PSR B0329+54: Substructure in the scatter-broadened image discovered with RadioAstron on baselines up to 330,000 km

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PSR B0329+54: Substructure in the scatter-broadened image discovered with RadioAstron on baselines up to 330,000 km

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ABSTRACT
We have resolved the scatter-broadened image of PSR B0329+54 and detected substructure within it. These results are not influenced by any extended structure of a source but instead are directly attributed to the interstellar medium. We obtained these results with the ground-space interferometer RadioAstron supported by the 14×25-m Westerbork Radio Telescope, and the 64-m Kalyazin Radio Telescope at 324 MHz on baseline projections up to 330,000 km in 2013 November 22 and 2014 January 1, 2. Observations conducted with the Robert C. Byrd Green Bank Telescope in November 2012 were used for calibration. At short 15,000 to 35,000 km ground-space baseline projections the visibility amplitude decreases with baseline length providing a direct measurement of the size of the scattering disk of 4.8 ± 0.8 mas. At longer baselines where no visibility detections from the scattering disk would be expected, significant visibilities were obtained with their amplitudes of 3 to 5% of the maximum scattered around a mean and approximately constant up to 330,000 km. These visibilities reflect substructure from scattering in the interstellar medium and offer a new probe of ionized interstellar material. The size of the diffraction spot near Earth is 17,000 ± 3,000 km. With the assumption of turbulent irregularities in the plasma of the interstellar medium, we estimate that the effective scattering screen is located 0.6 ± 0.1 of the distance from Earth toward the pulsar.

Key words: scattering – ISM: general – radio continuum: ISM – techniques: high angular resolution – pulsars: individual: PSR B0329+54

1 INTRODUCTION
All images of radio sources from outside our solar system are influenced by scattering in the interstellar medium (ISM). Determining the properties of the scattering is essential for studying the characteristics of the ISM and for a proper interpretation of astronomical radio observations. Pulsars are an almost ideal type of a celestial source for such studies. They are almost point-like so that the results of the study are not influenced by the structure of the celestial source but almost completely attributable to the influence of the plasma turbulence of the ISM. Scattering of the pulsar signal in the ISM results in angular broadening of the pulsar image, temporal broadening of the pulses, modulation or scintillation of their intensities and, through diffraction patterns, distortion of their radio spectra. Scattering effects of the ISM have been the subject of studies by several authors. Theoretical studies were made by, e.g., Prokhorov et al. (1975); Rickett
PSR B0329+54 is the strongest pulsar in the northern hemisphere. With a galactic longitude of 145° and latitude of −1°2, and at a parallax distance of 1.03^{+0.13}_{-0.12} kpc (Brinken et al. 2002), the pulsar is located just at the outer edge of the Orion spiral arm. The scattering disk remained unresolved. An early upper limit of the angular size at 2.3 GHz is \( \theta_{\text{scat}} < 1 \) mas (Bartel et al. 1985).

Extending baselines into space, the first ground-space VLBI observations of a pulsar were made with VSOP by Yangalov et al. (2001). The observed pulsar was PSR B0329+54. With the VSOP observations its scattering disk was not resolved. The upper limit of the angular size at 1.7 GHz was determined to be \( \theta_{\text{scat}} < 2 \) mas (Yangalov et al. 2001). However, the VSOP observations were also done at a relatively high frequency and with baselines only up to about 25,000 km. Ground-space VLBI with RadioAstron allows observations at a frequency as low as 324 MHz, where scattering effects are expected to be much stronger and with baselines about 15 times longer. Since the scattering size increases as \( \nu^{-2} \), the size of \( \theta_{\text{scat}} \) < 2 mas at 1.7 GHz and the size of \( \theta_{\text{scat}} \) < 1 mas at 2.3 GHz from the ground-ground VLBI observations correspond to a size of \(< 50 \) mas at 324 MHz. At this frequency RadioAstron has an angular resolution of about 1 mas at its longest baselines. Therefore observations with RadioAstron may promise to resolve PSR B0329+54’s scattering disk and perhaps reveal hitherto unknown structure in the ISM. Here we report on such investigations with RadioAstron with baselines up to 330,000 km.

This paper is the second one in a series. The first paper (Paper I, Gwinn et al. 2016) gives a mathematical description of the functions obtained from the interferometer observations and leading to an evaluation of the scattering structure in the interstellar medium along the line of sight to PSR B0329+54. In this second paper we focus on the visibility magnitude as a function of projected baseline length and on a comparison between angular and temporal broadening. This will allow us to draw conclusions about the size of the scatter-broadened image of PSR B0329+54 as well as the characteristics of the diffraction spot near Earth and the distance of the scattering screen.

