CMB Optics Overview

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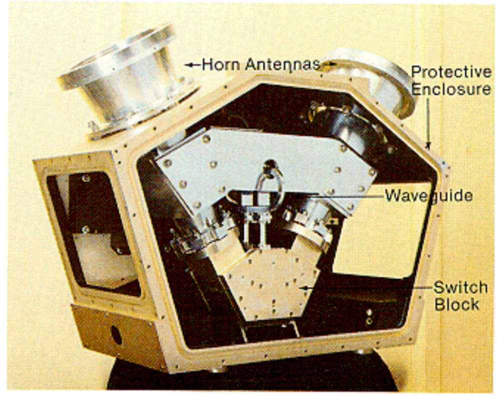
B-modes from Space Workshop
5 Dec 2017

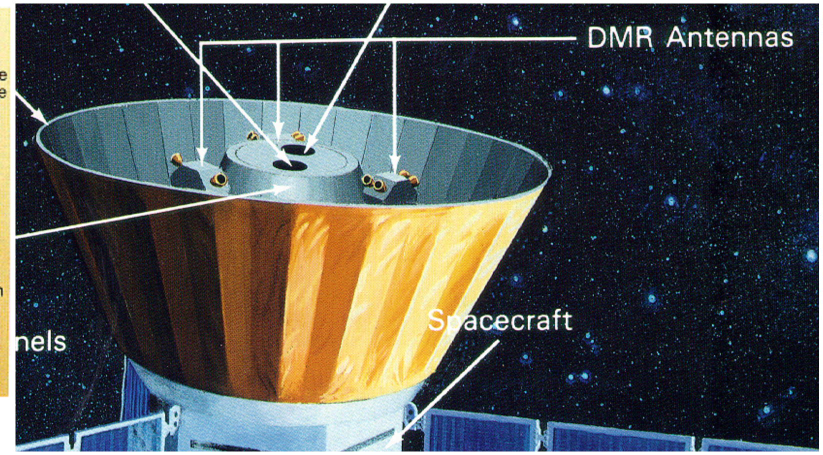
Fundamantal Telescope Optics Design Considerations

- Angular resolution
- Sensitivity
  - Throughput AΩ
  - Mapping speed
  - Multichroic detectors
- Control of systematics
  - Main beam symmetry
  - Control of spillover and sidelobes
  - Thermal stability
  - Signal differencing/modulation
- Foreground mitigation
  - Large frequency range
  - Many (overlapping?) bands

COBE DMR c. 1989

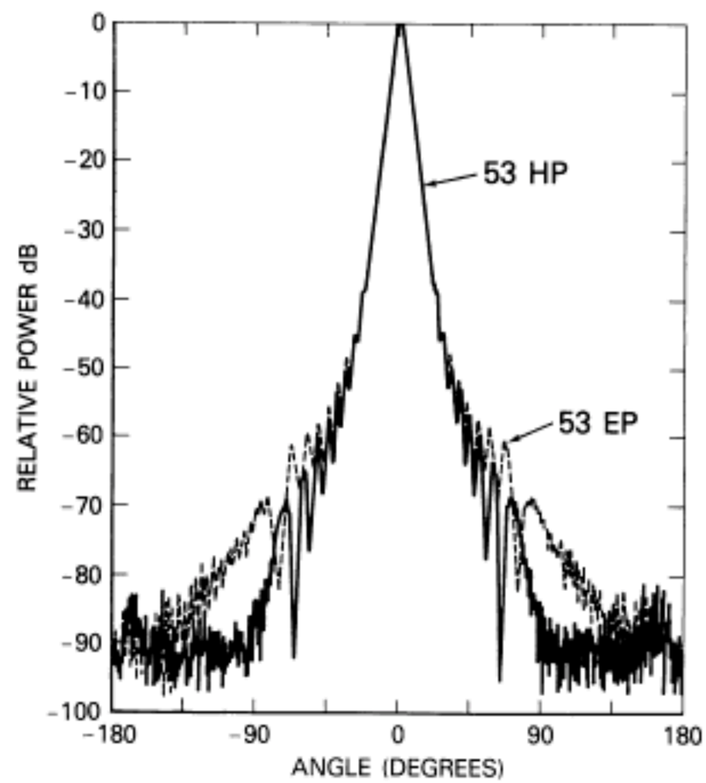


The 9.6 mm DMR receiver partially assembled. Corrugated cones are antennas.



- Differential radiometers, 2 each at 31, 53, 90 GHz
- Antennas are wavelength-scaled corrugated horns with 7° FWHM
- Inputs differenced at 100 Hz
- The satellite spins at 0.8 revolutions per minute to interchange the antenna directions every half-rotation

"There are two crucial aspects in making an anisotropy experiment. One is to design the experiment to minimize or cancel systematic errors and to reveal any significant unsuspected effects, and the second is to distinguish among the various cosmic sources of anisotropies."

