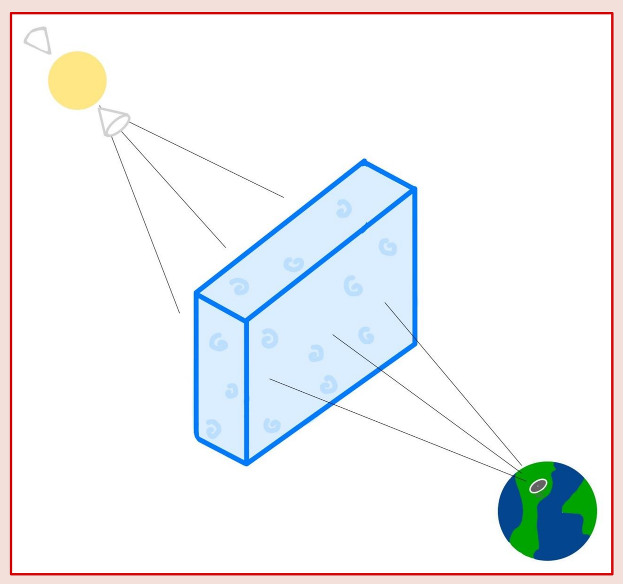
Probing Interstellar Turbulence and Precision Pulsar Timing with Pulsar J1903+0327

Abra Geiger[1], James Cordes[1], Shami Chatterjee[1], Michael Lam[2], Stella Ocker[3]
1 Cornell University | 2 SETI Institute | 3 Caltech and Carnegie Observatories

NANOGrav Physics Frontiers Center

Introduction

Pulsars are rapidly spinning, highly magnetized neutron stars that are precisely timed by pulsar timing array collaborations, such as the North American Nanohertz Observatory for Gravitational Waves (NANOGrav), to detect nanohertz gravitational waves. Turbulent free electrons within the interstellar medium (ISM) manifest propagation effects which limit pulsar timing precision. One such effect is **scattering**, the temporal and angular broadening of a signal due to diffraction through variations in electron density in the ISM. Pulsar J1903+0327 is an ideal probe of scattering because it has the highest dispersion measure (DM) of all NANOGrav pulsars. New methods of scattering correction are required to achieve the gravitational wave sensitivity desired.



Methods

Observed pulse profiles, U(t), are the result of convolution of the pulse shape intrinsic to the pulsar, I(t), and the interstellar **pulse broadening function** (PBF),

$$\mathrm{U(t) = I(t) * PBF(t,\tau)},$$

where τ is the scattering time. The PBF is determined by the spectrum of electron density variations with spectral index β and turbulence inner scale ∝ ζ. τ is a function of frequency, ν, of the form,

