Cylindrical Radio Telescope

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References

- R. Ansari, et al., "Reconstruction of HI power spectra with radio-interferometers to study dark energy," arXiv:0807.3967 (July 2008)
- Tegmark & Zaldarriaga, "The Fast Fourier Transform Telescope," arXiv:0805.4414v1 [astro-ph] (May 2008)
- Chang, Pen, Peterson, & McDonald, "Baryon Acoustic Oscillation Intensity Mapping as a Test of Dark Energy," arXiv:0709.3672v2 [astro-ph] (Jan 2008)
- Peterson & Bandura, "The Hubble Sphere Hydrogen Survey," arXiv:astro-ph/0606104v1 (June 2006)

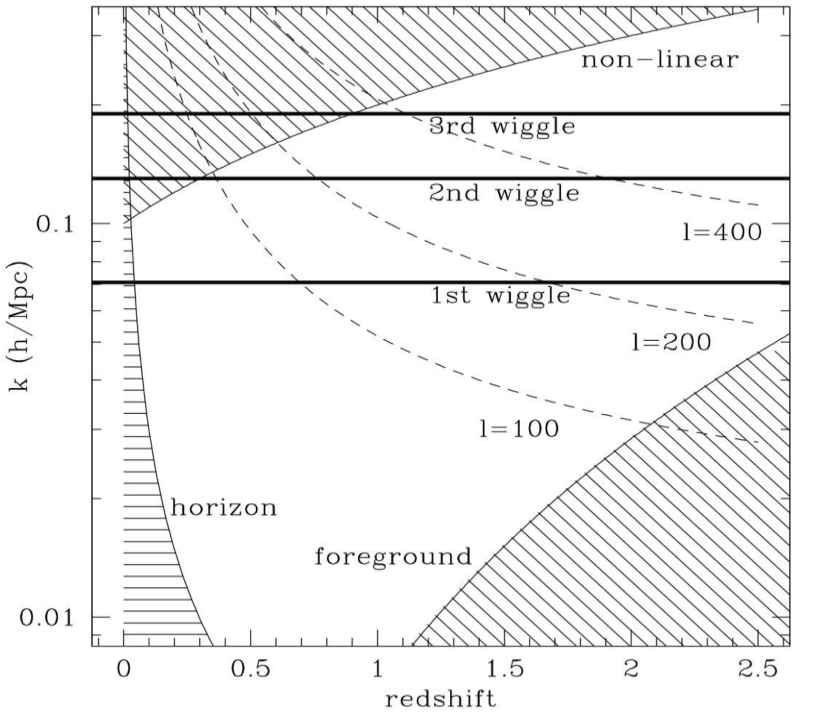
CRT Proposal Status

- Proposal to build the CRT in Morocco is pending. International collaborators include Carnegie-Mellon, Toronto, CEA, & FNAL.
- Proposal to build the CRT at Penticton, B.C. by a Canadian universities. At the moment the only non-Canadian participant is Peterson from Carnegie-Mellon.
- There are no pending requests to U.S. agencies for construction funds.

BAO Region of Interest

Limitations

- Non-linear region?
- Angular coverage and cosmic variance?
- Foreground?
- Coverage of 2 to 3 BAO peaks is possible in the redshift range 0.5 to 2.0



