21 cm Radio Telescope Design

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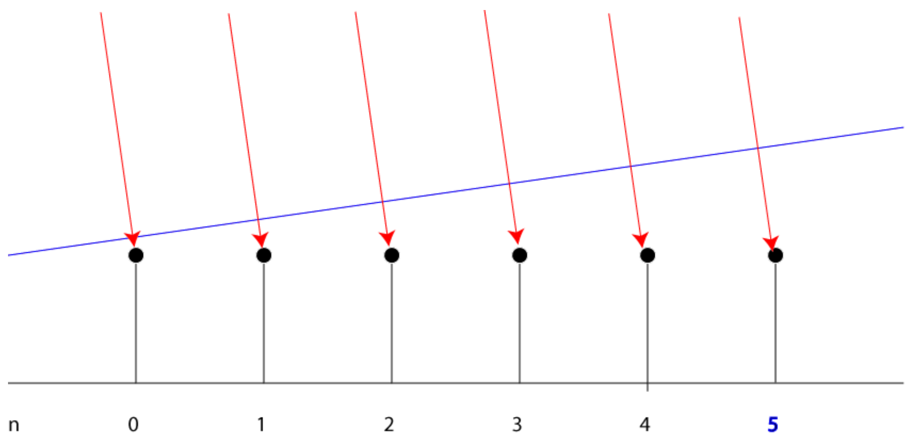
21 cm Internal Review

Interferometers

- Basic information (visibility) results from the cross-correlation of 2 receivers as a function of the distance between receivers.
- In an array of receivers there are combinations $(N+1)N/2$
- An image is given by the Fourier transform of the visibilities



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

$$\phi = nkd\theta$$

Enabling Technologies

- Inexpensive low noise amplifiers (T<<300 °K)
- High speed transmission (fiber optics, gigabit ethernet, etc.)
- FFT processing* $\left(N \log N\right)$
- High speed, low power, low cost digital signal processing (CPU's, FPGA's, GPU's)

*Omniscopes: Large Area Telescope Arrays with only N log N Computational Cost, M. Tegmark - http://arxiv.org/abs/0909.0001v1

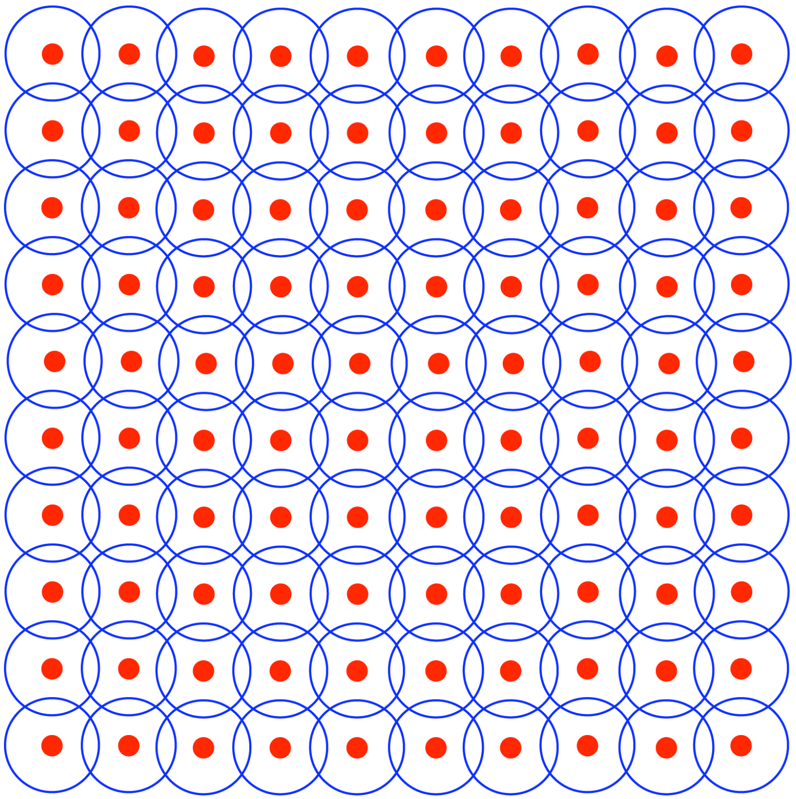
Radio Telescope Design

- We do not have a detailed design, but I will discuss some design concepts.
- We have a good understanding of the requirements for the observation of a BAO signal
- Key requirements
  - Resolution → Overall size (~100 m array size)
  - Sky coverage → Channel count ($\pi/\Delta\Theta \times 11.5$ cm)
  - Redshift range → High bandwidth (~200 MHz)
- The goal is to produce a concrete design report.

