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LOFAR Tied Array All-sky Survey (LOTAAS) Periodicity Search for Pulsars

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LOTAAS Team

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Sander ter Veen	ASTRON

Collaborator

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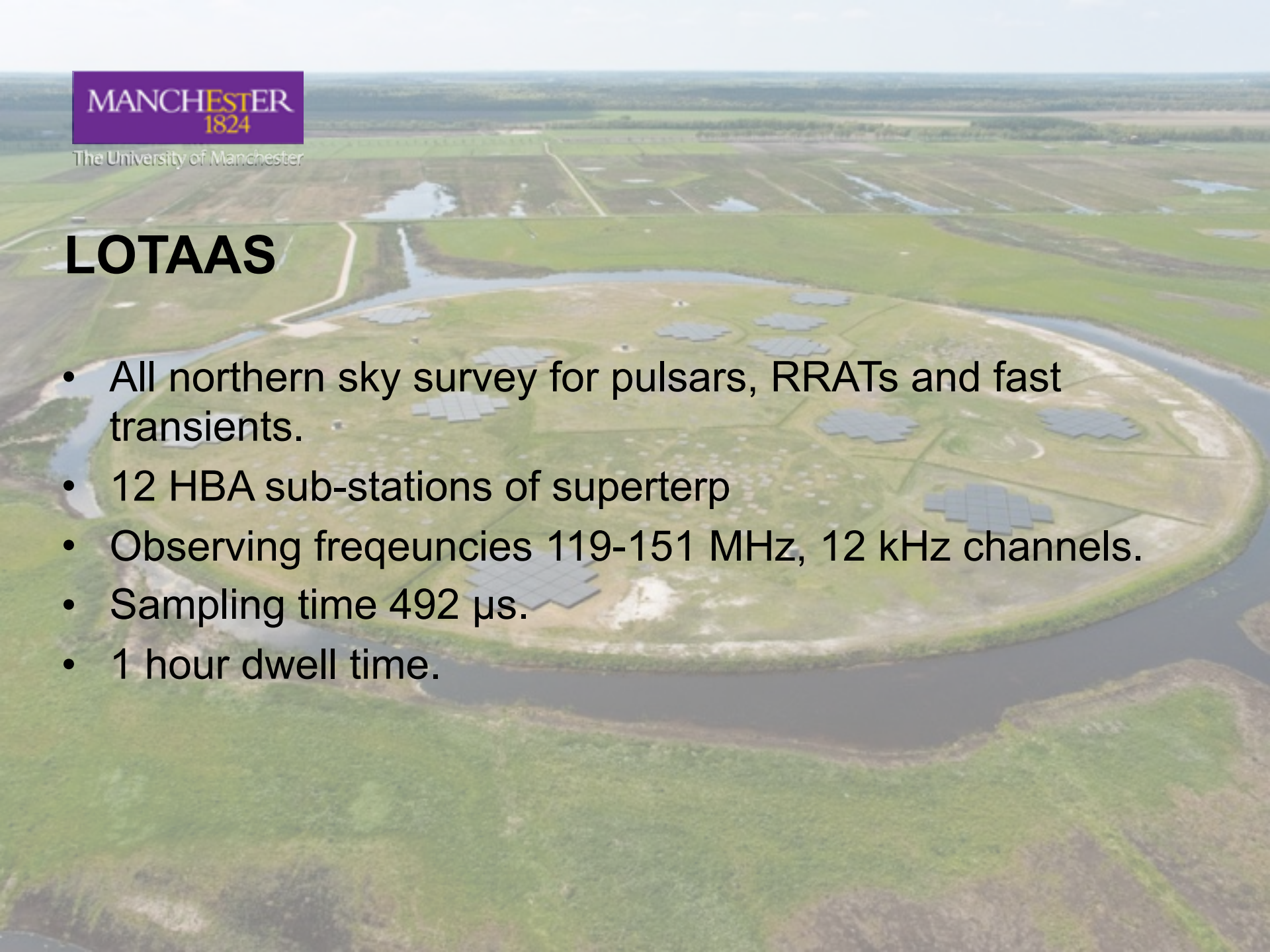

