Scintillating Pulsars

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Why Observe Pulsars with VLBI?

- Astrometry
- Scattering
  - Scattering disks
    - Dist of scattering material
      - Nearby pulsars for radioastron!
    - Shape of Scattering Disk
      - Cusps or Parabolic Arcs?
  - Structure of pulsar emission regions
- Technical Notes on Pulsar VLBI
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Introduction
Interferometer sees amplitude changes with time and frequency, and phase changes if the antennas are far apart relative to the speckle size.
Closer pulsars tend to be less heavily scattered, with smaller scattering disk angle $\theta$, larger bandwidth $\Delta\nu$, and shorter temporal broadening $\tau$. Nearby pulsars are usually seen in the speckle limit.
Distribution of Scattering Material
$\tau$-DM Scaling differs for Nearby and Distant ISM

Break in power-law suggests:
- nearby scattering is uniform,
- distant scattering is clumpy.
\( \tau \)-DM Scaling differs for Nearby and Distant ISM

Break in power-law suggests:
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For nearby pulsars, \( \tau \) must be estimated from \( \Delta \nu \) in the speckle limit:
\[
\Delta \nu \approx \frac{1}{2\pi} \tau.
\]
Angular broadening $\theta$ is *larger* (relative to temporal broadening $c\tau$) when scattering material is *closer* to the observer.

In principle, comparison of $\theta$ and $c\tau$ yields the distance to scattering screen.
Pulse Broadening $\tau$ (mas) (expressed as angular broadening for a uniform medium)
Pulse Broadening $\tau$ (mas)

Observed Angular Broadening $\theta$ (mas)

From: Britton 1998

Scatters closer to Earth
Scatters closer to Pulsar

Scaling for uniform distribution

(expressed as angular broadening for a uniform medium)
Paradox: The measured $\tau-\theta$ relation suggests:
- SNR scatter pulsars inside;
- distant scattering is uniform;
- nearby scattering is clumped.

This is opposite the usual picture.

(Expressed as angular broadening for a uniform medium)
Radioastron
Can measure θ’s reliably for many nearby pulsars--
and so improve understanding of the distribution of nearby scattering material.

Radioastron-Earth
(λ=92 cm, apogee)

(expressed as angular broadening for a uniform medium)
Shapes of Scattering Disks
**Simple theory says: Scattering smooths images**

- Deflections resemble a random walk
- Theory predicts nearly* Gaussian distribution of intensity
  *Important correction from V. Kolmgorov

**Some observations say: not completely**

- Elevated visibility at long baseline

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**High Visibility on Long Baseline: Cusp? Substructure?**
Theoretical Pictures May Explain Non-Gaussian Structure

• Cusps from non-Gaussian statistics?
  • Levy flights? (Boldyrev & Gwinn 2003,…)

• Subimaging from small-scale structure in the ISM?
  • Parabolic scintillation arcs? (Stinebring 2001,…)
    – (See V. Shishov talk)

Suggested Observational Test:
Resolve pulsar scattering disks using Radioastron.
  – Pulsars: intrinsically very small
  – Radioastron: Baselines are long enough to explore small-scale structure
Structures of Pulsar Emission Regions
Structure of Pulsar Emission Regions

• Scattering acts as a lens to form a corrupt image of the source in the observer plane: the speckle pattern

• Finite source size affects the distribution of observed scintillations: we can measure source size and shape!

• Accurate understanding of noise is critical to setting limits on, or measuring, size (and shape?) of the source
For 0 baseline, the distribution of visibility is exponential along $\text{Re}[V]$ (=distribution of intensity for a single dish).
As the baseline lengthens, the distribution broadens in $\text{Im}[V]$.

$$P(V) = \frac{1}{\pi(1-\rho^2)} K_0 \left( \frac{1}{(1-\rho^2)} |V| \right) \exp \left( \frac{1}{(1-\rho^2)} \rho \text{Re}[V] \right)$$

For long baselines, the distribution is circular (phase is random).

Stars Twinkle, Planets Don’t

Extended source narrows the distribution of visibility and softens its sharp peak.

For a small, elliptical-Gaussian source: distribution of visibility is the convolution of 3 $K_0 \cdot \exp$ distributions.
Noise Affects the Observed Distribution

Noise includes source noise (self-noise), which changes with intensity and visibility; And sky, instrumental, and other noise, which don’t.

We assess all of the noise by comparing samples within one element of the scintillation pattern.
If the source is resolved, the peak is “softer”, narrower, and shifted toward +Re[V]; the distribution is wider in Im[V].

Added instrumental and source noise soften the peak and widen the distribution, but do not shift it.
Fit a Model to the Data:
We fit simultaneously to the distribution projected onto bins along the real axis and to the mean square imaginary part in each bin.
Sizes of Several Pulsars Are Accessible to Radioastron

Size measurement requires:
• High angular resolution by scattering disk
• Good SNR in one scintillation time and bandwidth
• Sufficient samples of scintillation in one observing session

\( \lambda = 92 \text{ cm} \)
Technical Factors

• Interference
• Recording & Correlation
  – Lag statistics
Interference

Are $\lambda=92$-cm observations feasible from interference standpoint?

At $\lambda=18$-cm, interference environment is better, and similar science is accessible to Radioastron baselines.
For Useful Observations of Speckles Recorders and Correlator Must Possess:

• High spectral resolution
• Rapid writeout of spectra (lots of data!)
• Stable and well-documented statistics and noise

Challenges:
• Tsys varies over each pulsar pulse and with scintillation
  - effective quantizer levels vary
• Fractional bit-shift correction
  - rate may alias with pulsar period (!!)
  - (Integration time) = (N pulsar periods) -- can help
• “Wrap” assumption
  - noise may vary with lag

Prescription: Software correlator
Wrap Problem

Large Correlator Lags May Approach Width of Narrow Pulsar Gates
Larger Lags are Sampled Less than Smaller Lags

So: Higher Noise in Large Lags
So: Noise is correlated across spectrum
Wrap Problem
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So: Higher Noise in Large Lags
So: Noise is correlated across spectrum

Solution: “Wrap” the lags.
Recall: Fourier transform is circular!
Summary

Pulsar VLBI is tricky, but can be rewarding!

Radioastron can provide unique observations of pulsars to help understand:

- distribution of scattering material
- cusps or substructure in scattering disks
- spatial structure of pulsar emission regions