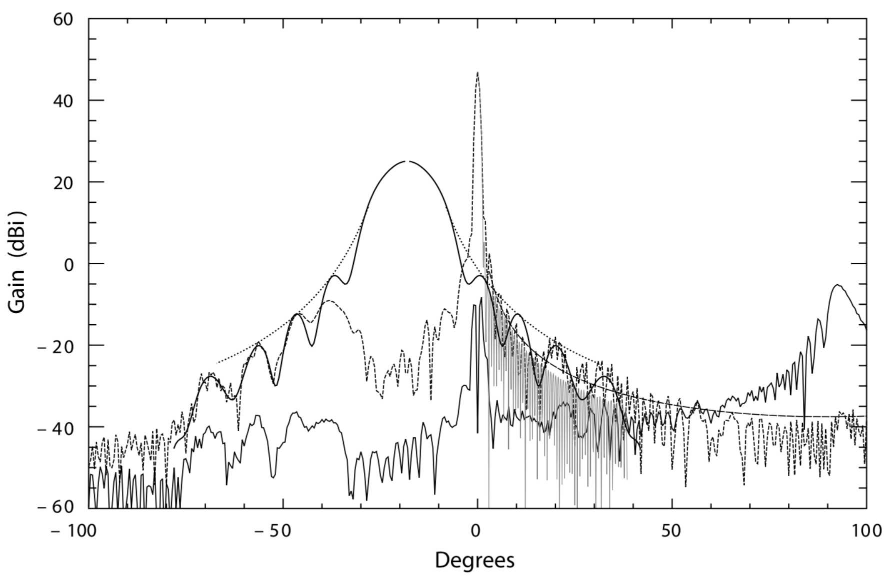


COBE DMR 53 GHz Beams

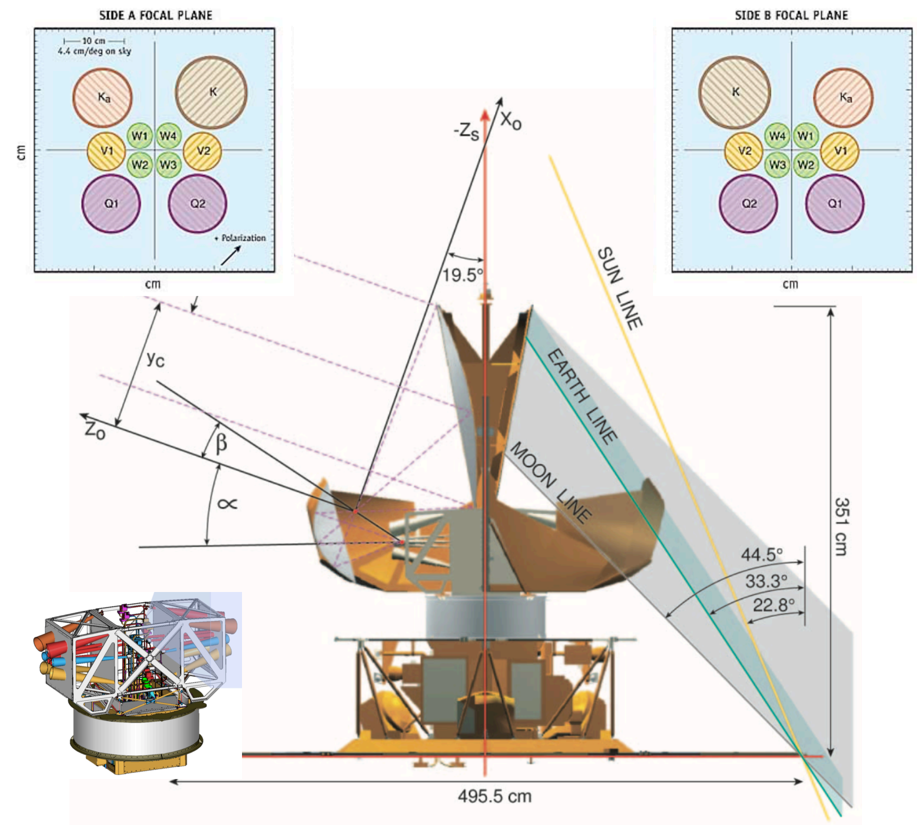
Smoot et al., ApJ 360, 685S, 1990

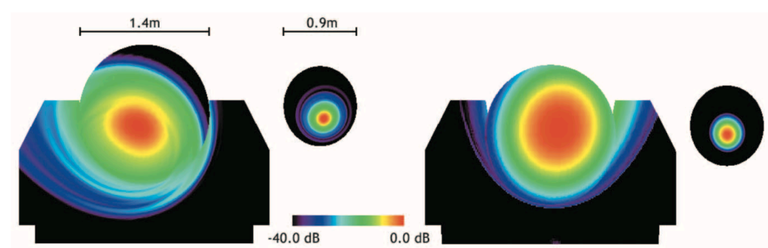
WMAP c. 2001

- Two back-to-back off-axis (shaped*) Gregorian telescopes with 1.4 m x 1.6 m primary reflectors and 0.9 m x 1.0 m secondary reflectors.
- 10 polarization-sensitive differential radiometers using corrugated horn feeds, 23-93 GHz.



Optical response of a prototype design with a K-band feed at the focus of the telescope.