Chang, et al., 2008

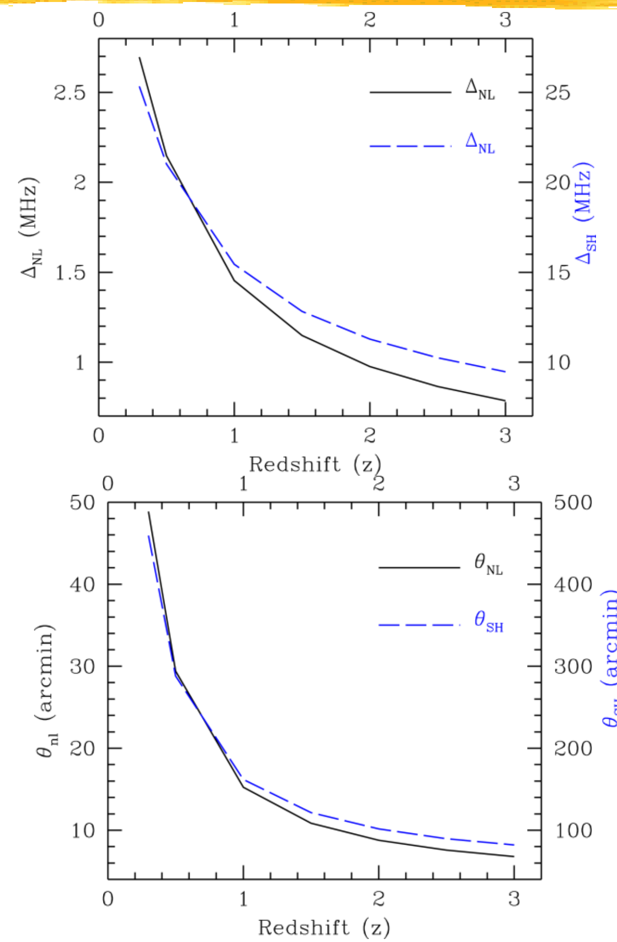
Design Parameters

- Antenna size
  - Spatial resolution
  - Spatial coverage
- Signal-to-Noise
  - Number of Channels
  - Dense versus sparse packing

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.



Antenna Array Size

- Angular resolution determines a minimum antenna array size.

$$\Delta\theta = \lambda / D$$

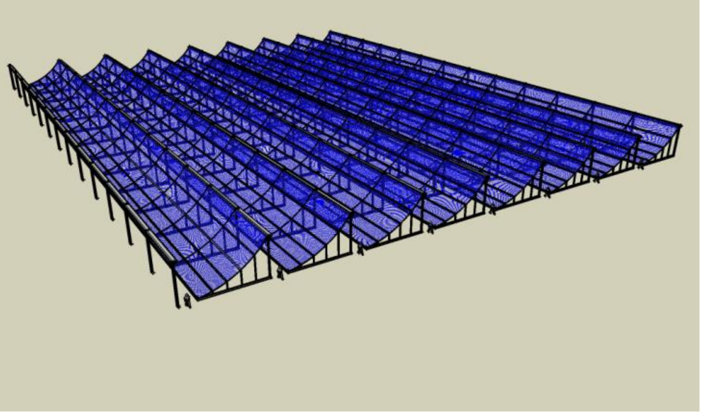
- A 100m×100m antenna gives a resolution of ~10 to 20 arc-minutes
- An array of pickups enables the formation of many beams
  - The maximum number of beams is equal to twice the number of baselines.
  - A critically sampled fully packed array will yield N independent measurements of N/2 baseleines (in each dimension).
  - A sparsely sampled area would have one measurement of each baseline and would require ~sqrt(N) detectors

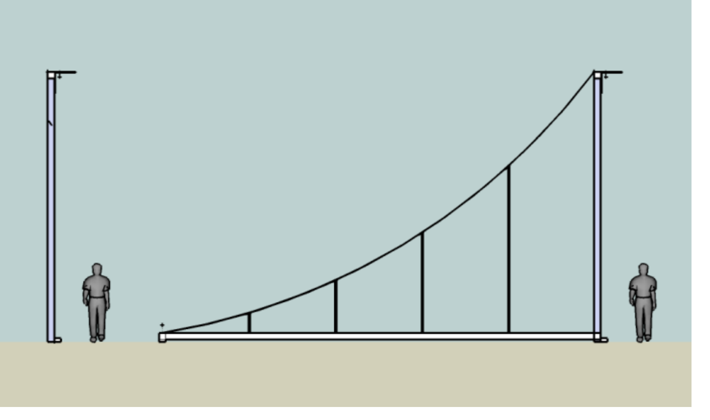
Cylindrical Telescope

- Focussing options
  - No focussing (LOFAR)
  - Focussing in one dimension (cylinders: this proposal)
  - Focussing in two dimensions (array of dishes)
- Focussing reduces the number of channels required (lower cost) but also reduces the angular coverage (more time to complete the survey).
  - A cylinder oriented in the N-S direction allows full sky coverage with a fixed array.
  - Large channel counts require economical design and efficient signal processing.

