Study of scattering material with Radioastron-VLBI observations

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Overview

- The RadioAstron spacecraft presents a unique opportunity to measure properties of interstellar scattering.

- The fluctuations responsible for scattering radio waves from astronomical sources are small-scale (~ 0.1 AU) fluctuations in the electron density of the interstellar medium.

- There are three main components of interstellar plasma inhomogeneities – A (galactic scale ~ 10kpc), B (50-300pc), C (10 pc) components.

- Scattering of nearby pulsars and intra-day variable quasars point to the existence of a component of the interstellar medium (B,C) which has properties quite different from the more distant, diffuse ISM (A).

- We observed several nearby pulsars as part of RadioAstron's Early Science Program (ESP).These included pulsars B0329+54, B0950+08 and B1919+21. We present here results concerning the distribution and properties of scattering material in the direction to pulsar B1919+21.

Introduction

•Scattering convolves the electric field of the source with an impulse-response function $g(\tau)$:

$$E_{obs}(t)= g(\tau)\otimes E_{source}(t-\tau)$$

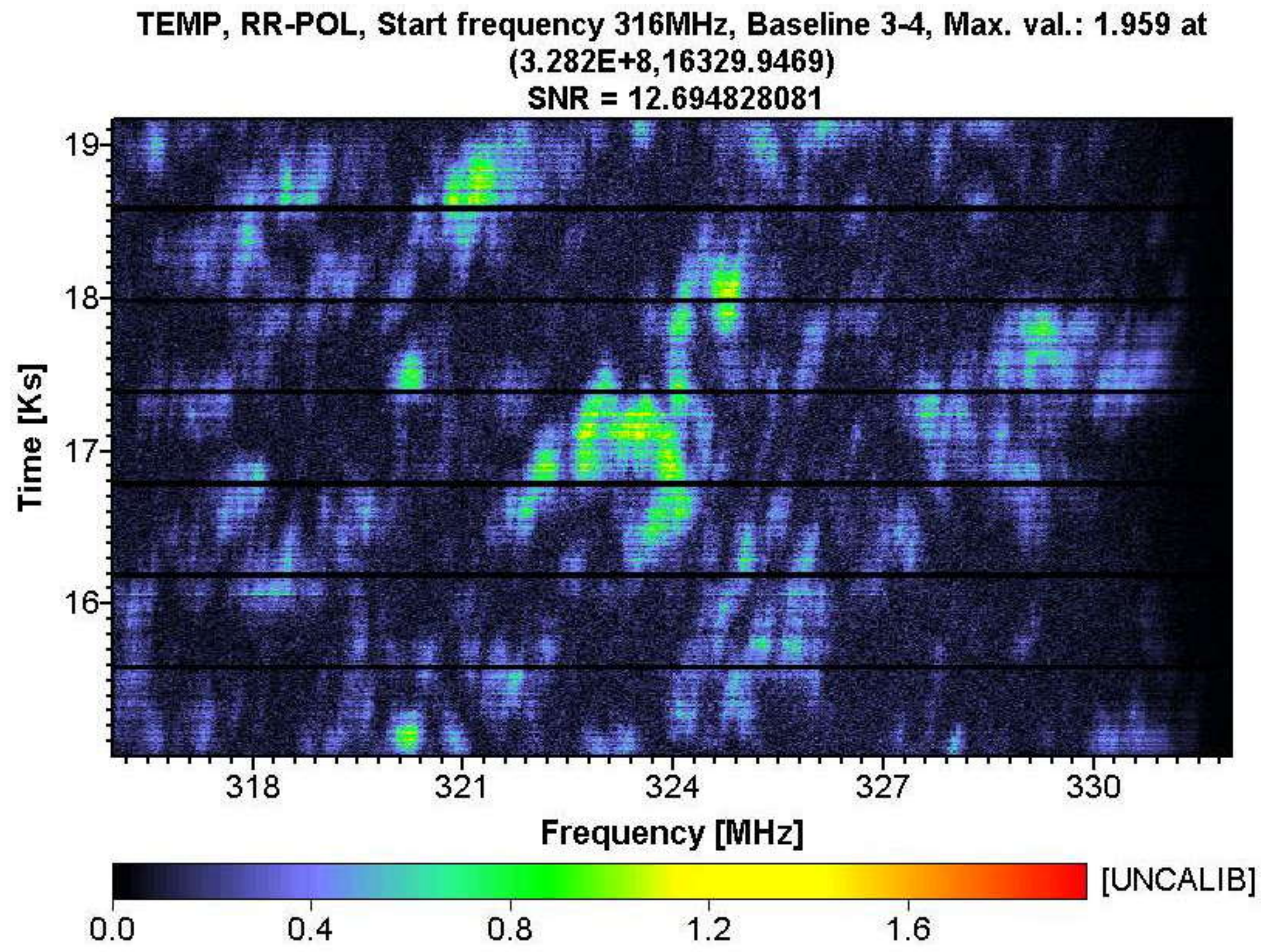
•$g(\tau)$ varies over a lateral scale S_{ISS} ~ few radius of the Earth ($R_\oplus$). and changes as the Earth moves across the observer plane.