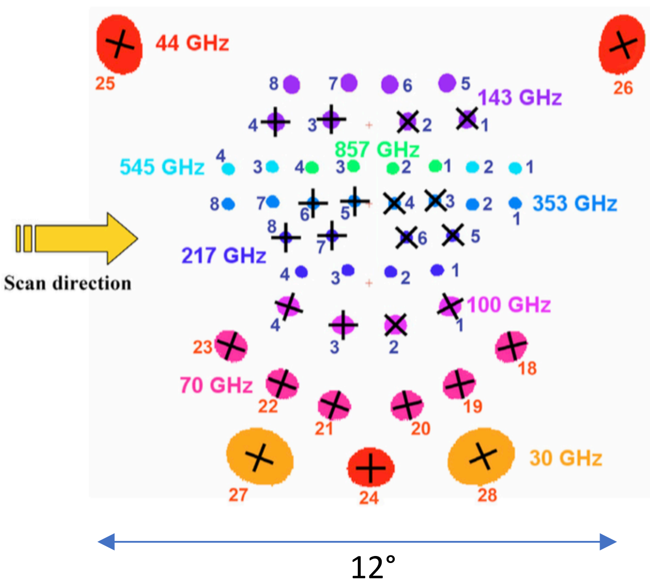
Current density on the primary and secondary reflectors for K band (22 GHz; left) and W band (90 GHz; right).

* “In retrospect, we should not have shaped the reflectors. It added time to the manufacturing process, and the cooldown distortions of the primary reflectors negated its benefits.”

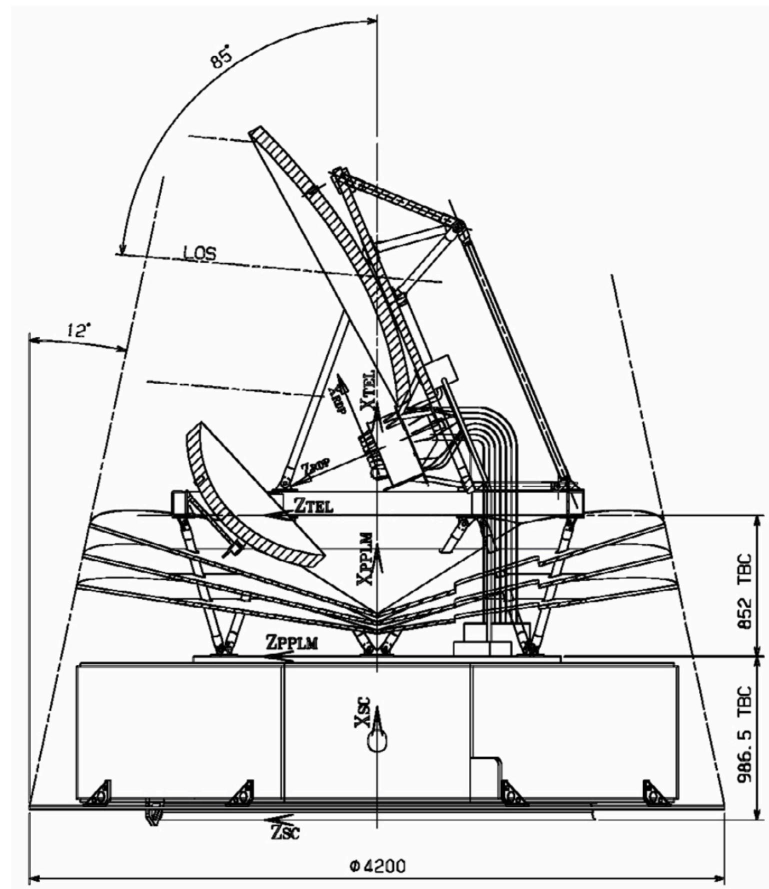
Page et al., ApJ 585, 566, 2003

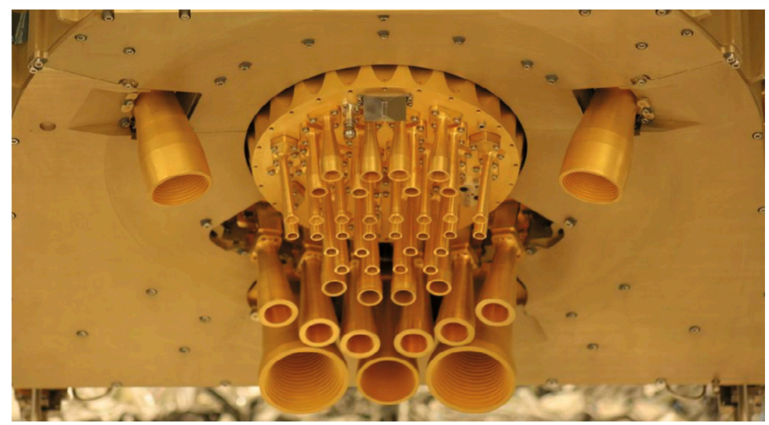
Planck c. 2009

- Single off-axis (shaped) Gregorian telescope with 1.6 m x 1.9 m primary reflector and 1.0 m x 1.1 m secondary reflector.
- LFI: 30-70 GHz, 22 HEMT-based differential pseudo-correlation radiometers
- HFI: 100-857 GHz, 20 spiderweb bolometers (unpol) 32 polarization-sensitive bolometers