Antenna Array

- Reflecting shape is a tensioned wire mesh.
- Cylinder shape is a segment of a parabola.
- Cylinder height ~5 m.
- Cylinder width ~10 m.
- Array consists of 8 uniformly spaced cylinders.
- Feed line attached to pole/antenna support.





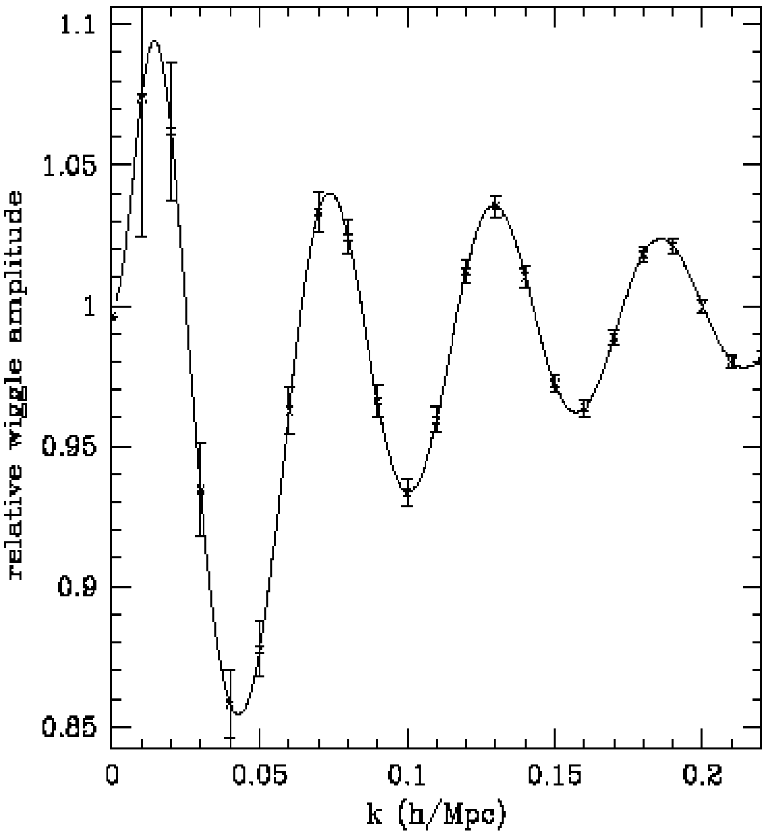
Feed Spacing

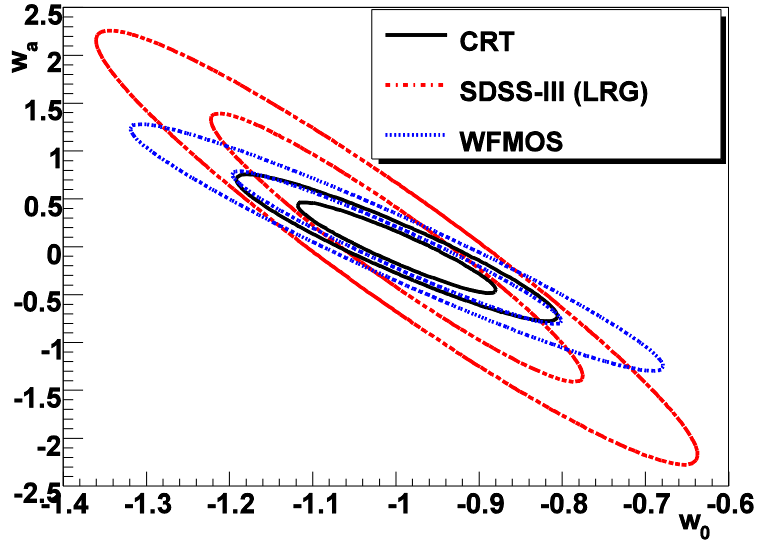
- If unfocused
  - Critical sampling requires a spacing of $\lambda/2$ – assuming sensitivity to the horizon.
  - The effective area coverage of a short dipole antenna is $\lambda^2/8\pi$
- If focused
  - The antenna spacing requirements scale inversely with the aperture but are sensitive to sidelobe shape
  - Aliasing ambiguities are resolved by sensitivity pattern changes as the earth rotates.