2 OBSERVATIONS

The observations were made in two sessions, on 2013 November 22, and 2014 January 1 to 2 with the 14 × 25-m Westerbork Synthesis Radio Telescope (WB), the 64-m Kalyazin Radio Telescope (KL) and the 10-m RadioAstron Space Telescope (RA) on projected baselines from 17,000 km to 330,000 km. RadioAstron operated during six relatively short periods of 80 to 120 min. with large gaps in between necessitated by thermal constraints on the spacecraft. Additional observations were made in an earlier session, on 2012 November 26–29 with the 110-m Robert C. Byrd Green Bank Telescope (GBT) on projected baselines from 56,000 to 235,000 km. However, the decorrelation bandwidth and the scattering time for this session are not compatible with those for the other sessions. We therefore use the data from this session only for purposes of calibrating antenna sensitivities and determining the average profile of a pulse and its phase in the pulsar period. The latter observations and those from 2014 January 1, 2 were already described in Paper I. We summarize the observations, including those from 2014 January 1, 2 in Table 1.

In all observations only the upper sideband of the 316–332 MHz band was recorded, with one bit digitization at the Radioastron space radio telescope (SRT) and with two bit digitization at the WB and KL. The auto-level (AGC), phase-cal, and noise diode were turned off during our observations to avoid interference with pulses from the pulsar. The data from the observations with RA were transmitted in real time to the telemetry station in Pushchino (Kardashev et al. 2013). For the recording of the data we used the RadioAstron data recorder (RDR) at Pushchino and KL and the MkVb recording system at WSRT. The recorded data were then transferred via internet to the Astro Space Center (ASC) in Moscow for processing by the ASC correlator.

3 DATA REDUCTION

3.1 Correlation

Our primary observable obtained from the ASC correlator is the interferometric visibility \( \tilde{V} \) in the domain of frequency, \( \nu \) and time, \( t \). This is the product of the Fourier transforms of electric fields at two antennas \( A \) and \( B \), averaged over a time interval large in comparison to the inverse of the Nyquist sampling rate, with

\[
\tilde{V}_{AB}(\nu,t) = \left\langle \tilde{E}_A(\nu,t) \tilde{E}_B^*(\nu,t) \right\rangle.
\]

\( \tilde{V}_{AB}(\nu,t) \) is also known as the cross-power spectrum or cross spectrum or dynamic cross spectrum. In Paper I we show how the visibility \( V \) can be represented in four domains given by the four combinations of \( \nu, t, \tau, \) and \( f \), where the latter two parameters are delay and fringe rate (see also Brinken et al. 2010). In this paper we are concerned with the visibility in the domain of delay and fringe rate, \( \tilde{V}_{AB}(\tau,f) \), from which we derive the size of the scatter-broadened image of the pulsar. This is the two-dimensional inverse Fourier transform of \( \tilde{V}_{AB}(\nu,t) \) with

\[
V_{AB}(\tau,f) = \hat{\delta}^{-1}_{\nu} \left[ \delta_{\nu} \left[ \tilde{V}_{AB}(\nu,t) \right] \right] .
\]

To provide maximum sensitivity for the correlation, the data were correlated only during the ON-pulse time interval of the average pulse profile. We determined the phase of this interval, or window, within the pulse period from the autocorrelation spectra (auto-spectra), \( \tilde{V}_{AA}(\nu,t) \), computed for each of the three ground stations, including GBT, and RA. This is the product of electric fields in the domain of frequency \( \nu \) at antenna \( A \) where \( A \) stands for any of the four antennas:

\[
\tilde{V}_{AA}(\nu,t) = \left\langle \tilde{E}_A(\nu,t) \tilde{E}_A^*(\nu,t) \right\rangle .
\]

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We modified the visibility data in three steps. First, we corrected for strong narrow-band interference by replacing the affected data in a scan with properly scaled random numbers. Second, we applied corrections for the RA in the total power mode in space (Kennedy et al. 2014). Similar computations give $SEF_{WB}^{pulsar} = 255 \ Jy$ and $SEF_{KL}^{pulsar} = 650 \ Jy$ for WB and KL, respectively.

