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Multi-Frequency Scintillation Arc Study of Pulsar B1133+16

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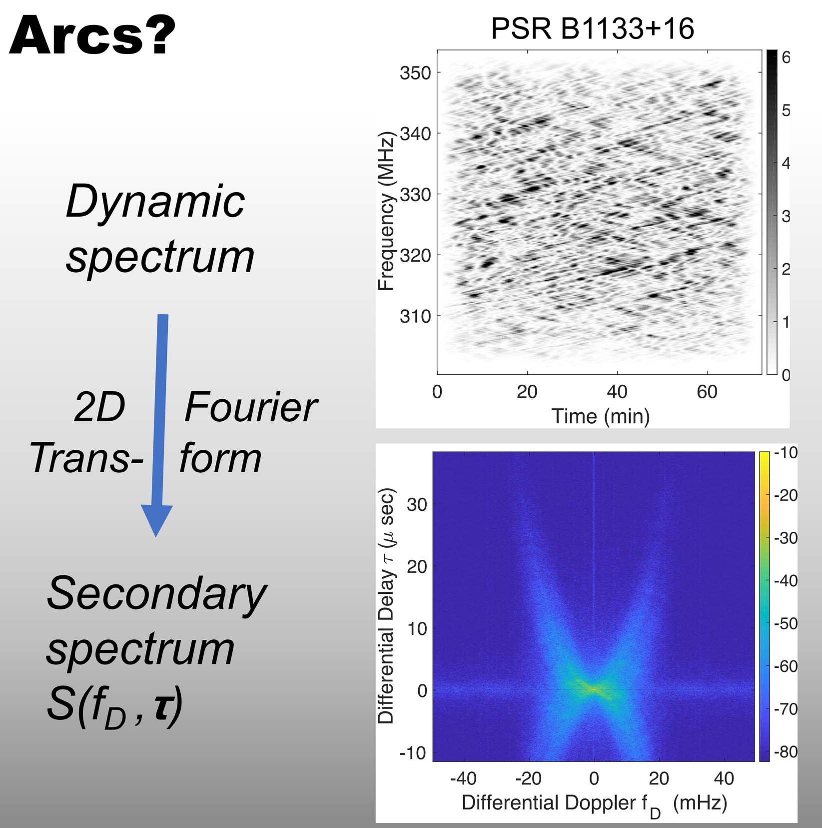
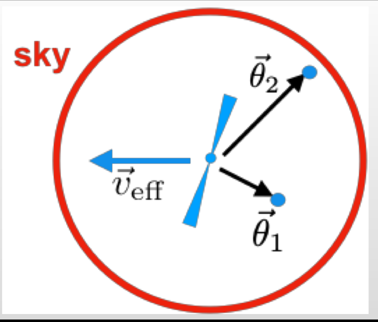
What are Scintillation Arcs?



Pulsar viewed through thin screen in interstellar medium (ISM) [1, 2]:



Scintillation arc: $\tau = \eta f_D^2$,

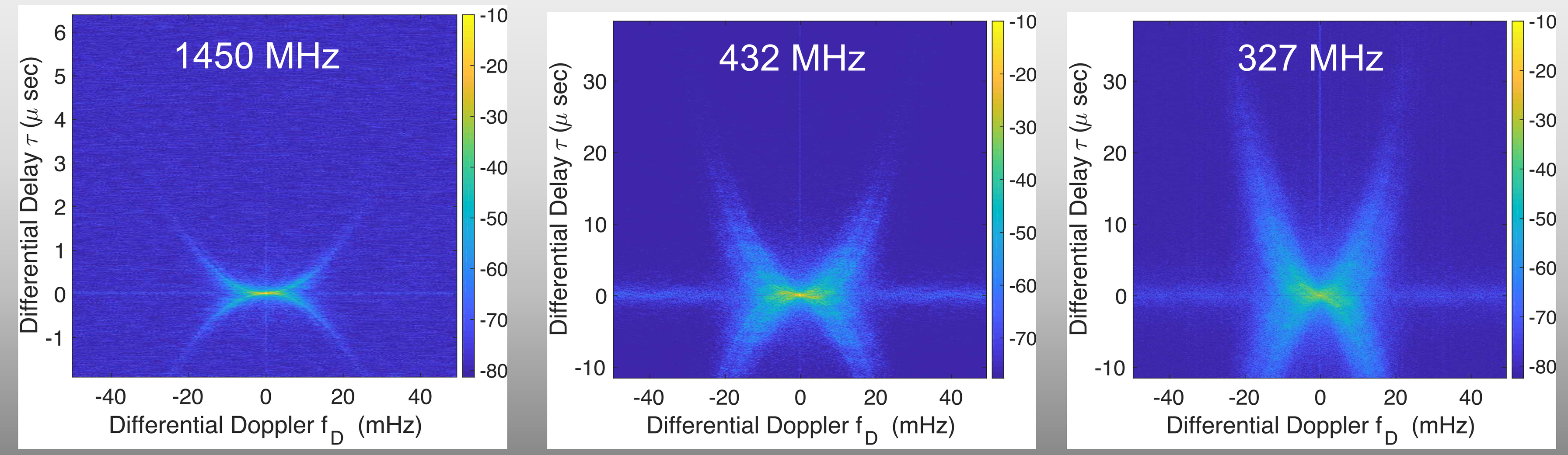
$$\tau = D_{\rm eff}(\theta_2^2 - \theta_1^2)/2c \quad (1)$$

$$f_D = \nu(\boldsymbol{\theta}_1 - \boldsymbol{\theta}_2)\cdot \boldsymbol{v}_{\rm eff}/c \quad (2)$$

$$\theta_{1,2} = \sqrt{\frac{c\eta}{2D_{\rm eff}}}\left[-\frac{\tau}{\eta f_D} \pm f_D\right] \quad (3)$$

Motivation for a Multi-Frequency Study of B1133+16

Scintillation arcs are observed to broaden at lower observing frequencies, but before this work the frequency dependence of scintillation arc widths had not been quantified or explained. Secondary spectra of PSR B1133+16 (below) exhibit this broadening.

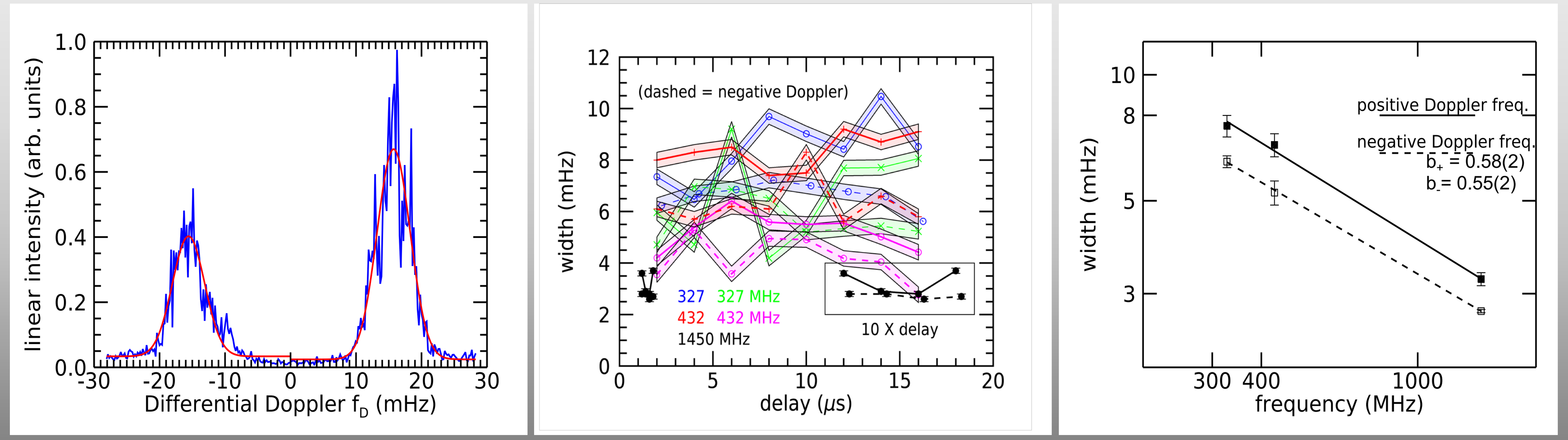


Observations with Arecibo

We observed PSR B1133+16 in spring 2015 for 21 epochs at three observing frequencies: 327, 432, and 1450 MHz. At the end of the program we had useful data at 11, 18, and 8 epochs for 327, 432, and 1450 MHz, respectively. At 1450 MHz, up to three well-defined scintillation arcs are evident, with curvatures consistent with Putney & Stinebring [3]. The arc thickness is quantified by measuring the arc widths for 5 data sets: 327 MHz on MJD 57175 and 57185, 432 MHz on MJD 57173 and 57179, and 1450 MHz on MJD 57179.