Signal to Noise Ratio

- 21 cm signal is ~300 μK (total)
- 21 cm large scale structure is ~150 μK at the third BAO peak (d~18h^{-1} Mpc)
- 21 cm BAO signal is ~300 nK modulation on the large scale structure.
- There are LOTS of pixels (10^{11})
- The Chang et al. paper estimated the accuracy that could be obtained with a 200 m x 200 m array assuming 100 μK per pixel thermal noise.
- The estimated observing time per pixel was 18 h/pixel.
- For a smaller array (100m x 100m) and accounting for the duty factor caused by the rotation of the earth, the same accuracy could be reached in ~1year of observation.

Experimental Precision





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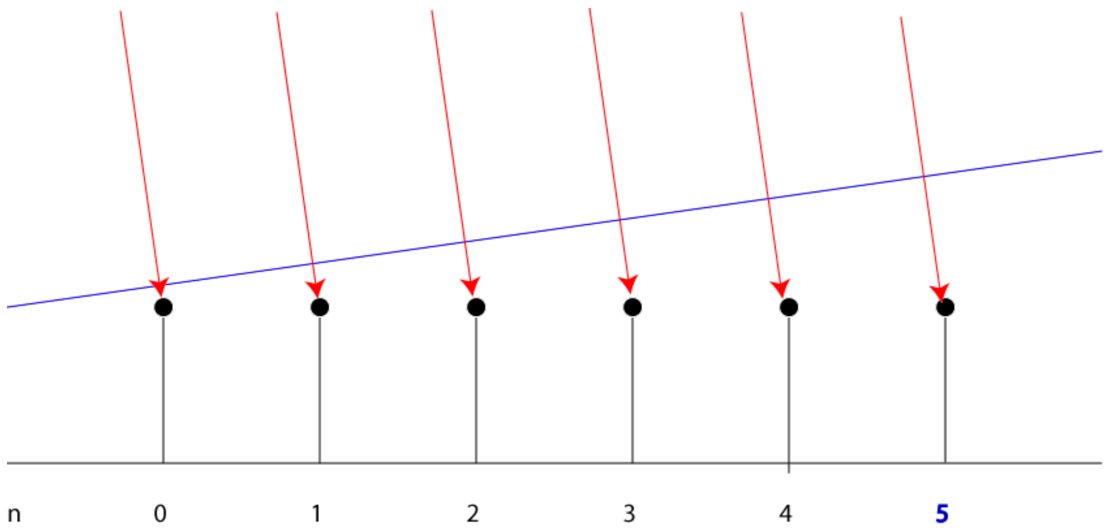
Data Processing