Focal plane footprint on the sky

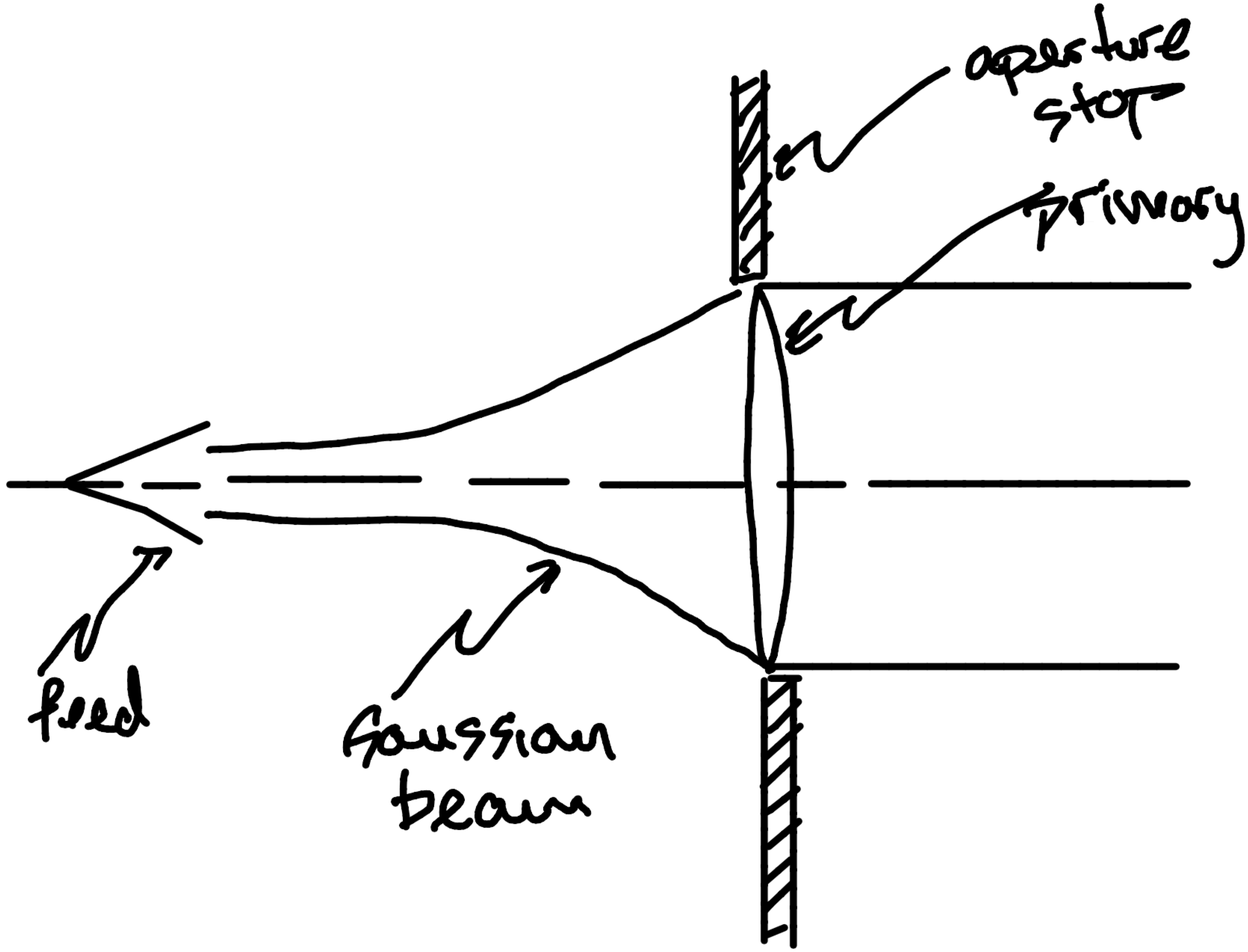




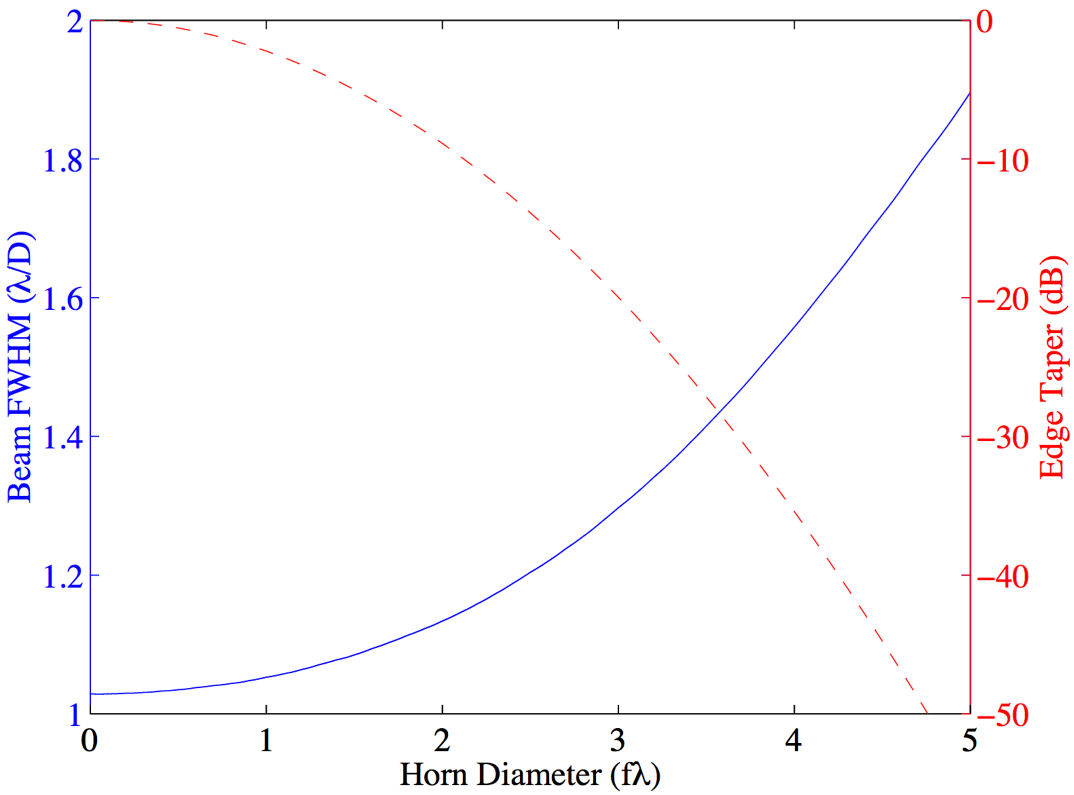
Focal plane layout

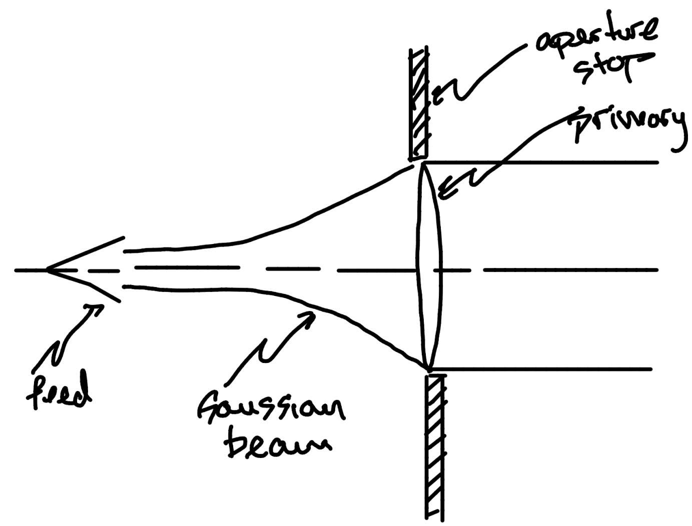
Tauber et al., A&A 520, A2, 2010

Basic Telescope Schematic



Feed Diameter vs Angular Resolution and Edge Taper





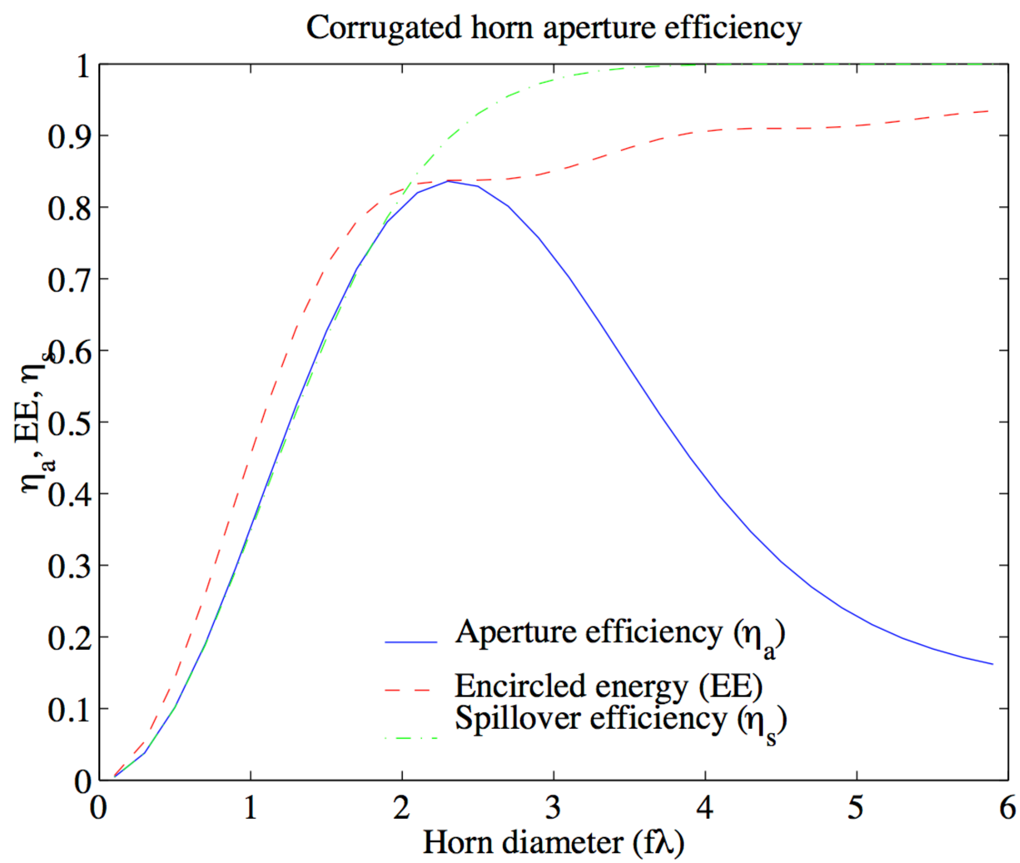
“The trade-off between the angular resolution (which impacts the instrument’s ability to reconstruct the anisotropy power spectrum of the cosmic microwave background radiation at high multipoles) and the edge taper (which controls the systematic effect of straylight radiation) was identified as a critical design step.” – Planck pre-launch status: LFI Optics, Sandri et al., A&A 520, A7, 2010.

