Low Frequency VLBI as a Probe of Interstellar Scintillation

VLBA Astrometry Workshop

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Abstract

Application of the 2-D Fourier transform to single-dish dynamic spectrum of certain pulsars results in a vivid parabolic arc image. A novel technique involving Very Long Baseline Interferometry extracts spatial information of the scattering process and provides new insight into the scattering phenominon. 100 microarcsecond resolution images of the scattering screen are produced via astrometric techniques at 327 MHz where the effects of scattering are very strong.

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submitted to ApJ. on July 17

Discovery of Scintillation Arcs

Dynamic Spectrum

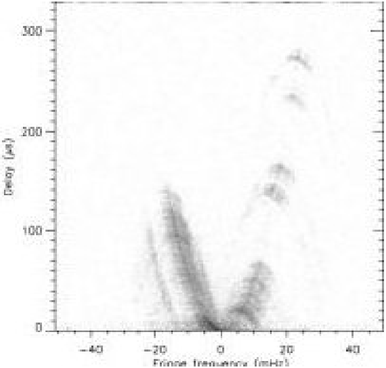
$I(\nu, t)$

Discovery of Scintillation Arcs

Dynamic Spectrum

$I(\nu, t)$

Secondary Spectrum

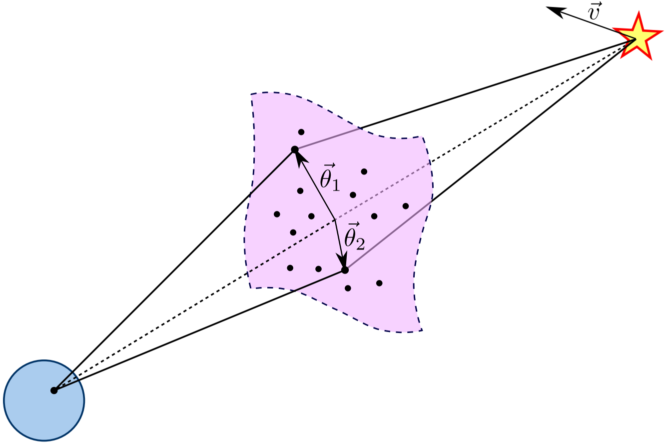


∗ Take 2-D Fourier transform:

$$S(T, R) \equiv \mathcal{F}\left[I(\nu, t)\right]$$

Stinebring et al., 2001 and Walker et al., 2005

Diffractive Scintillation Thin Screen Geometry



- Distance to pulsar $\equiv D_{\rm psr}$
- Distance to screen $\equiv D_{\rm scr} = (1-s)D_{\rm psr}$
- Effective distance $\equiv D_{\rm eff} = \frac{1-s}{s}D_{\rm psr}$
- Effective velocity $\equiv \vec{V}_{\rm eff} = \frac{1-s}{s}\vec{v}$

Stationary Phase Points I

Delay model

Akin to VLBI model: $\tau(\vec{\theta}) = \frac{D_{\rm eff}}{2c}\theta^2$ with *direct path*: $\tau(\vec{\theta} = 0) \equiv 0$

Propagation via Fresnel-Kirchhoff integral

$$\vec{E}(\nu) \propto \nu \int e^{-2\pi i \nu \tau(\vec{\theta})} d\vec{\theta}\, \vec{E}_{\rm psr}(\nu)$$

In diffractive scintillation, this integral is dominated by a few points where constructive interference gives rise to high magnification,

$$\vec{\nabla}\tau(\vec{\theta}) = 0,$$

which are called *stationary phase points*. Their brightness contribution is related to their magnification

$$\mu = \left[\nu \nabla^2 \tau(\vec{\theta})\right]^{-1}$$

Stationary Phase Points II

Propagation (cont.)