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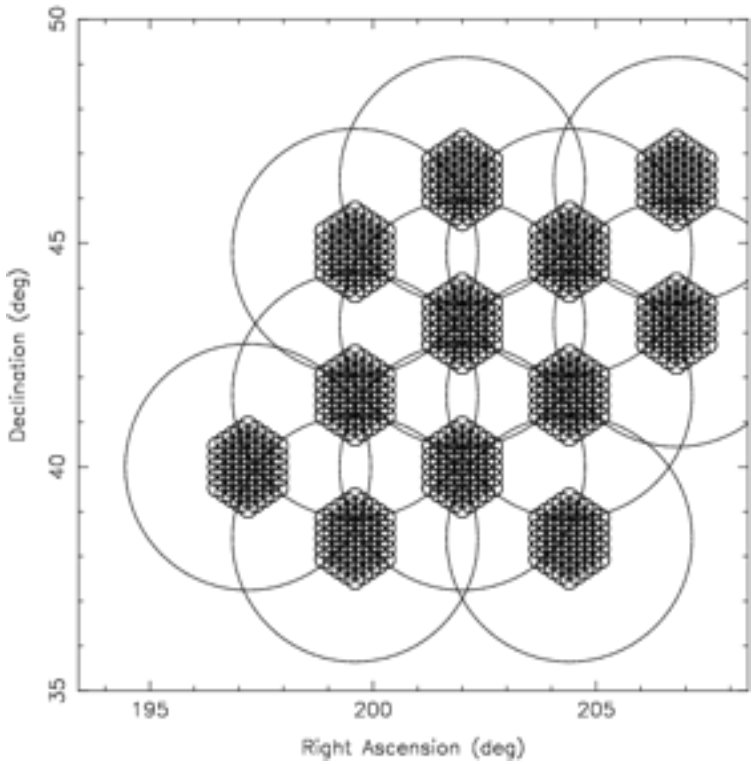
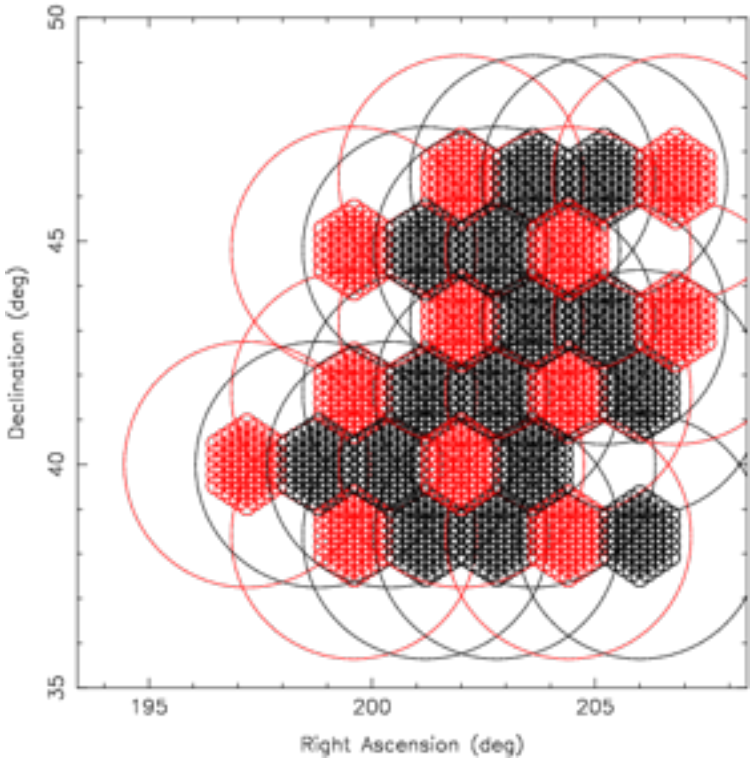
LOTAAS

- All northern sky survey for pulsars, RRATs and fast transients.
- 12 HBA sub-stations of superterp
- Observing freqeuncies 119-151 MHz, 12 kHz channels.
- Sampling time 492 μs.
- 1 hour dwell time.

Field of View (FoV)

- 222 beams per pointing — First SKA-like pulsar survey
  - 3 sub-array pointings (SAP), incoherent beams (IB), 30 deg^2 FoV
  - 183 tied-array beams (TAB), 61 per SAP, 9 deg^2 FoV
  - 12 free TAB per SAP, known sources within SAP or “random”





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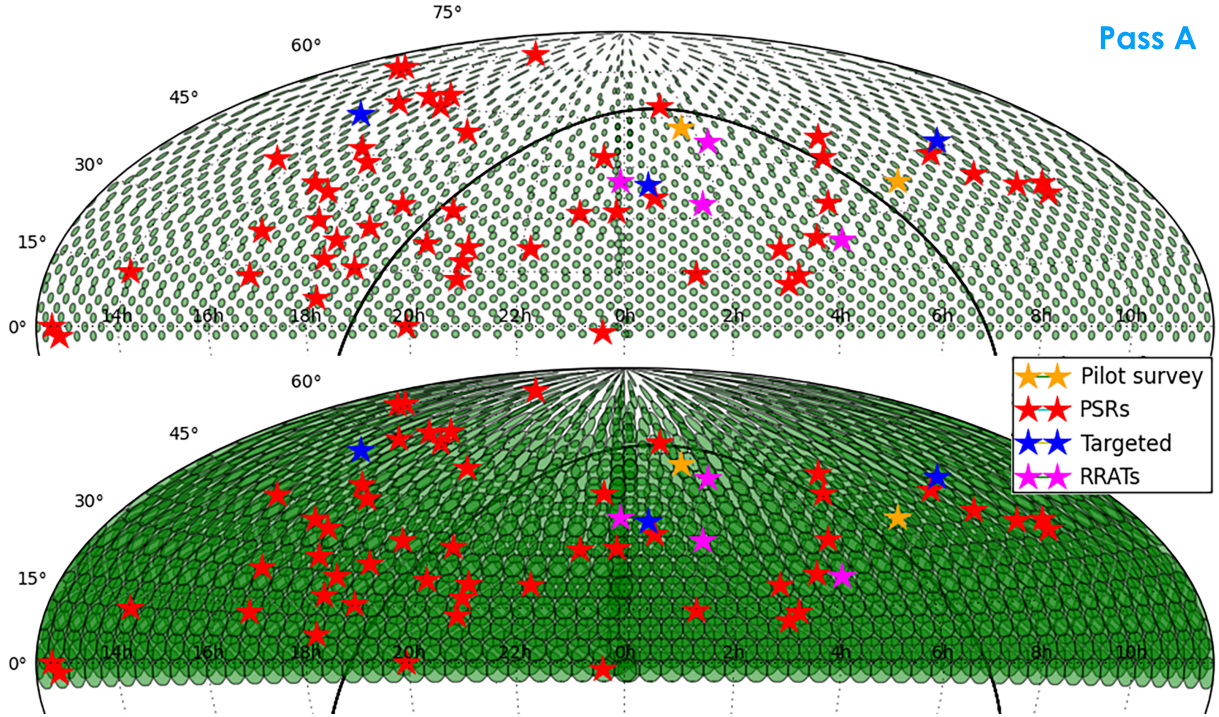
Sky Coverage



