Probing of interstellar plasma distribution in the direction to pulsars PSR 0525+21 and 1919+21 with RadioAstron mission

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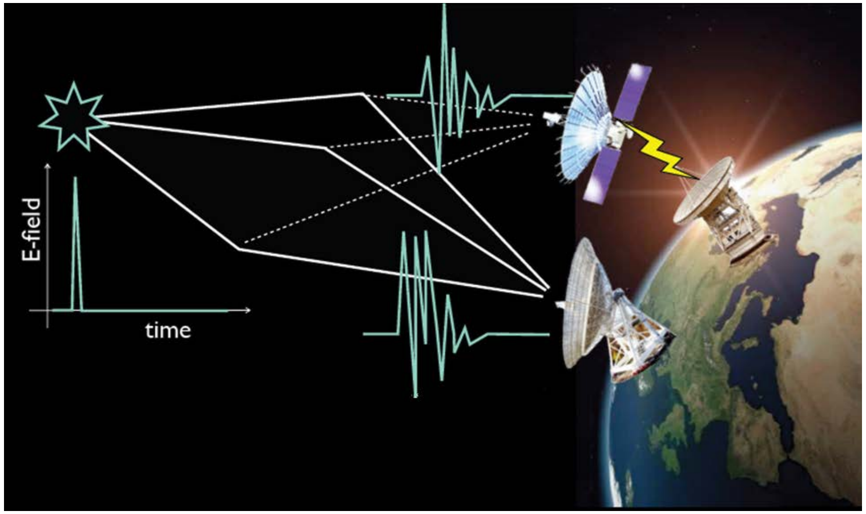
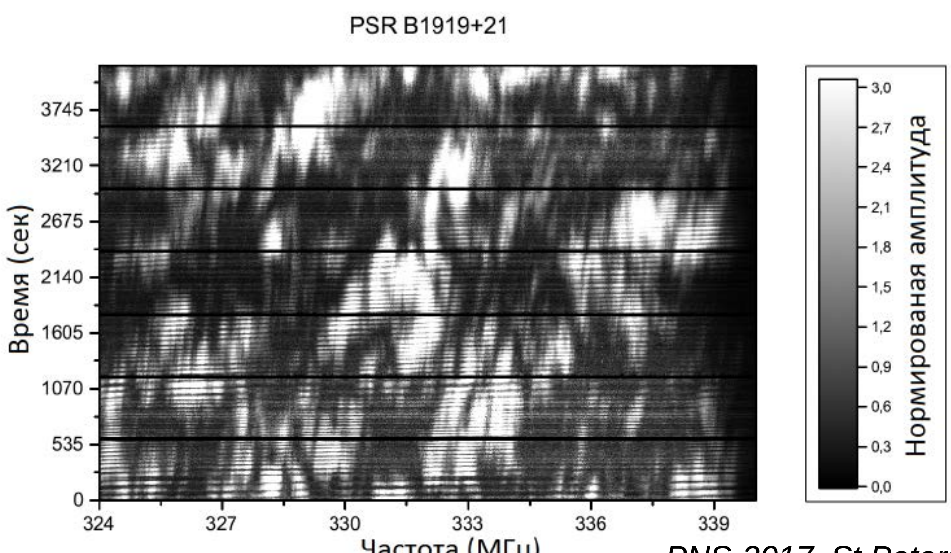
Overview

- 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 Science Program. We present here results concerning the distribution and properties of scattering material in the direction to pulsar B1919+21 and pulsar B0525+21.

Interstellar scintillation



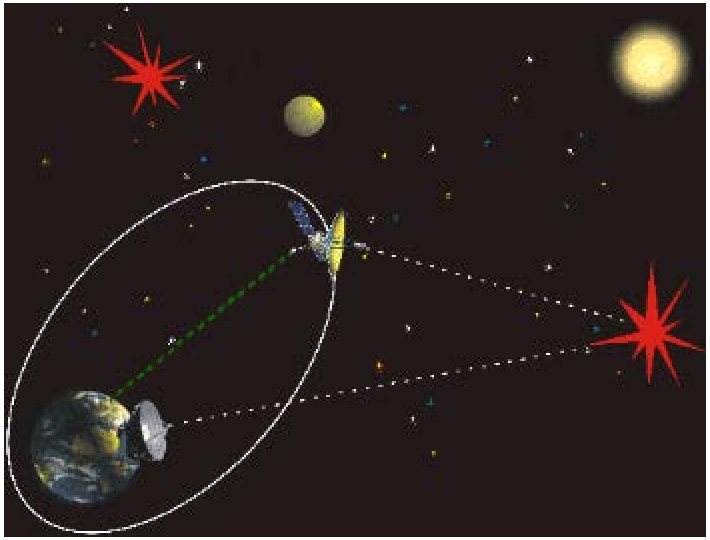
$$E(\vec{\rho},f,t) = u(\vec{\rho},f,t)h(f,t)$$



- The scattering causes angular broadening, pulse broadening, intensity modulation, or scintillation, and distortion of radio spectra. Scattering convolves a signal emitted at the source with an impulse-response function, reflecting reinforcement or cancellation of radiation from along different paths, with different lengths.
- Relative lengths of the different paths change with observer position, so that the impulse-response function changes with position. For most sources and wavelengths of interest, the lateral scale of that change is greater than the diameter of the Earth; however, in many interesting cases it is smaller than the distance between Earth and the radio telescope aboard the Spektr-R spacecraft in high Earth orbit. Thus, only RadioAstron, in concert with ground antennas, can simultaneously observe the impulse-response function in two locations.

$$t_{dif} = \frac{\rho}{V_\perp}, \rho = \frac{1}{k\theta_{scat}}; f_{dif} = \frac{c}{\pi Z \theta_{scat}^2}$$

RadioAstron



- RadioAstron – space-ground interferometer with maximum baseline projection up to 350 000 km
- Frequency bands:

  P(327МГц)

  L (1668 МГц)

  C (4828 МГц)

  K (22 ГГц)