3.2 Calibration

3.2.1 Determining the SEFD values for the telescopes

The amplitudes of the average profiles allowed us to accurately determine the sensitivities of all radio telescopes, including RA. On empty sky the GBT system temperature is known to be $T_{sys}^{GBT} = 90 \ K$ and the system equivalent flux density $SEFD^{GBT} = 45 \ Jy$. The sky temperature in the direction of the pulsar at a frequency of $\nu = 408 \ MHz$ is $T_{sky} = 56 \ K$ (Haslam et al. 1982). With a spectral index, $\alpha = -2.5$ and flux density, $S_\nu \propto \nu^\alpha$, we estimate $T_{sky} = 100 \ K$ at $\nu = 324 \ MHz$. This corresponds to an extra 50 Jy for the SEFD. Therefore, the total SEFD for GBT in the pulsar direction is $SEFD_{GBT}^{pulsar} = 95 \ Jy$. The peak flux density of the pulsar $\Delta S$ in a selected scan was 3.33 times larger than $SEFD_{GBT}^{pulsar}$; i.e. $\Delta S = 325 \ Jy$. For the SRT and the same scan, $\Delta S/SEFD_{RA}^{pulsar}$ was found to be 0.008. After correction for the one-bit sampling factor of 1.57, this ratio becomes 0.0125, yielding $SEFD_{RA}^{pulsar} = 26,000 \ Jy$. This value is somewhat in excess of the $SEFD_{RA} = 19,000 \ Jy$ measured for RA in the total power mode in space (Kovalev et al. 2014). Similar computations give $SEFD_{WB}^{pulsar} = 255 \ Jy$ and $SEFD_{KL}^{pulsar} = 650 \ Jy$ for WB and KL, respectively.

3.2.2 Calibration of the visibility data

For the subsequent analysis we used the CFITSIO package (Pence 1999). We modified the visibility data in three steps. First, we corrected for strong narrow-band interference by replacing the affected data in a scan with properly scaled random numbers. Second, we applied corrections for the RA, GBT, KL and WB receiver bandpasses using OFF-pulse auto-spectra as a template. Third, we used OFF-pulse auto-spectra to take into account strong intensity fluctuations of pulsar radio emission caused by both intrinsic variability of the pulsar emission and scintillation of that emission in the ISM. Of course, these fluctuations also affect the amplitude of the visibility function. In cases where corrections were

### Table 1. RadioAstron Space Radio Telescope, Kalyazin, WSRT observations log

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Start of obs. (UT, hh:mm)</th>
<th>Length of obs. (min)</th>
<th>Length of scans (s)</th>
<th>Number of scans</th>
<th>$b^c$ (MA)</th>
<th>Telescopes$^d$</th>
<th>Polarization$^e$</th>
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<td>01:10</td>
<td>120</td>
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<td>RCP + LCP</td>
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<td>1170</td>
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<td>350</td>
<td>KL, RA</td>
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</tr>
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<td>1170</td>
<td>4</td>
<td>24</td>
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<td>RCP</td>
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<td>1170</td>
<td>5</td>
<td>111</td>
<td>KL, RA</td>
<td>RCP</td>
</tr>
</tbody>
</table>

Note: In addition to the shown observing epochs, RadioAstron-GBT data were used in this paper for the amplitude calibration (see §3.2). They are discussed in details by Gwinn et al. (2016).

$^a$ Length of observations from the start time;

$^b$ Length of each scan with a 30 s gap in between;

$^c$ Mean projected baseline length;

$^d$ (14 × 25-m Westerbork Synthesis Radio Telescope), KL (64-m Kalyazin Radio Telescope), RA (10-m RadioAstron Space Radio Telescope);

$^e$ Recorded polarization, RCP (right circular polarization), LCP (left circular polarization).

![Figure 1](image-url) **Figure 1.** The average pulse profile of PSR B0329+54 shown as observed with GBT and RA. The four components of the pulsar are indicated by numbers. The main component is indicated by number 3. The ON-pulse window was centered on this component. Pulsar period is equal to 714 ms.

Also,

$$V_{\Delta A}(\tau, t) = \delta_{\nu,\nu^\prime} \left[ V_{\Delta A}(\nu, t) \right].$$

The correlator output was sampled synchronously with the pulsar period of 0.714 s (single pulse mode). We used the ephemerides computed with the program TEMPO for the Earth center. Integration over time yielded the average pulse profile and the phase of the ON-pulse window.

The ON-pulse window was centered on the main component of the average profile, with a width of 8 ms. We also chose an OFF-pulse window, offset from the main pulse by half a period and with the same width as the ON-pulse window. With the phase and duration of the windows determined, all VLBI data were correlated with gating and dedispersion applied using 2048 channels. The correlator computed the cross-spectra, $V_{\Delta A}(\nu, t)$ which were then written in standard FITS format for further analysis.

