Survey for Pulsars and Extra-galactic Radio Bursts

Ewan Barr
SKA Senior Research Fellow,

Tuesday, 17 June 14
HTRU Discoveries

Radio loud magnetar  
(Levin et al. 2010)

Fast Radio Bursts  
(Thornton et al. 2013)

“Diamond planet” pulsar  
(Bailes et al. 2011)
WHAT NEXT?

- Desire to keep momentum with new Parkes discoveries
- Many pulsars to be found before MeerKat, FAST and company come online
- Exotic systems often require multiple passes of any given survey field to be detected (scintillation is your frenemy)
- New processing tools available due to the wide availability high performance accelerator hardware
- New facilities available to perform shadowing and follow-up
- Many mysteries still to be solved and much science to be done (pulsars just keep giving)
Survey for Pulsars and Extra-galactic Radio Bursts
SUrvey for Pulsars and Extra-galactic Radio Bursts
KEY SCIENCE

- MSPs for GW experiments
- Find extreme systems
- FRB localisation, spectrum and polarisation properties
- Technology demonstration for next-generation instruments
TARGET FIELD

- Extends the HTRU medium latitude survey out to ±25 degrees
- Fills in “gaps” in HTRU high latitude tessellation pattern
- Probing latitudes known to contain FRBs

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tobs</td>
<td>9 minutes</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>340 MHz</td>
</tr>
<tr>
<td>Gain</td>
<td>~0.6 K/Jy</td>
</tr>
<tr>
<td>Nbeams</td>
<td>86372</td>
</tr>
<tr>
<td>Ttotal</td>
<td>1000+ hours</td>
</tr>
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TECHNOLOGY

- gSTAR / swinSTAR cluster
- 249 C2070, M2070 and K10 class GPUs
- BPSR pulsar search backend
- 14 C2070 class GPUs
REAL-TIME TRANSIENTS

HEIMDALL
(Barsdell et al. in prep.)

• Searches out to a DM of 2000 pc/cc
• Sensitive to pulses as narrow as 64 us
• Discovered several FRBs and RRATS
REAL-TIME ACCELERATION SEARCH

PEASOUP (Barr et al. in prep.)

- Capable of high speed linear acceleration correction
- Required for detection of relativistic binaries
- Fastest ever pulsar searching system (100 times)

Pea soup

Pea soup or split pea soup is soup made typically from dried peas, such as the split pea. It is, with variations, a part of the cuisine of many cultures. [Wikipedia]

Nutrition Facts
Pea soup

<table>
<thead>
<tr>
<th>Amount Per 100 grams</th>
<th>Calories 61</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Fat 1.1 g</td>
<td>1%</td>
</tr>
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</table>

% Daily Value*
MACHINE LEARNING & CANDIDATE CLASSIFICATION

SPINN
(Morello et al. 2014)

- “Minimalist” neural network implementation
- Implements multibeam candidate pre-selection
- Overcomes overspecification issues of predecessors
- 0.01% false positives for 100% recall rate
PEASOUP + SPINN

- Pipeline tested on HTRU medlat survey (50 m/s/s and 0-400 pc/cc)
- 7 new pulsars discovered (3 confirmed in real time)
- 3 MSPs including fastest pulsar outside of a globular cluster (669 Hz)
SYNERGIES

Shadowing

MOST

Multi-λ followup

ATCA

Swift

LIGO

Magellan

Thai

PTF

Faulkes
• Key science objectives:
  • 24/7 burst monitoring for FRB population statistics
  • Timing of 500+ pulsars per day (glitch monitoring, timing noise investigations)

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<tr>
<td>FOV</td>
<td>9.76 sq.deg</td>
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MOLONGLO

Key science objectives:

- 24/7 burst monitoring for FRB population statistics
- Timing of 500+ pulsars per day (glitch monitoring, timing noise investigations)

Key SUPERB synergies:

- Confirmation of the astrophysical origin of FRBs !!!
- Better FRB localisation for optical/x-ray/radio follow-up
- Much better constraints on the intrinsic spectra of FRBs (and on DM sweep index)

