Charting the Transient Radio Sky on Sub-Second Time-Scales with LOFAR
Jason Hessels (ASTRON / UvA)

with the LOFAR Pulsar Working Group
(Stappers, van Leeuwen, Krämer, Karastergiou, Alexov, Hassall, Noutsos, Kondratiev et al.)
Run 3 telescopes: Westerbork, LOFAR, and EMBRACE
Working hard towards the SKA!
www.astron.nl
Outline

- The LOFAR telescope.
- Pulsar/fast transient observations with LOFAR.
- Some early results from LOFAR commissioning.
The LOFAR telescope.
LOFAR is now rapidly coming online!

http://www.astron.nl/dailyimage/

Bordeaux - Atelier Pulsars - 15 novembre, 2010
LOFAR Officially Opened June 12th, 2010 by her Majesty Queen Beatrix
Lowest Radio Frequencies Visible from Earth

LOFAR covers the lowest 4 octaves of the “radio window”

- Cut-off at 10MHz due to ionospheric reflection.
- Differential phase delays in the ionosphere need to be calibrated in order to add stations together in phase.
- Ionospheric calibration is a big challenge.
LOFAR’s Long Baselines

The Netherlands: 36 - 50
Germany: 4 - 7
England: 1 - 4
Sweden: 1
France: 1
Poland, Italy, Austria, Ukraine: 1 each?
Wide Area Network

- Dedicated fibre CORE-CEP
  - ~ 800 Gb/s BW
  - length ~ 70 km
- Remote stations
  - 10 GbE technology
  - data rate 2Gb/s + mon + other sensors
LOFAR Antennas

Low-band antennas (LBAs)
10-80MHz
30-4m

High-band antennas (HBAs)
110-240MHz
3-1m

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The Evolution of High Technology

Dutch Golden Age

New Golden Age
LOFAR Data Flow

Trans.: station <-> subband

Comp: channels, beams, and Stokes

Storage: freq. vs. time

Synthesize 200+ beams
Pathfinder to the Square Kilometer Array

Techniques also vital to future instruments in other areas of astronomy.
Pulsar/fast transient observations with LOFAR.
Aperture Synthesis

WSRT: 12hr to fill in uv plane
Aperture Synthesis Imaging

One of the coolest techniques in astronomy

~1s time resolution
Roughly speaking, beam-formed modes trade spatial resolution for time resolution.
Tile-out Primary Beam with Many “Tied-Array” Beams

Important to regain FoV
Pulsars/fast transients at Low-Frequency

\[ \nu_{\text{sky}} \sim 10 - 300 \text{ MHz} \]

**Advantages**

- Steep spectral indices?
- Only visible at low frequency?
- Low-DM sources distinguishable from RFI.
- Large field of view / dwell times (high F.O.M.).
- Respond to high-frequency triggers (DM delay).

**Disadvantages**

- Scattering \( \nu^{-4.4} \)
- Many dispersion trials \( \nu^{-2} \).
- Lower effective time resolution.
- Ionosphere.
- Propagation effects in the ISM are stronger.

**More luminous, different behaviour**
Beam-formed modes ...there are many possible.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Description</th>
<th>Data Rate</th>
<th>FoV (sq. deg.)</th>
<th>Res. (deg.)</th>
<th>Sens. (norm.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incoherent (par. imaging)</td>
<td>Stations added without proper phase correction.</td>
<td>2-250 GB/hr</td>
<td>12,5</td>
<td>2</td>
<td>6,0</td>
</tr>
<tr>
<td>Tied-array</td>
<td>Stations added properly in phase.</td>
<td></td>
<td></td>
<td>0,03</td>
<td>36,0</td>
</tr>
<tr>
<td>Single Station</td>
<td>For projects with high time, but lower sensitivity requirements.</td>
<td></td>
<td></td>
<td>12,5</td>
<td>1,0</td>
</tr>
<tr>
<td>Superstation</td>
<td>Interesting balance of sensitivity and FoV.</td>
<td>Up to 23TB/hr</td>
<td>9,0</td>
<td>0,2</td>
<td>12,0</td>
</tr>
<tr>
<td>Fly’s Eye</td>
<td>Maximize total FoV for bright transient survey.</td>
<td>Up to 8TB/hr</td>
<td>450</td>
<td>2</td>
<td>1,0</td>
</tr>
</tbody>
</table>
Fly’s Eye Mode
Pulsars at Low Frequency

- Pulsars originally discovered at 82MHz (now 300-3000MHz pop.).
- Most have steep spectra (for some $a = -3$!) and many appear to peak around 150MHz.
- MSPs may increase in flux to even lower frequencies (LOFAR LBA).
- Region in which significant evolution can be seen in the emission.
What we will do with LOFAR

For example: study radio-frequency mapping
What we will do with LOFAR
(for more details see the 10 LOFAR pulsar commissioning and science proposals... 40 thrilling pages!)