Mapping Speed

Assuming the detectors are photon noise dominated, the mapping speed for an array of N detectors is given by:

$$S \propto \frac{N\eta_a^2}{P_{\rm photon}}$$

$$\propto \frac{N\eta_a^2}{\eta_s B_{\rm ext} + (1-\eta_s)B_{\rm int}}$$



Where:

- B_{ext} is the brightness temperature seen by the fraction of the feed beam that illuminates the primary,
- B_{int} is the brightness temperature seen by the horn spillover (e.g., terminated by the aperture stop)
- η_a is the aperture efficiency
- η_s is the spillover efficiency

Keys to Improving mapping speed

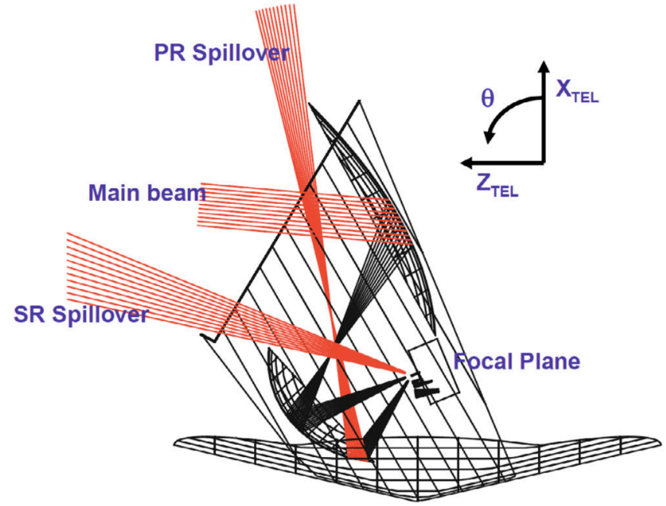
- Increase the number of detectors
  - Increase throughput
  - Decrease pixel size (to a degree)
- Reduce optical loading on the detectors
  - Get above the atmosphere
  - Cool the aperture stop (if it exists)
  - Cool and reduce the emissivity of the telescope optics

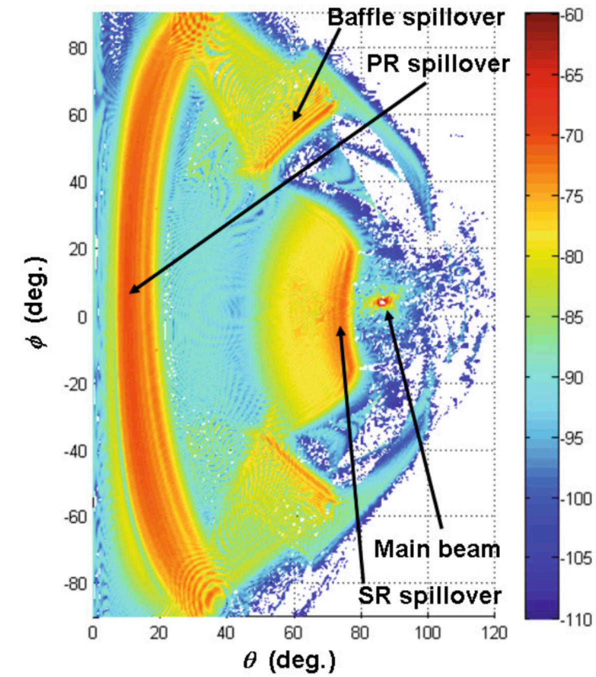
Control of Systematics

- Beam symmetry
- Control of spillover and sidelobes
- Thermal stability
- Signal differencing/modulation

