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)
B1508+55: a pulsar and its ghost?

- '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?

- $\tau \approx 50\,\text{msec}$ (period $\approx 0.74\,\text{sec}$)

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

- 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

<table>
<thead>
<tr>
<th>Baseline</th>
<th>Length [km]</th>
<th>Fringe-spacing [arcsec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>DE601–DE602</td>
<td>390</td>
<td>1.06</td>
</tr>
<tr>
<td>DE601–DE603</td>
<td>344</td>
<td>1.20</td>
</tr>
<tr>
<td>DE601–DE604</td>
<td>476</td>
<td>0.87</td>
</tr>
<tr>
<td><strong>DE601–DE605</strong></td>
<td><strong>53</strong></td>
<td><strong>7.80</strong></td>
</tr>
<tr>
<td>DE601–DE609</td>
<td>412</td>
<td>1.00</td>
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<tr>
<td>DE602–DE603</td>
<td>277</td>
<td>1.49</td>
</tr>
<tr>
<td>DE602–DE604</td>
<td>455</td>
<td>0.91</td>
</tr>
<tr>
<td>DE602–DE605</td>
<td>440</td>
<td>0.94</td>
</tr>
<tr>
<td><strong>DE602–DE609</strong></td>
<td><strong>585</strong></td>
<td><strong>0.70</strong></td>
</tr>
<tr>
<td>DE603–DE604</td>
<td>186</td>
<td>2.22</td>
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<tr>
<td>DE603–DE605</td>
<td>372</td>
<td>1.11</td>
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<tr>
<td>DE603–DE609</td>
<td>325</td>
<td>1.27</td>
</tr>
<tr>
<td>DE604–DE605</td>
<td>487</td>
<td>0.85</td>
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<tr>
<td>DE604–DE609</td>
<td>248</td>
<td>1.66</td>
</tr>
<tr>
<td>DE605–DE609</td>
<td>394</td>
<td>1.05</td>
</tr>
</tbody>
</table>
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 GLOW

Feb 2018 international
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)

1 its signif. for best time per pix

1e7

best time per pix

significance and time

delay [sec]

flux conv

profile

model

model centre

model rest

all

centre

rest

flux

delay [sec]

time [sec]
Delayed-profile-aware CLEAN (10 iterations)
Delayed-profile-aware CLEAN (20 iterations)
Delayed-profile-aware CLEAN (30 iterations)

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

**Images:**
- Left: 
  - Title: Delayed-profile-aware CLEAN (30 iterations)
  - Content: Graph showing delayed times.
- Middle: 
  - Title: best time per pix
  - Content: Heatmap indicating best times per pixel.
- Right: 
  - Title: significance and time
  - Content: Heatmap showing significance and time.

**Graphs:**
- Bottom left: 
  - Title: signed radius [arcsec]
  - Content: Line graph showing signed radius.
- Bottom middle: 
  - Title: delay [sec]
  - Content: Line graph showing delay.
- Bottom right: 
  - Title: flux conv
  - Content: Line graph showing flux convolution.

**Colors:**
- Red: all
- Green: centre
- Blue: rest

**Legend:**
- profile
- model
- model centre
- model rest
Delayed-profile-aware CLEAN (40 iterations)
Delayed-profile-aware CLEAN (50 iterations)

50 its signif. for best time per pix

best time per pix

significance and time

All plots show the results of applying the delayed-profile-aware CLEAN algorithm to an astronomical data set.

The left panel shows the signed radius in arcseconds as a function of delay in seconds. The middle panel shows the flux as a function of delay for different regions: all, centre, and rest. The right panel shows the flux convolved profile and model, with the model further divided into centre and rest components.
Delayed-profile-aware CLEAN (60 iterations)

Title page introduction summary bonus back forward

60 its

signif. for best time per pix

best time per pix

significance and time

∆RA [arcsec]

∆DEC [arcsec]

delay [sec]

flux

flux conv

profile

model

model centre

model rest

60 its

delay [sec]

signed radius [arcsec]

time [sec]
Delayed-profile-aware CLEAN (70 iterations)

