The Large European Array for Pulsars: a LEAP of the EPTA for gravitational wave detection

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On behalf of the LEAP team:

28th TEXAS Symposium, Geneva
05/01/2015
Outline

• Pulsars, Gravitational Waves, Pulsar Timing Array

• The European Pulsar Timing Array collaboration

• The Large European Array for Pulsars project

• Closing mark
Pulsars are:
• Fast-rotating magnetic dipoles;
• Emitting electromagnetic wave at radio / X-ray / γ-ray…;
• Cosmic “light houses”;

Millisecond Pulsars (MSPs) are:
• Rotational period < e.g. 20 ms;
• “Recycled” pulsars by accretion process;
• Highly stable rotators;
• Celestial “clocks”;

Credit: NRAO

[ Hartnett & Luiten 2011 ]
Gravitational wave & Pulsar Timing Array

Gravitational waves are:

• Ripples in the curvature of space-time propagating as a wave;
• Predicted by General Relativity and alternative theories;
• From stochastic background (GWB) and single sources.

Pulsar timing array (PTA) is:

• A group of MSPs with high precision timing, at different sky directions;
• Looking for a typical correlated timing signals between pulsars.

[ Helling & Downs 2011 ]
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Credit: D.J. Champion

[ Janssen et al. 2015 ]

observed frequency [Hz]

[ Helling & Downs 2011 ]
The community in Europe

**European Pulsar Timing Array (EPTA) is:**

- A European pulsar timing collaboration to detect gravitational wave;
- Part of the International Pulsar Timing Array collaboration (with PPTA and NanoGrav);
- Combing pulsar timing data from the largest radio telescopes in Europe:

  - **Effelsberg, 100-m, Germany**
  - **Lovell, 76-m, U.K.**
  - **Sardinia, 64-m, Italy**
  - **Westerbork, 94-m, Netherlands**
  - **Nancay, 94-m, France**
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[www.epta.eu.org](http://www.epta.eu.org)
EPTA in 2015

The collaboration is busy publishing this year...

• “High-precision timing of 42 millisecond pulsars with the European Pulsar Timing Array”
  [ Desvignes et al., recommended for publication ]

• “Noise properties of 42 millisecond pulsars from the European Pulsar Timing Array and impact on gravitational wave searches”
  [ Caballero et al., recommended for publication ]

• “European Pulsar Timing Array limits on an isotropic stochastic gravitational-wave background”
  [ Lentati et al., 2015 ]

• “Limits on Anisotropy in the Nanohertz Stochastic Gravitational Wave Background”
  [ Taylor et al., 2015 ]

• “European Pulsar Timing Array limits on continuous gravitational waves from individual supermassive black hole binaries”
  [ Babak et al., 2016 ]
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All the analysis were performed based on data from our legacy pulsar backend (narrow bandwidth, incoherent de-dispersion, low-bit sampling)...

We can do much better now !
New generation EPTA pulsar instruments

**ROACH Board** technique from CASPER:

- 8-bit A/D converter at Nyquist rate;
- Maximum 512 MHz bandwidth;
- Flexible firmware / channelisation;

**Improvement on pulsar backends:**

- Effelsberg: 64 MHz to 200 MHz bandwidth;
  2-bit to 8-bit sampling;
- Nancay: 128 MHz to 512 MHz bandwidth;
  2-bit to 8-bit sampling;
- Jodrell: 64 / 128 MHz to 400 MHz;
  1-bit to 8-bit sampling;
- Westerbork: 80 MHz to 200 MHz;

[ Lazarus et al., submitted ]  
[ Karuppusamy et al., in prep. ]
Pulsar timing is all about measuring the pulse time-of-arrivals (TOAs) precisely!
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To improve, make a bigger telescope!
Pulsar timing

To improve, make a bigger telescope!
The Large European Array for Pulsars

The experimental design:
- Coherently combines raw voltage data from the five European telescope to form a **phased-array**, with reference to **Effelsberg**;
- Delivers sensitivity equivalent to a 192-m dish, similar to **SKA Phase I** \( \rightarrow \) Pathfinder of the next generation radio telescopes!
- Enable declination range from +85 to -30 deg;

The project:
- Supported by ERC Advanced Grant (2M euro);
- Started on Sep. 2009;
- Funding ended officially on Sep. 2014;
- Now has 5 permanent staffs, 6 postdocs, 1 PhD student (another to join next year);
The Large European Array for Pulsars

Advantage from phasing-up:

- Improve TOA accuracy by number of telescopes;
- Calibrate instrumental offsets & instabilities;
- Flexible data form enabling many pulsar projects;

Project overview published this year!

Bassa et al. 2015, MNRAS
Observing setup & data management

Observations:

• Monthly 24 h sessions since Mar. 2012;
• 20-30 MSPs;
• Simultaneously with all 5 telescopes;
• Observe pulsars and phase calibrators;
• Use the ROACH-board backends to record data at Nyquist rate;
• Baseband voltage data stored on disk;

Data management:

• Transfer the data to Jodrell Bank, by either disk shipment or copying over internet;
• Place the data on storage cluster (with 288 slots) for processing;
• Store the coherent-added voltage data (with one backup) on tape archive;
• Store the timing data on both disks and tape archive;
• Ship back the disks for the future observations;
• Keep some voltage data on disks online for sub-projects.