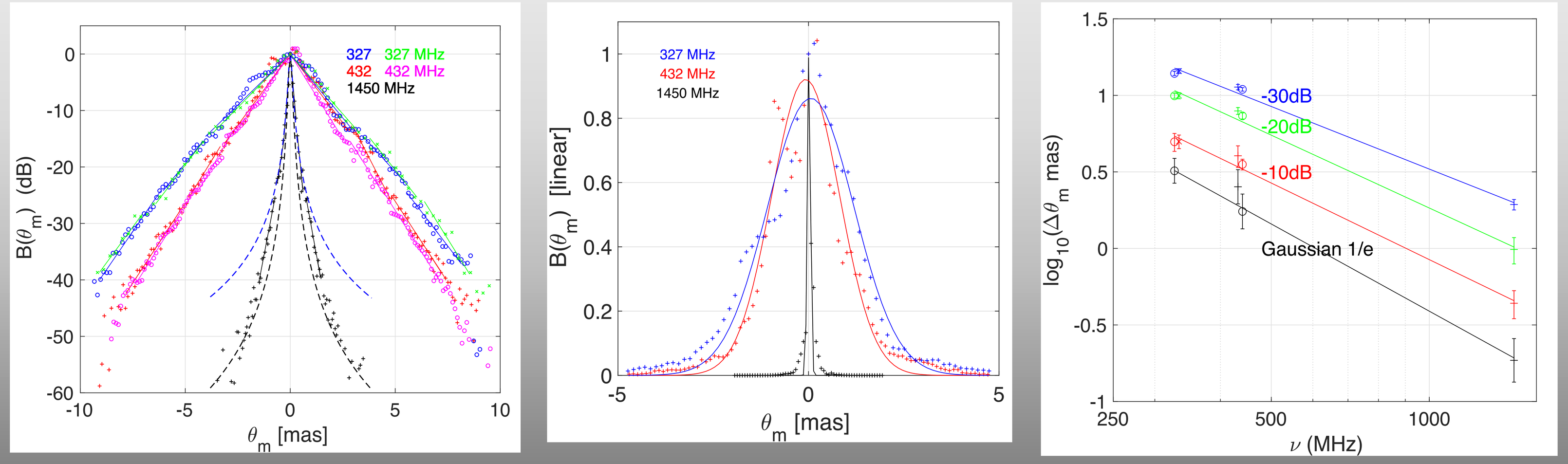
Frequency Dependence of B1133+16 Arc Widths

Left: Cross-cut of the scintillation arc at 10 μsec delay with fitted Gaussians (327 MHz, MJD 57173). **Center:** Results of cross-cut analysis for the five data sets. Plotted are the Gaussian widths to 1/e in f_D vs. delay. The shaded areas indicate 1σ errors for 327 and 432 MHz. The boxed inset shows the 1450 MHz data with 10x the delay value. **Right:** Average arc widths as a function of delay (log-log). An unweighted average width was calculated at each frequency for the positive and negative Doppler arcs separately. The best fit lines for the positive and negative arcs have slopes $b_+ = 0.58 \pm 0.04$ and $b_- = 0.55 \pm 0.02$, where $\Delta f_D \propto \nu^{-b}$.