The Fresnel-Kirchhoff integral

$$\vec{E}(\nu) \propto \nu \int e^{-2\pi i\nu\tau(\vec{\theta})} d\vec{\theta}\ \vec{E}_{\rm psr}(\nu)$$

can then be turned into a sum over stationary phase points, $\vec{\theta}_j$:

$$\vec{E}(\nu) \propto \nu \sum_j \mu_j e^{-2\pi i\nu\tau(\vec{\theta}_j)}\ \vec{E}_{\rm psr}(\nu)$$

Simplifying assumption

Geometry of screen remains fixed

$$\frac{d\vec{\theta}_j}{dt} = 0$$

Example of Stationary Phase Points

Image from http://www.free-slideshow.com

Model of Parabolic Arcs (Walker et al., 2005)

Delay coordinate

* From geometry

$$T \equiv \tau_1 - \tau_2 = \frac{D_{\text{eff}}}{2c}(\theta_1^2 - \theta_2^2)$$

Doppler rate coordinate

* From time derivative of τ:

$$R = \vec{V}_{\text{eff}} \cdot (\vec{\theta_1} - \vec{\theta_2})$$

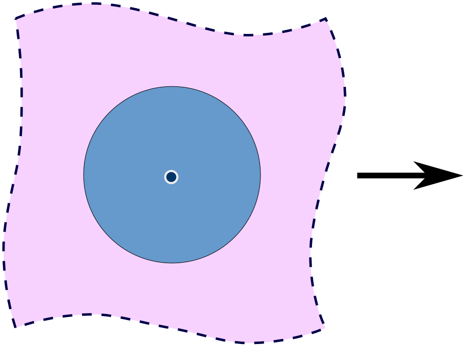
The parabola

* Assume dominating central concentration near $\vec{\theta_2} = 0$
* Then:

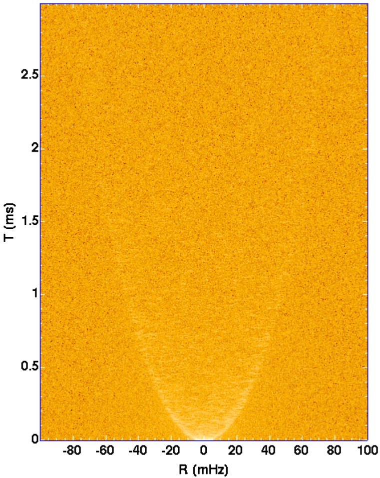
$$T \geq \frac{\lambda^2 D_{\text{eff}}}{2cV_{\text{eff}}^2} R^2$$

* Equality occurs for $\vec{\theta_1} \parallel \vec{V}_{\text{eff}}$

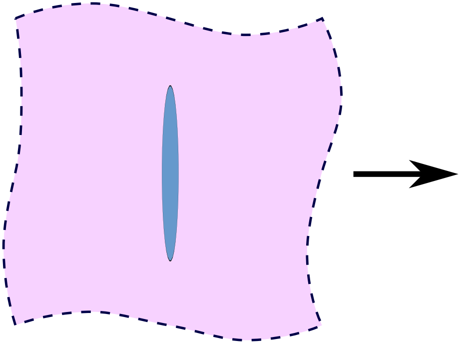
Simulation Example 1

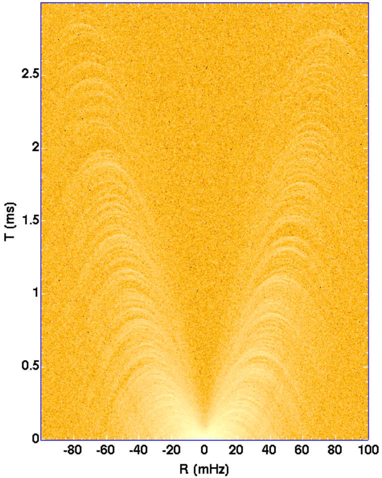


Core Disk Distribution



Simulation Example 2





$10{:}1$ Axial ratio $\parallel$ to velocity

VLBI Study of Scattering Screen

Goal 1

* Validate model
* Make model-independent image of scattering screen

Goal 2

* Break degeneracies
  - Measure anisotropy of scattering
  - Determine model parameters for improved interpretation of single-dish data