•The cross-power spectrum is the product of Fourier transforms of the impulse-response functions getting from two telescopes A and B:

$$V_{AB}(\omega)= g_A(\omega) * g_B (\omega)$$

•If the baseline B << S_{ISS} , $g_A (\omega) \approx g_B (\omega)$ and V_{AB} is real and positive.
•If B >> S_{ISS}, $g_A (\omega) \neq g_B (\omega)$ phase of V_{AB} varies randomly between π and -π. Amplitude of V_{AB} is a dynamic cross-spectrum of pulsar.

Dynamic spectra of PSR B1919+21 observed in our observation for GB-WB baseline.

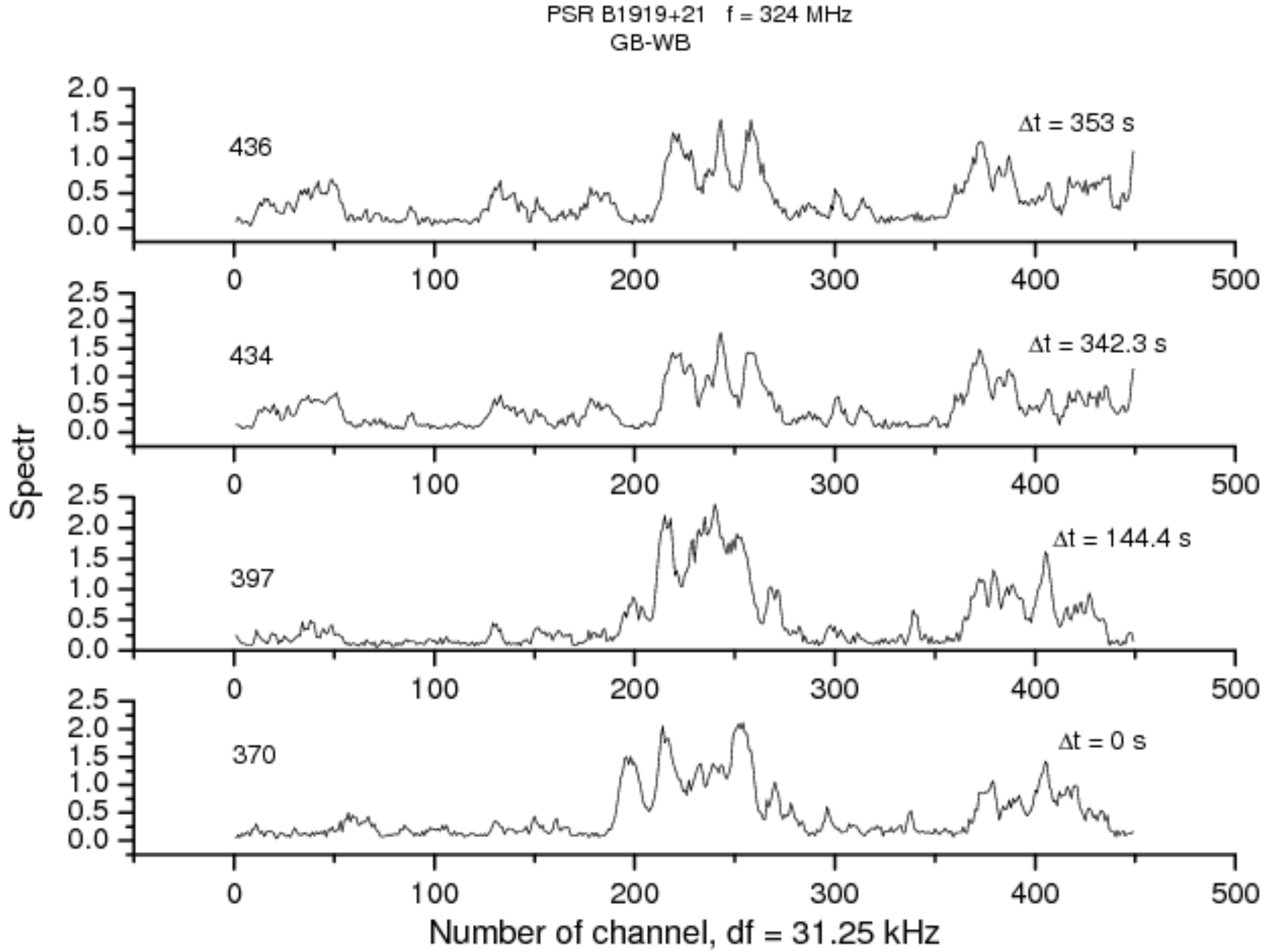


Observations of PSR B1919+21

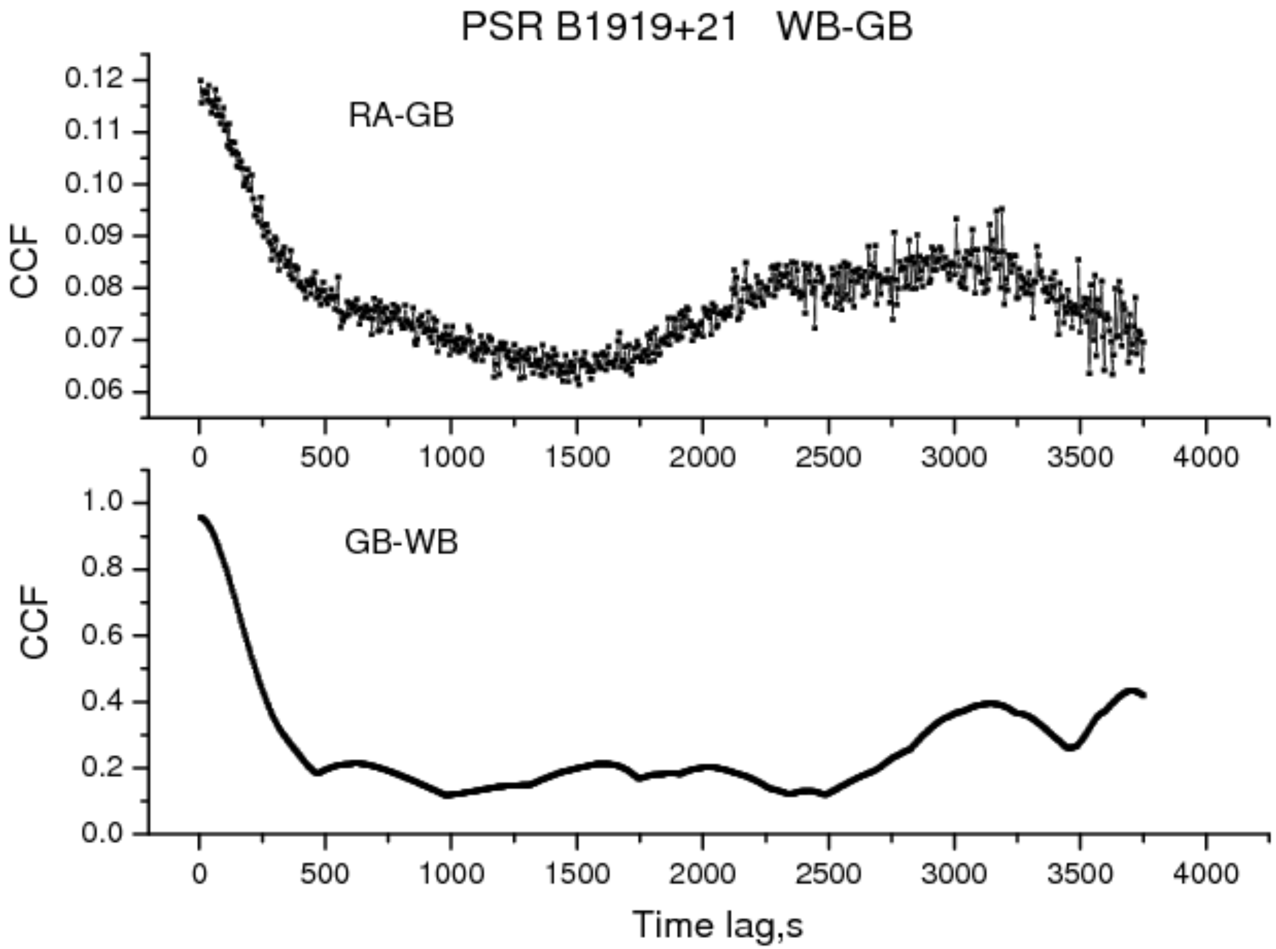
- 04.07.2012, Projection of base is 60 000 km
- Frequency 316 MHz, Bandwidth is 16 MHz
- Time duration is 69.5 min
- Telescopes: RA, Green Bank, Westerbork
- DM = 12.43, R = 1.1 kpc, P_1 = 1.337 s, (b = 3.5°, l = 55.8°)

- Data were recorded in 570 s scans with 30 s gaps between scans. On-pulse window includes intensities inside of mean profile on its 0.3 amplitude level (80 ms). The off-pulse window was offset from the pulse by half of period.
- Correlator ASC FIAN for getting complex cross-spectra.
- Time resolution Δt = 5.35 s ($4P_1$ averaging) Δf = 31.25 kHz (512 channels)

Spectra of individual pulses separated in time. Two scales: Δf_1 = 300 kHz and Δf_2 = 2 MHz.



