The LOFAR Transients Key Science Project: status and updates on image plane transients

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and the LOFAR Transients Key Science Project

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LOFAR is detecting image-plane transient and variable sources
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Outline

• Methods to detect image-plane transients and to calculate transient surface density

• Examples of detections of image-plane transient and variable sources
Transient Pipeline

- Provides lightcurves catalogue, list of transients and variable sources for radio image stack in near real-time.
- Images can be multiple overlapping pointing, different wavebands, different integration times, etc.
- Web-based analysis interface (banana).
- Paper published (Swinbank et al., 2015)
- Open-source! (available on github)
- Used by multiple radio facilities.
Transient Pipeline
Transient Pipeline
Variability parameters

Weighted $\chi^2$ of a fit to a constant flux:

$$\eta_\nu = \frac{N}{N - 1} \left( \frac{\omega I^2}{\frac{\omega I^2}{\omega}} \right)$$

Variability index:

$$V_\nu = \left( \frac{S}{\bar{I}} \right)$$

$S$ = Unbiased standard deviation
$I$ = Integrated flux
$N$ = Number of datapoints
$$\omega = \frac{1}{e^2} = \frac{1}{(\text{Flux error})^2}$$
Radio Sky Monitor sources - constant

- Radio Sky Monitor Sources
- Gaussian distributions

\[ V_v \]

Reduced weighted $\chi^2$

Dario Carbone, Assen – 02/06/2015
How do transients behave in this space?

- 440 transient and variable sources with different lightcurve shapes and fluxes
- 55 different combinations of max flux and quiescent flux for each type of transient source

Dario Carbone, Assen – 02/06/2015
How do transients behave in this space?

- 440 transient and variable sources with different lightcurve shapes and fluxes
- 55 different combinations of max flux and quiescent flux for each type of transient source
- Separated by straight lines

Reduced weighted $\chi^2$
4D space: more accurate

- 4d space:
  - Reduced weighted
  - Variability index
  - Max Flux
  - Max / Average Flux

- Variable and non-variable sources separated by a straight line in N-dimensions

- Supervised machine learning technique

- Training requires labeled data

Rowlinson et al., in prep.
Non detections

- Literature: out of the whole dataset derive one upper limit
- Applied to a LOFAR survey of 4 fields, for a total of 63 snapshots of 11 minutes each.
Non detections

- Literature: out of the whole dataset derive one upper limit
- We can eliminate the worst image and calculate a new method – iteratively
- Applied to a LOFAR survey of 4 fields, for a total of 63 snapshots of 11 minutes each.

![Snapshot Surface Density vs Flux Density](chart.png)

We can constrain the snapshot surface density over a range of sensitivity.
Non detections

- Literature: out of the whole dataset derive one upper limit
- We can eliminate the worst image and calculate a new method – iteratively
- We can assume a power-law distribution in flux for the transients and calculate the u.l.
- Applied to a LOFAR survey of 4 fields, for a total of 63 snapshots of 11 minutes each.

We can express the snapshot surface density as a function of the sensitivity.
Non detections

Carbone et al. 2015, submitted to MNRAS
Timescales

- Calculate transient upper limit vs Timescale

Carbone et al. 2015, submitted to MNRAS
LOFAR is detecting image-plane transient and variable sources
Adam's transient

- NCP monitoring project during MSSS-LBA
- Transient seen in one, 11 min snapshot at 60 MHz
- Brightness of 15-20 Jy
- Passed exhaustive validity tests
- No counterpart at higher frequencies
- At present the origin is unknown - attempt to find more events, using data from Cycles 2 & 3.
- Paper about to be submitted

Stewart et al., in prep.
PSR J2251+5135
An eclipsing redback pulsar in the RSM

- Variable image-plane source first spotted by eye, but also picked up by the TraP.

124 MHz observations

2013 February 10  2014 January 15

Full RSM dataset (e.g. 28 x 11 min images) → eclipses observed
PSR J2251+5135
An eclipsing redback pulsar in the RSM

- Variable image-plane source first spotted by eye, but also picked up by the TraP.
- Position coincident with PSR J2215+5135 (Hessels et al. 2011). Discovered at 350 MHz with the GBT (survey of faint, unidentified Fermi gamma-ray sources).
- Paper submitted to MNRAS (Broderick et al.).

124 MHz observations

2013 February 10

2014 January 15

Full RSM dataset (e.g. 28 x 11 min images) → eclipses observed

Dario Carbone, Assen – 02/06/2015
Eclipse is longer at lower frequencies

- $\sim v^{-0.4}$ dependence
- We could have had a much finer orbital phase resolution, using beamformed data. (also relevant to FRB detections; e.g. see Hassall, Keane & Fender 2013).

- Very steep radio spectrum ($\sim v^{-2.8}$).

74 MHz VLSSr data point from observations where PSR J2251+5135 is partially eclipsed.
TKP Jets Working Group

- SS 433 paper to be submitted very soon (Broderick et al.).
- GRS 1915+105; marginal detection (~20-30 mJy).
- Searches for 'missing' SNRs (Anderson, Lizancos, Broderick et al. in prep.).
- LOFAR HBA + KAT-7 1.4 GHz (Broderick, Rushton et al. in prep.)

