The LOTAAS survey: progress report and new discoveries

Sotiris Sanidas
on behalf of: LOFAR Pulsar WG

Anton Pannekoek Institute for Astronomy, University of Amsterdam

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LOFAR Pulsar Working Group

Jason Hessels (co-lead)	ASTRON/Universiteit van Amsterdam
Ben Stappers (co-lead)	University of Manchester
Cees Bassa	ASTRON
Anya Bilous	Universiteit van Amsterdam
Rene Breton	University of Manchester
Thijs Coenen	Universiteit van Amsterdam
Sally Cooper	University of Manchester
Heino Falcke	Radboud Universiteit Nijmegen
Marisa Geyer	University of Oxford
Jean-Mathias Griessmeier	LPC2E/CNRS/Universite d'Orleans
Daniele Michilli	ASTRON/Universiteit van Amsterdam
Aris Karastergiou	University of Oxford
Evan Keane	SKA HQ
Vlad Kondratiev	ASTRON
Michael Kramer	MPIfR/University of Manchester
Joeri van Leeuwen	ASTRON/Universiteit van Amsterdam
Aris Noutsos	MPIfR
Stefan Osłowski	Universität Bielefeld
Maura Pilia	INAF/Osservatorio Astronomico di Cagliari
Ziggy Pleunis	Universiteit van Amsterdam
Nataliya Porayko	MPIfR
Sotiris Sanidas	Universiteit van Amsterdam
Maciej Serylak	University of the Western Cape
Charlotte Sobey	Curtin University/CASS
Chia Min Tan	University of Manchester
Sander ter Veen	ASTRON
Joris Verbiest	Universität Bielefeld
Patrick Weltevrede	University of Manchester
Kimon Zagkouris	University of Oxford

LOFAR Tied Array All-sky Survey

All-northern-sky survey for pulsars, RRATS, and fast transients

- *High Sensitivity*
  12 HBA sub-stations of superterp
  $32\,\mathrm{MHz}$ BW, $119 - 151\,\mathrm{MHz}$, $12\,\mathrm{kHz}$ channels, $S_{\min} \sim 1\,\mathrm{mJy}\,@\,135\,\mathrm{MHz}$
  $493\,\mu s$ sampling - sensitive to MSPs up to DM $50\,\mathrm{pc\,cm}^{-3}$

  The most sensitive very-low-frequency pulsar survey ever performed

- *Great Field-of-View*
  3 sub-array pointings (SAP)/incoherent beams (30 sq. deg.)
  183 tied-array beams (61 per SAP) (9 sq. deg.)
  12 tied-array beams "free" (targeting known sources within SAP)
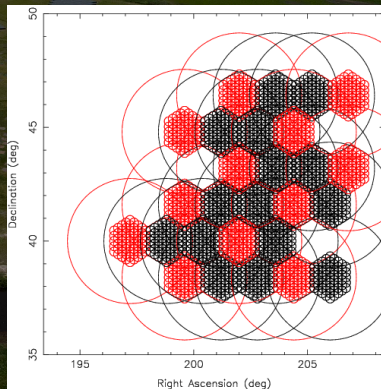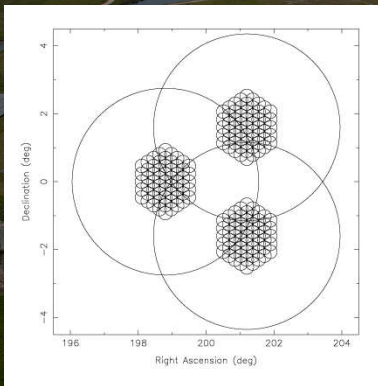
- *Unique dwell time*
  1-hr integrations - essential for transients/intermittent pulsars

