Imaging pulsar echoes at low frequencies

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Imaging pulsar echoes at low frequencies

- LOFAR
- The ghost in B1508+55
- Offline VLBI with LOFAR
- First attempt 2016
- Relative motion 2016–2018
- New deconvolution method
LOFAR station (Tautenburg)
Low-band antennas (10-80 MHz, Ireland)
High-band antennas (110-250 MHz)
• ‘ghost’ component found by Stefan Osłowski with LOFAR
• moving relative to main component
• interpretation: scattering ‘echo’ [Osłowski & Macquart in prep.]
Interstellar scattering: geometric delay

Does the echo have a positional offset?

\[ c\tau = \frac{1}{2} \theta^2 D \]

\[ D = \frac{D_s D_d}{D_{ds}} \]
Can we localise the echo of B1508+55?

- $\tau \approx 50$ msec (period $\approx 0.74$ sec)

- $D_s = 2.13$ kpc $= 2.19 \cdot 10^{11}$ sec $\cdot c$

- assumption: $D_d \approx D_{ds} \Rightarrow D = D_s$

- $\theta = \sqrt{\frac{2c\tau}{D}} = 0.14''$ (more if closer to us)

- at high SNR this can be measured with LOFAR-VLBI!

- can test echo hypothesis and maybe determine $D$

- later: use two paths as interstellar interferometer
## VLBI: German LOFAR (GLOW) baselines

Length, fringe-spacing at 150 MHz

| Baseline         | [km] | [arcsec] |
|------------------|------|----------|
| DE601–DE602      | 390  | 1.06     |
| DE601–DE603      | 344  | 1.20     |
| DE601–DE604      | 476  | 0.87     |
| DE601–DE605      | 53   | 7.80     |
| DE601–DE609      | 412  | 1.00     |
| DE602–DE603      | 277  | 1.49     |
| DE602–DE604      | 455  | 0.91     |
| DE602–DE605      | 440  | 0.94     |
| DE602–DE609      | 585  | 0.70     |
| DE603–DE604      | 186  | 2.22     |
| DE603–DE605      | 372  | 1.11     |
| DE603–DE609      | 325  | 1.27     |
| DE604–DE605      | 487  | 0.85     |
| DE604–DE609      | 248  | 1.66     |
| DE605–DE609      | 394  | 1.05     |
Offline VLBI with LOFAR

- LOFAR correlator limited (e.g. time resolution)
- need more flexibility
  - arbitrary resolution
  - pulsar gating
  - re-correlations

→ record locally, correlate centrally! (non-e VLBI)
  - GLOW recording in Bonn, Jülich
  - other stations recording locally (3 Gbps / station)
  - core centrally in Groningen
  - demanding logistics, huge effort
Correlation and calibration

- own software correlator
  - standard FX architecture
  - flexibility, not efficiency!

- calibration (own software)
  - pulsar gating, main pulse as reference
  - full station-based fringe-fitting for phases with dispersive/non-dispersive delays, rates, DFR
  - bandpass calibration

- imaging and non-imaging analysis
Folded amplitudes and phases (DE603–DE605)
Echo position(s)

preliminary distance: 124 pc, very close to us!
The full array: LOFAR + KAIRA
Main pulse and echoes (dirty maps)

October 2016

Feb 2018

GLOW
Delayed-profile-aware CLEAN

- gating mixes intrinsic tail and echo
- deconvolve dirty beam and intrinsic profile
- standard CLEAN components
  - explicit: position
  - implicit: flux
- generalised CLEAN components
  - explicit: position (offset), delay
  - implicit: flux, spectrum
Delayed-profile-aware CLEAN (1 iteration)
Delayed-profile-aware CLEAN (10 iterations)
Delayed-profile-aware CLEAN (20 iterations)

![Graphs and images](image-url)
Delayed-profile-aware CLEAN (30 iterations)
Title: Delayed-profile-aware CLEAN (40 iterations)

- **40 its** - signif. for best time per pix
- **best time per pix**
- **significance and time**

Graphs showing:
- **ΔRA [arcsec]**
- **ΔDEC [arcsec]**
- **delay [sec]**
- **flux**
- **flux conv**
- **time [sec]**

Legend:
- red - all
- green - centre
- blue - rest

Profiles and models compared.
**Delayed-profile-aware CLEAN (50 iterations)**

| \( \Delta RA \, [\text{arcsec}] \) | 50 its | signif. for best time per pix |
|-----------------------------------|--------|------------------------------|
| \( \Delta DEC \, [\text{arcsec}] \) | 1.0    | 0.5                          |
|                                   | 0.0    | 0.5                          |

