Practical application of cyclic spectroscopy to pulsar signals

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on behalf of the NANOGrav IMM group:
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Outline

• Motivation
• Intro to cyclic spectroscopy – what is it?
• Deconvolution with CS
• Results from real observations
• How well can we expect CS deconvolution to perform?
• Towards routine use of CS
Motivation: Improving pulsar timing

• Careful measurement of time of arrival of pulsar signals provides a unique probe of exotic physics.
• At frequencies below ~1 GHz, pulsar time of arrival estimation is strongly influenced by scattering in the interstellar medium.
• Projects like NANOgrav need more pulsars which can be accurately timed.
Motivation: Deconvolving the ISM

Dispersion

\( H_{\text{disp}}(f) \)
all-pass, one parameter

Scattering

\( H_{\text{scatter}}(f) \)
stochastic, time variable

Dedispersion

\( H^{-1}_{\text{disp}}(f) \)
all-pass, one parameter

Descattering/Deconvolution?

\( H^{-1}_{\text{scatter}}(f) \)
stochastic, time variable

The dream...
Intro to pulsar signals

Idealized pulsar signal

More realistic pulsar signal

After convolution

\[ v(t) \]  \[ h(t) \]

\[ v(t) \ast h(t) \]
A more realistic transfer function

\[ h(t) \quad v(t) * h(t) \quad |v(t) * h(t)|^2 \]
Aside: What does ISM scattering look like?

Phase perturbations from clumpy ISM

Electric field at earth

Dynamic spectrum

Impulse response functions

Simulations based on code from Coles et al. 2011
Evolving complex impulse response function and secondary spectrum
Pulse profiles and Harmonics

Plots from P. Demorest PhD thesis
Intro to cyclic spectroscopy:
A simple simulated example

$h(t)$

Periodic Spectrum

Cyclic Spectrum

Periodic Correlation

Cyclic Correlation
Traditional spectrum of filtered noise:
Only magnitude is retained

Observed signal \[ y(t) = h(t) \star x(t) \]
ISM scattering
Original pulsar signal

\[ Y(\nu) = H(\nu)X(\nu) \]

\[ S_y(\nu) = |H(\nu)|^2 S_x(\nu) \]
Cyclic spectrum of filtered noise:
Phase information can be retrieved

\[ y(t) = h(t) \ast x(t) \]

\[ Y(\nu) = H(\nu)X(\nu) \]

\[ S_y(\nu; \alpha) = H(\nu + \alpha/2)H^*(\nu - \alpha/2)S_x(\nu; \alpha) \]

\[ S_y(\nu; \alpha_n) = H_{ISM}(\nu + \frac{\alpha_n}{2})H^*_{ISM}(\nu - \frac{\alpha_n}{2})I(n)S_0 \]
First data set: B1937+21 at Arecibo

- Single 4 MHz subband using ASP @ 430 MHz
- Written up in P. B. Demorest 2011 arXiv:1106.3345
B1937+21 Deconvolution step-by-step
Iteration 2

Source: B1937+21 Freq: 428.0 MHz Feval #0001 Merit: 1.998e+06 Grad: 8.571e+03
Iteration 4

Source: B1937+21
Freq: 428.0 MHz
Feval #0003
Merit: 1.991e+06
Grad: 8.517e+03

/psr/53791.47842.07.all.cyc
isub: 0
ipol: 0
nopt: 0
Iteration 5

\(/\text{psr}/53791.47842.07.\text{all.cyc isub: 0 ipol: 0 nopt: 0}
\)

Source: B1937+21 Freq: 428.0 MHz Feval #0004 Merit: 1.972e+06 Grad: 8.343e+03

![Graphs and charts related to the frequency analysis and model fit with various metrics such as log(|CS|), angle(CS), log(|CS model|), angle(CS model), log(Δmerit), and profiles.](image-url)
Iteration 7

Source: B1937+21  Freq: 428.0 MHz  Feval #0006  Merit: 3.713e+06  Grad: 1.129e+05
Iteration 8

Source: B1937+21 Freq: 428.0 MHz Feval #0007 Merit: 1.784e+06 Grad: 5.104e+03

Profiles
- Reference
- Intrinsic
- Measured
Iteration 9

Source: B1937+21 Freq: 428.0 MHz Feval #0008 Merit: 1.742e+06 Grad: 5.485e+03
Iteration 10

Source: B1937+21  Freq: 428.0 MHz  Feval #0009  Merit: 1.707e+06  Grad: 2.073e+03
Iteration 31