Decorrelation of pulse spectra separated in a time for two baselines. Characteristic time scale of scintillation is 250 s.



Structure function analysis

- Analysis of dynamic spectra gave us scintillation time t_d and decorelation bandwidth f_d.
- A mean structure function (SF) is defined using intensities:

$$SF_I(\Delta f, \Delta t) = \langle [I\,(f, t) - I(f+\Delta f, t+\Delta t)]^2 \rangle$$

Main relations for structure function analysis

- Spatial spectra of plasma inhomogeneities:

$$\Phi_S(q) \propto |q|^{\alpha+2}\,,\quad q = 2\pi/l \text{ is a spatial frequency.}$$

- Structure function (SF) of phase fluctuations:

$$D_s(\Delta\rho) = \langle(\psi(\rho) - \psi(\rho+\Delta\rho))^2\rangle,$$

  where ρ is a spatial coordinate in the observer plane and $\Delta\rho$ is a baseline of interferometer.

- If we have phase changing screen then

$$D_s(\rho) = k(\theta_{scat}|\rho|)^{\alpha}\,,$$

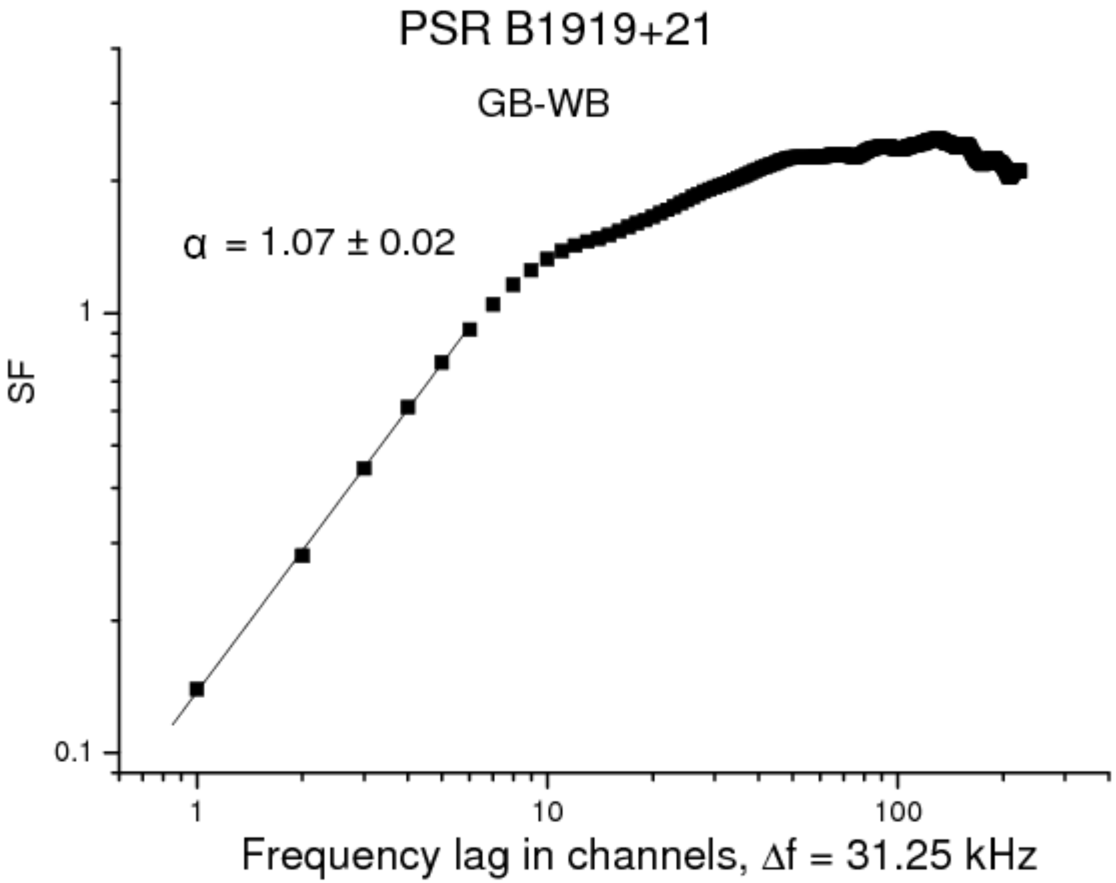
  where θ_{scat} is a scattering angle.

- In presence of **cosmic prism** in the line of sight we will have deflection radiation from the pulsar at a frequency-dependent refractive angle, θ_{ref}.