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applied to single pulses, we normalized the cross-spectra by using the normalization factor $R_{\text{corr}}$:

$$R_{\text{corr}}^{-1} = \sqrt{(\sigma_{1\text{on}}^2 - \sigma_{1\text{off}}^2)(\sigma_{2\text{on}}^2 - \sigma_{2\text{off}}^2)}$$  \hspace{1cm} (5)$$

Here, $\sigma_{1\text{on}}^2$ and $\sigma_{1\text{off}}^2$ are the variances for the pulses observed at the ground radio telescopes used for cross-correlation, computed in ON-pulse and OFF-pulse windows as the sum of all harmonics in the power auto-spectra. Similarly, $\sigma_{2\text{on}}^2$ and $\sigma_{2\text{off}}^2$ are the corresponding variances for the RA spectra computed in the same way.

The relatively low sensitivity of RA renders the measurement of $\sigma_{2\text{on}}^2 - \sigma_{2\text{off}}^2$ rather uncertain. It can even give negative values. We therefore replaced this ratio with the ON-pulse intensity for a given ground radio telescope (GBT), but reduced to an expected value for the RA using the coefficient $\eta = \text{SEFD}_{\text{GBT}}/\text{SEFD}_{\text{RA}}$. This coefficient was taken to be equal to 0.0024, 0.0063, and 0.016 for GBT, WB, and KL respectively, which, with the sampling factor taken into account, correspond to the ratios of the SEFD values given in §2. Then, equation 5 can be written as

$$R_{\text{corr}}^{-1} = \frac{\sigma_{2\text{off}}}{\sigma_{1\text{off}}}(\sigma_{2\text{on}}^2 - \sigma_{1\text{on}}^2) \sqrt{\eta}.$$  \hspace{1cm} (6)$$

Instead of corrections to individual cross-spectra $\tilde{V}_{AB}(\nu, t)$ we applied the corrections to visibility amplitudes $V_{\text{amp}}$ in the following way. For 1170-s scans we calculated 16 raw complex visibility functions $V_{AB}(\tau, f)$ for every 100 pulses (array dimension $2048 \times 100$). Then we took the visibility amplitude as $V_{\text{amp}} = \sqrt{R_{\text{corr}}^{-1} + I_{AB}^2}$ at a point of maximum (close to $\tau = 0$ and $f = 0$) as it is used in any VLBI study (R and L being real and imagine components of complex function). We applied the same routine to the auto-spectra ON-pulse and OFF-pulse longitudes: computing $V_{\text{amp}}$ (ON), $V_{\text{amp}}$ (OFF), $V_{\text{amp}}$ (ON), and $V_{\text{amp}}$ (OFF). These quantities are equivalent to the corresponding variances $\sigma_{1\text{on}}^2$, $\sigma_{2\text{off}}^2$, $\sigma_{2\text{on}}^2$ and $\sigma_{2\text{off}}^2$, averaged over integration time $\Delta t_{\text{int}} = 71.4$ s. Then we corrected raw values of $V_{\text{amp}}$ using equation 5 for WB-KL baseline combination, and using equation 6 for WB-RA and KL-RA baseline combinations with the coefficient $\eta$ mentioned above. We have averaged 16 corrected values of visibility amplitude $V_{\text{amp}}$ for every 1170-s observing scan, and these values are displayed in Figure 4 as a function of projected baseline length.

### 4 Visibility as a Function of Projected Baseline Length

Important parameters for the subsequent analysis are the scintillation time $t_{\text{diff}}$ and the decorrelation bandwidth $\Delta \nu_{\text{diff}}$. We have estimated these parameters by computing the two-dimension cross-correlation function (CCF) between the ON-pulse dynamic auto-spectra obtained over 1170-s scans at KL and WB. More specifically, we used sections of the CCF along time and frequency delays, fitted with gaussian and exponential functions respectively. The parameters, $t_{\text{diff}}$ and $\Delta \nu_{\text{diff}}$ are listed in Table 2.

For our 2013 November and 2014 January observing sessions each visibility function $V_{AB}(\tau, f)$ was computed over 100 pulse periods ($\Delta t_{\text{int}} = 71.4$ s), short enough so that no coherence losses were expected and no correction for it needed to be applied. This time is also smaller than the scintillation time, $t_{\text{diff}}$, and therefore small enough to be in the so-called snapshot regime (Goodman & Narayan 1989) where no damping of visibility amplitudes is expected.

In Paper I we showed an example of the distribution of visibility as a function of delay and fringe rate, $[V(\tau, f)]$, for four different baselines, each for a fixed fringe rate near zero where the maximum of the distribution occurred. The curves are plotted according to baseline length, with the shortest baseline of 2 Mλ at the bottom of the figure and with the longest baseline of 120 Mλ at the top.