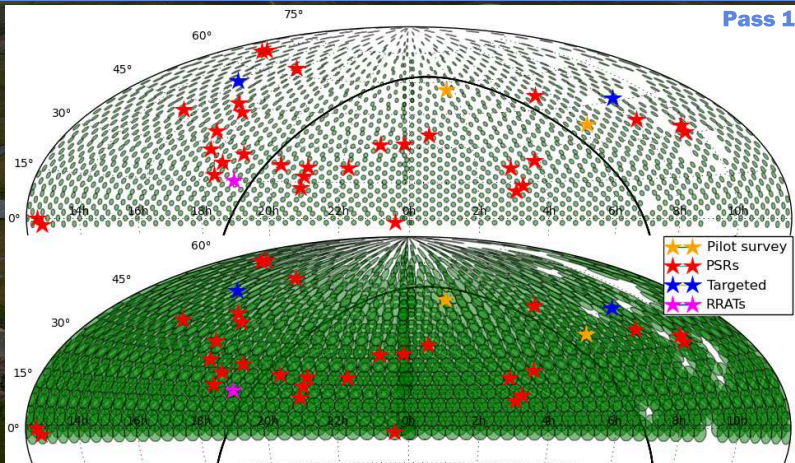See Coenen et al. 2014 for more info

Observing setup

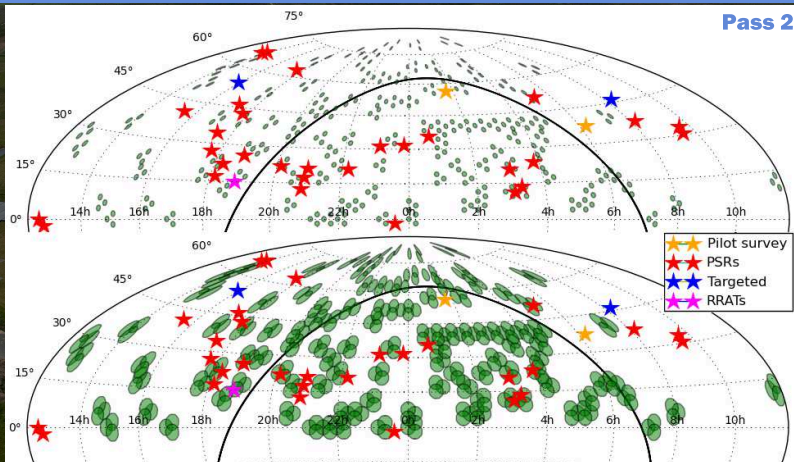222 beams per pointing!
The first SKA-like pulsar survey

- Coherent beams x4 more sensitive than incoherent beams → deeper search
- Data Rate: 35Gbps, 16TB/pointing (4TB by downsampling to 8-bit data)

Sky Coverage

- 3 passes of 651 pointings each (1953 total) for full sky coverage with TABs
- ~ 10 observations/week. Pass 1 (633 successful) completed!
- Total survey's raw data: ~ 8 PB

- Already in Pass2. Observation rate: 260hrs/Cycle
- Long Term proposal successful: 1040hrs granted within Cycles 5-8

Raw Data Processing

CPU time requests:

- ► 1st proposal:10M CPU hours - used!

- ► 2nd proposal:25M CPU hours
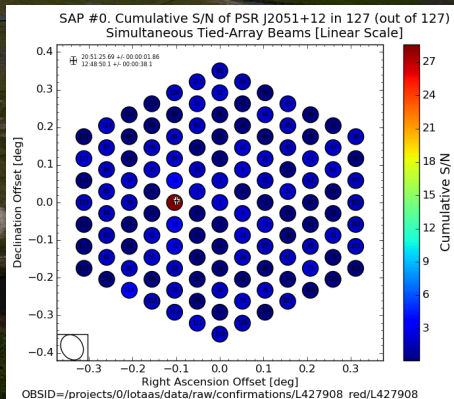
Millions of periodicity candidates:

- ► ~20000 periodicity candidates per pointing

- ► ~40 million candidates expected

- ► Machine Learning classifier: ~500 candidates/pointing Lyon et al. 2016 arXiv:1603.05166