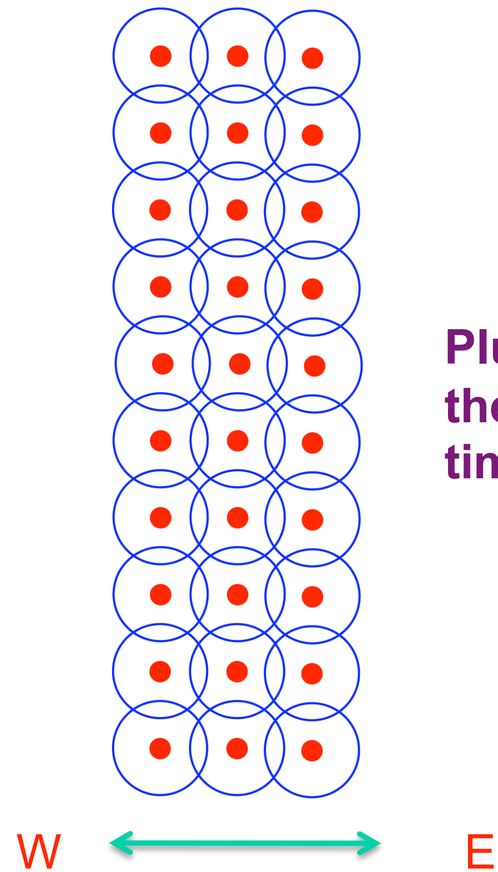
Focusing

- Traditional radio telescopes use dishes to focus the energy to a single receiver.
- By comparison an interferometer array
  - Has the same angular resolution as an equivalent size dish.
  - Has the same sensitivity as an equivalent size dish.
  - Has many pixels (beams) as there are receivers (feeds)
- A cylinder telescope focuses in 1 dimension only

Sky Coverage



100m x 100 m on 11.5 cm centers



Plus ~10x the observing time

Tracking or Drift Scan?

- Drift scan ✔
  - Cost advantage (no moving parts)
  - Maintenance & operation advantage (no moving parts)
  - Stability advantage
    - fixed w.r.t. ground
    - instrument response averages over right ascension
    - gravity is constant
- Tracking
  - Selectively better S/N ratio

Uniform vs Non-uniform Feed Spacing

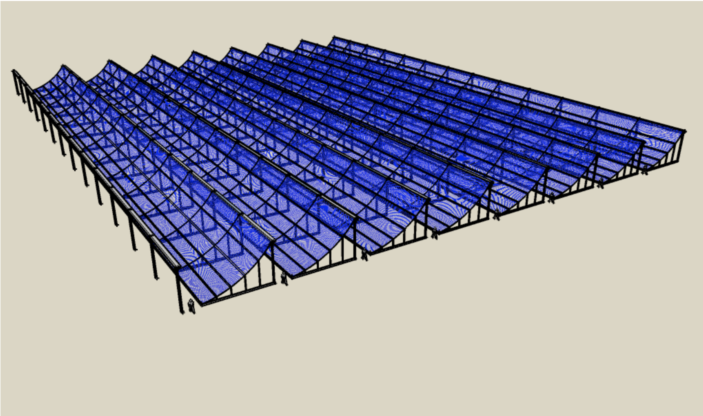
- Uniform feed spacing ✔
  - A natural match to digital processing via FFT
  - Redundant baselines provide
    - Better S/N per baseline
    - A natural attack point for systematics and calibration
- Non-uniform spacing allows an extra degree of freedom for beam shaping.
  - Can be accommodated into an FFT scheme with a MOFF correlator (at some cost)
  - Allows for more baselines (higher resolution).