It is apparent that the highest visibility amplitude occurs at the shortest baseline with one spike near zero delay. This spike is due to the scatter-broadened image of the pulsar. The two curves at intermediate baselines of 20 Mλ length still show the spike at zero delay but at diminished strength. The pulsar appears to be partly resolved on these baselines. The top curve at 300 Mλ baseline length does not show a pronounced spike anymore. The scatter-broadened

<table>
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<th>Table 2. Pulsar scattering parameters</th>
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<tr>
<td></td>
</tr>
<tr>
<td>(1)</td>
</tr>
<tr>
<td>2013 November 22</td>
</tr>
<tr>
<td>2014 January 1, 2</td>
</tr>
</tbody>
</table>

Note: Columns are as follows: (1) date of observations; (2) scintillation time from single-dish autocorrelation spectra as the half width at 1/e of maximum; (3) scintillation bandwidth from single-dish autocorrelation spectra as the half-width at half maximum (HWHM); (4) HWHM of an exponential function fit to the visibility amplitude distribution along the delay axis.

![Figure 2. Examples of the cross section, $|V(\tau, f)|$, of the distribution of the visibility magnitude $|V(\tau, f)|$ at the fringe rate, $f_{\text{max}}$, with maximum magnitude. This fringe rate is near zero. The upper curves correspond to the longest baseline projections and the lower curves to correspondingly shorter baselines, with the telescopes indicated and the approximate baseline projections given in Mλ in parentheses. The four upper curves are offset by constants for ease of viewing and the two top curves is, in addition, magnified by a factor 10.](image-url)
The expected visibility amplitude as a function of baseline length due to angular broadening is given by Gwinn et al. (1988), apart from a scaling factor, as

\[ V_{AB} = \exp \left\{ -\frac{1}{2} \left( \frac{\pi \theta_B b}{(2 \ln 2)^{1/2} \lambda} \right)^{\alpha-2} \right\} \]  

(7)

These values were then averaged for every 16 \times 100-pulse periods, that is for 1170 s, and they are displayed in Figure 4 as \(|V_{AB}(\text{max})|\) with open circles and open and filled squares for different baselines. However, while for projected baselines up to about 40 M\(\lambda\) \(|V_{AB}(\text{max})|\) occurred at or close to the origin of zero delay and fringe rate, for baselines longer than about 40 M\(\lambda\) \(|V_{AB}(\text{max})|\) occurred in general considerably away from the origin (see, Figure 2). To determine \(|V_{AB}|\) at the origin for the long baselines comparable to \(|V_{AB}(\text{max})|\) at the shorter baselines we computed the average of the cross section \(|V(\tau, f_{\text{max}})|\) visibilities for 1170 s as displayed in Figure 3 for one scan, but now for all such scans. We then fit an exponential to the averages and determined the peak visibility magnitudes which were always close to the origin. These averages are equal to the rms values over time of the scans since the visibilities are Chi-square distributed with two degrees of freedom. In this sense, they are important for comparisons with theoretical predictions.

There are four groups of points in Figure 4: visibility amplitudes on short, \(\sim 2\) M\(\lambda\) ground-ground baselines, on intermediate, 15 to 40 M\(\lambda\) and long, 60 to 120 M\(\lambda\) ground-space baselines, and on the longest, about 350 M\(\lambda\), baselines. We estimate the \(1\sigma\) uncertainties of the visibility amplitudes to be about as large as the symbols. Larger variations may be caused by the varying baseline and/or by scintillation.
with, e.g., $\alpha = 4$, for a Gaussian and where $\theta_H$ is a full width at a half maximum (FWHM) of a Gaussian image of scattering disk. The parameter, $\alpha$, is the spectral index of density fluctuations and, $b$, the projected baseline of the interferometer. It is clear that this function cannot provide a good fit to the visibility amplitudes for all baselines. Only those on the short and intermediate baselines provided a good fit with the fitting function shown as a solid line. The power index $\alpha$ for PSR B0329+54 was measured by Shishov et al. (2003) in their multi-frequency study; they found $\alpha = 3.50 \pm 0.05$. We used this value for our fit.