Raw data storage
- ● SARA LTA

Raw data processing
- ● Cartesius (SURFSARA) 500 nodes (24-cores, 64GB RAM)

- ● ~3 hours processing/beam/node DM range:$0 - 500\,\mathrm{pc\,cm^{-3}}$

- ● Single Pulse searches

Follow-up Observations

Localization of periodicity/single pulse candidates

- Follow-up observations arranged immediately (Kondratiev / ter Veen)

- 15-30 min duration

- Full-core/superterp

- All discoveries/confirmations appear immediately on

http://www.astron.nl/lotaas

SAP #0. Cumulative S/N of PSR J2051+12 in 127 (out of 127)
Simultaneous Tied-Array Beams [Linear Scale]

OBSID=/projects/0/lotaas/data/raw/confirmations/L427908_red/L427908

Observations/Processing status + future

- **■ *Higher time resolution - Hunting MSPs***
  - ▸ Reduce time sampling to $246\,\mu sec$ (or even $164\,\mu sec$) thanks to CEP4
  - ▸ 4/2-bit downsampling to maintain storage requirements
  - ▸ Expand survey's coverage down to $\delta = -10°$

- **■ *Up in time with observations (Sanidas):***
  - ▸ Backlog built up due to 2015 Cartesius failures cleaned!
  - ▸ Significant streamlining of the pipeline (processing/data archiving)
  - ▸ Attainable processing rate: > 5 pointings/day

- **■ *New Machine Learning classifier (Chia Min Tan):***
  - ▸ Search deeper into the already processed data
  - ▸ *see Chia Min Tan's talk tomorrow*

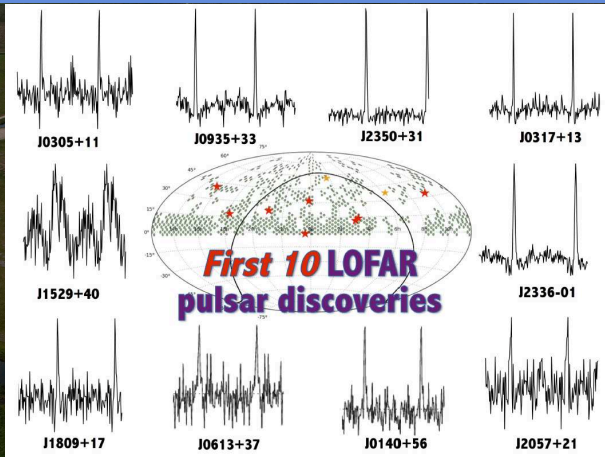- **■ *New single pulse pipeline (Michilli):***
  - ▸ Already in place - Reprocessing of all LOTAAS data products ongoing

- **■ *GPU version of the pipeline (Bassa / Kondratiev):***
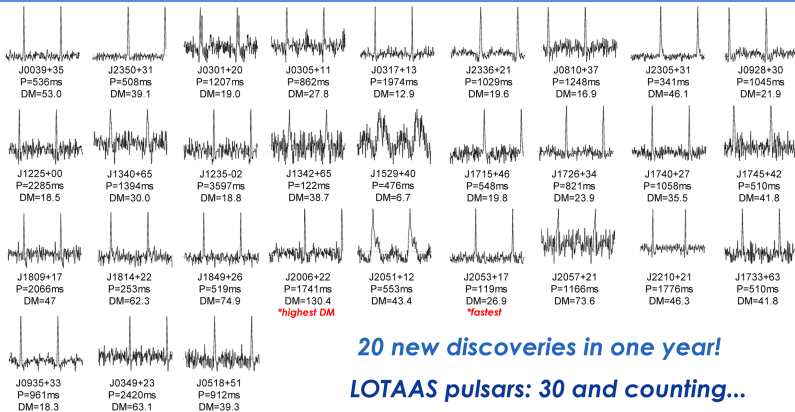 - ▸ Almost finished on *DRAGNET* - plans to use on Cartesius as well