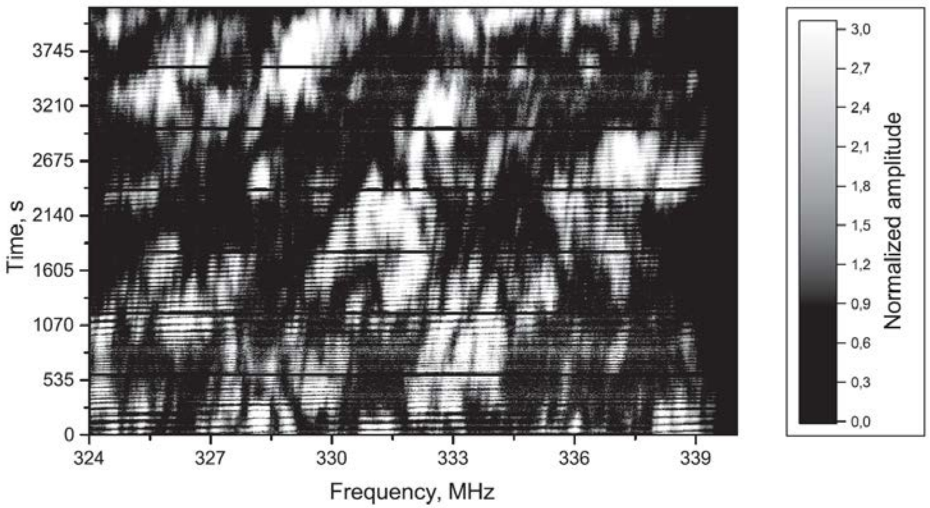
- Launched 18 July 2011 г.

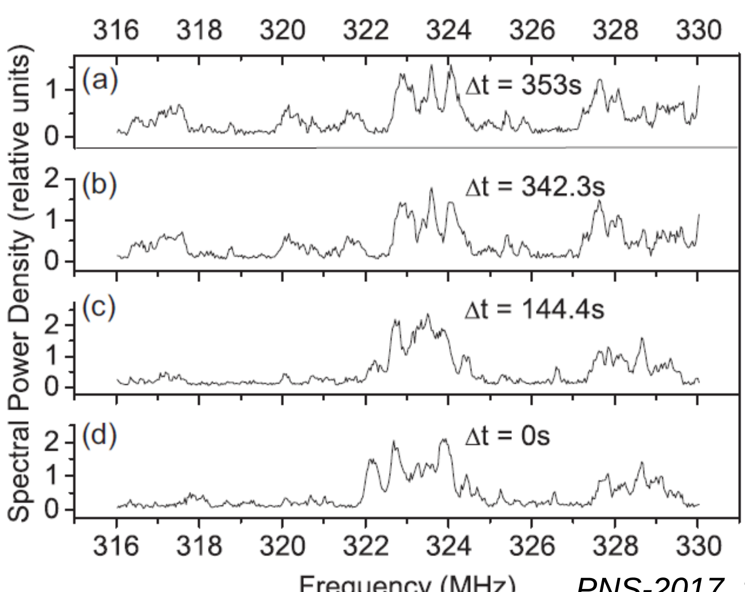
Observations of PSR B1919+21

- 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, Z = 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 0.1 amplitude level (40 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 = 1.34 s Δf = 31.25 kHz (512 channels)

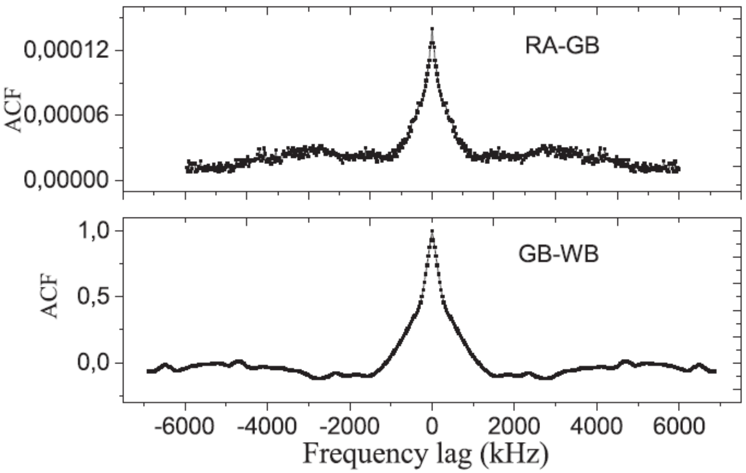
PSR B1919+21

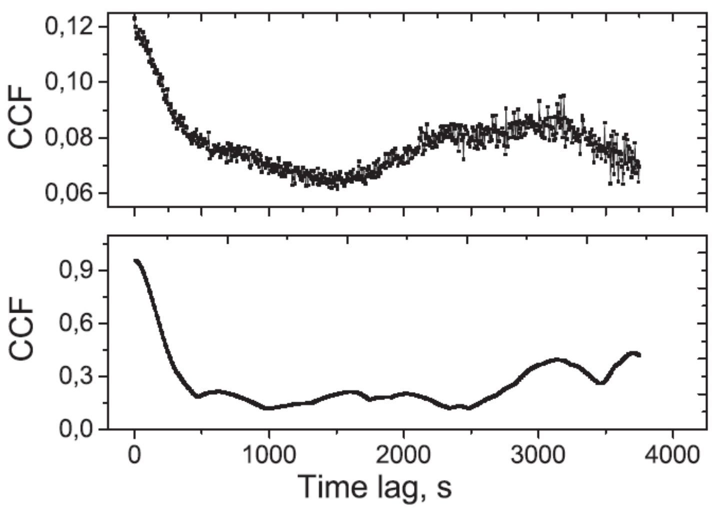




- Individual pulses show two frequency scales: narrow (400 KHz) and wide (1500 KHz)
- Slope in dynamic spectra due to refraction on cosmic prism
- Modulation index m ~ 0.7 – 1.0 on time scale ~ 500 sec.
- Strong scattering in direction to PSR B1919+21.

