Pulsar Science with the Large European Array for Pulsars

James McKee

Max Planck Institute for Radio Astronomy

The Big Impact of a Big Dish: Science with the Effelsberg 100-m Telescope
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jmckee@mpifr-bonn.mpg.de
LEAP: The Large European Array for Pulsars

Max Planck Institute for Radio Astronomy (Germany):
J. W. McKee
M. Gaikwad
R. Karuppusamy
M. Kramer
K. Liu
J. Antoniadis

University of Manchester (UK):
B. W. Stappers
S. A. Sanidas
(L. Wang)

University of Orléans (France):
I. Cognard

National Astronomical Observatories (China):
L. Wang
W. W. Zhu

Peking University (China):
K. J. Lee
LEAP: The Large European Array for Pulsars

- Tied-array consisting of combinations of Effelsberg Telescope (DE), The Lovell (UK), Nançay Radio Telescope (FR), Sardinia Radio Telescope (IT), Westerbork Synthesis Radio Telescope (NL)
- Equivalent dish size (all 5 telescopes): 195-m
- Monthly observations of MSPs (from 2012 until present)
- Phase up initially on nearby calibrator, then later on the pulsar itself
- Centre Freq. 1396 MHz
- Bandwidth: 128 MHz
- Polarisation calibrated
- Baseband data recorded, shipped to Jodrell Bank for offline processing
- Coherent addition of baseband data
- Combined baseband data saved to tape for future scientific use

Experiment overview: Bassa et al. (2016)
Software correlator overview: Smits et al. (2017)
LEAP offers a significant increase in sensitivity over that of the individual telescopes.

The simultaneous observations allow instrumental time and phase offsets between the telescopes to be precisely measured.

To date, ~4.5 years of observations have been reduced.

Here, I describe the experiment and report on the scientific projects which have made use of LEAP data.

Experiment overview: Bassa et al. (2016)

Software correlator overview: Smits et al. (2017)
- Observe an array of MSPs to directly probe the nanoHertz gravitational wave background (GWB)
  - Current limit on the stochastic GWB: \( A < 1.0 \times 10^{-15} \) \( (f_c = 1 \text{ yr}^{-1}) \)
  - Shannon et al. (2015)
- To make a detection, we need very high-precision data
- New generation of highly sensitive telescopes will eventually lead to a detection
  - FAST, MeerKAT, SKA
  - New telescopes are expensive to build, need long data sets to contribute to GWB detection \((\geq 10 \text{ yrs})\)
- LEAP is an interferometric array, which bridges the gap between the current generation of telescopes and those that will be employed by PTAs in the future

\[
\sigma_{\text{TOA}} \approx \frac{S_{\text{sys}}}{\sqrt{t_{\text{obs}} \Delta f}} \frac{P\delta^{3/2}}{S_{\text{mean}}} \]

\[
S_{\text{sys}} = \frac{T_{\text{sys}}}{g}
\]
Each month we observe a set of MSPs

- Effelsberg (Germany)
- The Lovell (UK)
- Nançay Radio Telescope (France)
- Sardinia Radio Telescope (Italy)
- Westerbork Synthesis Radio Telescope (The Netherlands)

Phase up on calibrators either side of the pulsars

- Bright radio sources (AGN, Seyfert galaxies etc.)

Fit for time delays between telescopes due to:

- Telescope geometry
- Observatory clocks
- Instrumental changes
- Atmospheric conditions

Total time delay calculated to within a fraction of a wave length

- 0.7 ns at 21cm
- Apply the solution from the calibrator to the pulsar
- Adjust delays, phasing up on the pulsar itself
- Apply the total solution to the observation
  - Include RFI mitigation
  - Produce baseband data for the LEAP virtual telescope
  - Produce archives for LEAP and the single telescopes
- Baseband data for coherently-added observations are saved to tape
  - Allow the original data to be reprocessed in the future
  - Not possible in standard timing observations
  - Enables science not possible with standard timing mode
Comparison with Single Telescopes

Coherent 5-telescope addition

LEAP S/N = sum of individual telescope S/Ns
Comparison with Single Telescopes

PSR J0613-0200 timing data

Effelsberg = orange  LEAP = blue

~2× improvement in TOA precision
Single-pulse studies offer an opportunity to understand the rotational variabilities of pulsars. These studies require bright pulsars and highly sensitive instruments, in order to discriminate single pulses from the background noise.

We have performed a single-pulse study of PSR J1713+0747:
- 15 minutes of data (~197,000 pulses at $P = 4.6$ ms)
- Pulsar was brightly scintillated.

Confirm the detection of periodic intensity modulation:
- Demonstrate to be phase-dependent
- The first detection of such behaviour in an MSP.

Drifting sub-pulses are found to have two modes:
- $P2 = 6.9 \pm 0.1 \, P$
- $P3 = 2.9 \pm 0.1 \, P$

Find that the fractional polarisation scales with flux density:
- Brightest pulses highly linearly-polarised
• Occasional single pulses of flux densities orders of magnitude greater than the mean
  – Rare, only observed in 11 pulsars to date.

• Searched for GPs in 13.4 hours of observations with LEAP
  – Detected 4265 GPs
  – The largest ever sample of GPs gathered for this pulsar

• Examined the distribution of polarisation fractions of GPs
  – No correlation between GP flux and fractional polarisation
  – No correlation between polarisation fraction and pulse phase

• Measured the power law index of the flux distribution
  – $A = -3.8 \pm 0.2$
  – Low-flux turnover at $\sim 4$ Jy

• Measured modulation indices for the GPs
  – Vary by $\sim 0.5$ towards the centre of the phase distributions
  – In contrast to the findings of Jenet et al. (2001) for the regular emission

• Compare the timing prospects of PSR B1937+21 using GPs and the average profile
  – No improvement in the GP timing
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Globular clusters (GCs) are dense regions of stars
- Binary formation more likely
- Gives rise to large populations of binary pulsars and MSPs
- Increases the probability of exotic binary systems forming (e.g. pulsar-black hole binaries).

GCs are attractive targets for pulsar searches (e.g. Hessels et al. 2007)

The tied-array beam of LEAP is small
- max. size: 50 mas

Sensitivity of LEAP makes it well-suited to targeted searches

Searching for pulsars in GC M28
- Phase up on the bright MSP B1821−24A

Focus our search on unknown X-ray sources within the cluster

Search is ongoing
- Produced re-detections of known pulsars within the GC
Future

- Increase bandwidth
  - Currently use only 128 MHz
  - Increase in bandwidth adds to the total signal
  - Improvement in TOA precision
  - Also makes fringe-finding easier

- Chinese collaboration
  - Follow up FAST discoveries
    - Similar declination range
    - LEAP is much more sensitive than individual telescopes
    - Build on L. Wang's pulsar search technique
  - Eventually add FAST to the array
    - uberLEAP
• LEAP is a valuable tool, giving the EPTA access to pulsar observations with sensitivities comparable to Arecibo
• Bridges the gap between the current generation of radio telescopes, and the SKA
• Allows systematics at individual telescopes to be identified quickly
• Enables pulsar science not possible with standard pulsar timing data
• Length of data set is now sufficient for scientific projects

Thank you! :)