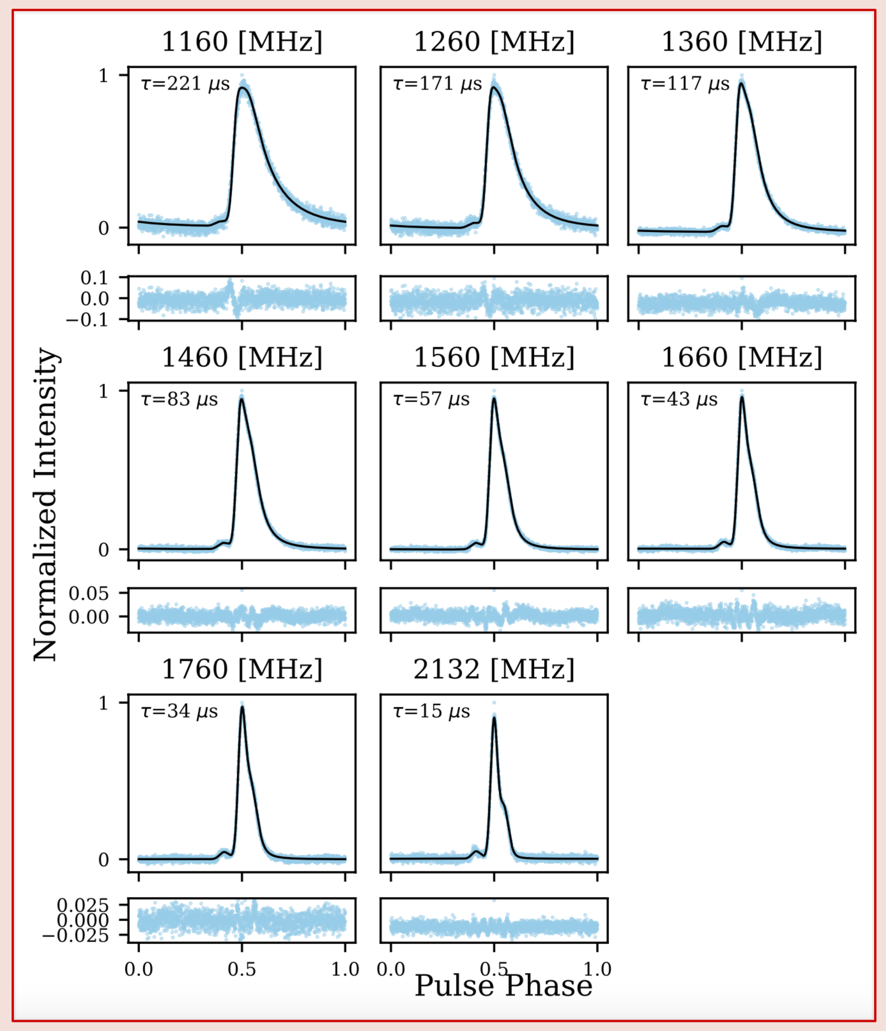
$$\tau(\nu) = \tau_0\,(\nu/\nu_0)^{-X_\tau}\,,$$

where $X_\tau = 2\beta/(\beta-2)$ for $2 < \beta < 4$. It is a challenge to reconcile the intrinsic and PBF shapes.

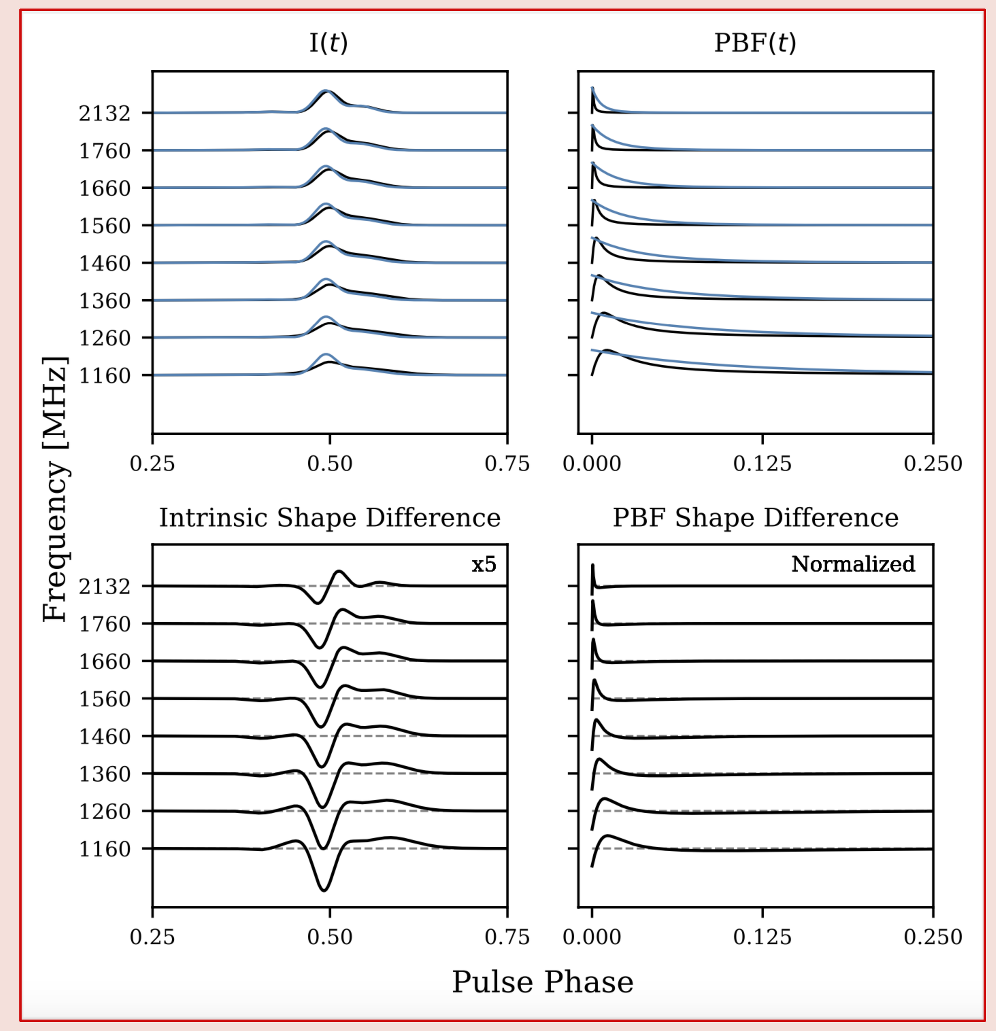
- We consider 19 PBFs, including both thin screen and extended ISM approximations, as well as the simple decaying exponential model often assumed in the literature.
- For each PBF, we fit for the J1903+0327 characteristic 3-component intrinsic shape and its evolution over frequency.