1919+21 CCF





- Coherence function on ground baseline:

$$J_2(\vec{b}, \Delta f) = \langle |I(\vec{\rho}, \vec{\rho} + \vec{b}, f, t) I^*(\vec{\rho}, \vec{\rho} + \vec{b}, f + \Delta f, t)| \rangle$$

- Space-ground baseline:

$$J_1(\vec{b}, \Delta f) = |\langle I(\vec{\rho}, \vec{\rho} + \vec{b}, f, t) I^*(\vec{\rho}, \vec{\rho} + \vec{b}, f + \Delta f, t) \rangle|$$

- Break in CCF on GB-WB baseline shows on two-scales structure.
- No break on RA-GB indicates the absence of wide-scale structure on a large baseline
- From CCF we determine frequency and time scales:

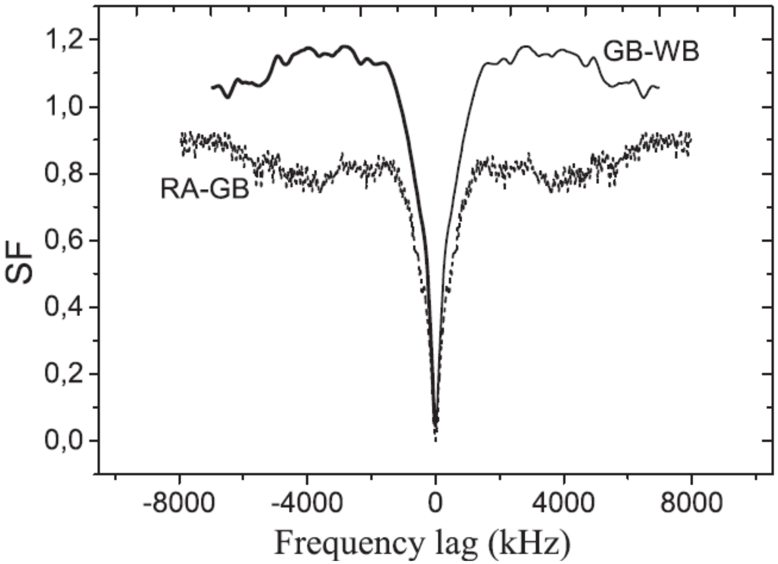
$$\Delta f_{dif} = 330\,\mathrm{kHz} \text{ и } \Delta f_{wide} = 700\,\mathrm{kHz} \quad \Delta t_{dif} = 290\,\mathrm{s}$$

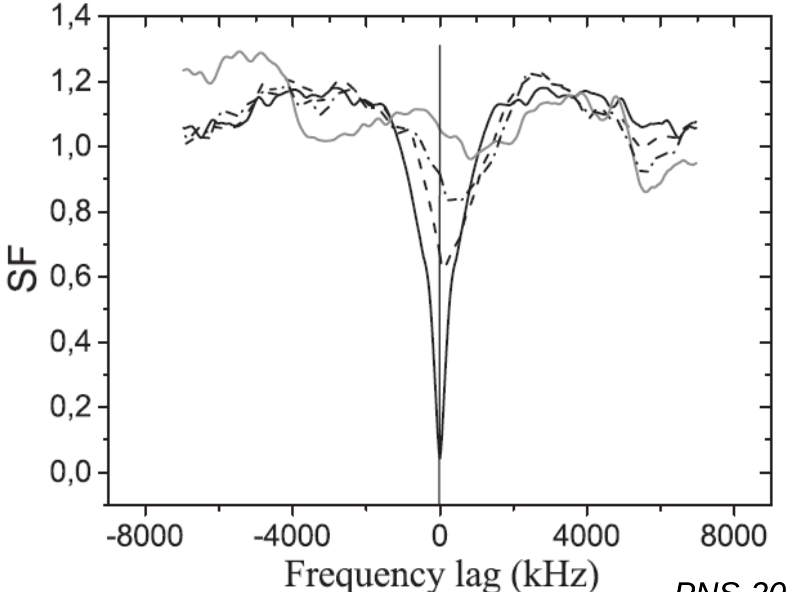
- In the regime of strong scintillation:

$$J_1(\vec{b}, \Delta f) = |B_u(f)|^2 + |B_u(\vec{b})|^2.$$

$$\frac{J_1(\vec{b}_s, \Delta f > \Delta f_{dif})}{J_1(\vec{b}_s, \Delta f = 0)} = \frac{\left|B_u(\vec{b}_s)\right|^2}{1 + \left|B_u(\vec{b}_s)\right|^2} = 0.17 \qquad \left|B_u(\vec{b}_s)\right|^2 = 0.20$$

Structure function

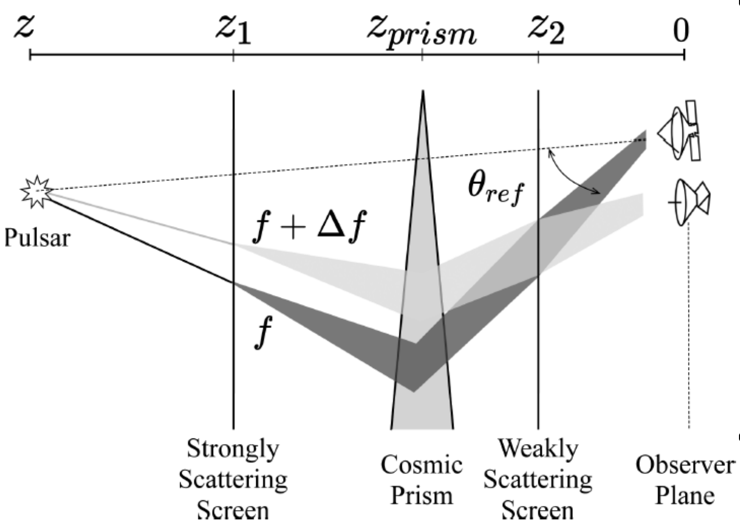




$$D_{\Delta I}(\Delta\vec{\rho}) = < (\Delta I(\vec{\rho} + \Delta\vec{\rho}) - \Delta I(\vec{\rho}))^2 >_s$$

- Short baseline comprises a narrow-bandwidth component and a broader-bandwidth component.
- The long baseline displays only the narrower frequency-scale component. For the space–ground baseline, a time shift of the structure function produces only a decrease in the amplitude of the structure function, without displacement of its minimum, even with time shifts as large as 800 s. This is consistent with the absence of a wide structure on a long baseline.
- 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.
- The shift of SF minimum with increasing time shift is due to refractive shift of the diffraction pattern – the presence of a prism on the line of sight behind the near screen.