We obtained $\theta_H = 2.4 \pm 0.4 \times 10^{-8}$ rad or $4.8 \pm 0.8$ mas. The visibility amplitudes at zero baseline are, as expected, smaller than unity since $\Delta t_{\text{d}}$ is much larger than $\Delta t_{\text{diff}}$ and we are therefore integrating in frequency over many scintules. Our fit function (Eq. 7) falls toward zero very rapidly for baselines longer than $\sim 60$ M$\lambda$ being many orders of magnitude smaller at the longest baselines than the visibility amplitudes we measured and which are approximately constant varying only between $\sim 0.11$ and $\sim 0.07$ for baselines from 60 to 350 M$\lambda$. Clearly the scatter-broadened image of PSR 0329+54 is resolved and substantial substructure exists in it.

5 THE SCATTERING MATERIAL IN THE ISM ALONG THE LINE OF SIGHT TO THE PULSAR

At a parallax distance of $D = 1.03 \pm 0.13$ kpc (Brisken et al. 2002), PSR 0329+54 is located at the outer edge of the Orion spiral arm, while the Sun is close to the inner edge of the arm. A comparison of angular and temporal broadening provides information on the distribution of the scattering material in this arm along the line of sight to the pulsar. Expressions for the angular diameter $\theta_H$ and the broadening time $\tau_{\text{scat}}$ have been derived by Blandford & Narayan (1985). These expressions contain the function $\psi(z)$ which defines the mean scattering angle per unit length, $z$, measured from the source to the observer.

If we assume the extreme case that the scattering material is uniformly distributed along the line of sight to the pulsar, then $\psi(z)$, according to Britton et al. (1998), is a constant, and $\theta_H = 16 \ln 2 (\tau_{\text{scat}}/D)$ with $D$ being the distance to the pulsar. This relation gives for our values of the broadening time, $\tau_{\text{scat}}$ of $12.1 \pm 0.5$ ms value of $\theta_H = (3.6 \pm 0.1) \times 10^{-8}$ rad which is significantly larger than the measured value of $\theta_H = (2.4 \pm 0.4) \times 10^{-8}$ rad. Therefore, for this relatively simple case, a model of uniformly distributed scattering material along the line of sight to the pulsar is inconsistent with our result.

If we assume another extreme case that the scattering material is only distributed in a thin screen located at a distance $d$ from Earth, then $\psi$ becomes a function of $z$, $D$, and $d$ and $\theta_H = [8 \ln 2 c \tau_{\text{scat}} (D - d)/D^2]^{1/2}$ (Britton et al. 1998). This relation gives us for our measured values of $\theta_H$ and $\tau_{\text{scat}}$ from the January session, $d = (0.5 \pm 0.1) D$ which means that the effective screen is located approximately in the middle of the distance to the pulsar.

However, Shishov et al. (2003) suggested that interstellar plasma along the line of sight to PSR B0329+54 consists of two types of inhomogeneities: turbulent irregularities, which produce the diffractive scattering, and large scale irregularities, which produce the frequency dependent angular refraction. In this more realistic case a difference relation between $\theta_H$ and the distances, $D$ and $d$, needs to be considered. This relation includes the diffractive scintillation time, $t_{\text{diff}}$, the associated diffractive length-scale, $\lambda_{\text{diff}}$, in the plane of the observer normal to the line of sight to the pulsar, and the velocity of the scintillation pattern with respect to the observer, $v_{\text{diff}}$, with

$$r_{\text{diff}} = v_{\text{diff}} t_{\text{diff}}$$

The velocity, $v_{\text{diff}}$, is a geometrical function of the velocities of the observer, $v_{\text{obs}}$, the scattering screen, $v_{\text{scr}}$, and the pulsar, $v_{\text{psr}}$, as well as the distances, $D$ and $d$, and is given by

$$v_{\text{diff}} = v_{\text{obs}} - \frac{D}{d_s} v_{\text{scr}} + \frac{D - d_s}{d_s} v_{\text{psr}}$$

Here $d_s$ is a distance from the pulsar to the screen. We estimated $r_{\text{diff}}$ by comparing the expression for the visibility amplitude versus baseline, given by (Goodman & Narayan 1989; Prokhorov et al. 1975)

$$V_{AB} = \exp[-\frac{1}{2} \frac{b}{r_{\text{diff}}^{\alpha-2}}]$$

with equation 7. We obtained

$$r_{\text{diff}} = \left(\frac{\lambda}{\theta_H \pi}\right) \sqrt{2 \ln 2},$$

and $r_{\text{diff}} = (1.7 \pm 0.3) \times 10^4$ km, with the error reflecting the error of $\theta_H$. The mean value of $v_{\text{diff}}$ is 170 km/s. The pulsar velocity was taken from (Brisken et al. 2002) as $v_{\text{psr}}=90$ km/s. We assume $v_{\text{obs}}=0$, and $v_{\text{scr}}=34.6$ km/s for January 1 2014. With these values we get $\frac{b}{r_{\text{diff}}} = 0.37 \pm 0.06$ or $\frac{\lambda}{\theta_H \pi} = 0.63 \pm 0.06$. This estimate is somewhat larger than the previous one of $\frac{\lambda}{\theta_H \pi} = 0.50 \pm 0.1$ but still consistent with it within the combined error. Combining the two results we get $\frac{d}{r_{\text{diff}}} = 0.60 \pm 0.1$.

