Data Acquistion, Calibration & Foregrounds

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Data Acquisition

- We imagine an array that produces
  - 4096 channels of data
  - 500 MS/sec (Mega-Samples/sec) per channel
  - 32 bits per sample
- A few Gb size DDR3 SDRAM memory chips *per channel* should be sufficient.
  - Separate read/write chips
  - Double buffer for accumulate/readout

Data Acquistion (con't)

- A single computer PCI express can accommodate 32 bits at 500 MS/sec and is therefore adequate for the entire system if a minimum of 4096 accumulations is made.
- A single disk drive could maintain a rate of 100 MB/sec. This would require a minimum of 20x4096=81920 accumulations (about 10 sec for a record length of 131 μsec)
- Total amount of data per day (18 hrs) is 6.5 TB
- Data disks can be "mailed" to a remote site (s).

Data Monitoring

- Sequence data acquisition
  - Survey data
  - Calibration data
- Calculate & update calibration constants
- Monitor
  - ADC: mean, rms, minimum, maximum
  - Digital processing: exceptions
  - Power distribution: voltages & currents
  - Temperatures?
- Alarm on abnormal conditions

Calibration the Problem

- We need to calibrate
  - Frequency response for foreground subtraction
  - Polarization response for foreground subtraction
  - Spatial response for BAO power spectrum (Is spatial response necessary for foregrounds?)
- Requirements
  - Frequency of calibration (~minutes?)
  - Accuracy of frequency calibration (10^{-5}?)
  - Accuracy of spatial calibration (10%?)

Calibration: Solutions

- The ultimate goal is to have a good model of the instrument response. We don't really care what the data look like if we can back out the correct sky model.
- Some features of the instrument have to be calibrated in real time: Gain and phase equalization of different channels (?)
- Some features are difficult or impossible to calibrate in real time: Antenna shape parameters

Instrument Model

- Each electronics channel has a complex gain that varies rapidly (faster than 1 day) with time.
- Each antenna has average properties that are fixed in time (changes much slower than 1 day).
  - Identical antennas with pointing errors?
  - Assume perfect spacing?
  - Antenna gain variations (field pattern shape)?
  - Can antenna-LNA mismatches and feed-to-feed coupling be compensated with an overall gain?

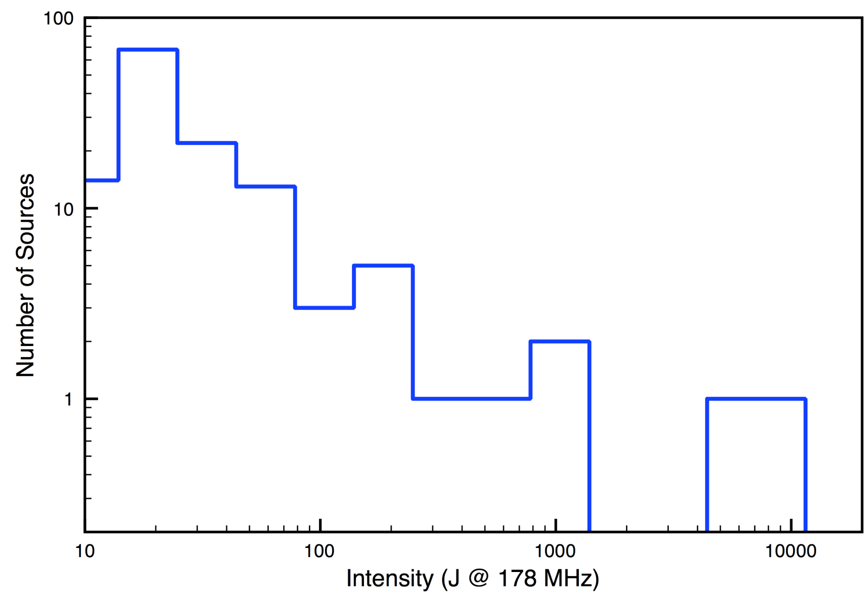
Calibration-Artificial Sources

- Pulse LNA via capacitive coupling (Doesn't measure antenna match, cabling might be awkward)
- Excite feed via radiation (difficult to get in far field at a reasonable angle)
- Balloon on a tether (labor intensive, need position)
- Airplane (expensive, need to track position)
- Satellites (no control, fixed frequency)