- 3 passes of 651 pointings required to cover the northern sky with TABs
- Pass A completed (survey area covered by IBs)

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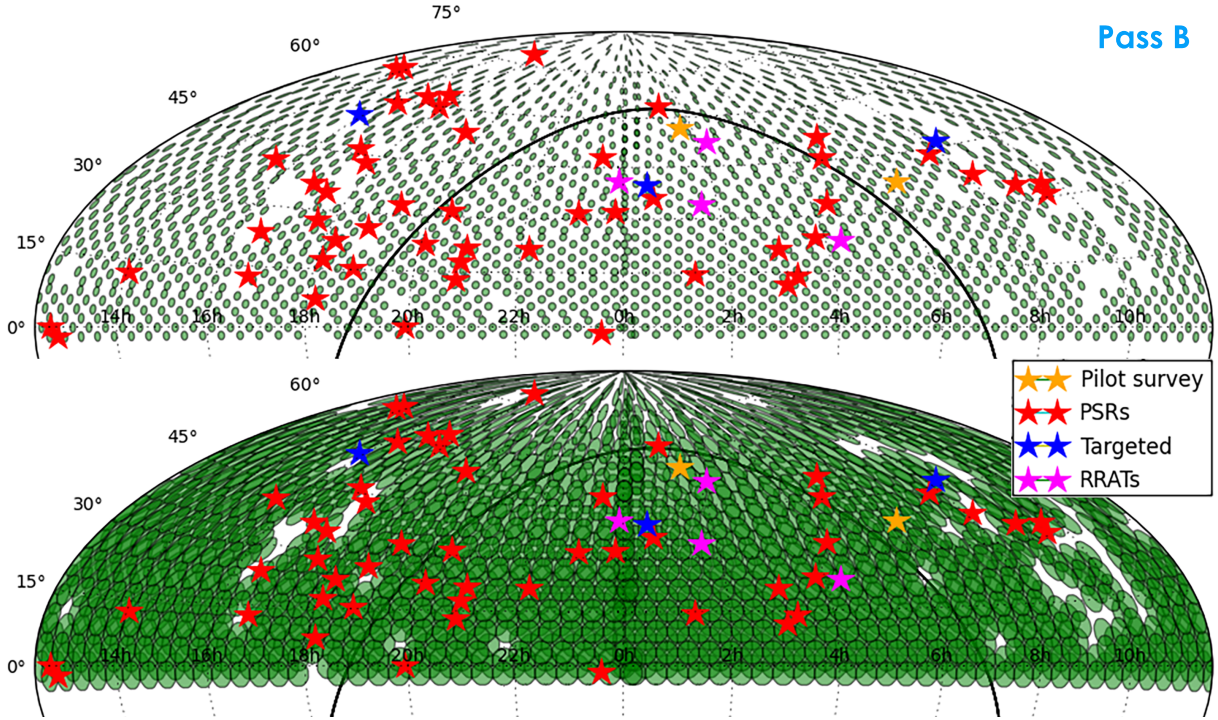
Sky Coverage



- 612/651 pointings completed in Pass B
- ~10 observations/week

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Data Processing

- Cartesius (SURFsara) — 1500 nodes (24 cores, 64 GB RAM)
- Dedispersion of DM 0-500 pc cm^{-3}
- Fourier-based periodicity searches
- Single pulse searches (see Michilli)
- ~3 hours processing time/ beam/node