Source: B1937+21 Freq: 428.0 MHz Feval #0030 Merit: 1.659e+06 Grad: 7.851e+02
Second dataset: J1713+0747 at Arecibo

- 327 MHz, 430 MHz, and 1400 MHz
- 10 MHz subbands
- Best timing NANOGrav pulsar (~40 ns RMS)
- Nipuni Palliyaguru leading this effort
J1713+0747 Iteration 1

Source: J1713+0747, Freq: 426.996 MHz, Feval #0000, Merit: 7.462e+03, Grad: 1.533e+02
J1713+0747 Iteration 10
J1713+0747 Iteration 18

Source: J1713+0747 Freq: 426.996 MHz Feval #0017 Merit: 6.516e+03 Grad: 8.329e+00
J1713+0747 Iteration 30

Source: 1713+0747 Freq: 426.996 MHz Feval #0030 Merit: 6.503e+03 Grad: 7.207e+00
Third dataset B1937+21 at Arecibo at L-Band
Lead by Tim Dolch
32 x 6.25 MHz raw bands (PUPPI baseband)

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>$\Delta \nu_d$ (MHz)</th>
<th>$\Delta t_d$ min</th>
<th>$\tau_s$ (µs)</th>
<th>$T_{\text{ref}}$ (days)</th>
<th>flux (mJy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1420</td>
<td>0.9</td>
<td>7</td>
<td>0.3</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>430</td>
<td>0.004</td>
<td>1.7</td>
<td>40</td>
<td>120</td>
<td>240</td>
</tr>
<tr>
<td>327</td>
<td>0.001</td>
<td>1.1</td>
<td>120</td>
<td>180</td>
<td>400</td>
</tr>
</tbody>
</table>

1360.625 dynamic spectrum
B1937+21 Iteration 1

1937on9-28-12notfixed6-9.cyc.fix isub: 0 ipol: 0 nopt: 0
Source: B1937+21 Freq: 1323.125 MHz Feval #0000 Merit: 1.783e+05 Grad: 3.870e+03
B1937+21 Iteration 31

1937on9-28-12notfixed6-9.cyc fix isub: 0 ipol: 0 nopt: 0
Source: B1937+21 Freq: 1323.125 MHz Feval #0030 Merit: 3.701e+04 Grad: 4.262e+01

- log|CS|
- dB|h(t)|
- log|CS model|
- log(Δmerit)
- Profiles
  - Reference
  - Intrinsic
  - Measured
B1937+21 Iteration 193
B1937+21 Iteration 476
Full 200 MHz BW

/home/t dolch/py cyc/2012-09-28-22:22:00.gp all.fix isub: 0 ipol: 0 nopt: 2
Source: B1937+21 Freq: 1373.125 MHz Feval #0100 Merit: 8.278e+05 Grad: 7.842e+01
B1937+21 single 25 MHz band
How well can we realistically expect CS deconvolution to “work”?

• Need to define success criteria
  – Improving timing precision
  – Determine amplitude AND phase of transfer function
  – Determine amplitude of transfer function

• Limitations are determined by nature more than by instrumentation
  – Bandwidth set by scintillation bandwidth
  – Integration time set by scintillation timescale
  – Harmonic content determined by pulse profile
  – Flux determined by pulsar
  – Pulse period determines number of realizations of self-noise per scintillation timescale
P-DM Regimes for Deconvolution Based on empirical DM-Scattering relation

**$N_b = 100$**

Blue $\Rightarrow$ Deconvolution not feasible or not useful

- **$0.1$ GHz**
  - Pulse Broadening too large
  - Scintillation time too small

- **$0.4$ GHz**

- **$1.4$ GHz**
  - No correction needed
  - $\Delta\nu_d > B/2$

- **$2.0$ GHz**

**$N_b = 100 \Rightarrow (10$ per cent error $)$ $B/\nu = 0.2$**

Slide credit: Jim Cordes
P-DM Regimes for Deconvolution

$N_b = 10^4$

Blue ⇒ Deconvolution not feasible or not useful

$N_b = 10^{4.0} ⇒ 1\text{ per cent error}$ \quad $B/\nu = 0.2$

![Graphs showing regimes for deconvolution with dispersion measures and periods](image)