- Blazar monitoring: sources strongly variable at GHz-frequency.
- LOFAR: smooth behaviour; trends on timescales of months
- Turriziani et al. 2015
The gamma-ray binary LS I +61 303

- High Mass X-ray Binary

- Orbitally modulated emission from radio to TeV energies.

- At GHz frequencies the radio lightcurve shows an outburst per orbital cycle.

- LOFAR lightcurve: outbursts are not clear and phase delay with respect to 15 GHz observations.

- Paper accepted (Marcote et al.)
LOFAR is detecting image-plane transient and variable sources
END
<table>
<thead>
<tr>
<th>Survey</th>
<th>Sensitivity (mJy)</th>
<th>$\rho$ (deg$^{-2}$)</th>
<th>$t_{\text{char}}$</th>
<th>$\nu$ (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>This work</td>
<td>$&gt; 500$</td>
<td>$&lt; 0.001$</td>
<td>minutes - months</td>
<td>0.150</td>
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<tr>
<td>Bell et al. 2011</td>
<td>$&gt; 8$</td>
<td>$&lt; 0.032$</td>
<td>4.3 - 45.3 days</td>
<td>8.4, 4.8 and 1.4</td>
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<td>Gal-Yam et al. 2006</td>
<td>$&gt; 6$</td>
<td>$&lt; 1.5 \cdot 10^{-3}$</td>
<td>-</td>
<td>1.4</td>
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<tr>
<td>Croft et al. 2010</td>
<td>$&gt; 40$</td>
<td>$&lt; 0.004$</td>
<td>81 days - 15 years</td>
<td>1.4</td>
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<tr>
<td>Bower et al. 2007</td>
<td>$&gt; 0.09$</td>
<td>$&lt; 6$</td>
<td>1 year</td>
<td>8.4 and 4.8</td>
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<tr>
<td>Bower et al 2010(A)</td>
<td>$&gt; 1$</td>
<td>$&lt; 1$</td>
<td>1 month</td>
<td>3.1</td>
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<tr>
<td>Bower et al 2010(B)</td>
<td>$&gt; 10$</td>
<td>$&lt; 0.3$</td>
<td>1 month</td>
<td>3.1</td>
</tr>
<tr>
<td>Bower &amp; Saul 2010(A)</td>
<td>$&gt; 70$</td>
<td>$&lt; 0.003$</td>
<td>1 day</td>
<td>1.4</td>
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<tr>
<td>Bower &amp; Saul 2010(B)</td>
<td>$&gt; 3000$</td>
<td>$&lt; 9 \cdot 10^{-4}$</td>
<td>1 day</td>
<td>1.4</td>
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<tr>
<td>Lazio et al. 2010</td>
<td>$&gt; 2.5 \cdot 10^6$</td>
<td>$&lt; 9.5 \cdot 10^{-8}$</td>
<td>5 minutes</td>
<td>0.0738</td>
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<tr>
<td>Bell et al. 2014</td>
<td>$&gt; 5500$</td>
<td>$&lt; 7.5 \cdot 10^{-5}$</td>
<td>minutes - year$^1$</td>
<td>0.154</td>
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<tr>
<td>Alexander et al. 2014</td>
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<td>$&lt; 17$</td>
<td>minutes - months</td>
<td>4.9</td>
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<tr>
<td>Bannister et al. 2011</td>
<td>14</td>
<td>$1.3 \cdot 10^{-2}$</td>
<td>days - years</td>
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<td>Bower et al. 2007</td>
<td>0.37</td>
<td>$1.5 \pm 0.4$</td>
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<td>Bower et al. 2007</td>
<td>0.20</td>
<td>2</td>
<td>2 months</td>
<td>8.4 and 4.8</td>
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<td>Jaeger et al. 2012</td>
<td>2.1</td>
<td>0.12</td>
<td>1 day - 3 months</td>
<td>0.325</td>
</tr>
</tbody>
</table>
Why is this interesting?

* A demonstration that we can detect variability in the LOFAR RSM.
* Low-frequency image-plane searches for eclipsing (and isolated) pulsars:
  - if spectrum very steep (e.g. often the case for MSPs), then a detection may not be possible at ~GHz frequencies.
  - scattering $\nu^{-4}$; pulses potentially smeared out in some cases, and imaging data needed for a detection.
* Interesting physics as well! Redbacks (+ black widows) thought to be 'missing link' between accreting LMXRBs and recycled MSPs.
* State transitions observed in a few other similar systems so far (e.g. Archibald et al. 2009, 2014; Papitto et al. 2013; Bassa et al. 2014; Stappers et al. 2014; Deller et al. 2015).
* Most robust approach for future work: simultaneous image-plane and beamformed observations (also relevant to FRB detections; e.g. see Hassall, Keane & Fender 2013).

**Very steep radio spectrum. 74 MHz VLSSr data point from observations where PSR J2251+5135 is partially eclipsed → explains discrepancy**