Calibrating CHIME

- or -

Bootstrapping our way towards a measurement of Dark Energy

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CHIME Collaboration

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CHIME at a glance

- Full CHIME is an interferometer with
  - 5 cylinders (20m x 100m)
  - 1280 dual-pol feeds total
  - Operates between 400—800 MHz
- Measures the entire available sky in a day (~3/4 of the sky)

- Pathfinder is a shorter 2-cylinder interferometer test-bed
  - 2 cylinders (20m x 40m)
  - 128 dual-pol feeds
  - Fielded!
  - First light!

First Light! (Cas A)
CHIME: A 21cm Dark Energy Experiment

Survey Volume

Power spectrum, BAO

Error bars scale with survey volume

Simulations

CHIME averaged to $z=1.5$
21cm not the only thing in the sky: Foregrounds

Foregrounds are $10^6 \times$ larger than our signal, but spectrally smooth
Can remove them!

Shaw et al 1401.2095

Power spectrum errors (400-500MHz)
(As long as we know our instrument)

Complex Gain Error

Shaw et al 1401.2095
(As long as we know our instrument)

Beam Error

Shaw et al 1401.2095
Calibration: Gain and Phase

• Noise Rigidization:
  • Insert known, common signal
  • Currently achieving ~-25dB gain calibration with our ‘hacked together’ system (need -30dB for 0.1%)
  • Have already managed to track changes from large RFI spikes destabilizing the gain in a single frequency bin
• Redundant Baselines: have multiple measurements of the same thing since our feeds are evenly spaced, should be able to use that to build a gain solution
Calibration: Beams

• Transit telescope
• Beam from a single feed is large
  • Can get transit data for a few very bright sources e.g. CasA, CygA, TauA, M87
• Not enough S/N for side lobe measurement
• Polarized sidelobes even more impossible
Calibrate with Holography

• Cross correlate with tracking telescope

• Correlation measures what is common between the two dishes

Put 400-800 MHz feed here

Track with this telescope

Correlate here
Holographically calibrating CHIME beams*

- Instrument response (gain, leakage) contained in Jones matrix $J$

For the 26m:

$$E_{\text{obs}}^{26} = J_{26}E_{\text{sky}}$$

For an $i^{th}$ feed on CHIME:

$$E_{\text{obs}}^i = J_iE_{\text{sky}}$$

* Neglecting noise
Holographically calibrating CHIME beams*

- We don’t get to observe electric fields:

\[ V = \langle E_{\text{obs}} E_{\text{obs}}^\dagger \rangle \]

For the 26m:

\[ V_{26} = \langle E_{\text{obs}}^{26} E_{\text{obs}}^{26\dagger} \rangle \]

\[ V_{26} = \langle J_{26} E_{\text{sky}} E_{\text{sky}}^\dagger J_{26}^\dagger \rangle \]

With known \( J_{26} \), we can solve for the Coherency matrix (C) using our measurement

\[ V_{26} = \langle J_{26} C J_{26}^\dagger \rangle \]

* Neglecting noise
Holographically calibrating CHIME beams*

• Use this to solve for CHIME Jones matrix

\[ V_{\text{hol}} = \langle E_{\text{obs}}^i E_{\text{obs}}^{26\dagger} \rangle \]

\[ V_{\text{hol}} = \langle J_i E_{\text{sky}} E_{\text{sky}}^{\dagger} J_{26}^{\dagger} \rangle \]

\[ V_{\text{hol}} = \langle J_i C J_{26}^{\dagger} \rangle \quad J_i = V_{\text{hol}} V_{26}^{-1} J_{26} \]

* Neglecting noise
Holography seems great! What do we look at?

- We would really like sources which are
  - Not extended
  - Polarized
  - Pretty bright
  - Lots of them at a range of declinations
Pulsars?