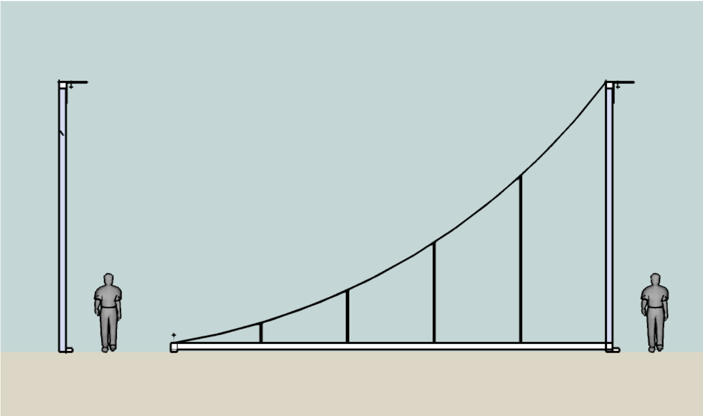
Why cylinders?

- Reduce the number of feeds in the E-W direction
  - Sky coverage is not compromised
  - Survey cost and speed are reduced
- Good choice for drift scanning, but not for tracking
- Good symmetry properties for uniform spacing

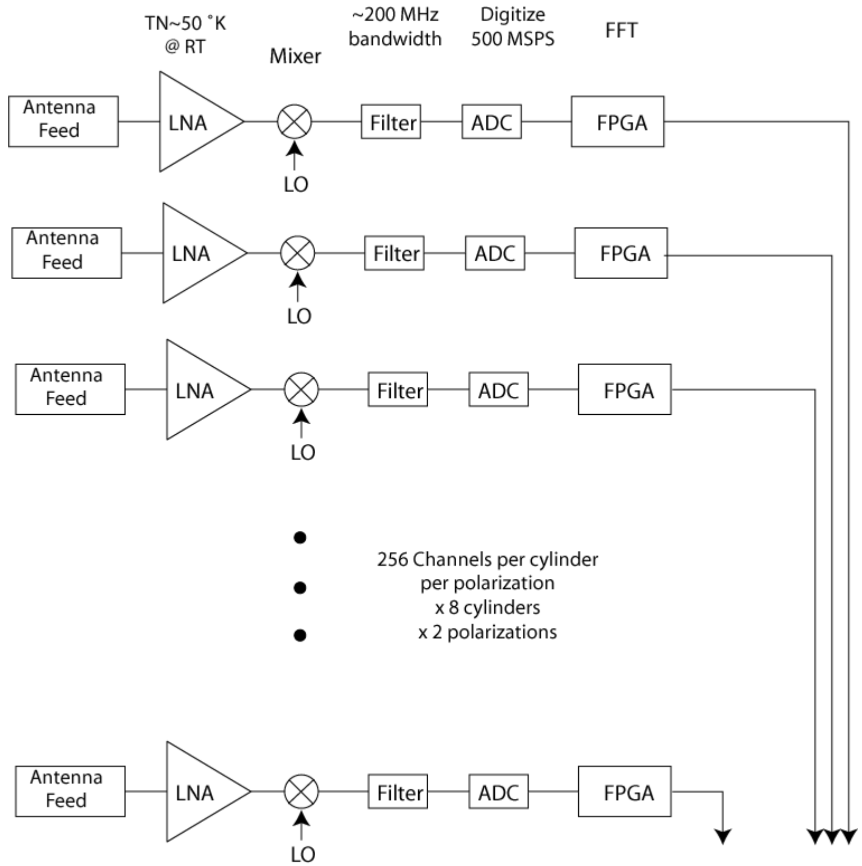
Antenna Array

- 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.