Spatial: Point Sources

- Many 10 to 100 J point sources
- Good absolute calibrators: positions are known much better than the CRT resolution and the fluxes are known accurately.
- Source is within aperture for limited period of time
- Good S/N if angular resolution is adequate.
  - 1J @ 178 MHz = 30 °K over 20′x20′
  - 1J @ 178 MHz = 15 m°K over 90°x2.5°
- Accuracy is limited by S/N

Intensities of 3C catalog sources



Spatial: Full Sky

- Simply require that visibilities with the same baseline be equal, *i.e.*, for all *m*, *n*

$$\langle a_m a^*_{m+\ell} \rangle = \langle a_n a^*_{n+\ell} \rangle$$

- Many advantages over using point sources
  - No knowledge of the sky is required
  - Variable sources do not affect the result
  - Integration time does not depend on aperture
- Calibration depends on sky pattern if the feed responses are not identical.
- Calibration limited to relative gain responses.

Frequency & Polarization

- All-sky surveys (c.f. Oliveira-Costa 2008 compilation)
- Measurements of single point sources (e.g., Kellermann 1969)
- Are there any calibrated broad spectrum measurements?
- We will have to *assume* that the average sky has a smooth spectrum and fit to that model.
- We will have to *assume* that the average sky is unpolarized.
- Polarized sources will be assumed to have a smooth power spectrum.

Calibration from FFT data

- With a known sky, we can determine at most 1 parameter per beam. We can't, for example, determine a complex gain for each channel.
- It is "easy" to measure the (absolute) antenna response in the azimuthal direction since the sky rolls across the antenna pattern.
- The polar angle is calibration is more problematic
  - Known sky
  - Known point sources
  - Artificial sources (satellites, airplanes, balloons)

Dithering
for Increased Spatial Resolution

- In principle, we can achieve higher spatial resolution by changing the telescope pointing by an amount that is small compared to the telescope resolution.
- Higher resolution comes at a price of S/N: you get higher resolution by subtracting overlapping bins.
- The azimuthal dithering happens naturally: the only price is how finely you want to log the data.
- The declination dithering requires the addition of a phase shift to each channel: this can be done digitally.

FFT Concept

$$\left|d_n\right|^2 = \frac{1}{N^2}\sum_{\ell=1}^{N}\sum_{m=1}^{N} e^{2\pi i(\ell-m)/N} a_\ell a_m^*$$

$$P = \sum_{m=1}^{N} a_m a_m^*$$

$$\left|d'_n\right|^2 = \frac{1}{N^2}\sum_{\ell=1}^{N}\sum_{m=1}^{N} e^{2\pi i(\ell-m)/N} a_\ell a_m^* - P$$