- FFT concept
- Signal processing

FFT Concept



$$\phi = nkd\theta$$

$$a_m = \frac{1}{N}\sum_{n=1}^{n} v(\theta)\, e^{in(\theta kd - 2\pi m/N)}$$

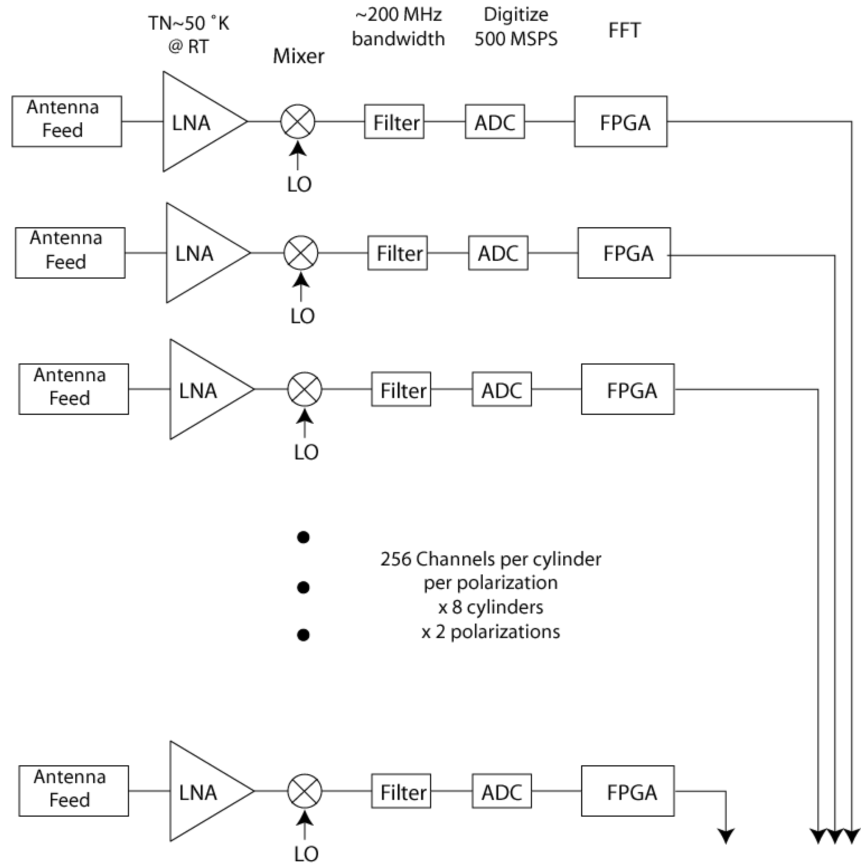
More FFT Concepts

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

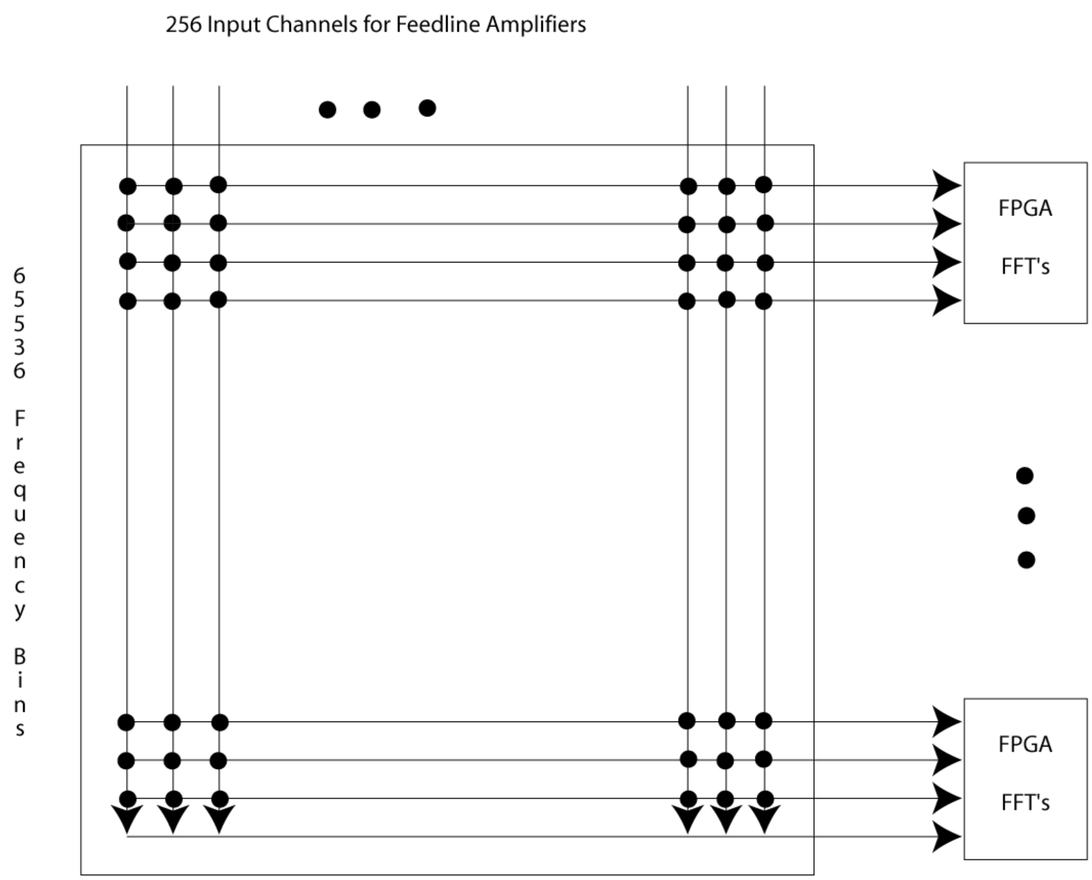
$$P = \sum_{m=1}^{N} a_m a_m^*$$

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

Signal Processing
First Stage



Signal Processing
Second Stage



Analysis

- Make raw pixel map (average of 3 dimensional FFT power spectrum)
- Apply inverse instrument model to get a corrected sky map
- Fit and remove synchrotron foreground spectra on a pixel-by-pixel basis
- Compute power spectrum of 21 cm
- Extract BAO signal

Calibration

- Big problem: Gain versus frequency
  - External radio transmission monitors time variation.
