Measuring Interstellar Scintillation with LOFAR

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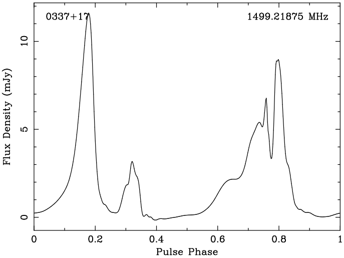
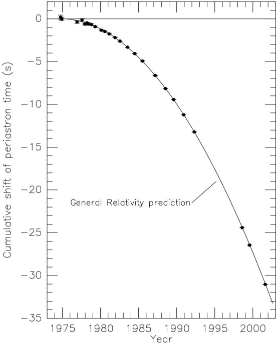
Millisecond pulsars can be very stable clocks



Pulse profile for PSR J0337+17

- Millisecond pulsars are old, rapidly spinning pulsars with a weak magnetic field
  - Very high moment of inertia
  - Very few sources of torque
- Pulse arrival times can be measured very precisely
  - Average 1–60 minutes of pulses
  - Cross-correlate with standard template
  - Scatter from 1 μs down to 50 ns

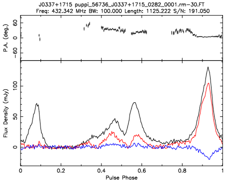
Precision timing of pulsars yields interesting science



Cumulative shift in periastron time in PSR 1913+16; figure from J. Weisberg via www.cv.nrao.edu

- Gravitational-wave losses from Hulse-Taylor system
- First exoplanets detected (Wolszcan et al.)
- $2.2M_\odot$ pulsar detected (Antoniadis et al.)
- Millisecond pulsar in stellar triple (Ransom et al.)
- Gravitational-wave search with pulsar timing array

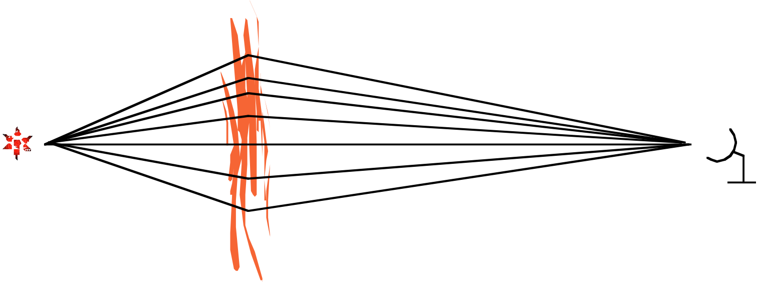
Sub-microsecond timing requires accounting for subtle effects



430-MHz profile of PSR J0337+17; the red line indicates the amplitude of linear polarization while the top panel shows its orientation.

- Polarization miscalibration can distort profiles
- Profiles evolve with frequency
- Subtle geometric effects, for example orbital annual parallax
- Interstellar medium effects
    - Dispersion measure variations
    - Scattering variations

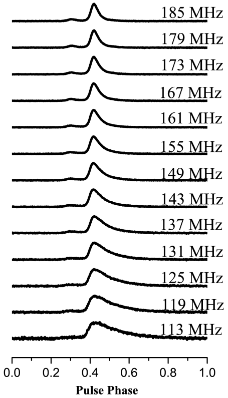
The ISM scatters pulsar signals



Scattering by a thin screen in the interstellar medium.

- The ISM is a turbulent plasma with a frequency-dependent refractive index
- Signal consists of a sum of images from “speckles”
- Multipath propagation introduces “scattering tail” with exponential profile

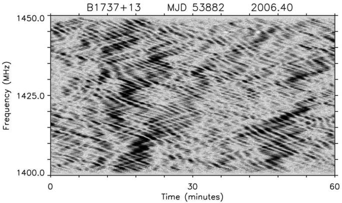
Measuring scattering in the time domain is hard



Evolution of an observed profile across the LOFAR band. From Zagkouris et al. 2014, in prep.

- Observed signal is a convolution of the tail with the pulsar intrinsic emission
- The scattering timescale is expected to evolve roughly as f^{-4}
- Pulsar intrinsic profiles also evolve with frequency

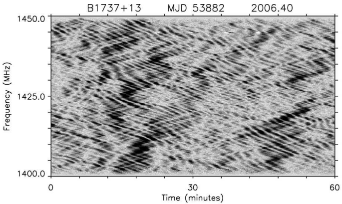
Scintillation is the frequency-domain analogue of scattering



Dynamic spectrum of PSR B1737+13.