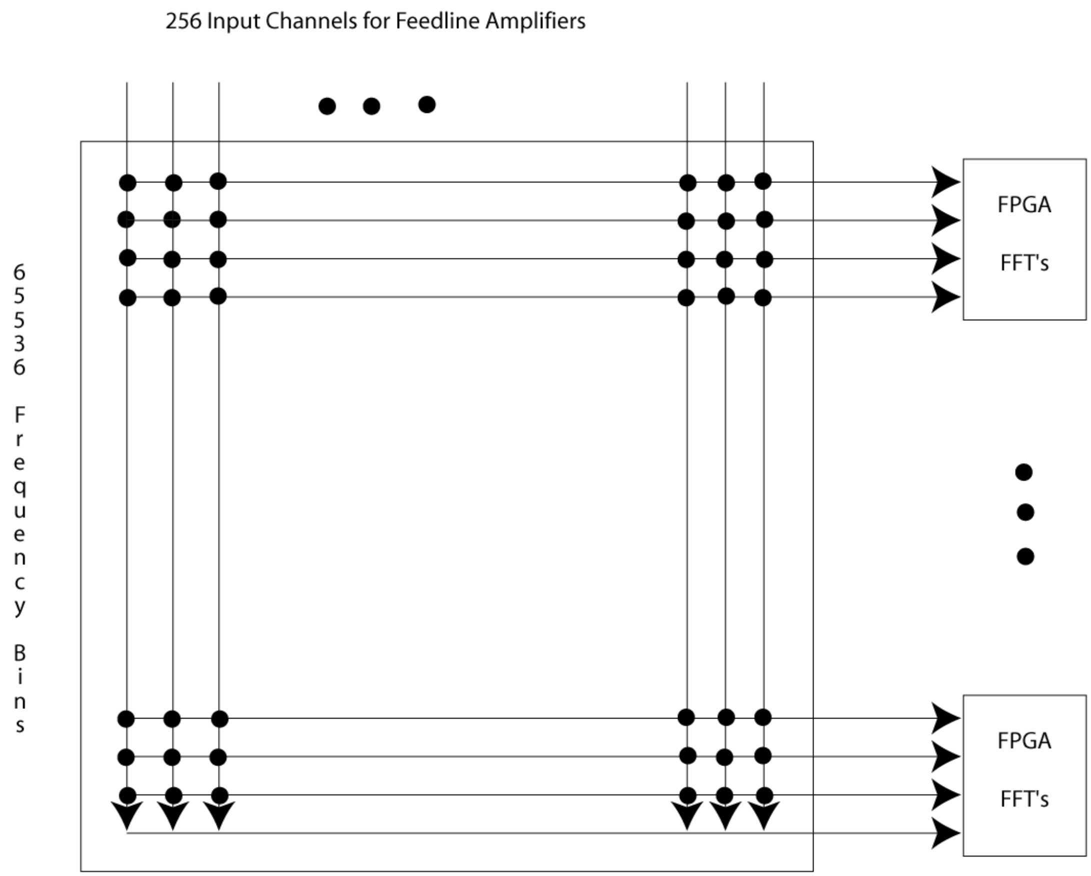




Signal Processing
First Stage



Signal Processing
Second Stage



Charge Element

- Is the specific technique explored by the R&D effort at FNAL (cylindrical radio telescope array) the best approach to a 21 cm survey?
  - We have indicated our reasons for exploring the cylindrical array geometry for the conceptual design report.
  - We have simulated the performance of such an array and found it to be adequate to measure BAO.
  - The scope of the review is probably not sufficient for the committee to be convinced that the CRT is the "best" approach.

Backup Slides

Calibration Issues

- The foreground subtraction relies on the existence of a "smooth" frequency spectrum, but calibration errors introduce spurious wiggles.
- Stray energy from bright sources scatters into dimmer parts of the image.
- The frequency calibration has to be accurate to $\sim 10^{-4}$, but a spatial calibration of $\sim 10^{-2}$ is good enough, provided that the scattered energy from bright sources looks like other foregrounds.

Calibration Strategy

- Time scales
  - Electronic gain varies with temperature (fast compared to 1 day)
  - Antenna gain – mechanics stable over longer periods (> 1 day)
- Main calibration techniques
  - Relative gain between channels can be calibrated quickly by comparing amplifier combinations with the same base lines.
  - Relative antenna shape can be calibrated with an external radio source with variable position.

More Calibration

- Gain versus frequency calibration will be based on a bright source or sources or maybe some average foreground signal.
- Drift scanning provides good constraints on antenna shape in the E-W direction.
- Bright point sources provide absolute calibration (pulsars are good also).
- Satellites can be good calibration sources.
- Daily repetition provides excellent cross-checks.

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.