Once the intrinsic and pulse broadening functions are set, we fit for τ at each frequency and epoch of observation using least-squares model fitting. We similarly fit for X_τ with linear least-squares fitting.

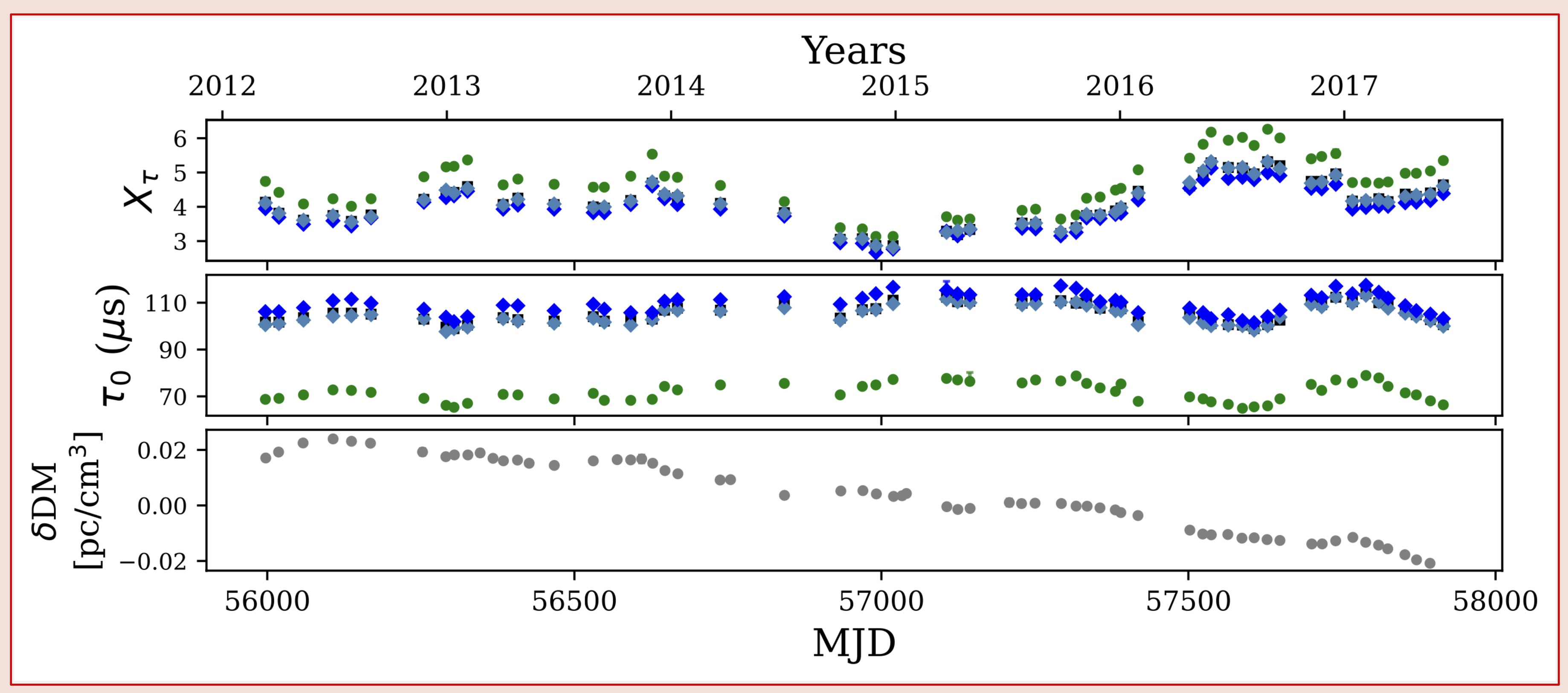
Results



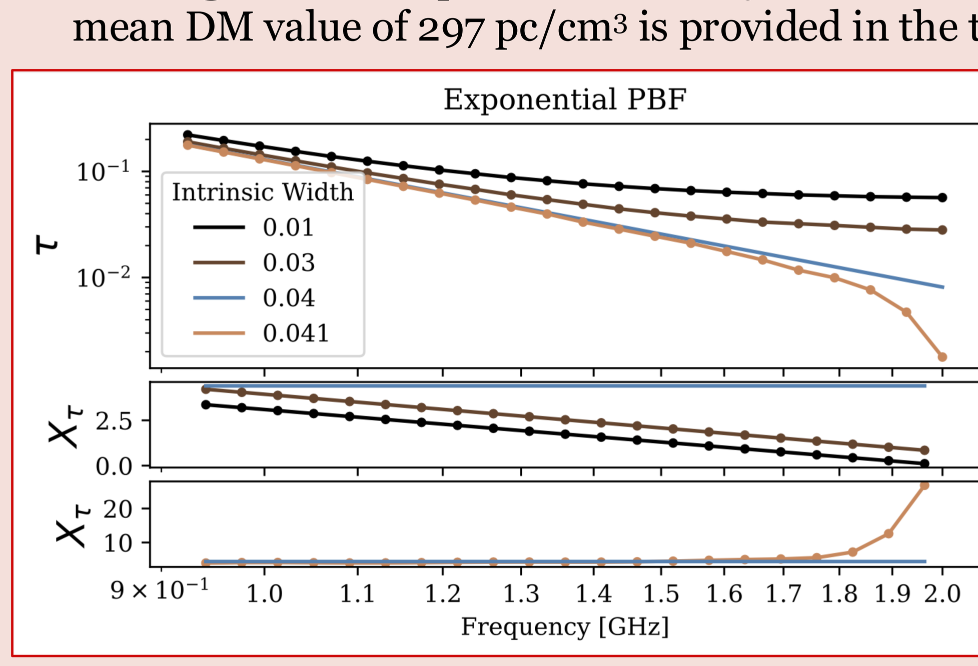
A fit (**black**) to the J1903+0327 frequency subaverages (**blue**) assuming a thin screen PBF with β = 11/3 and ζ = 1.0. This PBF resulted in the best fit to these profiles, with a χ2 of 1.183.