  - All channels see the same sky when equalized.
  - Will probably *assume* that the average spectrum fits a smooth (power law-like) function.
- Small problem:
  - Channel to channel electronic gain balance
  - Channel-by-channel antenna pattern

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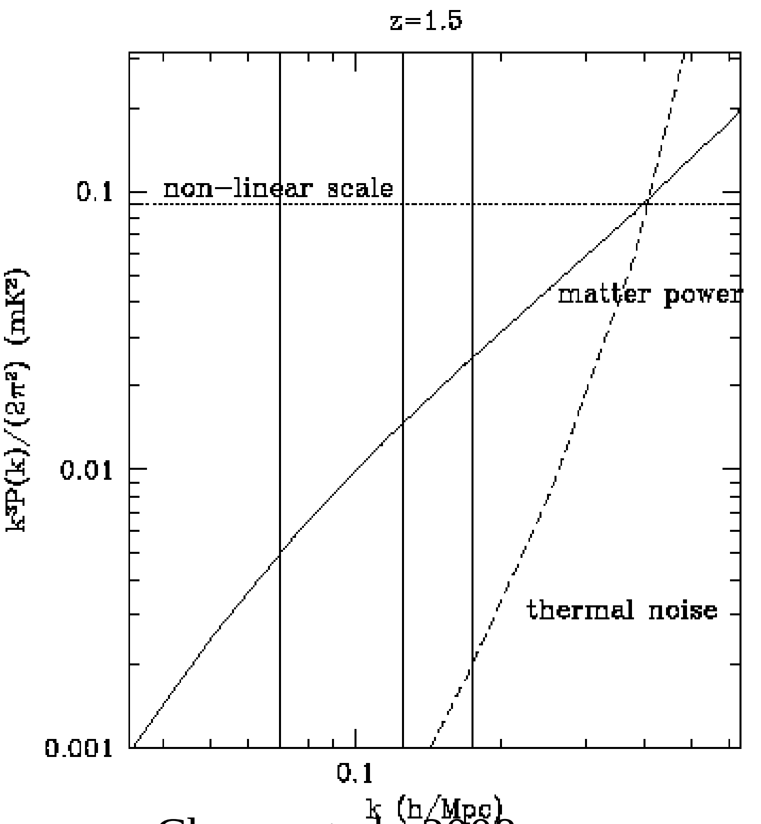
Summary

- 100m x 100m packed array seems to meet the requirements of a BAO experiment
- High channel count requires low cost per channel and inexpensive reflectors
- Cylindrical telescope arrays seem to be a good compromise between cost and performance.
- Instrument stability and calibration are critical issues.
- High data rate at low cost requires careful design.
- Project appears feasible – no apparent “show-stoppers”

Signal to Noise Limit

- Assume 18 hour integration per pixel
- Results in 100 μK per pixel



Chang, et al., 2008