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Research for Interstellar Scattering of Pulsar B0329+54 with VLBI

K. V. Semenkov[1], M. V. Popov[1] and V. A. Soglasnov[1]

Profsoyuznaya str., 84/32, Astro Space Center of Lebedev Physical Institute, 117997, Moscow, Russia

Abstract. The talk deals with data reduction and result interpretation of SVLBI observations of pulsar B0329+54 at 1.6 GHz. The purpose of observations was scattering angle measurement. Additional steps for amplitude calibration of pulsar data (bandpass correction, correction for incommensurability of pulsar period and correlator integration time, correction for intrinsic pulsar variability) are invented. Software implementing these techniques was developed. Estimated size of scattering angle is less than 1.6 mas. An attempt to trace apparent source position changes induced by scattering has been made.

1. Introduction

For an observer, pulsars are compact (angular size is less than $1 \cdot 10^{-7}$ mas) sources of pulsing periodical radiation. Their periods lie in range from 1.5 ms to 8.5 sec, intensity variations from pulse to pulse are stochastic (modulation index of pulsar intrinsic variability ≈ 1), whereas every pulsar has a definite spectrum of fluctuations.

Pulsar radiation is subject to scattering on inhomogeneities of interstellar electron plasma (interstellar scattering). Some scattering effects like interstellar dispersion, scintillations (i.e. intensity variations versus time), distortion of spectrum, angular broadening of a source are considerable for VLBI.

Below we discuss results of space VLBI observations of pulsar B0329+54. The purpose of observations was measuring of scattering disk size. This value is a characteristics of the interstellar plasma turbulence. It is shown (see e.g. Cordes et al. 1985) that visibility function of a source radiation propagating through scattering plasma is:

$$V(\mathbf{r}) = V_0(\mathbf{r}) \exp\left[-D(\mathbf{r})/2\right], \tag{1}$$

where $\mathbf{r}$ is baseline vector, $V_0(\mathbf{r})$ is visibility in absence of scattering and $D(\mathbf{r})$ is phase structure function defined as:

$$D(\mathbf{r}) \stackrel{\text{def}}{=} < [\varphi(\mathbf{s}+\mathbf{r}) - \varphi(\mathbf{s})]^2 >= 8\pi r_e^2 \lambda^2 \int dz' \int dq q [1 - J_0(qr) P(q, z'),$$

where r_e is classical radius of electron, λ is wavelength, $P(q, z')$ is is spatial spectrum of electron density fluctuations. If the spectrum has the form of power law, for example Kolmogorov spectrum:

$$P(q) = C_n^2 q^{-\gamma}, \quad q_0 \le q \le q_1, \quad C_n^2 = \text{const}$$

the Eq. 1 becomes

$$V(\mathbf{r}) = V_0(\mathbf{r}) \exp\left[-(r/r_c)^{\gamma-2}\right], \tag{2}$$

Angle $\theta_s = \lambda/2\pi r_c$ is referred to as scattering angle or angular diameter of scattering disk and r_c is related to C_n^2 by the following equation:

$$r_c \propto [L C_n^2 f(\gamma)]^{-1/(\gamma-2)}. \tag{3}$$

So measurements of scattering angle allow to get information on the line-sight turbulence. VLBI observations is a direct way for scattering disk measurements and can be also used as a test for other techniques estimating the value.

2. Observations and data processing

PSR B0329+54 is one of the brightest pulsars, its average flux at 1.4 GHz equals 203 mJy, period is 0.714 s, dispersion measure is 26.776 pc cm^{-3}, equivalent pulse width is 8.70 mc (see Taylor et al. 1993). Other authors (Bartel et al. 1985, Britton et al. 1998) performed ground-based VLBI observations of the source earlier at different frequencies. Space VLBI observations increase angular resolution and therefore allows to measure small enough scattering disks.

The observations were carried out on August, 22, 1998 during 12 hours. eleven antennas including 8 VLBA sites, 43-feet telescope in Green Bank, 2 DSN antennae and HALCA participated in the experiment. Two adjacent IFs at 1634 and 1650 MHz were recorded. Each IF has 32 frequency channels at 500 kHz. The correlation was performed at VLBA correlator, both gated and non-gated data were produced. (The duration of pulsar impulse is about 10% of the pulsar period. Therefore it is convenient to correlate pulsar data within windows containing a pulse. Such a correlation technique is referred to as gating and implemented for example in VLBA (Romney 1995), S2 (Carlson et al. 1999), K4 (Sekido et al. 1998) correlators.)

The data were processed in AIPS. Numerous imaging attempts (see Fig. 1) showed the source is unresolved, its angular size is less than 1.6 mas. The result is in accordance with data of other authors.