6 SUBSTRUCTURE IN THE SCATTER-BROADENED IMAGE OF PSR 0329+54

6.1 Visibility amplitudes as a function of projected baseline length

The diffraction scatter-broadened image of PSR 0329+54 with angular size $\theta_H$ is reflected in the rapidly decaying visibility amplitudes up to $b \sim 40$ M$\lambda$. For longer baselines the image should be completely resolved, and on the basis of the fitting function (Eq. 7) no visibilities expected to be detected. However, visibilities are detected and their amplitudes are scattered but otherwise approximately constant up to the longest baselines of $\sim 350$ M$\lambda$. Further, as shown in Figure 2, the cross sections of the secondary spectra are qualitatively different for different baselines. For shorter baselines, the cross sections consist of a broad component and a central narrow spike whereas for long baselines the central narrow spike disappeared and only a broad distribution of low amplitude spikes along delay remains. How can that be understood?

It is important to consider general aspects of the
ground-space interferometer and the scattering medium. For radio waves through the ISM, scattering is considered to be strong, meaning that the lengths of the many paths the scattered radio waves take from the pulsar to the observer differ by many wavelengths. Goodman & Narayan (1989) and Narayan & Goodman (1989) distinguished three cases for strong scattering of which two are of relevance for our space VLBI data, the snapshot and the average regime. In the snapshot regime, the relative phases of the radio waves traveling along different paths remain mostly unchanged during the observations. The interferometer observes a pattern of speckles whose parameters are a function of the size of the source and of small and large-scale electron density variations in the ISM. The average regime is characterized by some averaging over several different paths smoothing out to zero visibility due to small-scale density variations and only leaving the visibility from the large-scale variations.

For our observations, the size of the source is very small. Pulsar radio emission is generated in a very compact region inside the magnetosphere of a neutron star. Even if the size of the emission region is as large as the light cylinder, the angular size of that region for PSR 0329+54 would be only 2.3 × 10^{-12} rad or 0.5 μas, smaller than 0.001 times the angular resolution of VLBI with RadioAstron at 324 MHz on any baseline. Therefore, pulsars are essentially “point-like” radio sources for us and all signatures of the visibility data are therefore due to the small and large-scale density variations in the ISM. Further, the averaging of our cross spectra over 100 pulse periods or 71.4 s, is less than $t_{\text{diff}}$ and therefore small enough to be in the so-called snapshot regime where no damping of visibility amplitudes is expected. However, the receiver bandwidth, $\Delta f_{\text{rad}}$ of 16 MHz is much larger than the decorrelation bandwidth $\Delta f_{\text{diff}} \sim 7$ kHz, resulting in a decrease of the visibility amplitudes.

In our observations the $b/r_{\text{diff}}$ ratio varies from 0.1 to about 15. For a small ratio (up to about 1) the projected baseline was small and the corresponding beam size of the interferometer averages over many paths the scattered radio waves took from the pulsar to Earth. The ground telescope and the SRT were clearly still in a diffraction spot. This is the average regime where the visibilities from any possible small-scale density variations of the ISM were averaged to zero and only those from large-scale density variations survived. On these baselines our interferometer only measured the scatter-broadened image of the pulsar. For larger ratios of $b/r_{\text{diff}}$ (up to 15) the two telescopes were not in the same diffraction spot anymore. The scatter-broadened image was completely resolved resulting in essentially zero visibility. However, any small scale variations if they existed would be less prone to averaging and could become detectable. Indeed, at baseline projections greater than $r_{\text{diff}}$ significant visibilities were detected and their amplitudes were scattered around a mean of 10 to 15% of the maximum at short baselines that remained approximately constant up to the largest ground-space baselines of 330,000 km. Clearly, substructure in the scatter-broadened image of PSR 0329+54 was detected, most likely due to small-scale electron density fluctuations in the ISM.