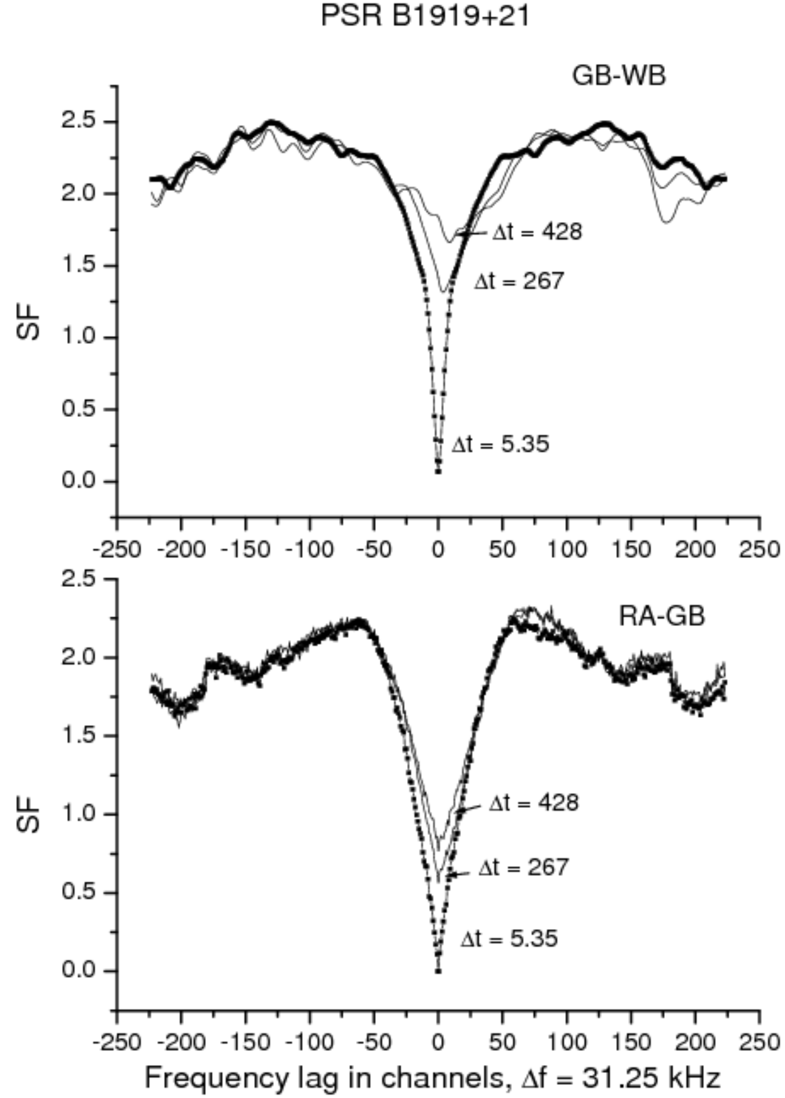
- If $\theta_{ref} >> \theta_{scat}$, then we will see the displacement of source at the angle

$$\theta_f = 2(\Delta f/f_0)\theta_{ref}\,,\ f_0 \text{ is observing frequency.}$$

Structure function for Green Bank – Westerbork baseline in log-log scale. The fit gives the slope $\alpha = 1.07 \pm 0.02$ that corresponds to power of inhomogeneities spectra as $\gamma = \alpha + 2 = 3$. It is much flatter than Kolmogorov one.



Structure function for different time lags in sec for Ground and Space-ground baselines