ISM structure in direction to PSR B1919+21



- From CCF value on space-ground baseline we can find distance to far screen and scattering angle: $b_1 = 6\times10^9$ $\left|B_u(\vec{b})\right|^2 = 0.20$

$$D_s(\vec{b}) = \left(\frac{|\vec{b}|}{\rho}\right)^{\alpha},\ \alpha = n-2 \qquad b_{dif} = \frac{z}{(z-z_1)}\frac{1}{k\theta_{scat,1}} = 4.6\times10^9 \text{ см}$$

$$z_1/(z-z_1) = b_{dif}/(\left|\vec{V}_p\right|\Delta t_{dif}) = 0.78 \Rightarrow z_1 = 0.44\,z = 440\text{pc},\quad \theta_{scat,1} = 1.2 \text{ mas}$$

- In observer plane

$$\theta_{obs,1} = [(z-z_1)/z]\theta_{scat,1} = 0.7 \text{ mas}$$

- From the shift of the SF minimum with the maximum time separation, we find the Fresnel scales for the near screen

$$f_{2,0} = 1.1 \text{ МГц} \Rightarrow t_{2,0} = f_{2,0}(df/dt)^{-1} = 700 \text{ сек.} \Rightarrow \Delta\rho_{2,Fr} = 2^{1/\alpha_2}V_{obs}t_{2,0} = 2.5\times10^9 \text{ см}$$

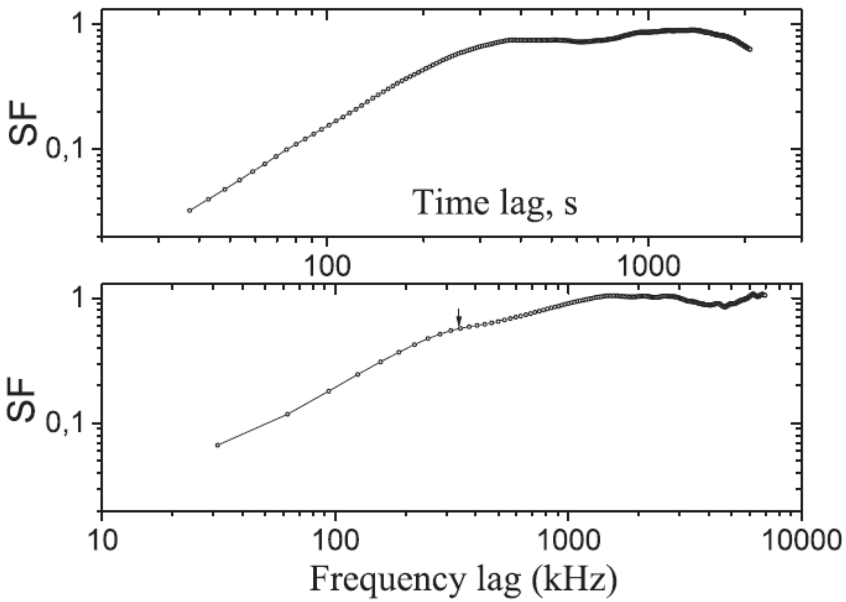
and distance to the screen $\Delta\rho_{2,Fr} = \sqrt{\frac{z_2}{k}} \Rightarrow z_2 = 0.14 \text{ pc}$ $\quad \Delta\vec{\rho}_{2,f} = -2z_2(f/\nu_0)\vec{\theta}_{ref,0} \Rightarrow \theta_{ref,0} = 110 \text{ mas}$

$$D_{S,2}(\Delta\rho_{2,Fr}) = (k\theta_{scat,2}\Delta\rho_{2,Fr})^{\alpha_2} = 0.15 \Rightarrow \theta_{scat,2} = 0.4 \text{ mas}$$

Provided that the refractive displacement is smaller than the scale of the diffraction pattern of scintillations, it is possible to estimate the distance to the prism:

$$2(f_{dif}/\nu_0)z_{prism}\theta_{ref,0} < b_{dif} = 4.6\times10^9 \text{ см} \Rightarrow \begin{cases} f_{dif} = 330 \text{ КГц} \\ \theta_{ref,0} = 110 \text{ мас} \end{cases} \Rightarrow z_{prism} \le 2 \text{ pc}$$

Spectrum of density inhomogeneities



- Structure function can be approximated by power-law functions

$$SF(\Delta f) = \frac{1}{2}\left(\Delta f / \Delta f_{dif}\right)^{\alpha_f} \qquad \alpha_f = 0.90 \pm 0.03$$

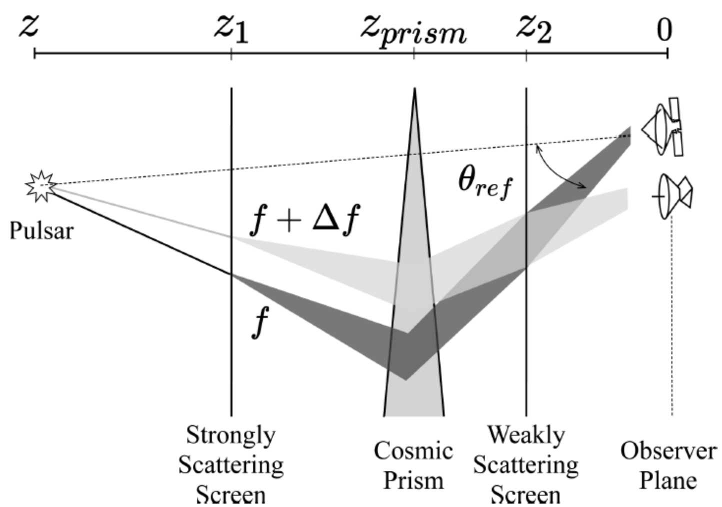
$$SF(\Delta t) = \frac{1}{2}\left(\Delta t / \Delta t_{dif}\right)^{\alpha_t} \qquad \alpha_t = 1.73 \pm 0.02$$