70 its signif. for best time per pix

best time per pix

significance and time

delay [sec]

flux conv
profile
model
model centre
model rest

0.0
0.2
0.4
0.6
0.8
1.0

delay [sec]

flux

-0.04 -0.02 0.0 0.02 0.04 0.06 0.08

signed radius [arcsec]

-0.6 -0.4 -0.2 0.0 0.2 0.4 0.6

-1.0 -0.5 0.0 0.5 1.0

∆RA [arcsec]

-1.0 -0.5 0.0 0.5 1.0

∆DEC [arcsec]

-1.0 -0.5 0.0 0.5 1.0

∆RA [arcsec]

0.00 0.01 0.02 0.03 0.04 0.05 0.06 0.07 0.08

delay [sec]

-0.04 -0.02 0.0 0.02 0.04 0.06 0.08

time [sec]

0.0 0.2 0.4 0.6 0.8

flux conv
Delayed-profile-aware CLEAN (80 iterations)

80 its

signif. for best time per pix

best time per pix

significance and time

\[ \Delta RA \ [\text{arcsec}] \]

\[ \Delta DEC \ [\text{arcsec}] \]

\[ \text{time} \ [\text{sec}] \]

\[ \text{flux conv} \]

\[ \text{profile} \]

\[ \text{model} \]

\[ \text{model centre} \]

\[ \text{model rest} \]

\[ \text{flux} \]

\[ \text{delay} \ [\text{sec}] \]

\[ \text{signed radius} \ [\text{arcsec}] \]

\[ \text{delay} \ [\text{sec}] \]

\[ \text{time} \ [\text{sec}] \]
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

1.0
0.5
0.0
0.5
1.0
∆ RA [arcsec]

1.0
0.5
0.0
0.5
1.0
∆ DEC [arcsec]

0.00.010.020.030.040.050.060.07
0.0
0.2
0.4
0.6
0.8
1.0
delay [sec]

0.0
0.010.020.030.040.050.060.070.08
0.0
0.2
0.4
0.6
0.8
1.0
flux conv

0.0
0.010.020.030.040.050.060.070.08
0.0
0.2
0.4
0.6
0.8
1.0
profile

0.0
0.010.020.030.040.050.060.070.08
0.0
0.2
0.4
0.6
0.8
1.0
model

0.0
0.010.020.030.040.050.060.070.08
0.0
0.2
0.4
0.6
0.8
1.0
model centre

0.0
0.010.020.030.040.050.060.070.08
0.0
0.2
0.4
0.6
0.8
1.0
model rest

0.0
0.010.020.030.040.050.060.070.08
0.0
0.2
0.4
0.6
0.8
1.0
flux

0.0
0.010.020.030.040.050.060.070.08
0.0
0.2
0.4
0.6
0.8
1.0
time [sec]
Delayed-profile-aware CLEAN (120 iterations)

120 it's signif. for best time per pix

best time per pix

significance and time

delay [sec]

fluence conv

profile

model

model centre

model rest

flux

0.00 0.02 0.04 0.06 0.08

time [sec]

0.0 0.2 0.4 0.6 0.8 1.0

delay [sec]

fluence

0.00 0.02 0.04 0.06 0.08

0.0 0.2 0.4 0.6 0.8 1.0

signed radius [arcsec]

0.0 0.2 0.4 0.6

0.0 0.2 0.4 0.6 0.8 1.0

best time per pix
Delayed-profile-aware CLEAN (130 iterations)
140 its signif. for best time per pix
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.
  - $\pi = (8.36 \pm 0.57)$ mas
  - distance $(120 \pm 8.2)$ pc

- compare with $D_d = 124$ pc

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

Mostly informal collaboration, great VLBI spirit!

GLOW: Andreas Horneffer, Caterina Tiburzi, Jörn Künsemöller, Julian Donner, Natasha Porayko

FR606: Jean-Mathias Grießmeier

SE607: Tobia Carozzi

UK608: Aris Karastergiou

PL610: Mariusz Pozoga, Barbara Matyjaśiak, Hanna Rotkaehl

PL611: Marian Soida, Wojciech Lewandowski, Bartosz Smierciak

PL612: Tomasz Sidorowicz, Leszek Blaszkiewicz, Andrzej Krankowski

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