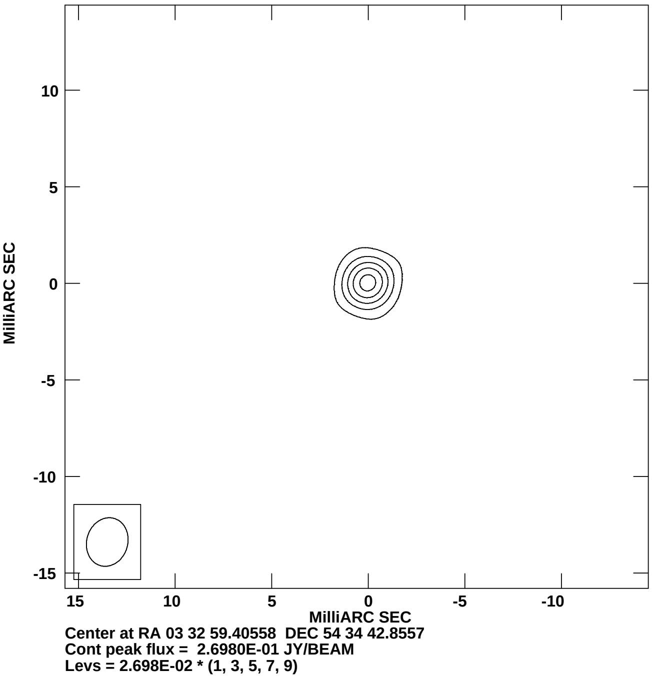

Fig. 1. Image of the PSR B0329+54 at 1.6 GHz.

3. Features of pulsar data processing and discussion

Some features are proper to pulsar radiation: incommensurability of pulsar period and correlator integration time, bandpass distortion with the scattering, intensity scintillations. Let us discuss these features and data processing techniques below.

1. Correlator output usually consists of integrated over a few seconds visibilities. On the other hand the interval contains non-integral number of pulsar periods. It results in visibility amplitude variation:

$$\frac{T_{int}/P}{\{T_{int}/P\}}, \tag{4}$$

where P is pulsar period, T_{int} is correlator integration time, $\{\}$ denotes an integer part. The beating increases dramatically if the correlator uses gating mode.
Although if the scientific task doesn't require precise amplitude calibration (for example parallax and proper motion measurements) one may neglect the beating. The beating also becomes small if pulsar period is rather less than correlator integration time. If the beating removal is required one should correct visibilities for the effect of incommensurability using the formula:

$$C_c = \frac{C_n}{kW_e/T_{int}} \tag{5}$$

where k is pulse amount contained in integration interval (mainly non-integral value), C_c is corrected visibility, C_n is visibility before the correction, W_e is equivalent pulse width, T_{int} is correlator integration time. Note that VLBA correlator output contains table of kW_e/T_{int} values. Fig. 2 illustrates the correction technique.

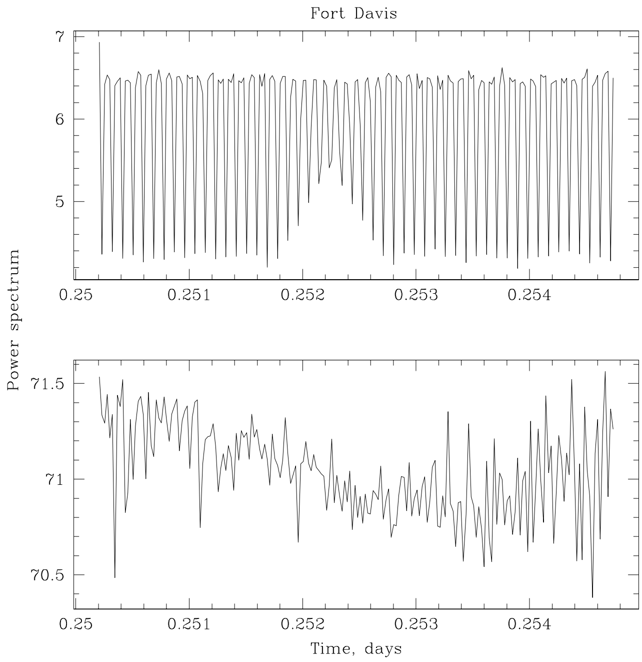

Fig. 2. Autocorrelation data corrected for incommensurability of pulsar period and correlator integration time. Top picture represents data before the correction, bottom — after the correction