CRT Simulated Data

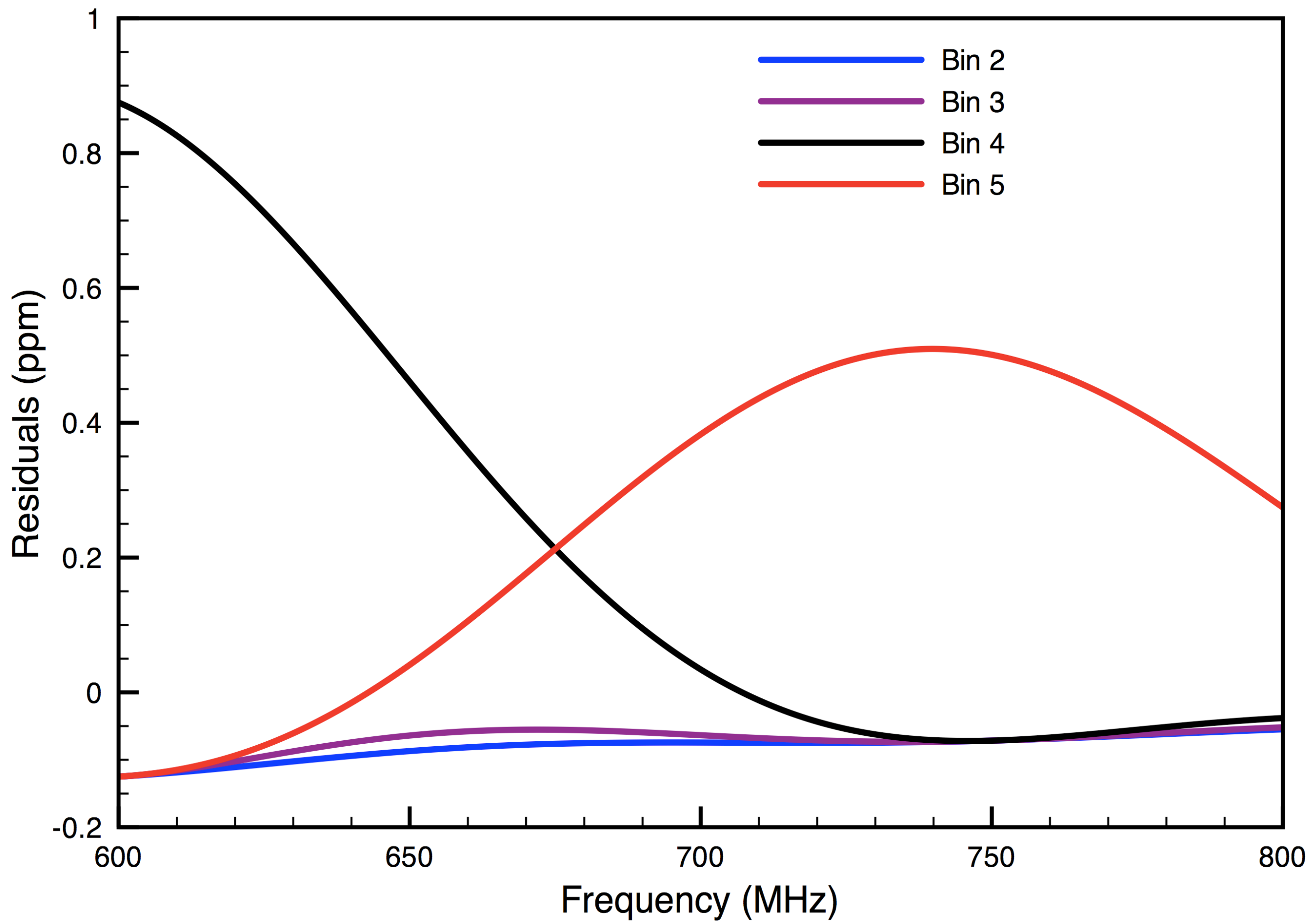
Simulated point source data for 8 azimuthal bins at Δf=50 kHz

0	-0.12500	-0.12500	-0.12500	-0.12500	0.87500	-0.12500	-0.12500	-0.12500
1	-0.12497	-0.12497	-0.12497	-0.12497	0.87482	-0.12497	-0.12497	-0.12497
2	-0.12495	-0.12495	-0.12495	-0.12495	0.87463	-0.12495	-0.12495	-0.12495
3	-0.12492	-0.12492	-0.12492	-0.12492	0.87445	-0.12492	-0.12492	-0.12492
4	-0.12490	-0.12490	-0.12490	-0.12489	0.87427	-0.12489	-0.12490	-0.12490
5	-0.12487	-0.12487	-0.12487	-0.12487	0.87408	-0.12487	-0.12487	-0.12487
6	-0.12484	-0.12484	-0.12484	-0.12484	0.87390	-0.12484	-0.12484	-0.12484
7	-0.12482	-0.12482	-0.12482	-0.12481	0.87371	-0.12481	-0.12482	-0.12482
8	-0.12479	-0.12479	-0.12479	-0.12478	0.87352	-0.12478	-0.12479	-0.12479
9	-0.12476	-0.12476	-0.12476	-0.12476	0.87333	-0.12476	-0.12476	-0.12476
10	-0.12474	-0.12474	-0.12474	-0.12473	0.87315	-0.12473	-0.12474	-0.12474
11	-0.12471	-0.12471	-0.12471	-0.12470	0.87296	-0.12470	-0.12471	-0.12471
12	-0.12469	-0.12469	-0.12468	-0.12467	0.87277	-0.12467	-0.12468	-0.12469
13	-0.12466	-0.12466	-0.12466	-0.12464	0.87258	-0.12464	-0.12466	-0.12466
14	-0.12463	-0.12463	-0.12463	-0.12461	0.87238	-0.12461	-0.12463	-0.12463
15	-0.12461	-0.12461	-0.12460	-0.12458	0.87219	-0.12458	-0.12460	-0.12461
16	-0.12458	-0.12458	-0.12458	-0.12456	0.87200	-0.12455	-0.12458	-0.12458
17	-0.12455	-0.12455	-0.12455	-0.12453	0.87181	-0.12453	-0.12455	-0.12455
18	-0.12453	-0.12453	-0.12452	-0.12450	0.87161	-0.12450	-0.12452	-0.12453
19	-0.12450	-0.12450	-0.12449	-0.12447	0.87142	-0.12446	-0.12449	-0.12450
20	-0.12447	-0.12447	-0.12447	-0.12444	0.87122	-0.12443	-0.12447	-0.12447