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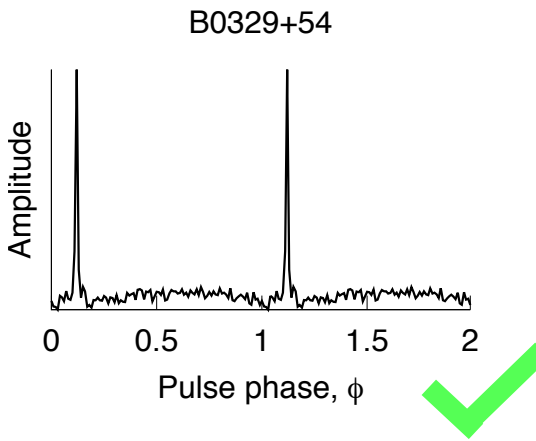
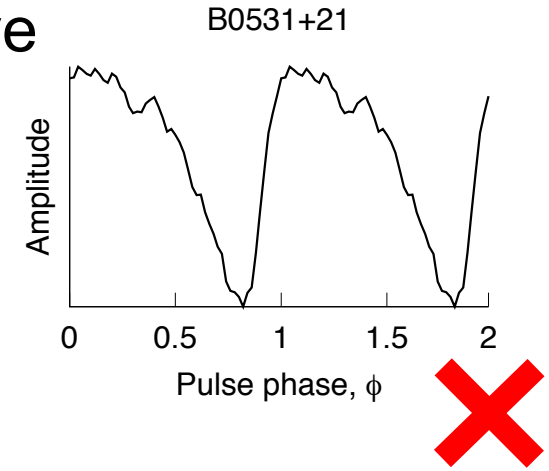
Periodicity Candidates

- ~20,000 periodicity candidates per pointing — expecting 40 million candidates for the whole survey
- Machine Learning (ML) classifier to choose the best candidate
- First ML classifier by Lyon et al. 2016
  - 8 features from pulse profile & DM curve
  - Very Fast Decision Tree (VFDT) binary classifier
  - ~500 candidates per pointing
- But less effective with pulsars with wide pulse profile





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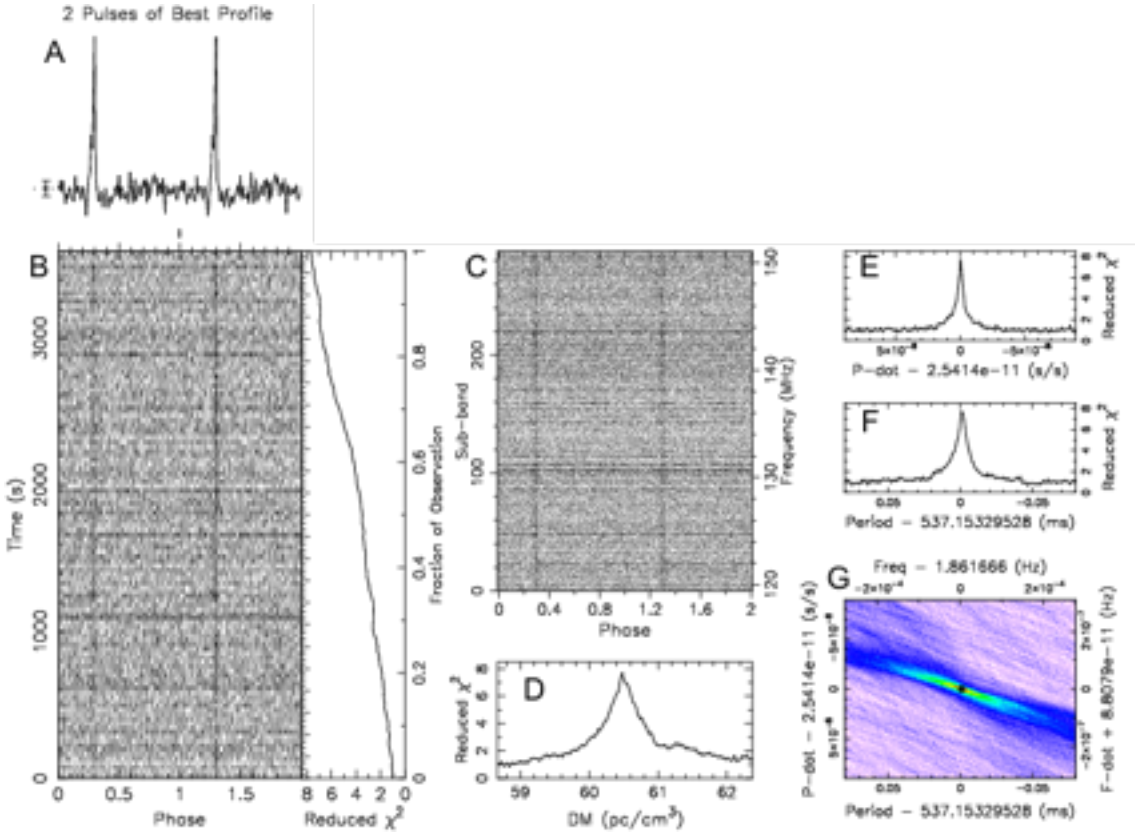
Periodicity Candidates — Important Bits

A. Pulse profile
B. Time against pulse phase
C. Sub-band against pulse phase
D. DM curve



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New ML Classifier — New Features

- 8 features from Lyon et al. + 12 new features
- 8 features from time against pulse phase & sub-band against pulse phase
  - correlation coefficient between each band & pulse profile
  - calculate statistics from coefficients
- 4 new features from DM curve
  - alternate method to calculate the statistics

$$\mu = \frac{1}{n}\sum_{i=1}^{n} y_i$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \mu)^2}{n}}$$

$$s = \frac{\frac{1}{n}\sum_{i=1}^{n}(y_i - \mu)^3}{\sigma^3}$$

$$k = \frac{\frac{1}{n}\sum_{i=1}^{n}(y_i - \mu)^4}{\sigma^4} - 3$$

Features from Lyon et al. — mean, standard deviation, skewness & kurtosis

Tan et al. 2017, in prep.