- The power-law index of spectrum of density inhomogeneities

$$n = \alpha_t + 2 = 3.73$$

PSR B1919+21: Main results

- We found for the first time that two scattering regimes are realized in the direction to PSR 1919+21: diffractive scintillations from inhomogeneities in a layer of turbulent plasma at a distance z_1 = 440 pc from observer and weak scintillations from a screen located at z_2 = 0.14 pc.
- We measured the scattering angles in the direction to PSR B1919+21 as 0.7 mas at 327 MHz.
- We also found that prism with a distance z < 2 pc exist in this direction.
- The power-law index of spectrum of density inhomogeneities n = 3.73



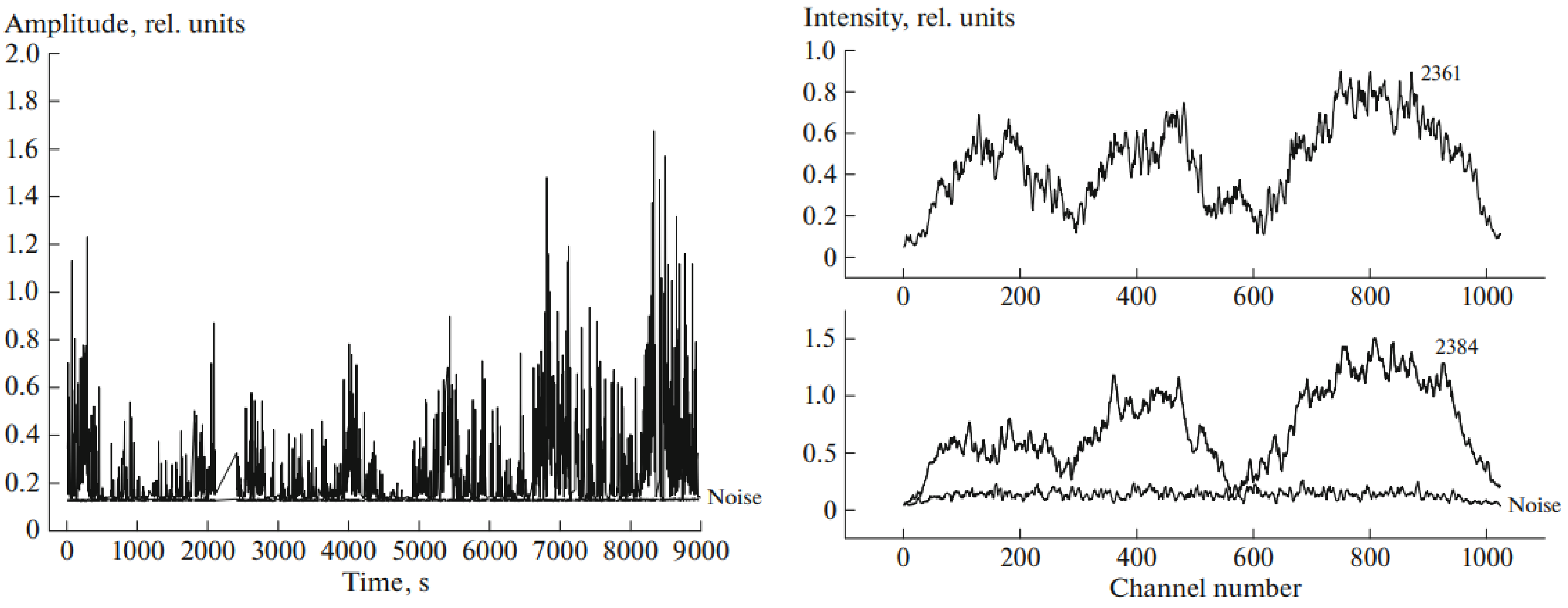
- *Shishov, V. I., Smirnova, T. V., Gwinn, C. R., Andrianov, A. S., Popov, M. V., Rudnitskiy, A. G., & Soglasnov, V. A.* MNRAS, **468**, 3709 (2017)

Observations of PSR B0525+21

•18.09.2013, Projection of base is 233 600 km
•Frequency 1668 MHz, Bandwidth is 16 MHz
•Time duration is 2.5 h
•Telescopes: RA, Green Bank, Arecibo, Kaliazin
•DM = 50.9, Z = 1.6 kpc, P_1 = 3.75 s, (b = -6.9°, l = 183.86°)

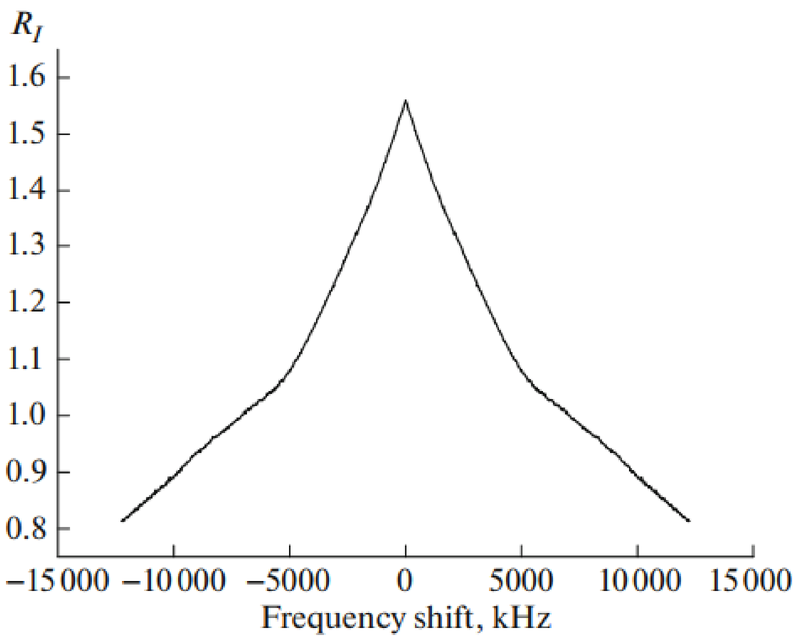
•Correlator ASC FIAN for getting complex cross-spectra.
•On-pulse window includes intensities inside of mean profile on its 0.1 amplitude level (37.45 ms). The off-pulse window was offset from the pulse by half of period.
•Time resolution Δt = 3.75 s Δf = 15.625 kHz (1024 channels)