• We would really like sources which are
  ✓ • Not extended
  ✓ • Polarized
  ✓ • Pretty bright
  ~✓ • Lots of them at a range of declinations

Courtesy Liam Connor
How do you use pulsars?

\[ V_{26} = \langle J_{26} C J_{26}^\dagger \rangle \]

- Difference of pulsar on and pulsar off

\[ V_{\text{hol}} = \langle J_i C J_{26}^\dagger \rangle \]

\[ J_i = V_{\text{hol}} V_{26}^{-1} J_{26} \]

- Like any source, the intrinsic pulsar signal (C) can be found from \( V_{26} \) if we know \( J_{26} \)

- Differencing also removes common-mode signals slower than the pulsar (signal picked up by sidelobes, RFI, ...)
• Must take very fast cadence data
• To do this for all CHIME channels, we will have to gate in real time
• Analysis is more complicated
• Pulsar polarization angle rotates during the pulse (can try to use this to help you calibrate, but with care)
Calibrating 26m Galt beams

- This started with the statement ‘Assuming I know the Jones matrix of the 26m John Galt’

\[
\begin{align*}
V_{26} &= \langle J_{26}CJ_{26}^\dagger \rangle \\
V_{\text{hol}} &= \langle J_{i}CJ_{26}^\dagger \rangle
\end{align*}
\]

\[ \rightarrow J_{i} = V_{\text{hol}}V_{26}^{-1}J_{26} \]

- I don’t

- And its equatorially mounted

Standard for Azimuth/Elevation mounted telescope:

1. Observe a polarized source
2. For enough time that the parallactic angle rotates
3. Extract coefficients that rotate with the beam, away from the beam, and constant to solve for the Jones matrix
Calibrating 26m Galt beams

This started with the statement: ‘Assuming I know the Jones matrix of the 26m John Galt’

\[ V_{26} = \langle J_{26}CJ_{26}^\dagger \rangle \overrightarrow{J_i} = V_{\text{hol}} V_{26}^{-1} J_{26} \]

I don’t

And its equatorially mounted

Standard for Azimuth/Elevation mounted telescope:

1. Observe a polarized source.
2. For enough time that the parallactic angle rotates.
3. Extract coefficients that rotate with the beam, away from the beam, and constant to solve for the Jones matrix (encodes gain, leakage, instrumental pol, etc).
Calibrating 26m Galt beams

• Traditional approach:
  • Measure some polarized sources
  • Measure an unpolarized source
  • Look at the North Celestial Pole

• Less traditional approach:
  • Calibrate a huge Az/El telescope (like the Algonquin Park ARO 46m)
  • Do very long baseline pulsar holography between those two dishes
  • Same Jones math applies, use the known 46m signal to get the 26m Jones matrix
Calibrating 26m Galt beams

Traditional Approach

• Pros:
  • No bootstrapping

• Cons
  • 0.1% calibration hard
  • Must calibrate the entire beam that well to figure out just the bit where the pulsar is

Non-traditional Approach

• Pros
  • Can calibrate only where the pulsar is and the (messy) 26m beam is differenced away

• Cons
  • 0.1% calibration still hard
  • Have to calibrate ARO better than 0.1%
  • Require accurate timing, consideration of Faraday rotation different between the two sites
Calibration Run!

- Made pulsar holography measurements in May with 26m and CHIME
- Made VLBI measurement in August between ARO and DRAO
- How did it go?
Holography achieved

- Pulsar holography between 26m and CHIME in May
  - Learned how to run the 26m John Galt telescope
  - Measurements went smoothly
  - Still analyzing the data (pulsars are complicated things)
Re-doing 1967

Team DRAO

Mateus Fandino

Liam Connor

Team ARO

(me)
Re-doing 1967: Day 1

Team DRAO pulls ahead as Team ARO has a small disaster
Re-doing 1967: Day 2

Team ARO recovers, and pulls ahead as Team DRAO has a small disaster
Re-doing 1967: Day 3

Team DRAO recovers (thanks actual team DRAO!) but only pulls even with team ARO, because of other disasters on both sides.

- Extremely accurate maser timing signal won’t cooperate with our readout boards!
- Overheard on intercom: ‘The telescope isn’t moving, nope, that didn’t work either’

Team ARO

Team DRAO

- Mateus cannot find a car rental because its a long weekend!
- Borrows car, which breaks down in Chilliwack, must turn back!
Re-doing 1967: Day 4

Its neck and neck!

Telescope moves!

Team
ARO

Team
DRAO

Mateus arrives!
Data is taken!!!!!!!!
(its even on schedule!)

... but we’re still analyzing it
Status & Summary

- Calibration for CHIME is important and difficult
- Plan underway to constrain beams with holographic measurements using the 26m
- Some initial data is in the can and currently being analyzed to figure out what we need to do better!

Thanks!