- 10 new LOTAAS periodicity search discoveries (Cooper)
- 1 from targeted searches (Kondratiev)
- 2 RRATS (Michilli - Single Pulse Pipeline v.1.0)
- 2 from commissioning survey (LOTAS)
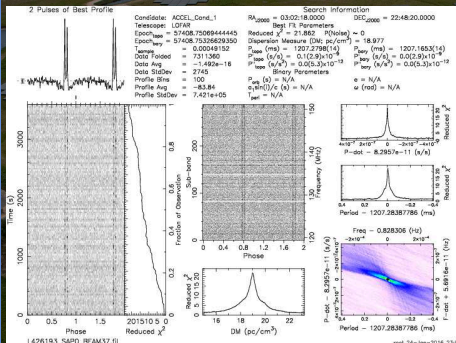
LOTAAS discoveries

20 new discoveries in one year!

LOTAAS pulsars: 30 and counting...

- 30 new LOTAAS periodicity search discoveries (Cooper/Sanidas)
- 1 from targeted searches (Kondratiev)
- 1 RRATS (Michilli - Single Pulse Pipeline v.1.0)
- 2 from commissioning survey (LOTAS)
- New pulsars also added for timing with LOFAR
- Also timed with the Lovell (1.4 GHz, if detected)

- Detected in the sp pipeline as RRAT

- Redetected in Pass2 from the periodicity search

- Initial discovery during Cartesius failure

- Benefits of LOTAAS observing strategy

- Every point in the sky is covered:
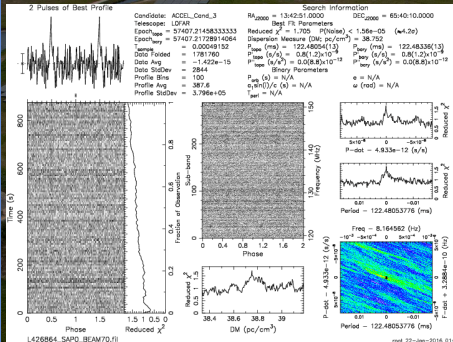 1) 3x with incoherent beams
  2) 1x with coherent beams
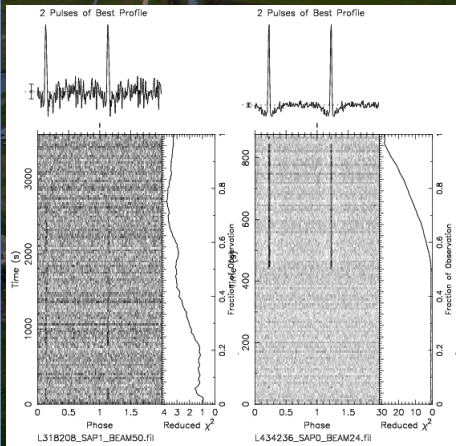
- Extreme nuller
- 4 follow-ups - no show
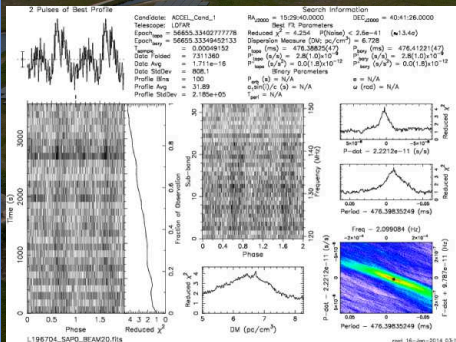- Confirmed with the supererp
- Localised with the full core
- Long dwell time pays off!!!
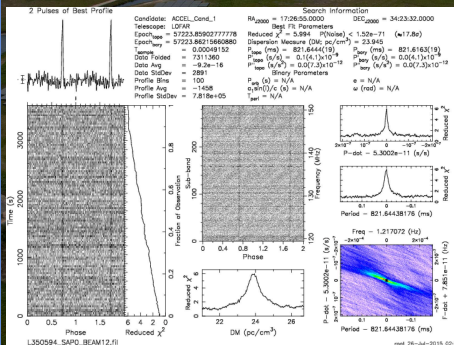
- Discovered in the incoherent beam