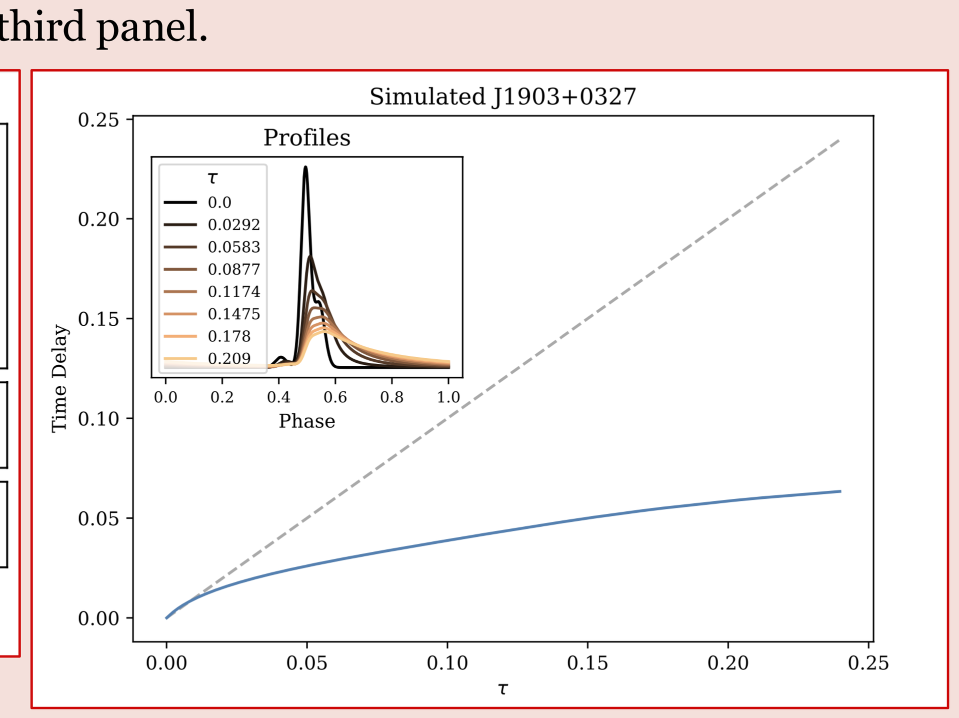
A comparison of the fitted intrinsic shapes and the corresponding fitted PBFs for the thin screen PBF with β = 11/3 and ζ = 1.0 (**blue**) and the extended medium PBF with β = 3.1 and ζ ≈ 0 (**gray**).



Time series results for select PBFs. For the upper two panels, **black**: thin screen, β = 11/3, ζ ≈ 0 PBF, **green**: thin screen, β = 11/3, ζ = 1.0 PBF, **dark blue**: extended medium, β = 11/3, ζ = 0.5 PBF, **light blue**: exponential PBF. τ_0 is calculated at 1.5 GHz. Variation from the J1903+0327 mean DM value of 297 pc/cm³ is provided in the third panel.



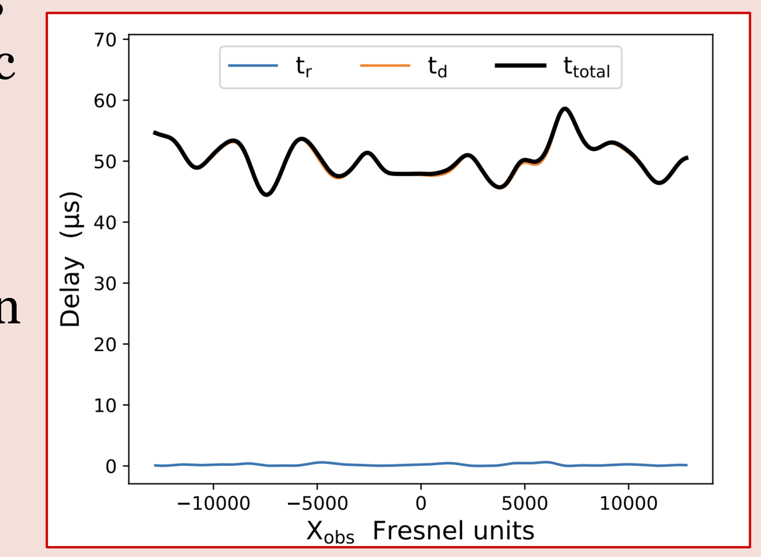
Simulation: Incorrect assumption of the intrinsic pulse shape width results in biased X_τ measurement. Similarly, when fitting an exponential PBF to a simulated Kolmogorov extended medium PBF, X_τ is underestimated.