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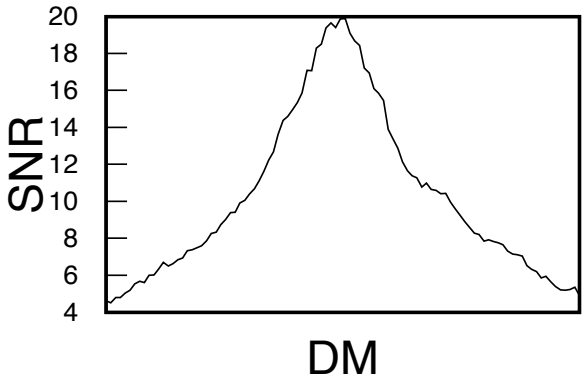
New ML Classifier — New Features

- 8 features from Lyon et al. + 12 new features
- 8 features
  pulse phas
  pulse phas
  - correla
    each b
  - calcula
    coefficients



- **4 new features from DM curve**
  - **alternate method to calculate the statistics**

$$\mu = \frac{\sum xy}{\sum y}$$

$$\sigma = \sqrt{\frac{\sum (x-\mu)^2 y}{\sum y}}$$

$$|s| = \left|\frac{\frac{\sum (x-\mu)^3 y}{\sum y}}{\sigma^3}\right|$$

$$k = \frac{\frac{\sum (x-\mu)^4 y}{\sum y}}{\sigma^4} - 3$$

Alternate method to calculate mean, standard deviation, skewness & kurtosis

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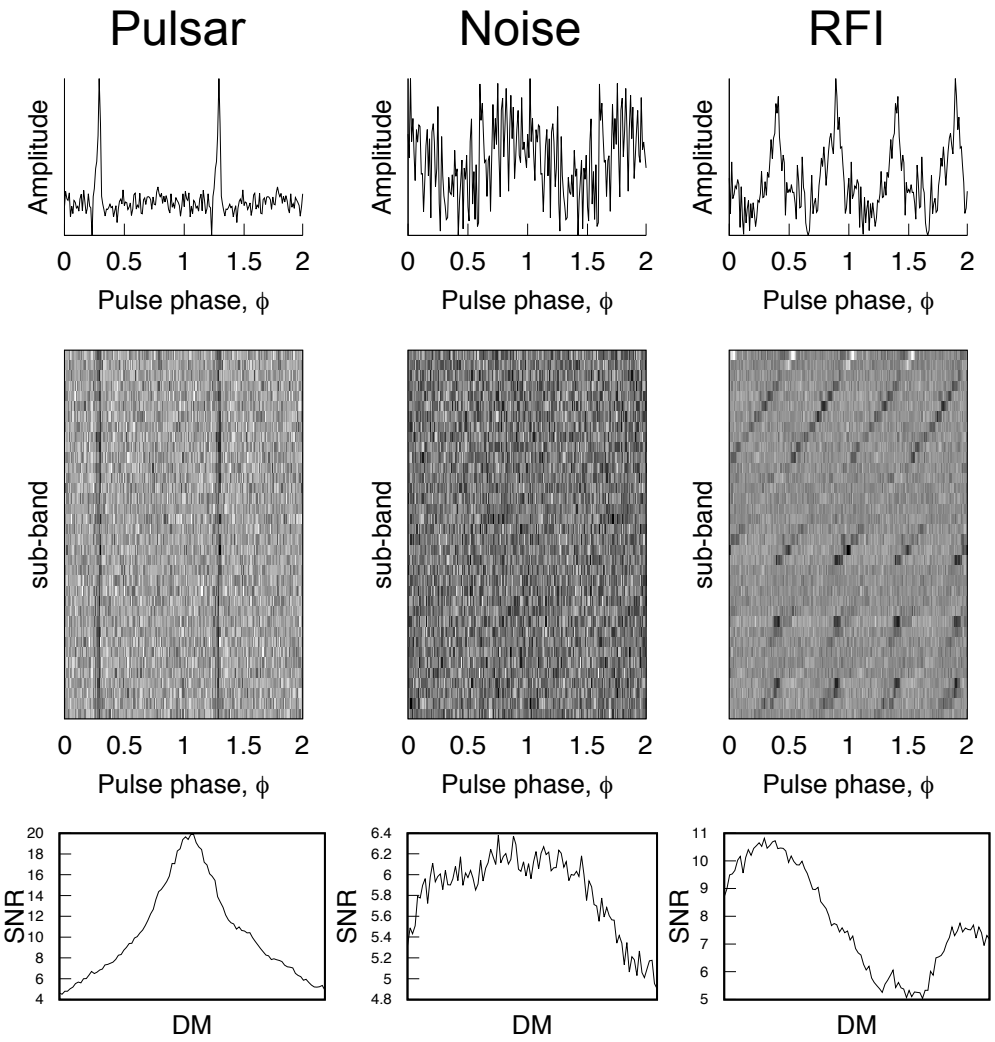
New ML Classifier — RFI class