Experimental Setup

The observation

* Target: pulsar B0834+06
* 2 hours on source
* Frequency: 310 to 342 MHz with dual circular polarization
* Four large antennas (see next slide)

Correlation

* Used Adam Deller's DiFX software correlator at Swinburne Univ.
* 131072 spectral channels (244 Hz resolution)
* 1.25 second integrations
* Pulsar gate used to boost signal-to-noise ratio

The Ad-hoc VLBI Array

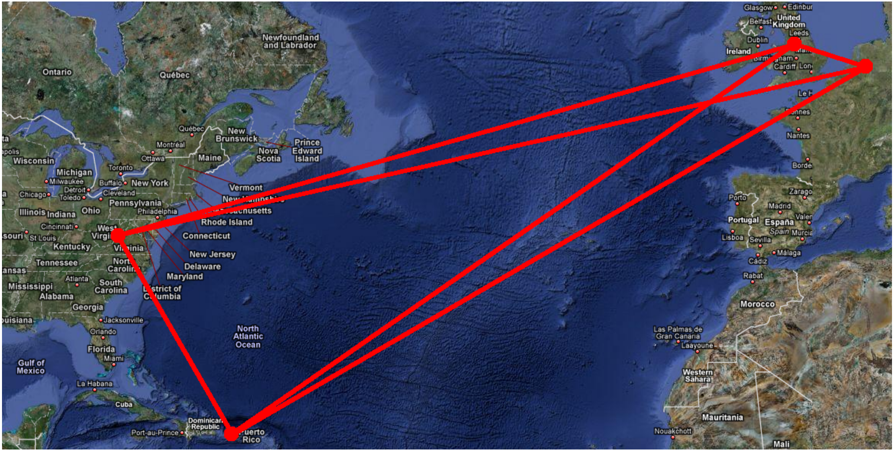
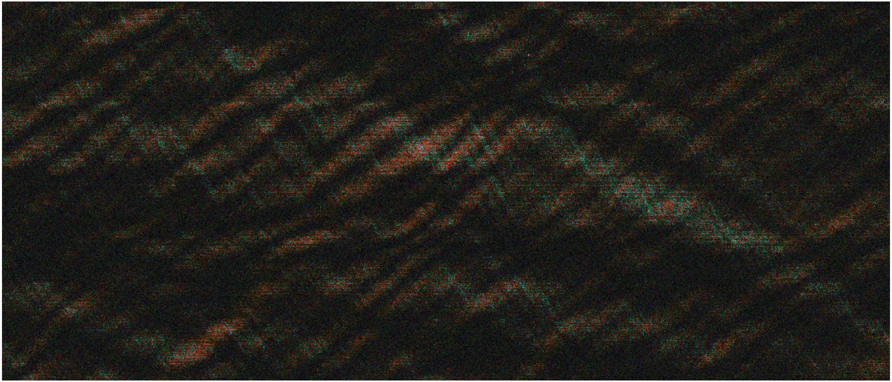


Image courtesy of Google

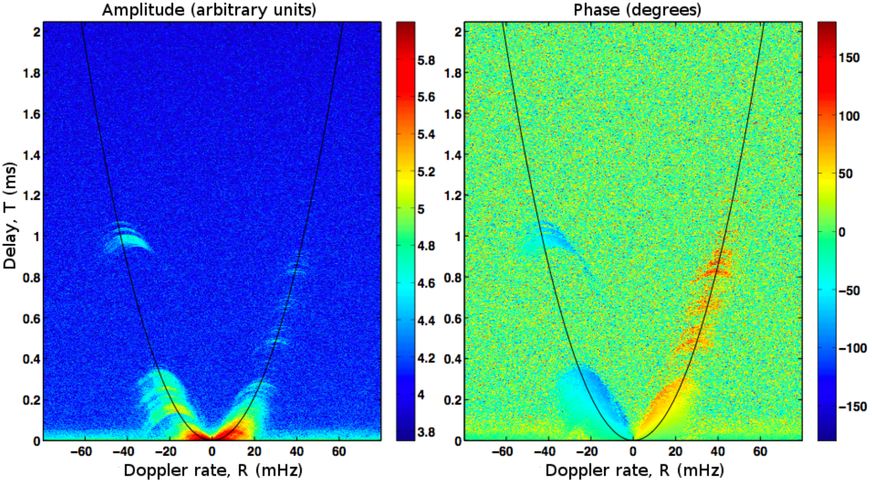
* Need: Low freq, long baselines, high sensitivity & mutual visibility
* Array: GB (100 m), AO (305 m), JB (76 m) and WB (93 m equiv.)