2. Standard bandpass correction techniques for SVLBI (used for example in AIPS) don't take into account the fact that pulsar band is distorted by the scattering. SVLBI differ from the ground VLBI in that the satellite telescope doesn't observe calibrators. Therefore it is unable to get noise bandpass and perform bandpass correction for bases containing a space telescope. Using a record of a source with noise spectrum from another observational set may allow to make at least amplitude bandpass correction.
3. Pulsar intrinsic variability and interstellar scintillations distort visibility amplitude vs. base dependence (see Fig. 3). The data are usually averaged over several minutes before imaging. If the pulsar has a short period (rather less than averaging interval) or the scattering is weak such a technique does allow to decrease the impact of pulsar variability. But there are pulsars (for example our pulsar B0329+54) where this is not the case.
Note the intrinsic short-term variability might not impact on image quality but it should be taking into account during flux calibration. Scintillations, however, might lead to false interpretation of the results.
Having records of individual pulses at each antenna one could perform the correction for the variabilities quite easy. However the correction still might be made if there are date correlated both in gated and non-

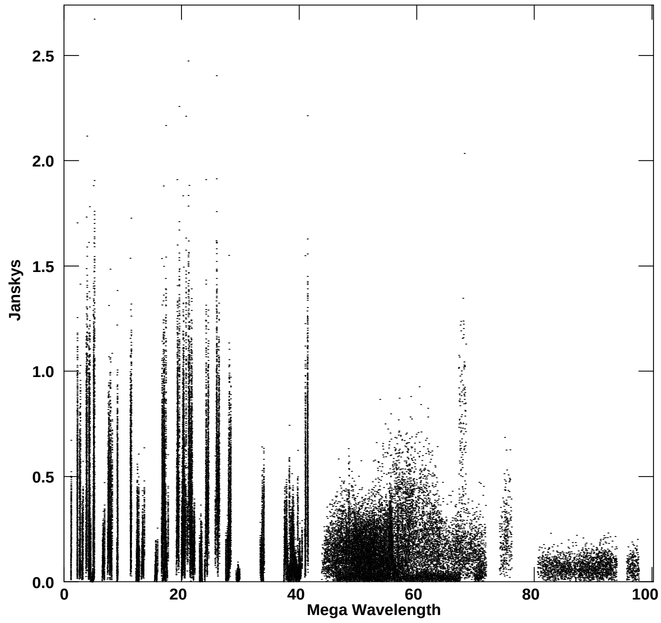

Fig. 3. Visibility amplitude of PSR B0329+54 vs. base. Amplitude calibration was performed in AIPS. Data are averaged over 1 minute.

gated mode. Let we have autocorrelation records A_g and A_k (subscript g or k corresponds to gated and non-gated data). Then

$$A_g = W_g S_n^2 + S_s^2 \quad (6)$$
$$A_k = W_k S_n^2 + S_s^2 \quad (7)$$
$$W_g = g W_k$$

where S_s is noise dispersion, W_g and W_k are integration times with gating and without it, coefficient g (see Eq. 4) is supposed to be known.
Solve the system ant receive

$$S_s^2 = \frac{A_g - gA_k}{g(1-g)} \quad (8)$$

Here we divided both sides of the Eq. 8 by g to eliminate beating. So at short bases where the source (pulsar) is supposed to be unresolved one can put

$$|V_{ij}^{exp}| = \sqrt{S_{i,s}^2 S_{j,s}^2} \quad (9)$$

where subscripts i and j denotes antenna numbers, V_{ij}^{exp} is visibility. Final formula for amplitude calibration looks like

$$V_{ij}^* = F V_{ij} / |V^{exp}| \quad (10)$$

where F is a priori flux, V_{ij}^* is the visibility after correction, V_{ij} is the visibility before correction, $|V^{exp}|$ is averaged over short bases $|V_{ij}^{exp}|$.
However the practice is much more complicated. First, even at shortest bases (about 400 km in our case) $|V_{ij}^{exp}|$ is two–three times greater than $|V_{ij}|$. Moreover properties of the coefficient for VLBA and non-VLBA sites differs. It might point to some instrumental effects that are not taken into account during data acquisition and/or correlation.
To make the fraction $|Vij|/|Vij^{exp}|$ close to 1 for short bases we found linear bi-sectorial least-square solutions (see Isobe 1990) for $|Vij|$ (separately for every IF) vs. $|Vij^{exp}|$ dependence and averaged the LSQ coefficients.
Then amplitude correction was performed using the formula:

$$V_{ij}^* = V_{ij} / W^{exp} \quad (11)$$
$$W^{exp} = a|V^{exp}| + b$$

where a and b are the averaged LSQ solutions.

4. Conclusions

The space VLBI observations of pulsar B0329+54 at 1.6 GHz were carried out. The source seems to be unresolved therefore its scattering disk size is less than 1.6 mas. The result is in accordance with the data of other authors.

Some pulsar features (incommensurability of pulsar period with the correlator integration time, bandpass distortion caused by scattering, intrinsic variability and scintillations) should be taken into account in amplitude calibration techniques during post-correlation data processing. The corresponding calibration methods are under development.

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