- Separate known RFI instances from other non-pulsars (noise)
- 3 class classifier



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New ML Classifier — Ensemble Classifier

- 5 VFDT classifiers with 5 different training datasets
- Pulsar class — 5 different detection (if possible) of 295 unique pulsars in each training set
- Noise and RFI class — 5 sets of 600 noise and 100 RFI instances sampled from a pool of 1267 noise and 150 RFI instances with replacement
- Ensemble classifier — candidate is pulsar if 3 or more VFDT classifiers said so

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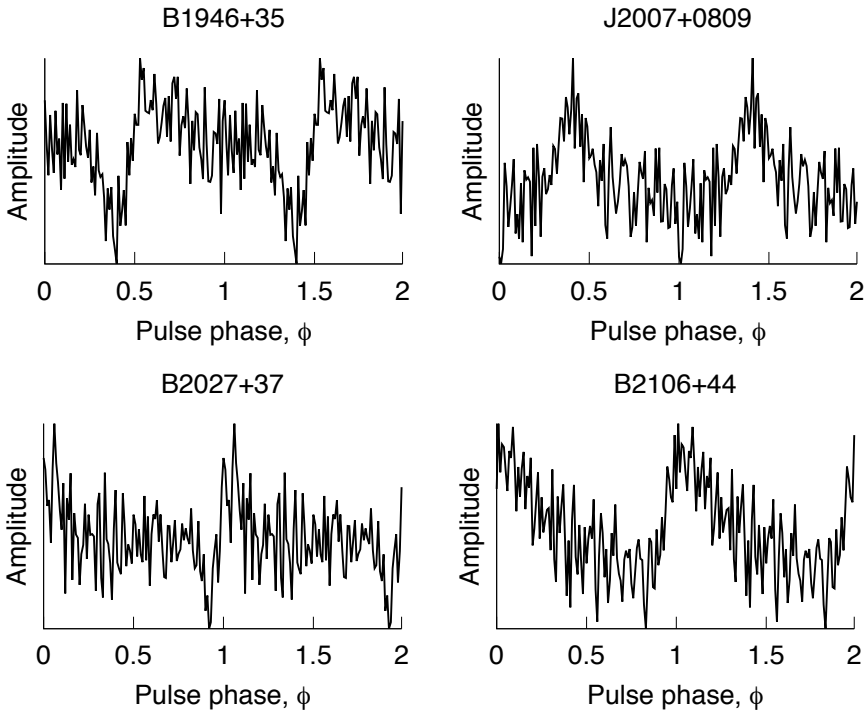
New ML Classifier — Performance

- Improved performance
  - Pulsar recall rate from 96.2% to 98.7%
  - False positive rate from 2.5% to 1% — 60% reduction in candidates
- More importantly, able to identify pulsars with wide pulse profile, amongst other previously misclassified pulsars



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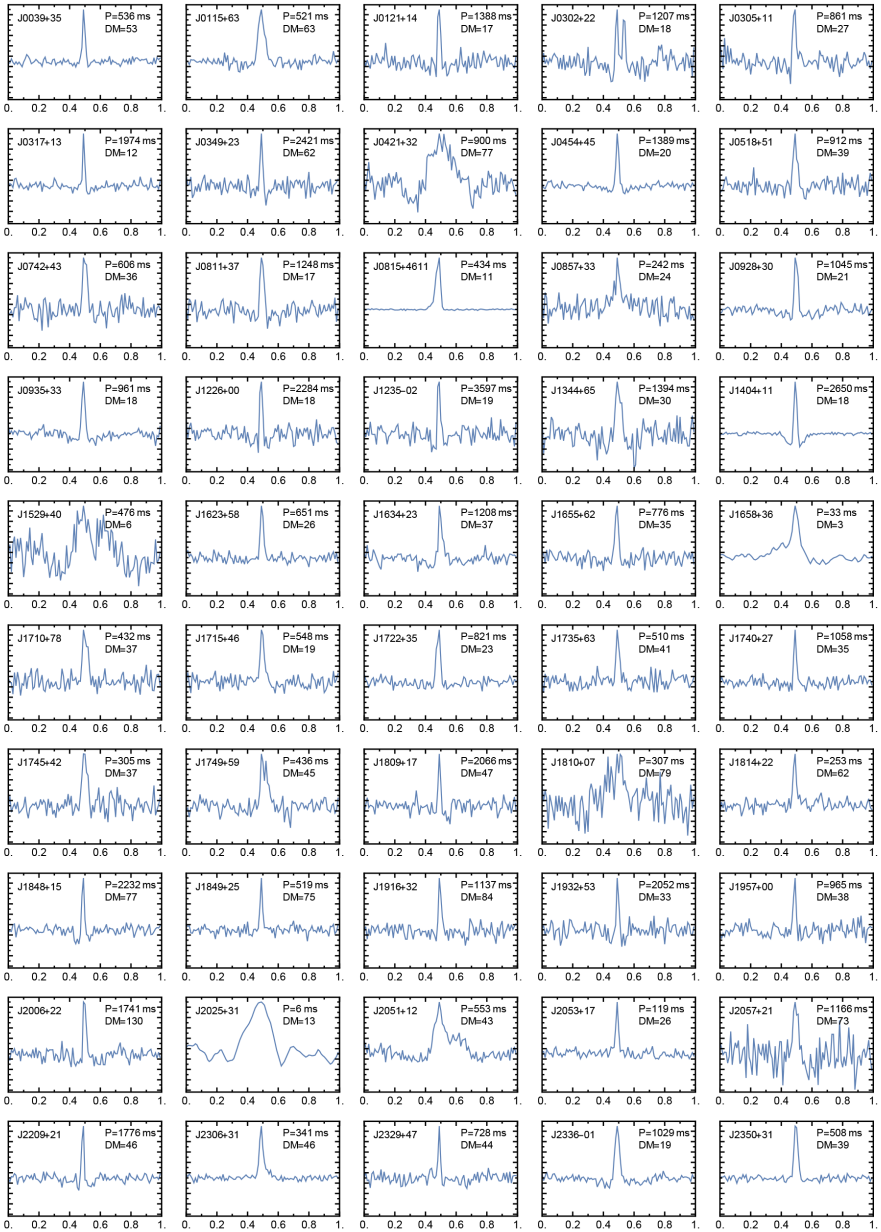
LOTAAS Discoveries