- The scattering tail at any moment is expected to look like noise with an exponential profile of length τ
  - The Fourier transform of such a tail is noise with frequency structure on a scale of $\Delta f_{\text{scint}} =\sim 1/\tau$
- As speckles move across the scattering disc, scintles appear and disappear on a timescale Δt_{scint}
  - This is itself a change in the scattering tail without changes in τ
  - Refraction causes changes in the scattering disk, changing τ on longer time scales

Scintillation can be directly measured



Dynamic spectrum of PSR B1737+13.

- Normal pulsar observing measures power as a function of pulse phase, time, and frequency
- A "dynamic spectrum" shows pulse intensity as a function of time and frequency
    - Scintles appear as blobs with a characteristic time and frequency scale
    - A two-dimensional autocorrelation can measure the characteristic size and shape of these blobs

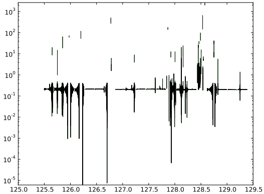
LOFAR is an excellent tool for measuring scintillation

- The signal-to-noise in the autocorrelation is:

$$R_\rho = \left(R^2_{p,N_b} \frac{N_b}{BT} \right) \Delta t \Delta f \sqrt{N_s}$$

  where N_s is the number of scintles in the dynamic spectrum.
- Δf decreases like f^4, roughly
- Δt decreases with f also
- But:
  - Scintles are random objects: fractional error of $1/\sqrt{N_s}$
  - Scintles are sparse: $N_s < (B/\Delta f)(T/\Delta t)$
  - In the LOFAR band we have lots of scintles!

We are measuring scintillation with LOFAR



4 MHz, 5 min of LOFAR data with automatic zapping only

- Complex-voltage beamformed data
- Use CEP1 to produce pulsar data cubes with high spectral resolution
- Excise RFI
- Compute on- minus off-pulse spectrum
- Compute ACF and fit Lorentzian
- Obtain scattering time as a function of frequency

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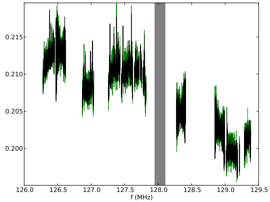

4 MHz, 5 min of LOFAR data with manual zapping

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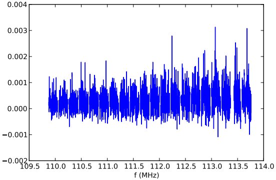

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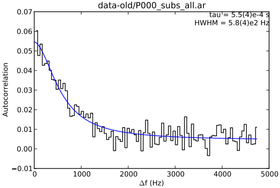

Lorentzian fit to the ACF peak

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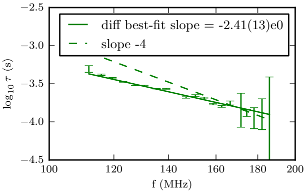

Preliminary plot showing τ as a function of frequency

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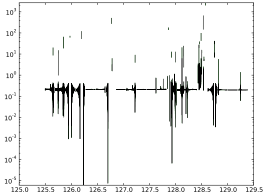
Challenges remain when trying to measure scintillation



4 MHz, 5 min of LOFAR data with automatic zapping only

- High spectral resolution requires cyclic spectroscopy
- RFI excision is difficult
- Scintles generally detectable only through autocorrelation
- Off-pulse region needed for bandpass correction and removal of residual RFI

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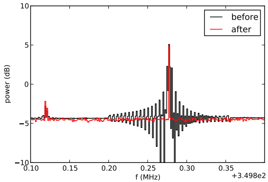

Leakage of narrowband RFI into nearby channels before and after our improvements.

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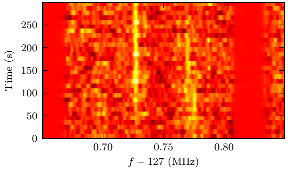

Small part of the dynamic spectrum

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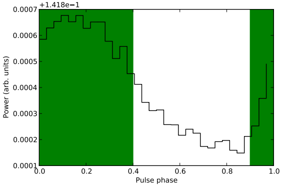

Pulse profile of J1810 at the bottom of the band. Note the absence of a usable off-pulse region.

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