Visibility Dynamic Spectrum (AR-GB)



- $\sim$ 600 seconds $\uparrow$ of data over $\sim$ 200 kHz $\rightarrow$
- Amplitude mapped to intensity
- Phase mapped to color (red to blue)
- Note, only 0.5% of the dynamic spectrum is shown

Visibility Secondary Spectrum (AR-GB)



Imaging a Spatially Coherent Object

Such objects are rare, mostly unnatural

* Radar reflections e.g., from asteroids & spacecraft
* Scattering of a point object by thin screen ISM
* Solar flares?

The van Cittert-Zernike theorem does not apply

* Visibility $\neq \mathcal{F}$[image]
* Standard synthesis imaging will fail
* Must exploit properties of the electric field specific to the application

Exploiting the Secondary Spectra

Secondary spectrum phase

* The phase is related to the *vector sum* of the locations of two stationary phase points:

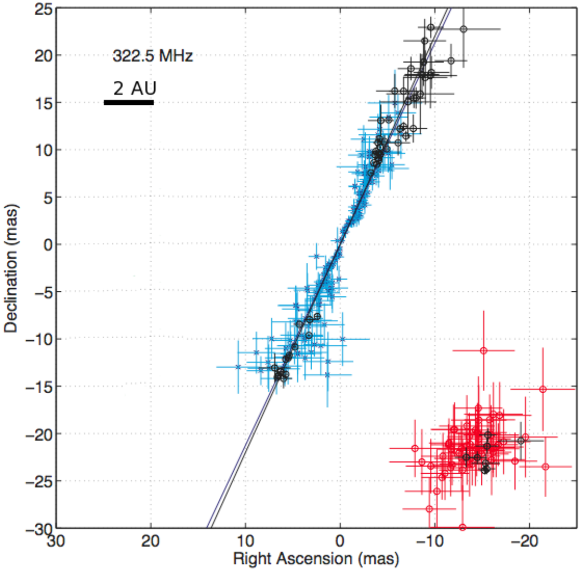
$$\phi_{\rm ss} = \frac{2\pi}{\lambda}\vec{B}\cdot(\vec{\theta_1}+\vec{\theta_2})$$

* Don't forget that multiple $(\vec{\theta_1}, \vec{\theta_2})$ pairs can map to the same SS point...

Dissecting the electric field

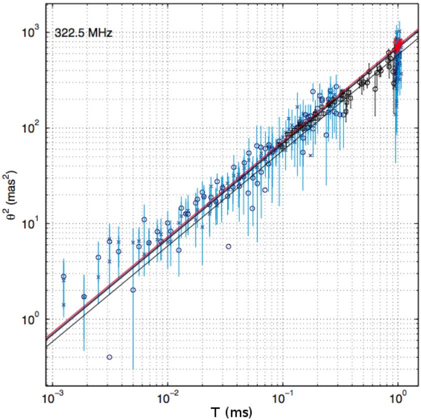
* Fourier transform on visdynamic spectra on each baseline
* Choose points from *arclet* apexes where $\vec{\theta_1} = 0$
* Perform phase-referenced astrometry separately for each such point