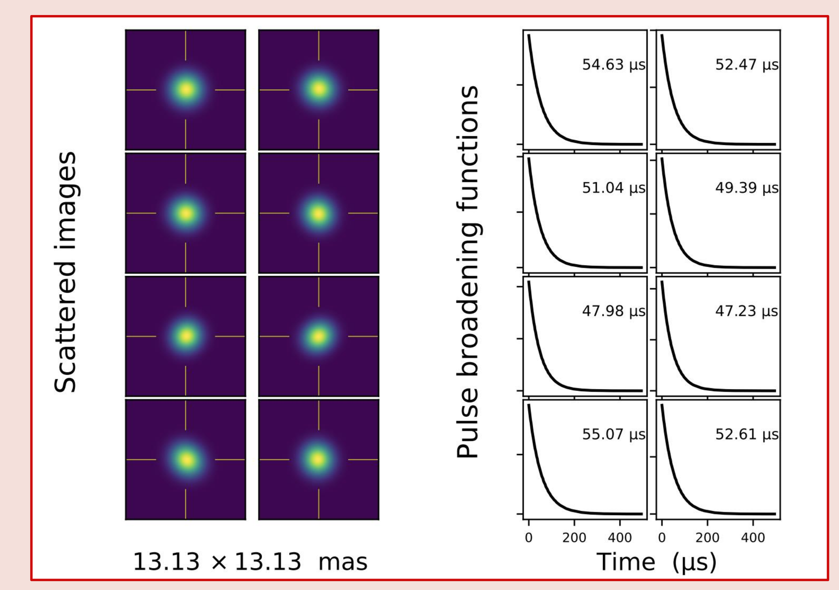


The true time delay resulting from scattering is a function of τ. This delay is the maximum of the cross correlation of the scattered pulse with the intrinsic pulse.

Discussion & Conclusions

- Thin screen PBFs perform better than extended medium PBFs for this dataset.
- Non-negligible ζ and approximately Kolmogorov β = 11/3 are generally favored.
- X_τ and τ_0 have correlated variations over time, independent of the assumed PBF.
- τ_0 and X_τ variations have a characteristic timescale of about 100 and 250 days, respectively.
- Refraction occurs on a similar timescale, so we expect this to be the cause of variation in τ_0.





These plots demonstrate simulated refraction and the resulting effects on τ and PBF shape for ν = 2.1 GHz and DM = 300 pc/cm³.

- Despite significant variation over time, $\overline{X_\tau}$ is consistent with Kolmogorov 4.4.
- We have quantified the dramatic, negative effects of assuming the incorrect intrinsic or PBF shape. This could explain claims of very shallow, non-Kolmogorov X_τ in the literature obtained using exponential PBFs and/or poor intrinsic modeling.
- DM is often misestimated due to poor correction of scattering effects since delays due to both dispersion and scattering increase in magnitude at lower ν.

The complexities of scattering revealed by this heavily scattered pulsar occur for all pulsars at varying degrees. **To precisely time pulsars, scattering delays must be more precisely modeled, accounted for, and reconciled from dispersion.**

References & Acknowledgements

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