6.2 Comparison with Theory and Other Observations

How does the level of the rms visibility amplitudes around the mean of 3 to 5% of the maximum at short baselines compare with predictions from theoretical considerations and how does it compare with other observations? Substructure in scattering disks falls into two separate regimes: diffractive and refractive. These two regimes correspond to different scales of fluctuations in electron density; diffractive effects arise from fluctuations on scales of $r_{\text{diff}} \sim 10^4$ km, while refractive effects arise from fluctuations on scales of $D\theta_H \sim 10^9$ km. These two dominant scattering scales can arise from a single power-law spatial spectrum for density fluctuations, such as the Kolmogorov spectrum (Rickett et al. 1984).

Diffractive substructure produces random visibility fluctuations of order unity that decorrelate rapidly in frequency and time (quantified by the scintillation bandwidth and timescale) (Gwinn 2001; Johnson & Gwinn 2013). Re-refractive substructure produces visibility fluctuations with smaller amplitudes, but these fluctuations have a decorrelation bandwidth of order unity and persist for weeks to months (Narayan & Goodman 1989; Goodman & Narayan 1989; Johnson & Gwinn 2015). Because of these properties, diffractive scintillation disperses source power in the delay-rate domain while refractive scintillation contributes power to a single peak (just as the unscattered source visibility does).

For an effectively pointlike source such as a pulsar, the expected level of diffractive substructure on long baselines depends on the number of averaged scintillation elements. Our 71.4 s averaging timescale is shorter than the scintillation timescale in both epochs but our averaged bandwidth (16 MHz) is much wider than the 7 kHz scintillation bandwidth (see Table 2). We therefore expect an rms visibility amplitude on long baselines from diffractive scintillation of approximately $\sigma_{\text{diff}} \approx \sqrt{(16 \text{ MHz})/(7 \text{ kHz})} = 0.021$, where this value corresponds to the fractional amplitude relative to the zero-baseline visibility.

The expected level of refractive substructure on long baselines depends on the scattering properties and also on the baseline length $b$ but does not depend on the averaging timescale or bandwidth. Taking $\alpha = 3.5$ (Shishov et al. 2003) and also using our derived values of the scattering, $d$ and $\theta_H$, we then find a fractional rms visibility from refractive substructure of (Johnson & Gwinn 2015):

$$\sigma_{\text{ref}}(b) = \sqrt{(\Delta A_{\text{ref}})^2} = 0.0091 \left(\frac{b}{10^6 \text{ km}}\right)^{-0.75}.$$  \hspace{1cm} (12)

For the range of baselines in Figure 4 that resolve the scattering disk, $b = 65$ to 350 MA = 60,000 to 280,000 km, we expect $0.013 \leq \sigma_{\text{ref}}(b) \leq 0.005$.

Comparing these values, we see that our detected visibilities on long baselines are roughly consistent with the expected properties and strength of diffractive substructure. Moreover, our non-detections of strong, persistent peaks in delay-rate space on long baselines are also consistent with the expected strength of refractive substructure. Our observations of PSR B0329+54 are the first to detect the signatures of diffractive substructure on baselines that entirely resolve the ensemble-averaged scattered image. And while refractive substructure has been detected in the galactic center
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radio source Sgr A* (Gwinn et al. 2014) and in the quasar 3C273 (Kovalev et al. 2016; Johnson et al. 2016), our results are the first detections of either class of substructure that are not sensitive to properties of the intrinsic source.

7 SUMMARY AND CONCLUSIONS

Here we summarize our observations and results and give our conclusions.

(i) We made VLBI observations of PSR B0329+54 with RadioAstron at 324 MHz on projected baselines up to 330,000 km or 350 MA. Our goal was to investigate scattering properties of the ISM which affect radio observations of all celestial sources. While the results of such observations are in general influenced by the convolution of source structure with the processing steps, pulsars are virtually point-like sources and signatures in the observational results can be directly related to the ISM scattering properties.

(ii) Visibility function at short ground-ground baselines manifests a single bright spike in delay-rate space that vanishes on long space-ground baselines. Thus, the scattering disk of PSR B0329+54 was completely resolved on ground-space baselines of 15,000 to 30,000 km. The FWHM of the angular diameter is 4.8 ± 0.8 mas.

(iii) The diffractive length scale or size of the diffraction spot near Earth is 17,000 ± 3,000 km.

(iv) With the assumption of turbulent and large-scale irregularities in the plasma, the effective scattering screen is located 0.6 ± 0.1 or somewhat more than half of the distance from Earth to the pulsar.

(v) At longer projected baselines, up to 330,000 km, significant visibility amplitudes were detected, although none were expected from the scattering disk. They are scattered around a mean which stays approximately constant up to the longest baselines. This result indicates that substructure was discovered in the scatter-broadened image of PSR B0329+54.

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