Aperture Arrays for Pulsars

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Pulsar Science with AAs

- Pulsar surveys at mid to high Galactic latitudes (0.5-1.4GHz is the sweet spot for this, but AA-low would also be very powerful).

- **Pulsar timing** and monitoring (e.g. glitches, gravitational waves).

- Wide-band studies of the pulsar emission mechanism.

- Searches for intermittent pulsars, rotating radio transients, and extra-galactic fast transients (large FoV x T factor).
AA for Pulsars

Technical Requirements

• A/Tsys is critical for these weak (S1400 < 0.1mJy) sources.

• Large FoV: surveys and monitoring of multiple sources.

• Multiple, independent FoVs for anti-coincidence (e.g. RFI rejection in a survey), calibration, and to get more time on sources that aren’t sensitivity limited.

• Sub-arrays for even larger FoV, frequency coverage, and monitoring more sources simultaneously.

• Potential for very short slew time.
AA for Pulsars

The Drawbacks

• Large N number of stations and elements means some part of the collecting area is always broken.

• Need to know what’s broken.

• Beam-formed modes require online RFI removal.

• Can’t do correct these problems post-facto.
Fitting Pulse Profile Evolution

- Two Gaussians with frequency dependent amplitudes, widths, and separation.

- Simultaneous, so no DM variation.

- Nice demonstration of sub-arraying and single-station use.

B0809+74

Hassall et al., submitted
Flexible Beam-forming
(sparse aperture array)

Element beam  Stations beam(s)  Tied-array beam(s)

This is driving the development of beam-formed modes, of which tens of different sub-modes are possible.
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>2.5</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></td>
<td></td>
</tr>
<tr>
<td>Single Station</td>
<td>For projects with high time requirements.</td>
<td>Up to 23TB/hr</td>
<td>9.0</td>
<td>0.2</td>
<td>12.0</td>
</tr>
<tr>
<td>Superstation</td>
<td>Interesting balance of sensitivity and FoV.</td>
<td></td>
<td></td>
<td></td>
<td></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>

Flexible to match different science goals!
Multiple Station Beams

Credit: Hessels
Multiple, widely separated FoVs

@ 24MHz

simultaneous multi-beam observations in the LOFAR low band

Credit: Hassall & Hessels
Propagation effects in the ionized interstellar medium

\[ I(t) = g_r g_d S(t) * h_{DM}(t) * h_d(t) * h_{Rx}(t) + N(t) \]

Scattering: multi-path propagation

Dispersion: freq. dependent arrival time

Scintillation: const./dest. interference

Not pure evil: show that the signal is astronomical and can be used to study the ISM

Current SKA-Low

AAVP2011 - Dwingeloo - December 13th, 2011
Detection of Crab Giant Pulses with LOFAR LBAs

Credit: Hassall & Stappers

140 MHz

50 MHz

Time (s)

AAVP2011 - Dwingeloo - December 13th, 2011
At ~100 MHz, one is limited to d < 2kpc for millisecond bursts in Galaxy.

SKA pulsar surveys would benefit from any system operating > 300MHz
Transient Parameter Space

Cordes et al. 2004

Survey for sources in the known area of parameter space, but maintain good sensitivity for serendipitous discoveries.

Large FoV for rare, bright events

Large instantaneous sensitivity for weak source classes

AAVP2011 - Dwingeloo - December 13th, 2011
On-going LOFAR Pilot Pulsar Surveys

- Incoherent beam(s): large FoV
- Tied-array beam(s): high sensitivity
- Online coherent dedispersion: highest time resolution, e.g. for millisecond pulsars.

Important input for Phase I SKA pulsar surveys
LOFAR Pilot Pulsar Survey (LPPS)

- Incoherent beams - all avail. (~20) stations
- 7 beams of 7 MHz each and 0.65ms samp.
- 57 minutes per pointing (82GB)
- ~167 sq. deg. total FoV per pointing
- ~250 pointings taken during Christmas 2010
- Data being processed on “Hydra” at the University of Manchester.

SKA could use a similar mode to find pulsars fast
LOFAR Pilot Pulsar Survey (LPPS)

Only ~400 7-beam pointings > -35 deg DEC
LOFAR Pilot Pulsar Survey (LPPS)

LPPS pointings contains 7 beams

Re-detection J1823+0550

Re-detection J1844+1454

Re-detection J1841+0912

RFI (DM = 0 cm-3 pc)

LOFAR Pilot Pulsar Survey (LPPS) information

#-.