- 53 pulsars discovered via periodicity searches
- 5 RRATs from single pulse searches (Michilli)
- 1 from targeted search (Kondratiev)

LOTAAS Overview Paper +
50 first discoveries
Sanidas et al. 2017, in prep.



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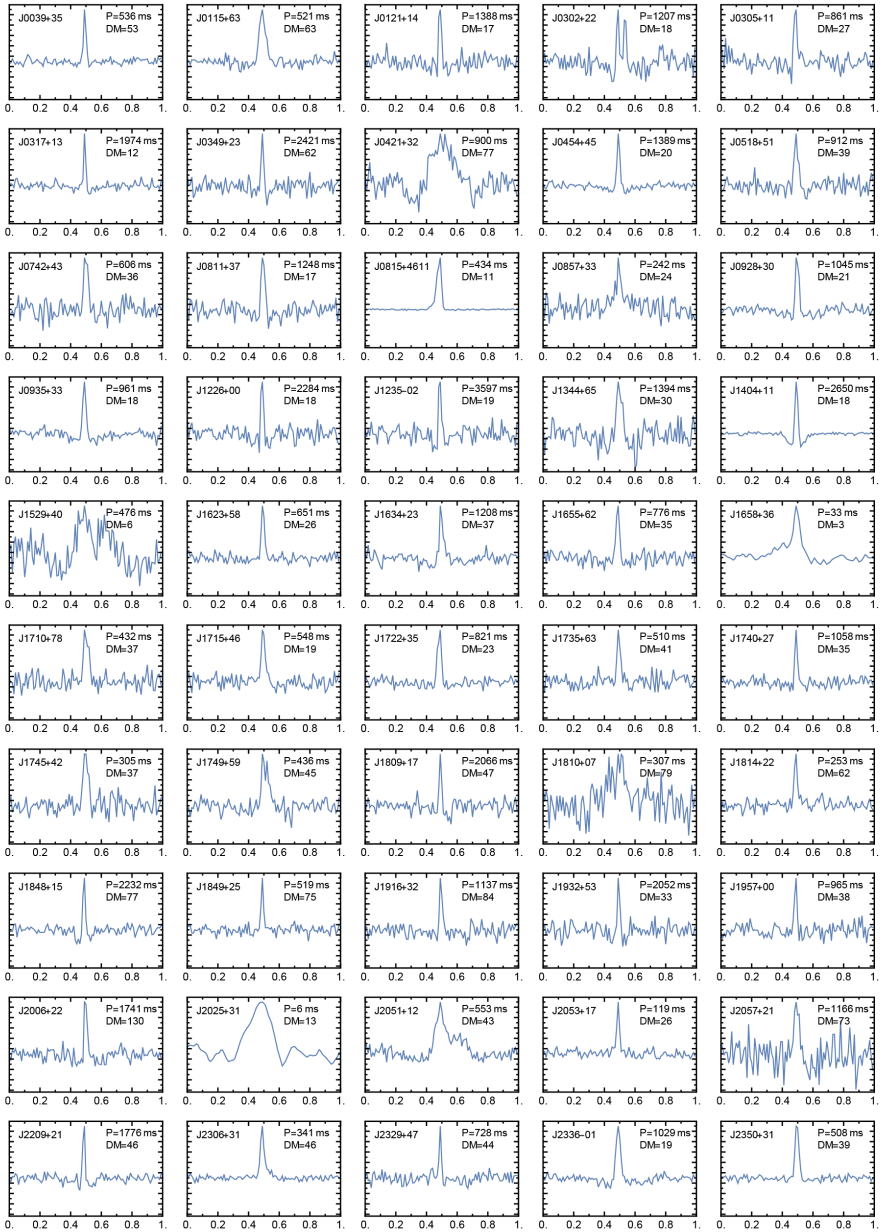
LOTAAS Discoveries