<table>
<thead>
<tr>
<th>Sampling bit</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central frequency</td>
<td>1396 MHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>128 MHz</td>
</tr>
<tr>
<td>Polarisation</td>
<td>Calibrated, I Q U V</td>
</tr>
<tr>
<td>Bin number / period</td>
<td>... / 1024 / 2048 /...</td>
</tr>
</tbody>
</table>
Scheduling

Constraints:

• Sources at different hour angles;  
• Phase calibrator in between pulsars;
• Maximise integration time on pulsars with minimal time on calibrators;
• Telescope specific slew speeds, cable wraps, and sky coverage constraints...
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**Solution:**

- 20h + 4h (15:30-19:30 LST twice);
- Fixed schedule with Nancay LSTs to get UT;

**Source list:**

<table>
<thead>
<tr>
<th>Red: EPTA sources with highest priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0030+0451 (+NC)</td>
</tr>
<tr>
<td>J0613-0200 (+NC)</td>
</tr>
<tr>
<td>J0645+5158</td>
</tr>
<tr>
<td>J0931-1902 (+NC)</td>
</tr>
<tr>
<td>J1022+1001 (+NC)</td>
</tr>
<tr>
<td>J1518+4904 (+NC)</td>
</tr>
<tr>
<td>J1640+2224</td>
</tr>
</tbody>
</table>
Correlation pipeline

[ Smits et al., in prep. ]
Polarisation calibration:

- Use the template matching method developed by van Straten 2006;
- Integrated into software correlator and applied directly to baseband data;
- Use template from European Pulsar Network (EPN) database;
- Use a few bright pulsars as calibrator: B1933+16, J1022+1001, B1937+21, J1713+0747;
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Software correlator

[Smits et al., in prep.]
Effectiveness

On profile data

On timing data
Effectiveness

On profile data

On timing data

With 3.2 yr baseline:
- **Current addition**: $10^{-14}$ for spectral index, $\alpha=-2/3$;
- **Full coherent addition**: $7.2 \times 10^{-15}$ for $\alpha=-2/3$ (to be achieved);
Other pulsar science: study of single pulses & “jitter” noise

- Single pulses of MSPs are seen to be variable, resulting in small phase variation in integrated pulse profiles (pulse phase jitter);
- MSP timing precision is now mostly limited by white noise, but will be limited by jitter noise with the next generation of radio telescopes (e.g., the SKA);
- Major aim: a). Quantify jitter noise; b). Characterize pulse variability; c). Mitigate jitter;

PSR J1713+0747: 10-s integrations → 600 ns residuals, consistent with previous results (Shannon & Cordes 2013; Dolch et al. 2014)!
Other pulsar science: pulsar searching

Plan & strategy:

• Target search for unknown sources (e.g. Globular Cluster, known DNS system);
• Phase up with nearby / in-beam known pulsars / calibrators;
• Pulsation search & upper limit on flux density for companions in double-neutron-star;

Redetection of J1518+4904 (a double-neutron star system)!

• Limit on the companion of J1518+4904: 0.31 mJy with 5-min integration;
Other pulsar science: study of interstellar medium

• Study the scattering screen along the line-of-sight, by looking at both pulse profile temporal broadening and imaging;

• LEAP observed the magnetar (J1745-2900) near the Galactic Centre, on Nov. 2013, repeated on Nov. 2014;

Summary

• Sgr A* and J1745–29 have same scattering properties

• temporal and angular broadening from one screen

• preliminary result \( \Delta = 0.50 \), \( D = 4.2 \text{kpc} \)

  ★ Lazio & Cordes (1998) \( 0.13 \text{pc} \)

  ★ Bower et al. (2014), Spitler et al. (2014) \( 5.9 \text{kpc} \)

For more details, see http://evn2014.oa-cagliari.inaf.it/EVN2014/Talks/06%20Fri%20Morning/Wucknitz_EVN2014.pdf
Project status

- Up to now, the project has collected 4.4 PB data!
- 2 PB (43%) have been processed!
- Currently performing three-week correlation campaign: No more backlogs!
- Started to reduce the amount of backlogs!

- LEAP has and will continue with multiple sources of funding support;
- LEAP data will be included in the next version of EPTA dataset;
- Interested in science with LEAP data? Talk to one of the team members!
To summarize...

**EPTA**
- Multi-frequency
- Single telescope
- High cadence
- Timing

**LEAP**
- Single frequency (multiple telescope)
- High-sensitivity timing

**Data Analysis**

**Input Streams**
- TOAs
- Interstellar weather
- Observatory/clock offsets
- Pulsar stability/jitter

**Output Streams**
- Imaging
- Searching

**Science Goals**
- GW Detection
- Gravity tests
- Interstellar Medium Studies
- Pulsar emission

*Primary* → Science Goals → *Secondary*
In the near future...

Polarization modes – Spin 2?

Amplitude, characteristic strain $h$

Locate the binary SMBH in the sky:

GW frequency ($nHz$)
In the near future...

Locate the binary SMBH in the sky:

Polarization modes – Spin 2?

Stay tuned for GW with pulsars!

Thank you!