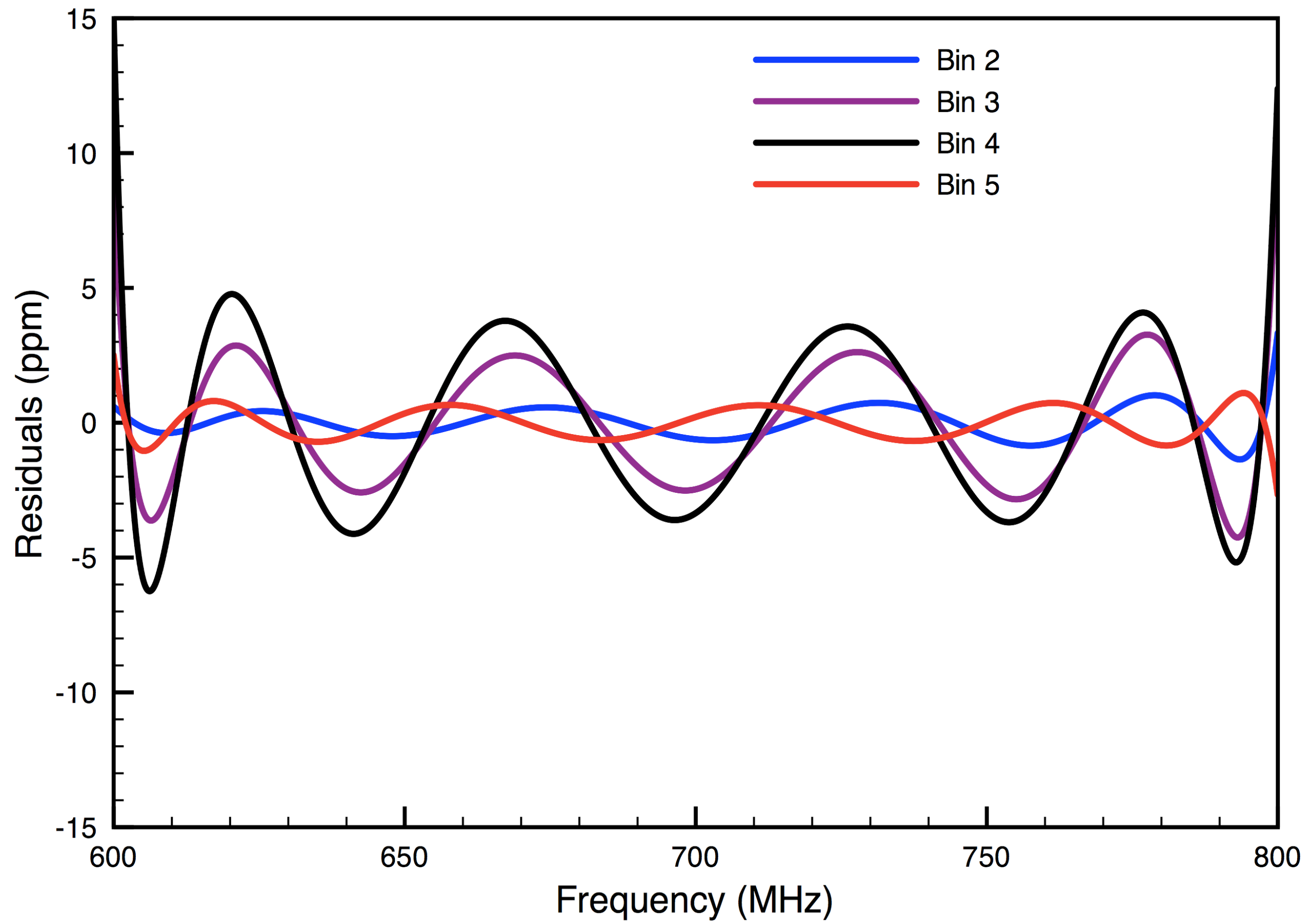
Frequency bins→

Azimuthal bins -→

Bin Population vs Frequency



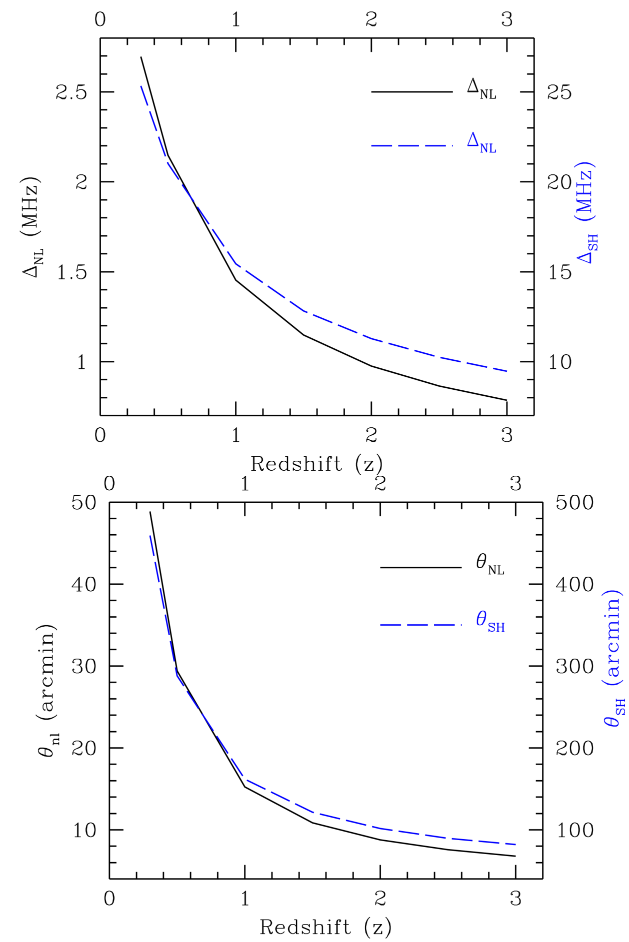
Residuals from Polynomial Fit



BAO Scale in Practical Units

- The non-linear regime set the requirement for angular and frequency resolution.
- The sound horizon is the minimum coverage range for BAO, but…
  - Synchrotron foreground
  - Large scale structure

require much larger angle and frequency coverage.



Instrument Correction

- If we have an instrument model, correcting the data is straight-forward.
- The instrument model can be expressed as an $N \times N$ matrix, where N is the number of channels.
- Calibration of each of N^2 elements is probably not feasible.

Conclusions

- Data Acquisition seems straight-forward and relatively low cost.
- Control and monitoring seems straight-forward.
- Foreground subtraction is a key driver
  - Work is need to understand the existing literature.
  - We need a strawman strategy for CRT.
  - We need some experimental work.
- Spatial resolution requirements appear to be modest provided we don't need high precision ($\sim 10^{-5}$) for foreground subtraction.
- Some ideas have been developed for calibration.
- A simple approach to foreground subtraction seems promising, but in apparent contradiction to the conventional wisdom.

Sensitivity Calculations

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Work in Progress