- 4 follow-ups to localise

- Initial detection in a sidelobe

- Correctly, J1722+34

- Found in the follow-up of J1340+65

- Search pipeline *always* performed on follow-ups as well

- 2 superterp follow-ups - no show

- *Weak source*

- Full-core follow-ups to be arranged

- Unusual profile for slow pulsar

- Rather small DM

- $\dot{P}$ entirely from Shklovskii effect? Very small spin-down rate?

DRAGNET

Dynamic Radio Astronomy of Galactic Neutron Stars and Extragalactic Transients

- A significant extension to LOFAR's capabilities for pulsar/fast transients research (and not only...)

- Installed in July 2015 @CIT, right next to COBALT

- Initial aims
  - ▶ Accelerate LOTAAS processing
  - ▶ Expand/Improve LOTAAS survey
  - ▶ Real time search for transients

DRAGNET Team:
Jason Hessels (PI, ERC Grant)
Alexander van Amesfoort (Tech. Dev.)
Cees Bassa (Sc. postdoc)
Vlad Kondratiev (Sc. postdoc)
Daniele Michilli (PhD)
Ziggy Pleunis (MSc)
Sotiris Sanidas (Sc. postdoc)

Many thanks to:
Mike Sipior
Edwin Stuut
Henk Jonkers
Arjen Koers
Hopko Meijering
Teun Grit

DRAGNET

DRAGNET backend:
23 nodes

- 2x Intel Xeon E5-2630v3
  (16 cores 2.4GHz)

- 4 Titan X consumer cards
  (12GB, 3072 cores, ~ 7TFLOPS)

- 128GB DDR4 RAM

- 16TB disk space

1 batch processing node

Overall GPU performance: ~ 600TFLOPS
Total storage:400TB

Direct links to COBALT/LOFAR network:

- 54Gb Infiniband

- 6x10Gb Ethernet

DRAGNET

- *Observing*
  - ▶ Observing *directly* to DRAGNET already performed (manually)
  - ▶ Incorporation of DRAGNET into the production observing system (MoM/Scheduler) within Cycle 6
  - ▶ Record LOTAAS observations *directly* on DRAGNET (sparing CEP4 time)
  - ▶ Possibility for LOFAR "filler" time
  - ▶ Recording data on DRAGNET commensally with other observations
  - ▶ Take station raw data and perform custom beamforming in *parallel* with other observations

- *Processing*
  - ▶ GPU version of LOTAAS pipeline almost ready for production runs.
  - ▶ Acceleration searches on all LOTAAS observations - MSPs!

DRAGNET

DRAGNET related projects

- *Fermi unidentified γ-ray sources search (PI:Pleunis)*
  - ▶ Targeted search for MSPs
  - ▶ Observations + processing *exclusively* on DRAGNET
  - ▶ Don't miss Ziggy Pleunis' talk tomorrow for progress report and some very nice results!

- *Shadowing of FRB121102 Arecibo observations (PI:Bassa)*
  - ▶ Proposal just submitted (Cycle 6)
  - ▶ Simultaneous observations with the Arecibo on the repeating FRB (Spitler et al. 2016, Nature)
  - ▶ Assess FRB detectability at very low frequencies
  - ▶ Potentially LOFAR will make the *first* FRB detection at these frequencies

Conclusions

LOTAAS:

- LOTAAS will be the deepest low-frequency pulsar survey ever performed
- 35 pulsars found so far. > 100 with current discovery rate
- *Already* the most successful very-low-frequencies pulsar survey since 1970
- LOTAAS has the potential to be one of the most successful pulsar surveys
  at any observing frequency

DRAGNET:

- Accelerate and improve LOTAAS searching
- Expand the observing capabilities of LOFAR

Stay tuned at

www.astron.nl/lotaas

for new discoveries!