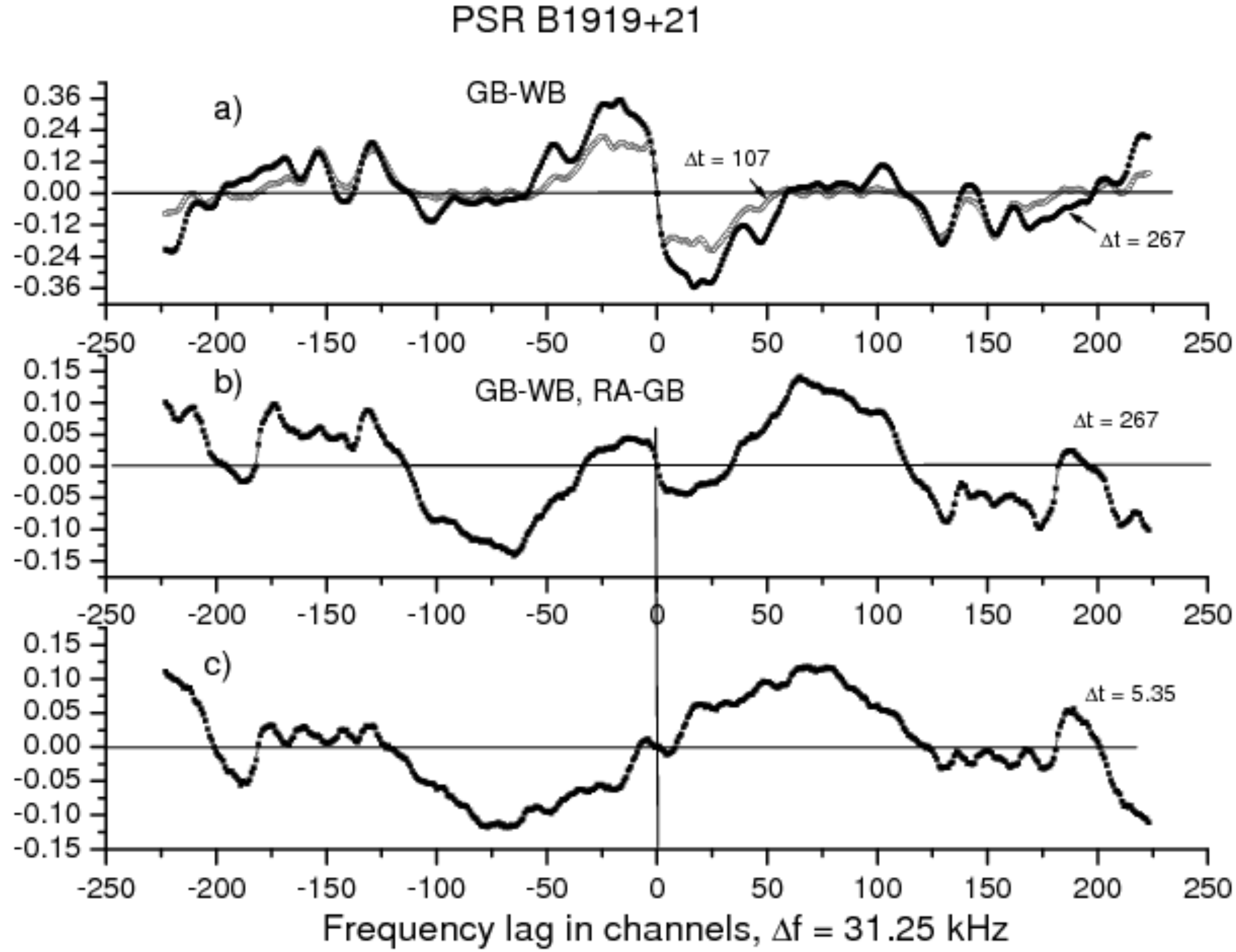
Shape of structure function analysis

- Short baseline comprises a narrow-bandwidth component and a broader-bandwidth component.
- The long baseline suppresses most of the narrowband structure and some of the wideband structure. It shows that for this pulsar cosmic interferometer resolves the small-scale structure.
- The narrower component also appears only at small time lags: about 250 s, whereas the broader component appears at both large and small time lags.
- The two frequency scales 0.3 MHz and 2 MHz correspond to two effective layers of turbulent plasma, separated in space, where scattering of pulsar emission take place.

Asymmetry of structure function analysis

- The cosmic prism disperses the scintillation pattern across the observer plane, so that particular intensity maxima and minima appear at different positions at different frequencies. The shift in frequency of the scintillation pattern with a time or position leads to an asymmetry in frequency Δf of the structure function: $SF_I(\Delta f, \Delta t, \Delta \rho)$, for nonzero time lag (Δt) or finite baseline length, Δρ.
- Asymmetry function we calculated as: $SF_I(\Delta f, \Delta t) - SF_I(-\Delta f, \Delta t)$.

Asymmetry function
SF(Δf) - SF(-Δf) for different time lags in sec



- There are two plasma screens: located at distance z_1 and z_2 that corresponds two different frequency and time scales (Δf_1 = 0.3 MHz and the time scale of t_{dif} = 250 s for z_1 and Δf_2 = 2 MHz)

- $|V(\rho)|^2 \approx 0.05$. In the regime of strong scintillation:

$$|V(\rho)|^2 = \exp[-(\rho/r_{dif})^{\alpha}].$$

From the shape of structure function α = 1, so

$$\mathbf{r_{dif} = 1/3\rho = 2*10^9\ cm}.$$

- Scattering angle **$\theta_{dif} \approx 1.5$ mas** and it is resolved by cosmic interferometer.

- The pulsar velocity, $V_{PSR} \approx 200$ km/s. In the plane of observer $r_{dif} / V_{PSR}t_{dif} = 2/5$, **$z_1 = (2/7)z = 300$ pc** from observer.

- From the shape of asymmetry function we can conclude that the base of cosmic interferometer is about the scale of the second component : $r_{weak} = (z_2/k)^{1/2} \approx \rho = 6 * 10^9$ см. So we have **$z_2 = k\rho^2 \approx (2/3)$ pc**.