Evidence of a 1D Brightness Function

Left: 1D brightness models $B(\boldsymbol{\theta}_m)$ were fit to the observed secondary spectra. The symbols are '+' for the observation on MJD 57179, '∘' for 57173 and 'x' for 57185, with straight lines fitted to 10 dB ranges centered at -10, -20 & -30 dB. At 1450 MHz, theoretical brightness distributions for isotropic and 1D Kolmogorov density spectrum are shown as dashed lines; the black dashed curve is the isotropic case. **Middle:** Linear plot of $B(\boldsymbol{\theta}_m)$. **Right:** The full width (FW) of $B(\boldsymbol{\theta}_m)$ was estimated at -10, -20 & -30 dB below the peak. The FW of the Gaussian model characterizes the width near the peak. The straight-line fits at the three levels gave slopes that are listed in Table 2.



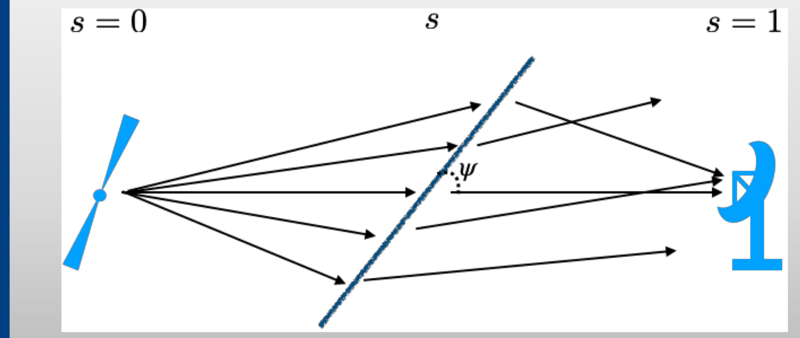
Freq. (GHz)	Width level	Slope
0.327	Gaussian	1.9(2)
0.432	-10 dB	1.7(2)
1.450	-20 dB	1.6(2)

Constraint on the Scattering Screen Location

Measurements of the scintillation arc curvature η can be used to constrain the fractional distance s to the scattering screen:

$$\eta = cD_{\rm eff}/2\nu^2 V_{\rm eff}^2 \cos\psi \quad (4)$$

$$D_{\rm eff} = D_{\rm psr}(1-s)/s \quad (5)$$

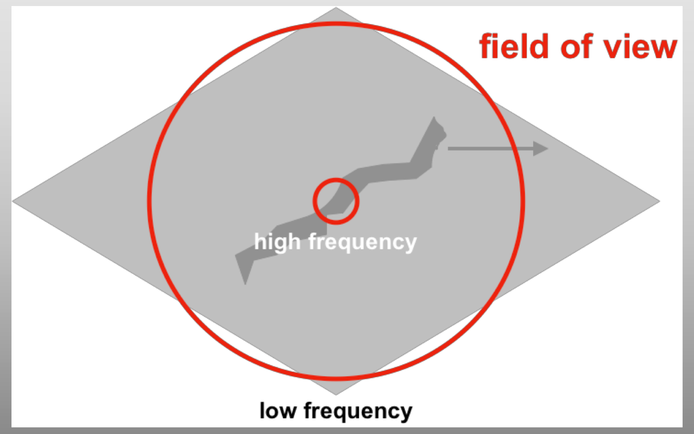


Freq. (GHz)	η (s^{-3})	s_0 (ψ=0)
0.327	0.06(1)	0.61(4)
0.432	0.040(5)	0.65(3)
1.450	0.0031(2)	0.62(2)

A screen location of $s \leq 0.62(1)$ is consistent with a screen at the edge of the Local Bubble (between 170 to 250 pc away [5,6]).

An Unsolved Problem

The expected frequency scaling for the width of angular broadening is $\nu^{-2.2}$ for Kolmogorov turbulence and ν^{-2} for plasma refraction. Shallower than expected frequency scalings might be due to a scattering screen with finite transverse dimension, as proposed by Cordes & Lazio [4]:



Relevance for Pulsar Timing

The detection of gravitational waves with pulsar timing requires extremely precise measurements of pulse times of arrival (TOAs) and thorough mitigation of any variation in the TOAs not caused by gravitational waves. The ISM is a major source of TOA variation. Scintillation arcs imply the existence of plasma structures in the ISM that delay the signal, but whose nature is still largely a mystery. We are working with our NANOGrav colleagues to understand how to correct TOAs for time-variable scattering delay based on secondary spectrum analysis.

References:
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For more information on the results on this poster see arXiv:1811.04519. This paper has been accepted for publication in ApJ.

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