Noto (RT-32, Italy), Simeiz (RT-22, Ukraine).*

Registration system **MK2**, correlator **MK2 "NIRFI-3"** (RRI, Russia)

Experiment	SOURCE	θ^0	S_{6cm}(Jy)
VLBR04.1	0534+193	7	2.5
June, 2004	3C138	11	3.8
	0528+134	12	4.3
	3C133	13	5.4
	DA193	16	5
	3C147	26	8.1
VLBR04.2	OJ287	5.5	2.3
July, 2004	0748+126	11.7	1.5
	0735+178	12.8	2.2
	0745+101	14.2	3.5
	0738+313	15.9	1.6
VLBR04.3	3C273	5	30
October, 2004	3C279	6	11.2
	3C270	10	3
	1337-125	15	4.3
	1127-145	18	4.6
	1127-185	23	1.9


Bear Lakes RT-64


Evpatoria RT-70


Simeiz RT-22


Urumqi RT-25

Conclusion

The theoretical analysis has demonstrated that interferometer's signal carries information about **intensity of phase disturbances, spatial spectrum of electron density distribution**, and **solar wind velocity.**

Experimental works are in satisfactory agreement with conclusions of theoretical analysis as regards to determination of **spectral index**.

Nevertheless determination of average **velocity** of irregularities transportation is embarrassed by weak source signal and existing sufficient fluctuations of velocity, as well as shortage of data.
Further theoretical and experimental testing is necessary to adjust procedure for solar wind velocity evaluation.

This work is supported by grants RFBR №-02-02-39023, GFEN, RFBR-04-02-27022, NSCF №10173015.