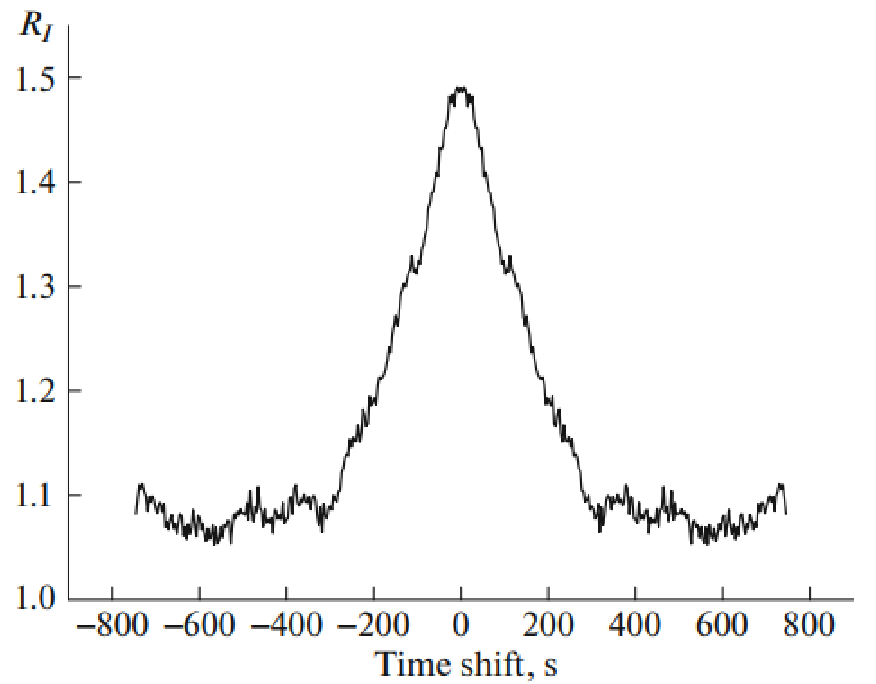
PSR B0525+21



- Modulation index m = 0.8 +- 0.2
- Strong scintillations

Typical scintillation scales



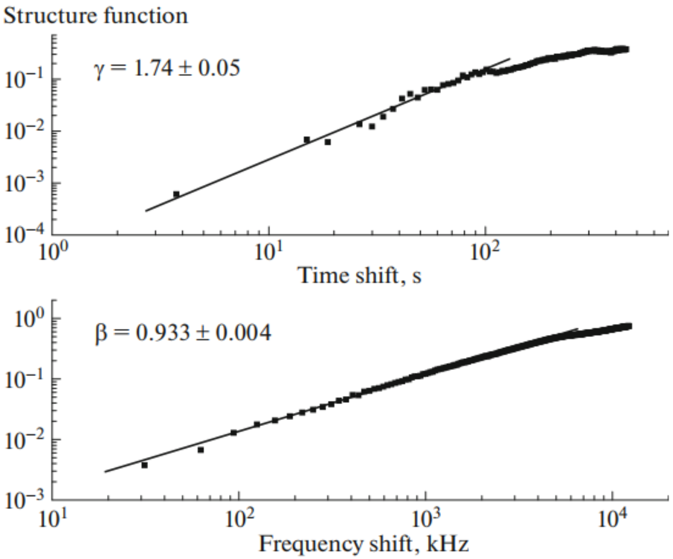


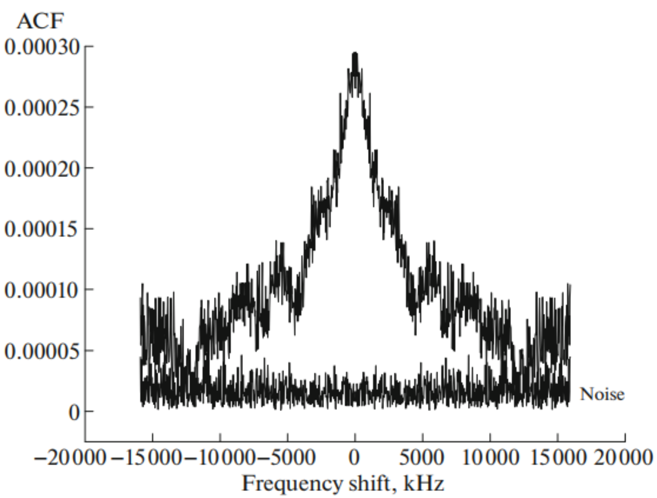
Analysis of mean CCF gives us typical frequency and time scintillation scales

$$f_{dif} = 3.9 \text{ MHz}$$
$$t_{dif} = 160 \text{ sec}$$

$$R_I(\Delta f) = < \frac{< |I(f,t)| \cdot |I(f+\Delta f)| >_f}{[< |I(f,t)| >_f]^2} >_t$$

Structure function





$$D_s(\Delta t) = R_I(\Delta t = 0) - R_I(\Delta t) \qquad D_s(\Delta t) = (\Delta t / t_{dif})^{\alpha} \qquad \Delta t \le t_{dif}$$

$$D_s(\Delta f) = R_I(\Delta f = 0) - R_I(\Delta f) \qquad D_s(\Delta f) = (\Delta f / \Delta f_{dif})^{\alpha/2} \qquad \Delta f \le \Delta f_{dif}$$