Astrometrically Recovered Image

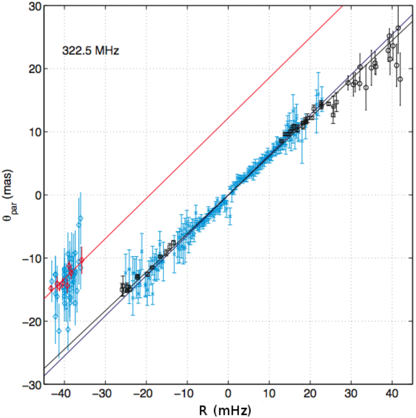


Physical Parameter Estimation

Distance fit

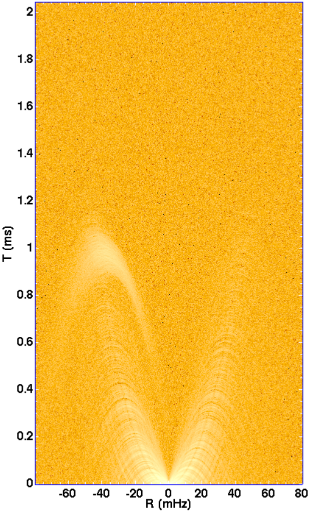


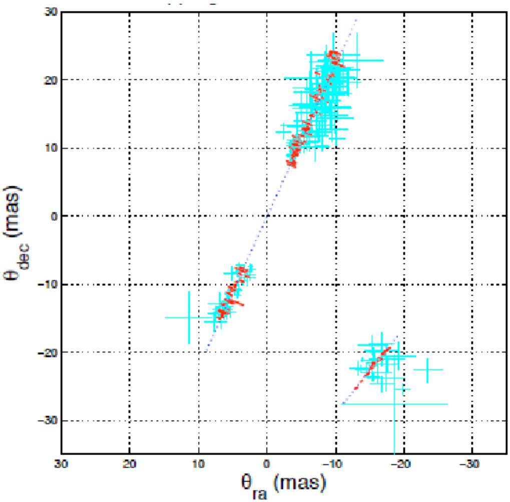
Velocity fit



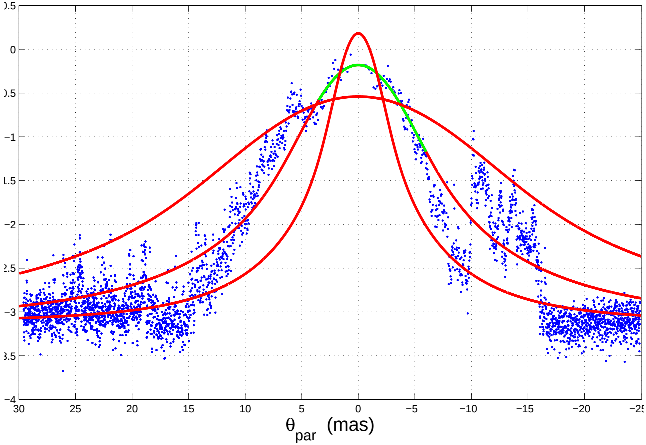
- $D_{\rm eff} = 1171 \pm 10$ pc $\rightarrow D_{\rm scr} = 415 \pm 5$ pc
- $V_{\rm eff,||} = 305 \pm 3$ km s^{-1}
- $V_{\rm eff,\perp} = -150 \pm 5$ km s^{-1}

Model Recovered Image





Brightness Distribution



* Central disc (green) fit well by Kolmogorov turbulence
  ◦ Electric field coherence scale $\sim 10^4$ km
* Significant deviations seen as well

Pulsar Emission Properties

* Fringes on $B = 10$ AU baseline restrict emission diameter

$$d_{\rm emission} < \frac{\lambda}{B}(D_{\rm psr} - D_{\rm scr}) \sim 4000 \text{ km}$$

* Pulsar size scales
  - $d_{\rm psr} \sim 20$ km; too small to be relevant
  - $d_{\rm light\,cyl.} \sim 120000$ km; 30 times larger
* Brightness temperature $T_{\rm B} > 10^{19}$ K

Conclusions

* B0834+06 exhibits extreme scintillation with features delayed more than 1 ms with impact on pulsar timing
* Peculiar properties of thin screen scintillation allow super-resolution imaging with 0.1 to 20 AU physical scale
* The ISM probed by this experiment indicates extreme anisotropy, providing new clues about its turbulent properties
* The ISM in turn can be used as an interferometer to directly probe the size of the pulsar emitting region