- Timing of new pulsars by LOFAR
- Only ~half detected & timed by Lovell (1.4 GHz) — steep spectrum



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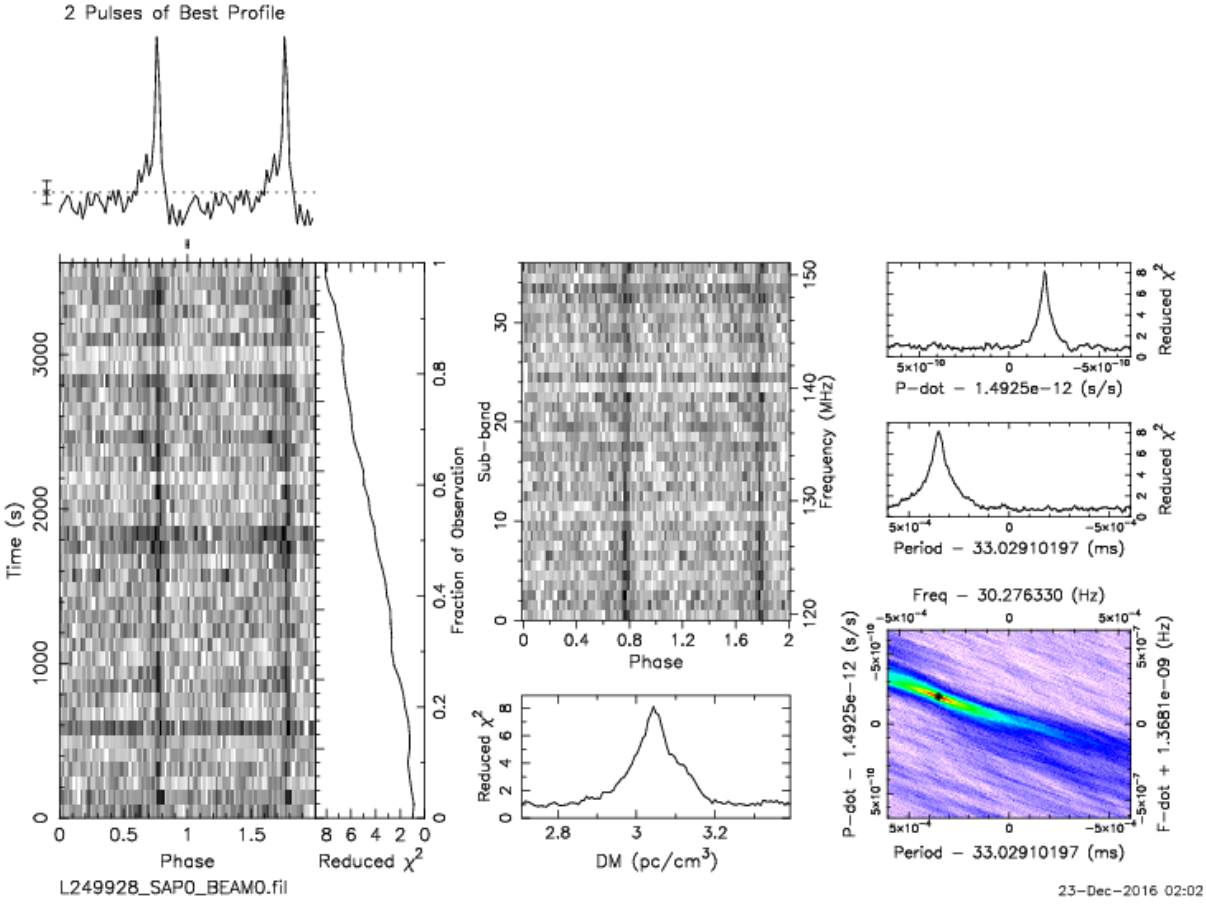
LOTAAS Discoveries — J1658+36

- 1st LOTAAS binary
- 33 ms period
- DM ~3 pc cm^{-3}
- ~3.0 days orbit
- Minimum companion mass ~0.87 M_{Sun}
- Not detected by Lovell at 1.4 GHz & 300 MHz



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Future

- New LOTAAS v2.0 pipeline (Sanidas)
  - various improvement (~30% performance increase)
  - to be deployed during summer
- Higher time resolution
  - reducing sampling time to 246 μs or 164 μs
- Expanding survey coverage to δ = -10
- Adding Fast Folding Algorithm (FFA) to search pipeline (Morello)
  - FFA more sensitive to long period pulsar and/or pulsars with small duty cycle

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Conclusion

- LOTAAS is the deepest low-frequency pulsar survey ever performed
- New ML classifier implemented to periodicity search pipeline
- 54 pulsars + 5 RRATs found so far — expect ~100 new discoveries by end of survey