Sidelobes due to diffraction spillover, and scattering

- Sidelobe response must be carefully controlled and characterized.
  - Polarized off-axis pickup from the galaxy, planets, earth, moon, sun, etc, will generate a spurious signal.
- Sidelobe response is controlled by:
  - Reducing scattering by, e.g., using off-axis optics, underilluminating optics, employing a stop
  - Baffling and shielding

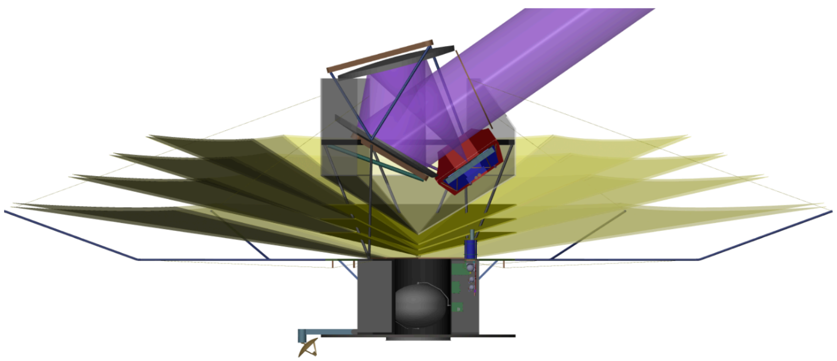


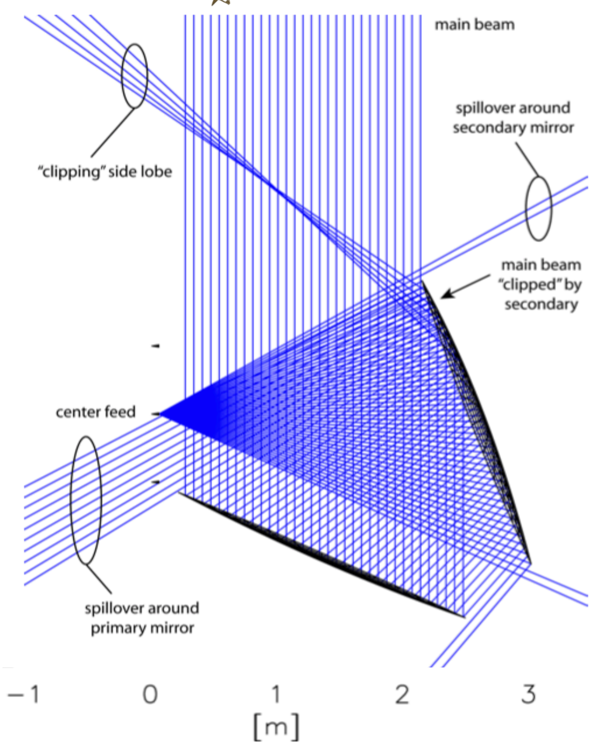


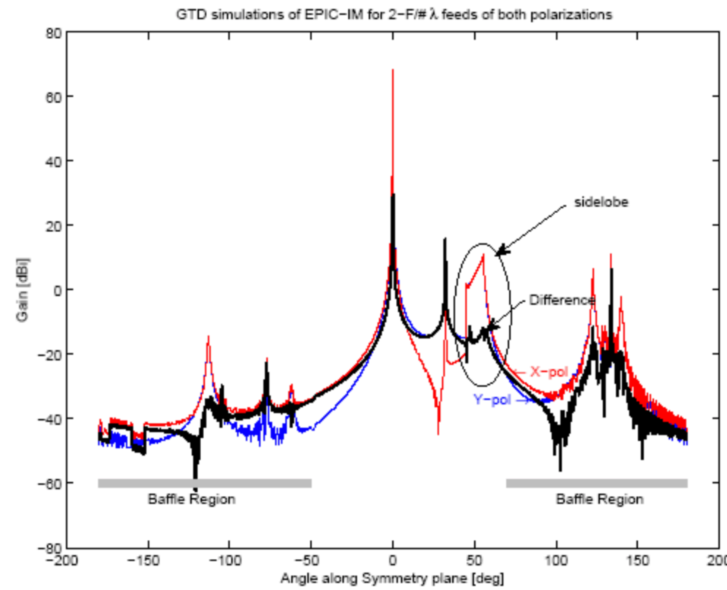
Far sidelobe pattern for Planck at 100 GHz (Tauber et al., A&A 520, A2, 2010)