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</table>
• Well on way to full operation, 80% of hardware in place
• GPU powered correlator, coherent dedispersion backend and burst searching systems
• Automatic baseband dump triggers from Parkes
• Socialist science... all timing data will be public “instantaneously”
• Co-observations with PPTA for precision DM discrimination
• Potential for HI mapping for BAO at $z \sim 0.7$
Conclusions

• SUPERB will:
  • Find a host of new pulsar systems ( ~20 MSPs and ~100 normal pulsars )
  • Find & localise FRBs
  • Constrain FRB spectra
  • Provide the first FRB polarisation information
  • Solve the “June problem” and improve rate estimates
  • Demonstrate the immense power of GPUs for pulsar and transient searching
  • ...much more
PULSAR SEARCH: DEDISPERSION

\[ D_{DM,t} = \sum_{\nu} A_{\nu,t+\Delta t(\text{DM},\nu)} \]

Sum all frequencies along lines of constant dispersion measure

\[ \mathcal{O}(N_t N_\nu N_{DM}) \]
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DEDISPERSION

\[ \Delta DM = \frac{-4\pi m_e c v_a^2 \beta (\epsilon \Delta \nu - \nu_a)^2}{e^2 \epsilon \Delta \nu (\epsilon \Delta \nu - 2\nu_a)} \]

\[ \beta = \sqrt{w_{int}^2 + t_{samp}^2 + t_{DM_{chan}}^2} \]

Typically \( \sim 3000 \) trials

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PULSAR SEARCH: ACCELERATION SEARCHING

• Spin frequency of pulse is Doppler shifted by motion in orbit.

• Spreads signal in the Fourier domain, lowering S/N.

• $df/dt$ dependent on orbital acceleration.

$$a(A_T) = -\Omega_b^2 \frac{a_p \sin i}{1 - e^2} (1 + e \cos A_T)^2 \sin(\omega + A_T)$$
PULSAR SEARCH: ACCELERATION SEARCHING

- Searching all orbital parameters is too costly.
- Approximate df/dt as constant over segments of orbit.
- Valid approximation for circular orbits where $T_{obs} < P_{orb}/10$. 
PULSAR SEARCH: ACCELERATION SEARCHING

- For eccentric orbits, approximation breaks down.
- Either break observation and re-search, or reobserve in the hope of a better orbital phase.

PSR J0737-3039
PULSAR SEARCH: 
TIME DOMAIN RESAMPLING

\[ A_{a,t} = B_t[1+a(t-t_{\text{obs}})/2c] \]

Stretch and compress time series to emulate frequency drift

\[ \mathcal{O}(N_a N_t N_{\text{DM}}) \]
\[ \Delta a = \frac{48 \beta c}{t^2_{\text{obs}}} \sqrt{\left( \frac{1}{\epsilon^4} - 1 \right)} \]

N\text{trials depends on } t_{\text{obs}}^2

(10 mins gives 700 trials)
PULSAR SEARCH: FAST FOURIER TRANSFORM

$\mathcal{O}(N_aN_{DM}N_t \log_2 N_t)$

Best performance with prime factorable $N$

Real to complex FFT, exploits Hermitian symmetry to reduce complexity
DFT response is imperfect at bin edges
Interpolate to improve response to arbitrary frequencies
PULSAR SEARCH:
SPECTRAL INTERPOLATION

\[ A_i = \max \left( B_i, \frac{1}{\sqrt{2}}(B_i + B_{i+1}) \right) \]

\[ \mathcal{O}(N_a N_{DM} N_t) \]
PULSAR SEARCH: HARMONIC SUMMING

- Pulse power spread in Fourier domain.
- Incoherently add harmonics to increase signal.
- For $N_h$ harmonic numbers.
PULSAR SEARCH:
HARMONIC SUMMING / PEAK FINDING

\[ A_{i,N_h} = \frac{1}{\sqrt{N_h}} \left( B_i + \sum_{h}^N B_{(ih/N_h)} \right) \]

\[ O(2^{N_h} N_a N_{DM} N_t) \]

- After each harmonic sum we threshold the spectrum and mark candidates above the threshold.
- Sort candidates above threshold by signal-to-noise or power.
- Store candidates for application of clustering algorithms.

\[ O(N_h N_a N_{DM} N_t) \]