- **All-sky survey for pulsars and fast transients** using >100 tied-array beams - “LOTAAS”. Find hundreds of pulsars, and make a full census of the local population. Find fast transients.

- **Deep observations of known pulsars** (single pulses: 1/3HBA, 1/4LBA) to investigate their spectra, single pulse behaviour, pulse morphologies, polarimetry.

- **Pulsar timing** for studies of the ISM, detect and resolve glitches, turn-on/off of transient pulsars.

- **Solid base to facilitate** other high-time-resolution science.
Pulsars peak in brightness around 150MHz, but we’re limited by scattering. Luminosity law below $L_{400} = 1 \text{ mJy kpc}^2$ is uncertain.

Potential for a 1,000+ new pulsars!
At ~100 MHz, one is limited to $d < 2\text{kpc}$ for millisecond bursts in Galaxy.

40,000+ DM trials required!!! _Can’t do realtime._
Why Nearby Neutron Stars?

Complete census of all radio-emitting neutron stars within ~2 kpc?

- Luminosity distribution.
- Other intrinsic properties of the population (e.g. birthrate, period distribution). Understand life cycle.
- True “off” fraction of intermittent pulsars (e.g. RRATs).
- Fraction of intermittent radio-emitting NSs.
- Multi-wavelength follow up.
- Proper motions.
- Local ISM.
Radio Sky Monitor

Imaging survey at 30, 120 MHz (dedicated and piggy-back)

1 sec sensitivity: 500, 50 mJy
Covers 1/4 of sky daily
Produce (public) light-curves
Provide triggers.
Some early results from LOFAR commissioning.
Keeping Busy...

LOFAR Pulsar "Busy Week"

Pulsar/Planet Busy Week VI

Dec 7-11, 2009

Bordeaux - Atelier Pulsars - 15 novembre, 2010
Busy Weeks
Using pulsars to diagnose the system.
17 Stations: Best Data Yet!

Taken in one night in an automated schedule

Bordeaux - Atelier Pulsars - 15 novembre, 2010
17 Stations: Best Data Yet!

B1133+16
L2010_06331

- Sharp features
  (dispersion correction)
- High SNR
  (single pulses visible)
- Flat baseline
  (low RFI, no other artifacts)

Should ultimately get 10x higher SNR with full LOFAR!
LBA Pulsar Observations

- Enormous fractional bandwidth (~100%).
- Clearly shows pulse profile variation with frequency within one observation!
- Our next goal is to go below 30MHz.
- Cover LBA/HBA simultaneously.
Effelsberg LBA Observations

Highlights the power of single station work

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“Double” Crab Giant Pulse

Average Pulse Profile
Giant Pulse

33ms

Power (arbitrary units)
Time (s)
Low-Band Crab Giant Pulse

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Low-Band Crab Giant Pulse
LOFAR’s First Millisecond Pulsar Detection!

J2145-0750: S=480mJy, $P=16\text{ms}$, DM=9pc cm$^{-3}$

$>10x$ shorter period than normal pulsars
LOFAR’s First Millisecond Pulsar Detection!

Stappers, Karuppusamy & Hessels 2007
Drifting Subpulses of B0809+74

van Leeuwen et al. 2003
with WSRT

LOFAR
70,000 single pulses in 24hr!

Bordeaux - Atelier Pulsars - 15 novembre, 2010
Drifting Subpulses of B0809+74

van Leeuwen et al.
2003
with WSRT

LOFAR Data
B1133+16 with 4 telescopes simultaneously

Effelsberg LOFAR!

Effelsberg 100-m!
Simultaneous Imaging + Pulsar Observations

PSR B0329+54

Thanks George Heald!

Obs. L2010_06928
Multiple Station Beams
Hot off the press!

Bordeaux - Atelier Pulsars - 15 novembre, 2010
Pulse morphology vs. frequency
LBA Station Calibration and related results

Again, consecutive observations
Roughly a factor of 3 increase in SNR!

5 stations summed: CS007,024,030,032,RS106
LBA Station Calibration and related results

Periods with bright single pulses.

Bordeaux - Atelier Pulsars - 15 novembre, 2010
Pulsar Survey Pipeline

7-beam HBA grid covers 166 sq deg!!!

NB: beams are 2x wider than shown here.
~400 7-beam pointings > -35 deg DEC
Summary

• LOFAR is *highly* capable of high-spatial-resolution imaging *and* high-time-resolution, beam-formed observations of pulsars.

• LOFAR will IS opening a new spectral window on the Universe and providing a powerful characterization of pulsars and the transient radio sky at high time resolution.

• Look for early scientific results in 2010 and keep an eye on [http://www.astron.nl/dailyimage/](http://www.astron.nl/dailyimage/)!