LPPS

LOFAR

LOFAR Pulsar Observations

Studying radio pulsar emission

For more information see

References

The high frequency end of the pulsar spectrum

Re-detection J1841+0912

Re-detection J1844+1454

LOFAR allows for efficient surveying

Transients and neutron stars provide constraints on

stellar evolution models and supernovae

Pulsars are awesome probes into

fundamental physics

Neutron stars provide constraints on

the Galactic free magnetic fields

Radio pulsar population is determined with half of the Northern Sky already observed and partially processed

Neutron stars provide constraints on the Galactic free magnetic fields

Neutron stars provide constraints on the Galactic free magnetic fields

A&A

ApJ

Because of its

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A&A

32(32):31

10.1051/0004-6361/201015413

10.1088/0004-637X/726/2/1511

The high frequency end of the pulsar spectrum
Independent Discovery of PSR J2317+68!

Candidate: ACCEL_Cand_2
Telescope: LOFAR
Epoch$_{topo}$ = 55859.6458330000
Epoch$_{bary}$ = 55858.64567106420
Text: 0.00065536
Data Folded = 5191680
Data Avg = 9.48e-08
Data StdDev = 9.508e+04
Profile Bins = 200
Profile Avg = 1.589e+04
Profile StdDev = 1.532e+07

Search Information
P$_{2000}$ = 23:17:26.5502
DEC$_{2000}$ = 68:44:25.4076

Folding Parameters
Reduced $\chi^2 = 3.279$
P(Noise) < 1.16e-49 (m 14.8$\sigma$)

Dispersion Measure (DM) = 71.876

P$_{topo}$ (ms) = 813.4076(11)
P$_{bary}$ (ms) = 813.4076(11)
P$_{topo}$ (s/s) = 0.0(2.4)x10$^{-9}$
P$_{bary}$ (s/s) = 0.0(2.4)x10$^{-9}$
P$_{topo}$ (s/s$^2$) = 0.0(4.6)x10$^{-12}$
P$_{bary}$ (s/s$^2$) = 0.0(4.6)x10$^{-12}$

Binary Parameters
P$_{orb}$ (s) = N/A
e = N/A
$a sin(i)/c$ (s) = N/A
$\omega$ (rad) = N/A

Credit: Green, Hassall & Stappers

AAVP2011 - Dwingeloo - December 13th, 2011
LOFAR Tied-Array Survey (LOTAS)

- Tied-array (coherent) beams (Superterp)
- 19 beams with full 48MHz and 1.3ms samp.
- 17 minutes per pointing (246GB)
- $\sim$3.7 sq. deg. FoV per pointing
- $\sim$200 pointings taken from May 11-15th
- Increase in sensitivity $\sim$10 x LPPS
- Less affected by RFI?

SKA could use a similar mode for a deep all-sky pulsar survey
Pulsar is 10x brighter in the correct beam (beam 7)!

Shifted 1 deg south

Credit: Alexov & Hessels
LOFAR 127-beam Tied-Array!!

S/N in each beam

Linear Scaling  
Log Scaling

Credit: Hessels & Alexov
- Working prototype for non-image processing
- Real-time searches for Individual Radio Pulses using CPU/GPU
- Dedispersion over 4000 DMs per beam in real time with GPUs
- Pilot survey 1: 6-8 beams tracking circumpolar targets
- Pilot survey 2: 6 beams fixed on the meridian from 8° to 28° dec
- Performed on 800 mbps streams
- Each node has: 12 Xeon CPU cores + 1 NVIDIA M2050 (or GTX)
- DM processing is ~10x better than real time
- RFI rejection performing well in very contaminated environment

Detecting known sources of dispersed pulses including pulsars and frequency swept radio emitters (HAMSAT).
Anticoincidence experiments with Effelsberg + Nancay will reveal nature of enigmatic detections
Low-Frequency Polarimetry

Close to the only pulsar polarimetry at < 100MHz

Credit: Sobey
Summary

• We don’t just want bigger telescopes. We also want more flexible telescopes (and “future proofing”).

• LOFAR pilot pulsar surveys are already providing competitive scientific data and are an important input for SKA Phase I.

• Early pulsar science coming from LOFAR’s wide-band coverage from 10-240MHz and polarimetric abilities.