- The frequency scale of refractive scintillation:

$$\mathbf{\theta_{ref} = \theta_{dif}/[2(\Delta f_2/f)] \approx 75 * \theta_{dif} \approx 110\ mas}.$$

- The frequency scale of difractive scintillation is defind by:

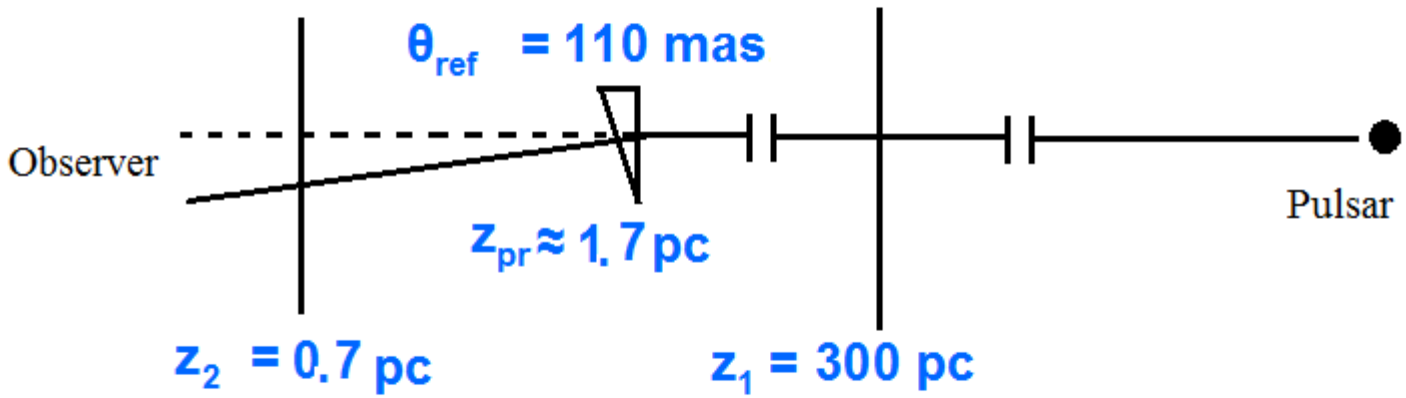
$$2(\Delta f_1/f)z_{pr}\theta_{ref} = r_{dif},$$

$$\mathbf{z_{pr} \approx (5/3)\ pc}.$$

Conclusion

- Interstellar scintillation of PSR B1919+21 is defined by two screens of plasma inhomogeneities. Two components of scintillation consist of diffractive scintillation on the screen located at the distance of 300 pc and weak scintillation on the layer at the distance 0.7 pc from observer.

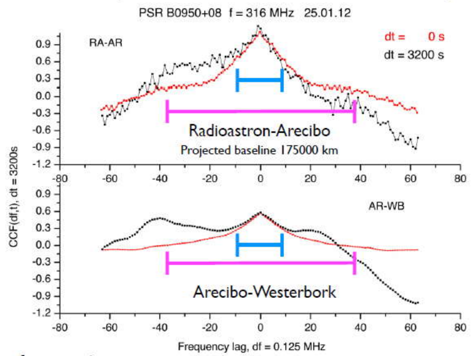
- Frequency structure of scintillation is defined by angular refraction of the cosmic prism located on the distance of 1.7 pc. We defined refractive angle as 110 mas. Cosmic interferometer resolves the scattering disk, the size of it: $\theta_{dif} \approx 1.5$ mas.



PSR B0950+08

- Two scales of scattering: narrow one decorrelates with a time of about 1000 s, disappears with a cosmic baseline, distance of scattering layer is d≈26-170 pc. Another one is broader than 16 MHz, its properties change with baseline length and time lag, it is asymmetric and has a shift in frequency, distance of scattering layer is d≈4.4-16.4 pc

Smirnova et al: Study of Pulsar B0950+08 from RA Fringe Search 12



2 scales of scattering:
Narrow: properties nearly constant with baseline length and time lag
Broad: asymmetric, properties change with baseline length and time lag

- For the first time we obtained a refractive angle in ISM which in the direction of PSR B0950+08 is $\theta_{ref} = 1.1\text{-}4.4$ mas, the refraction displacement of ray is $1.4\text{-}2.7 \cdot 10^{10}$ cm
- The spectrum of ISM turbulence in the direction of PSR B0950+08 has a power law with index $\gamma = 3.00 \pm 0.08$