- The slope of SF indicates a diffractive scintillations model

  $\alpha_t = 1.74 \qquad \alpha_f = 0.93$

- The power-law index of spectrum of density inhomogeneities

  $n = \alpha + 2 \quad \boxed{n = 3.74}$

- CCF on space-ground baseline

  $$J_1(\vec{b}, \Delta f) = |\langle I(\vec{\rho}, \vec{\rho} + \vec{b}, f, t) I^*(\vec{\rho}, \vec{\rho} + \vec{b}, f + \Delta f, t) \rangle|$$

- In the regime of strong scintillation:

  $$J_1(\vec{b}, \Delta f) = |\langle j(\vec{\rho}, \vec{\rho} + \vec{b}, f, t) j^*(\vec{\rho}, \vec{\rho} + \vec{b}, f + \Delta f, t) \rangle| = |B_u(f)|^2 + |B_u(\vec{b})|^2.$$

$$\frac{J_1(\vec{b}, f > \Delta f_{dif})}{J_1(\vec{b}, \Delta f = 0)} = \frac{|B_u(\vec{b})|^2}{[1 + |B_u(\vec{b})|^2]} = 0.23 \pm 0.05 \Rightarrow \boxed{|B_u(\vec{b})|^2] = 0.30 \pm 0.06}$$

ISM structure in direction to PSR B0525+21

- Spatial Coherence scale

$$B_u(\vec{b}) = \exp[-\tfrac{1}{2}D_s(\vec{b})]$$

$$D_s(\vec{b}) = \left(\frac{|\vec{b}|}{\rho}\right)^{\alpha}, \alpha = n-2$$

$$\mathrm{n} = 3.74$$

$$\Rightarrow \boxed{\rho = (2.1 \pm 0.2)\cdot 10^5 \text{ km}}$$

- Scattering angle: $\boxed{\theta_{scat} = 1/k\rho = (0.028 \pm 0.002)}$
- The temporal fluctuations of SF are determined by the motion of the

$$D_s(t) = \int_0^Z dz' D\left(\frac{Z-z'}{Z}\vec{V}t\right)$$

- Spatial Coherence scale >> $Vt_{dif} = 49600$ км The medium is not homogeneous

- We can estimate distance to the screen in thin screen model

$$\Delta f_{dif} = G(\gamma)(kb_s)^2/\pi z_{eff} \quad z_{eff} = z1(Z - z1)/Z, \quad b_s = \rho(z1/Z) \quad \mathrm{G} = 0.34$$

$$\frac{z1/Z}{1-z1/Z} = \pi Z \Delta f_{dif}/[G(\gamma)c(k\rho)^2]$$

$$f_{dif} = 3.9 \text{ MHz}$$
$$\rho = (2.1 \pm 0.2)\cdot 10^5 \text{ km}$$
$$\mathrm{Z} = 1.6 \text{ kpc}$$

$$\Rightarrow \boxed{z_1/Z = 0.1} \Rightarrow z_1 = 160 \text{ pc}$$

PSR B0525+21: Main results

- Analysis of time and frequency structure functions allowed to conclude that scintillations at 1668 MHz is strong and the diffractive scintillation model is realized.
- The characteristic time and frequency scales of scintillations were determined.
- It is shown that the spectrum of the inhomogeneities of the interstellar plasma is a power spectrum with a power-law index n = 3.74.
- The scattering angle in the direction to pulsar PSR B0525 + 21: 0.028 mas.
- We had shown that the scattering of emission from PSR 0525+21 takes place on the screen located close to pulsar: 0.1D, where D is a distance to pulsar. For D = 1.6 kpc we have z = 1.44 kpc from the observer.

- *Andrianov, A. S., Smirnova, T. V., Shishov V. I., Gwinn, C. & Popov, M. V.* Astronomy Reports, **61**, 513 (2017)

Thank you for attention!

Локальная межзвездная среда

Р. Лалльман, Дж. Линским и Б. ,Вудом, Спектроскопические исследования

- Локальное межзвездное облако ~ несколько пк
- T ~ 5-10 * 10^3 K   n ~ 0.1 см ^ -3
- Локальный пузырь ~ 100 пк
- T ~ 10^6 K   n ~ 0.002 см ^ -3

Анализ структурной функции

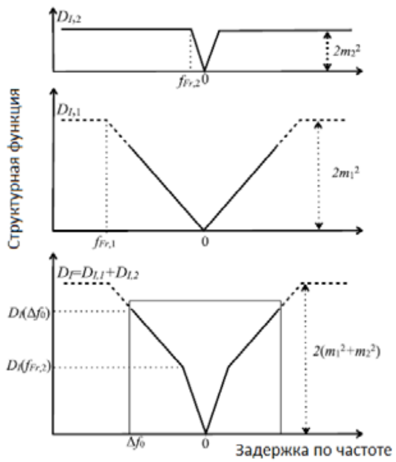


Рисунок 3.5: Схема разделения влияния на структурную функцию эффектов, обусловленных ближним и дальним экранами. Структурная функция для удаленного экрана $D_{I,2}(\Delta f)$ в зависимости от частотного сдвига Δf(верхний график) Структурная функция ближнего экрана $D_{I,1}(\Delta f)$(средний график). Сумма структурных функций от двух экранов $D_I(\Delta f)$, которой мы моделируем результа наблюдений на базе Аресибо-Вестерборк(нижний график). Прямоугольник ограничивает область, изображенную на Рис. 3.4. Совместный результат диссертанта и соавторов из работы [A1].