Best time per pix:

| Flux conv | 0.00 | 0.02 | 0.04 | 0.06 | 0.08 |
|-----------|------|------|------|------|------|
|           | 0.00 | 0.02 | 0.04 | 0.06 | 0.08 |

Significance and time:

| Delay [sec] | 0.00 | 0.02 | 0.04 | 0.06 | 0.08 |
|-------------|------|------|------|------|------|
| Flux       | 0.00 | 0.02 | 0.04 | 0.06 | 0.08 |

| Time [sec] | 0.00 | 0.02 | 0.04 | 0.06 | 0.08 |
|------------|------|------|------|------|------|
| Flux conv  | 0.00 | 0.02 | 0.04 | 0.06 | 0.08 |

**Diagram:**
- **Top left:** Map of \( \Delta RA \) and \( \Delta DEC \) with significance for best time per pixel.
- **Top middle:** Heatmap of best time per pixel.
- **Top right:** Map of significance and time.
- **Bottom left:** Graph of delay vs. signed radius.
- **Bottom middle:** Graph of flux vs. delay.
- **Bottom right:** Graph of flux conv vs. time.
Delayed-profile-aware CLEAN (60 iterations)
Delayed-profile-aware CLEAN (70 iterations)
Delayed-profile-aware CLEAN (80 iterations)

80 its signif. for best time per pix

best time per pix

significance and time

all
centre
rest

profile
model
model centre
model rest

delay [sec]

flux

delay [sec]

flux conv

time [sec]

signed radius [arcsec]

delay [sec]

flux

time [sec]

signed radius [arcsec]
Delayed-profile-aware CLEAN (90 iterations)
Delayed-profile-aware CLEAN (100 iterations)
Delayed-profile-aware CLEAN (110 iterations)

110 its

signif. for best time per pix

best time per pix

significance and time

Δ DEC [arcsec]

ΔRA [arcsec]

ΔRA [arcsec]

ΔRA [arcsec]

ΔRA [arcsec]

delay [sec]

delay [sec]

delay [sec]

delay [sec]

signed radius [arcsec]

flux conv

flux

flux

all centre rest

center

model

model centre

model rest

profile

profile

profile

profile

all

center

model

model centre

model rest

profile

profile

profile

profile

all

center

model

model centre

model rest

profile

profile

profile
Delayed-profile-aware CLEAN (120 iterations)

120 its

signif. for best time per pix

best time per pix

significance and time

△ RA [arcsec]

△ DEC [arcsec]

0.00 0.01 0.02 0.03 0.04 0.05 0.06 0.07 0.08

delay [sec]

flux conv

profile

model

model centre

model rest

0.0 0.2 0.4 0.6 0.8 1.0

flux

delay [sec]

time [sec]
Delayed-profile-aware CLEAN (130 iterations)
Delayed-profile-aware CLEAN (140 iterations)
Delayed-profile-aware CLEAN (150 iterations)
Ionised matter around hot stars?

- *Walker et al. (2017): Extreme Radio-wave Scattering Associated with Hot Stars*

- IDV sources with (hot) stars near l.o.s.
  - J1819+3845 with Vega
  - PKS 1322–110 with Spica (8′5)
  - PKS 1257–326 with Alhakim

- ‘dense’ neutral matter around star, ionised by UV

- elongated ‘elephant’s trunks’ may cause transverse lensing

- distances and orientation fit
Stars around B1508+55?

- A0 star Hip 74377 at 2.73 pc from l.o.s.
  - distance from us ca. 260 pc

- A2 star Hip 74458 at 1.37 pc from l.o.s.
  - $\pi = (8.36 \pm 0.57)\text{ mas}$
  - distance $(120 \pm 8.2)\text{ pc}$

- compare with $D_d = 124\text{ pc}$

- thanks to Mark Walker and Artem Tuntsov
Elephant’s trunk lensing ?
Thanks to all people involved!

Mostly informal collaboration, great VLBI spirit!

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KAIRA: Derek McKay
Summary

- offline-VLBI with LOFAR works!
- data can be calibrated
- ghost of B1508+55 really is echo
- distance of screen determined
- alignment with proper motion
- ongoing monitoring (data approaching 300 TB)
- will include GMRT, maybe others

✉️ other objects and projects
Bonus: Relative alignment in nature
Bonus: Cloud: no alignment
Bonus: Filament: relative alignment