Slide credit: Jim Cordes
Simulations

- Use simcyc code to simulate pulse profiles and transfer functions. Then compute CS
- Add noise to CS and attempt deconvolution
- Compare resulting transfer function to initial transfer function
- Experimented with a range of parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tau (microseconds)</td>
<td>2.0, 10.0, 100.0</td>
</tr>
<tr>
<td>Profile harmonic decay constant (~1/width)</td>
<td>3.0, 10.0</td>
</tr>
<tr>
<td>Pulsar period (milliseconds)</td>
<td>1.5, 4.0, 10.0</td>
</tr>
<tr>
<td>Signal to Noise Ratio (arbitrary units)</td>
<td>0.05, 0.10</td>
</tr>
</tbody>
</table>
Sharp profile, short period, moderate scattering → decent recovery
Sharp profile, longer period, significant scattering $\rightarrow$ partial recovery
Wide profile, long period, moderate scattering → poor recovery
Sharp profile, long period, slight scattering → recovery possible
Software for CS computation, deconvolution, and simulation

• CS computation:
  – dspsr http://dspsr.sourceforge.net/ (van Straten et al.)
  – Cudacyclo branch at https://github.com/gitj/dspsr : my effort to add GPU computation of CS

• Deconvolution:
  – CyclicModelling – Demorest and Walker: https://github.com/demorest/Cyclic-Modelling
  – pycyc & simcyc : my port of CyclicModelling to python with simulation capabilities: https://github.com/gitj/pycyc
  – Direct phase integration: Palliyaguru & Stinebring. Not yet released
Upcoming observations – 6 hours at Arecibo

• **Attempt to demonstrate real-time CS using GPUs**
• Hardware is available (borrow the PUPPI GPUs)
• 2 x 1 hour on B1937+21 @ 430 MHz to make sure everything’s working
• Science runs on B1953+29 and J2317+1439. For each:
  – 1 hour @ 327 MHz (312-342 MHz)
  – 1 hour @ 430 MHz (422-442 MHz)
  – 1 hour @ 1400 MHz
Upcoming observations – J1643-1224 @ GBT

• Bright pulsar with unusually high RMS timing residual – one of the worst in the NANOGrav sample
• Significant scattering
• → Hopefully a good candidate for correction!
• 12 hours awarded to observe at 350, 820, and 1400 MHz at multiple epochs

Table 1: Properties of PSR J1643–1224

<table>
<thead>
<tr>
<th>Flux (mJy)</th>
<th>350 MHz</th>
<th>450 MHz</th>
<th>820 MHz</th>
<th>1000 MHz</th>
<th>1400 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>τ_d (μs)</td>
<td>67</td>
<td>40.6</td>
<td>12.3</td>
<td>–</td>
<td>4.2</td>
</tr>
<tr>
<td>ν_d (Hz)</td>
<td>600</td>
<td>200</td>
<td>17</td>
<td>–</td>
<td>1.7</td>
</tr>
<tr>
<td>t_Diss (s)</td>
<td>270</td>
<td>770</td>
<td>9600</td>
<td>22000</td>
<td>90000</td>
</tr>
<tr>
<td>SEFD (Jy)</td>
<td>183</td>
<td>242</td>
<td>468</td>
<td>582</td>
<td>843</td>
</tr>
<tr>
<td>SNR per scintle</td>
<td>45</td>
<td>28</td>
<td>13</td>
<td>–</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>6</td>
<td>18</td>
<td>–</td>
<td>33</td>
</tr>
</tbody>
</table>
Simulation of J1643-1224 deconvolution
Towards real-time CS

- Current observations involve recording TBs of raw voltage data → not sustainable
- Once the data is recorded, processing takes forever (→ real time processing be limited to very small bandwidths)
- Correlation has high arithmetic intensity: well suited to GPUs
- Also working on overlapping filterbank front-end to avoid losses at subband edges
Adding CS Front-end to G/PUPPI

IF in

iBOB/BEE2 FPGA Filterbank

Network Switch

ROACH FPGA CS Overlapping Filterbank

CPU/GPU
CPU/GPU
CPU/GPU
CPU/GPU
CPU/GPU
CPU/GPU
CPU/GPU

Coherent dedispersion & Cyclic correlation
ROACH-based overlapping filterbank
GPU CS performance summary:
10-20 MHz per GPU node
GTX485
Conclusions

• Cyclic spectroscopy is a fascinating technique for studying pulsars and the interstellar medium.
• It is promising but there is no free lunch.
• Still very much under development; many avenues to pursue in intelligently constraining the optimization.
• Not guaranteed to “work” for any pulsar at any frequency: More observations underway!
• Exact deconvolution is difficult, but CS has other uses: RFI removal, excellent estimates of magnitude of transfer function
• Hardware advances will allow it to be used routinely