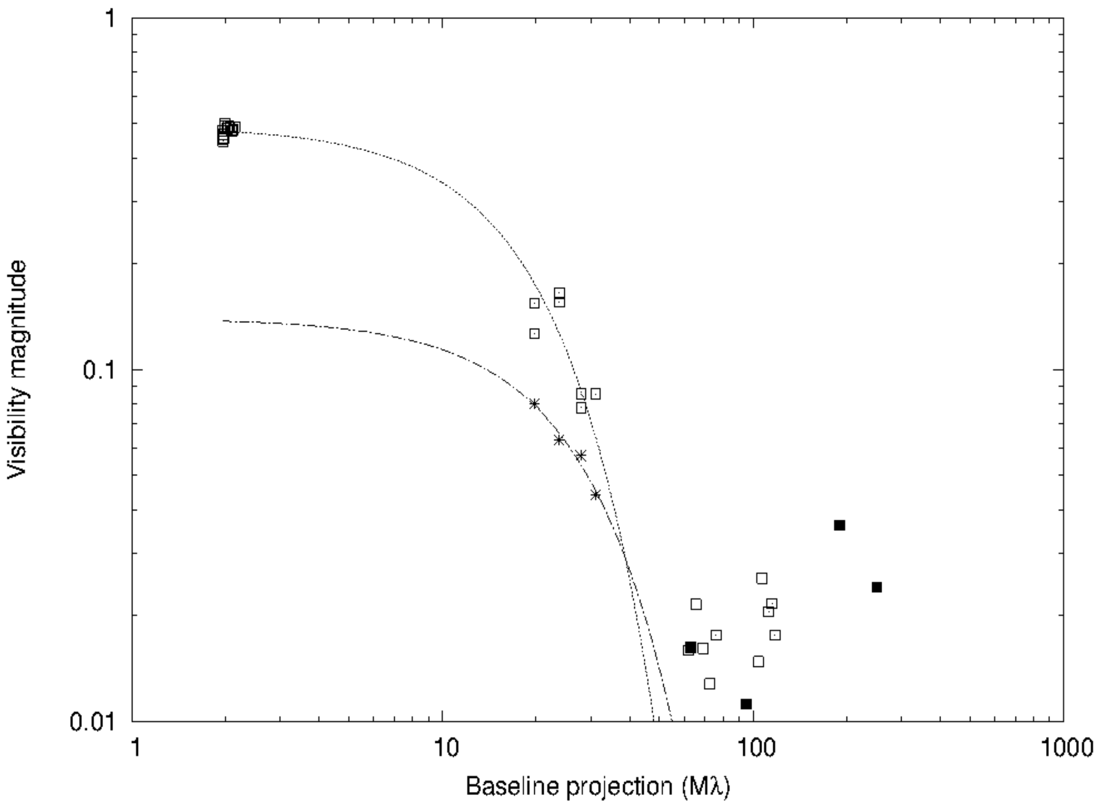
- Results published at ApJ - Smirnova et al. 2014, ApJ, 786,115

Results PSR B0329+54

- Radio telescopes: WSRT, GBT, Kalyazin
- Frequency: 316-332 MHz
- Dates: 26-29 November 2012;

  1 January 2014
- Baselines: 60,000-240,000 km

  15,000-120,000 km



Scattering disk is resolved with angular diameter of 5 mas

Measured parameters the PSR 1919+21, PSR 0950+08, PSR B0329+54

	1919+21	0950+08	0329+54
$\mathbf{r}_{\mathbf{dif}}$	6 $*10^{9}$ cm	1.4-2.7 $\cdot 10^{10}$cm	1.5 $*10^{9}$ cm
Scattering angle $\boldsymbol{\theta}_{\mathbf{dif}}$	1.5 mas	0.33-0.64 mas	4.6 mas
Scintillation time **t**	250 s	1000 s	115 s
$\mathbf{z}_{\mathbf{1}}$	300 pc	26-170 pc	300 pc
$\mathbf{z}_{\mathbf{2}}$	0.70 pc	4.4-16.4 pc	-
$\boldsymbol{\theta}_{\mathbf{ref}}$	110 mas	1.1-4.4 mas	-
$\mathbf{z}_{\mathbf{pr}}$	1.7 pc	-	-
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* Results published at ApJ - Smirnova et al. 2014, ApJ, 786,115

** Publication is prepared for the ApJ

Thanks for your attention!

Measured and derived parameters for the PSR B0329+54

Decorrelation band ***df***	15 kHz
Time broadening **τ**	5.8 μs
Scattering angle **θ**	4.6 mas
Scintillation time **t**	115 s
Distance to the pulsar **D**	1.0 kpc
Diatance to the screen **d**	0.30 kpc
Size of diffraction spot **r**	15000 km

Publication is prepared for the ApJ

$$B_I(t) = <I>^2 \exp[-D_S(t)]. \quad D_S(t_0) = 1$$

$$D_S(t) \simeq \frac{B_I(0) - B_I(t)}{<I>^2} \simeq \frac{1}{2}\frac{D_I(t)}{<I>^2}, \quad t \ll t_0,$$