Структурная функция флутуаций фазы на экране

$$D_{S,l}(\Delta\vec{x}_l) = (k\Theta_{scat,l}|\Delta\vec{x}_l|)^{\alpha_l}$$

$$\alpha_1 = \alpha_2 = 1$$

$$D_{I,l}(\vec{r}_l) = \begin{cases} m^2\frac{|\vec{r}_l|}{\rho_{Fr,l}}, & |\vec{r}_l| < \rho_{Fr,l} \\ m^2, & |\vec{r}_l| \geqslant \rho_{Fr,l} \end{cases}$$

$$\frac{|\vec{r}_l|}{\rho_{Fr,l}} = \left|\frac{\Delta\vec{\rho}}{\rho_{Fr,l}} + \frac{\Delta t}{t_{Fr,l}} + \frac{\theta_0\Delta f}{f_{Fr,l}}\right|$$

- Структурная функция на короткой базе:

$$D_{I,AR-WB} \equiv D_I = D_{I,1} + D_{I,2}$$

$$D_I(\Delta f) = \begin{cases} 2m_1^2\left|\frac{\Delta f}{f_{Fr,1}}\right| + 2m_2^2\left|\frac{\Delta f}{f_{Fr,2}}\right|, & |\Delta f| < f_{Fr,2} \\ 2m_1^2\left|\frac{\Delta f}{f_{Fr,1}}\right| + 2m_2^2, & f_{F1,1} > |\Delta f| > f_{Fr,2} \\ m_1^2 + m_2^2, & |\Delta f| > f_{Fr,1} \end{cases}$$

- Наклон меняется $\Delta f = f_{Fr,2} = 3.1$ МГц

$$D_I(f_{Fr,2}) \approx 0.5 D_I(\Delta f_0) \quad f_{Fr,2} = 3.1 \text{ МГц и } \Delta f_0 = 8 \text{ МГц}$$

$$2m_1^2\frac{f_{Fr,2}}{f_{Fr,1}} + 2m_2^2 \approx 0.5\left(2m_1^2\frac{\Delta f_0}{f_{Fr,1}} + 2m_2^2\right)$$

$$D_I(\Delta f_0) = 2m_1^2\frac{\Delta f_0}{f_{Fr,1}} + 2m_2^2 \approx 2m^2$$

$$m_1 = \sqrt{\frac{f_{Fr,1}}{2\Delta f_0 + 2f_{Fr,2}}}m$$

$$m_2 = \sqrt{\frac{\Delta f_0 - 2f_{Fr,2}}{2\Delta f_0 - 2f_{Fr,2}}}m = 0.15$$

- Используя $f_{Fr,1} > \Delta f_0 = 8$ МГц $\quad f_{Fr,1} < 15$ МГц

$$0.32 < m_1 < 0.43$$

- экран 1 ближе к наблюдателю т.к. частотный масштаб Френеля у него больше

Космическая призма

- Если наблюдатель движется со скоростью перпендикулярной направлению на пульсар, и если экран 1 движется, то пространственное смещение наблюдателя относительно картины мерцаний увеличивается с изменением времени

$$\vec{\rho}_{t,1} = \vec{V}_1 \Delta t \quad = (\vec{V}_{obs} - \vec{V}_{scr,1})\Delta t$$

- Если смещение наблюдателя параллельно направлению дисперсии космической призмы, то наблюдатель заметит сдвиг картины мерцаний по частоте, как функцию времени
- Для дальнего экрана учитываем сферичность волны:

$$\vec{\rho}_{f,2} = \frac{zz_2}{z - z_2}\vec{\theta}_f = \vec{V}_2 \Delta t = (\vec{V}_{obs} - \frac{z}{z - z_2}\vec{V}_{scr,2} + \frac{z_2}{z - z_2}\vec{V}_{PSR})\Delta t$$

- Таким образом, задержка во времени эквивалентна изменению местоположения в направлении линейной комбинации векторов $\vec{V}_{obs}, \vec{V}_{scr}, \vec{V}_{PSR}$

Асимметрия структурной функции

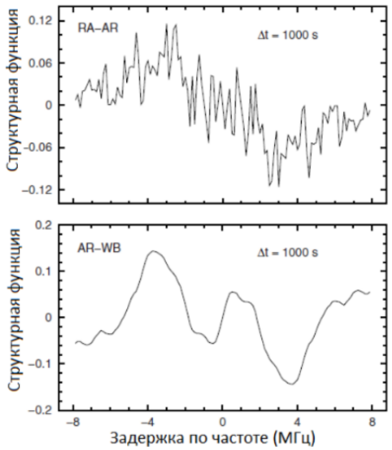


Рисунок 3.7: Отношение разницы структурных функций для положительных и отрицательных частотных сдвигов к их сумме в зависимости от частотного сдвига: для базы РадиоАстрон-Аресибо(верхний график) и Аресибо-Вестерборк(нижний график). Временной сдвиг 1000 сек. Совместный результат диссертанта и соавторов из работы [A1].

- Степень ассиметрии:

$$\mathcal{D}(\Delta f, \Delta t) = \frac{D_I(\Delta f, \Delta t) - D_I(-\Delta f, \Delta t)}{D_I(\Delta f, \Delta t) + D_I(-\Delta f, \Delta t)}$$

- На базе AR-WB два экстремума при $\Delta f > 0.$ $\Delta f_1 \approx 3$ МГц, $\Delta f_2 \approx 1$ МГц
- Проекции скоростей экранов имеют разный знак
- На базе RA-AR только минимум при $\Delta f_1 \approx 3$ МГц

  т.к. RA-AR чувствительна только к ближнему экрану то $\Delta f_1 \approx 3$ МГц связан с экраном 1, а $\Delta f_2 \approx 1$ МГц с экраном 2
- Для базы AR-WB максимум SF: $\rho_{Fr,2}/V_2 < \Delta t < \rho_{Fr,1}/V_1$, $|\Delta\vec{\rho}_{AW}| < \rho_{Fr,2}.$

$$\mathcal{D}(\Delta f, \Delta t) \approx \left(\frac{m_2}{m_1}\right)^2 \left(\frac{\rho_{Fr,1}}{\rho_{Fr,2}}\right) \cos\beta_2 \approx 0.05 - 0.1\cos\beta_2$$

$$\mathcal{D}(\Delta f_2, \Delta t = 10^3 \text{ сек}) \approx 0.05 \Rightarrow 0^\circ \leqslant \beta_2 \leqslant 60^\circ$$

- Аналогично по минимуму найдем β_1

$$\mathcal{D}(\Delta f, \Delta t) \approx cos\beta_1 \quad \mathcal{D}(\Delta f_1, \Delta t = 10^3 \text{ сек}) \approx -0.15 \Rightarrow \beta_1 \approx 100^\circ$$