EPIC IM Study

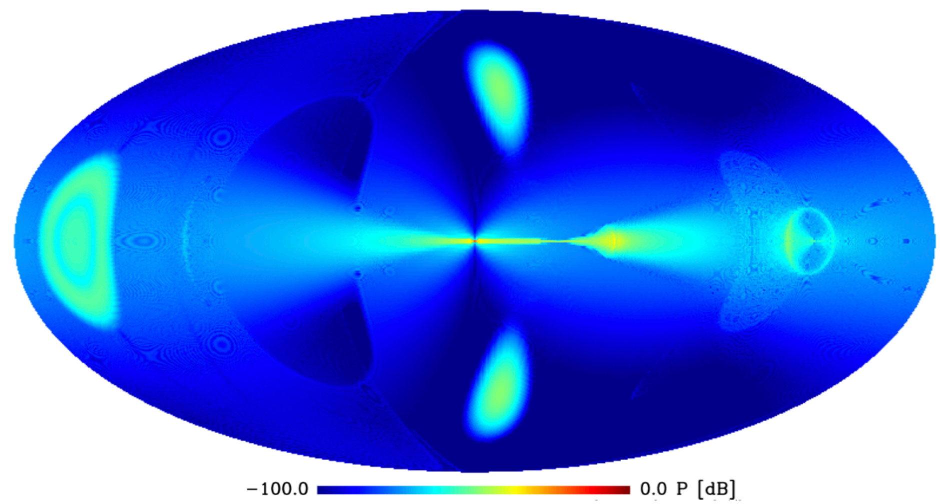
- 1.4 m crossed-Dragone telescope
- –80dB sidelobes (–20dBi), or ~0.1nK rms polarized pickup from the galaxy at 150GHz







GTD simulation of the EPIC-IM (cold), 2 fλ optics.



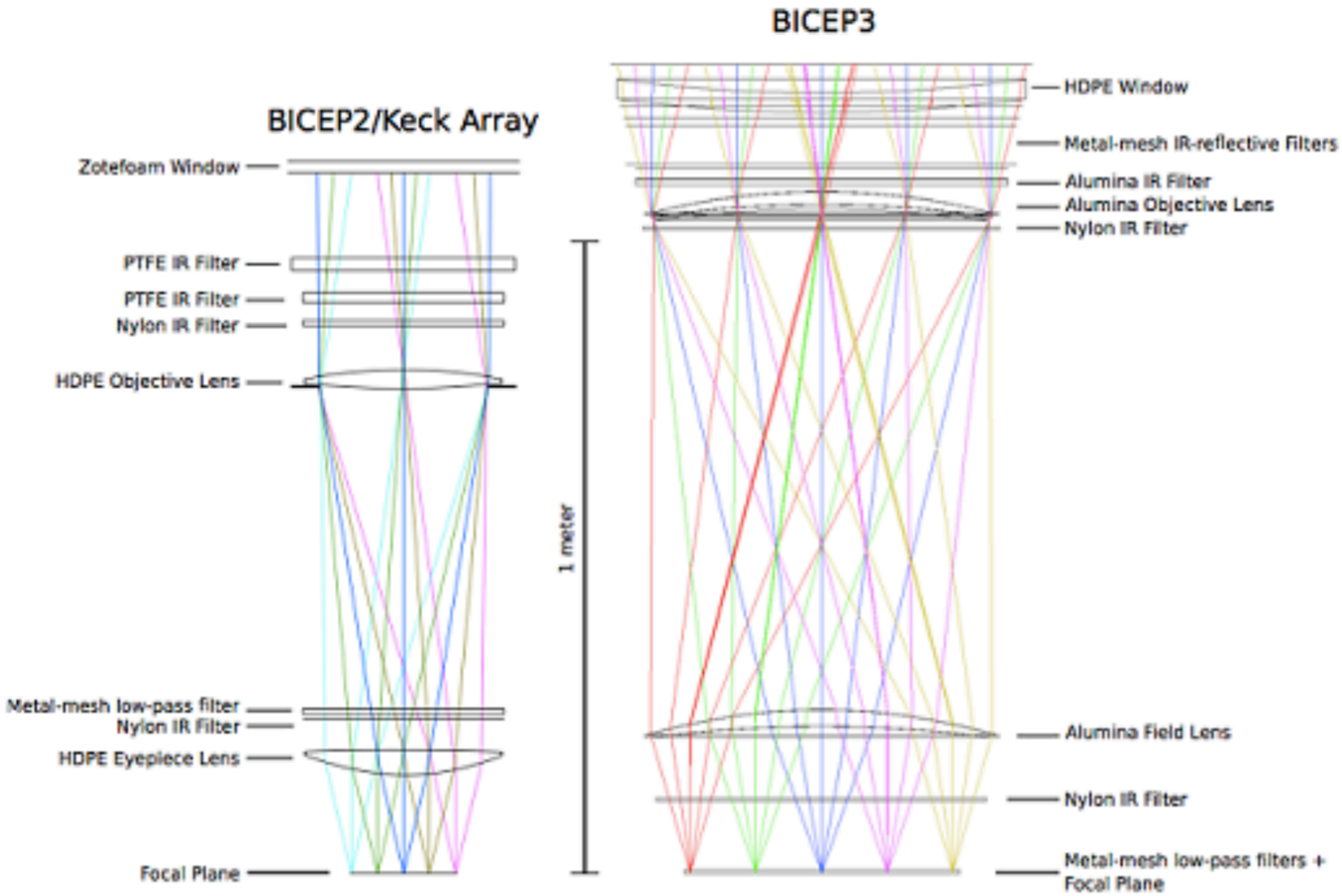
The polarization of the far side lobes. The forward gain of the TT beam is 54.1 dB.

Tran et al., Proc. of SPIE Vol. 7731 77311R-1, 2010

What can we learn from ground-based CMB experiments?

BICEP2/Keck Array/BICEP3/Spider

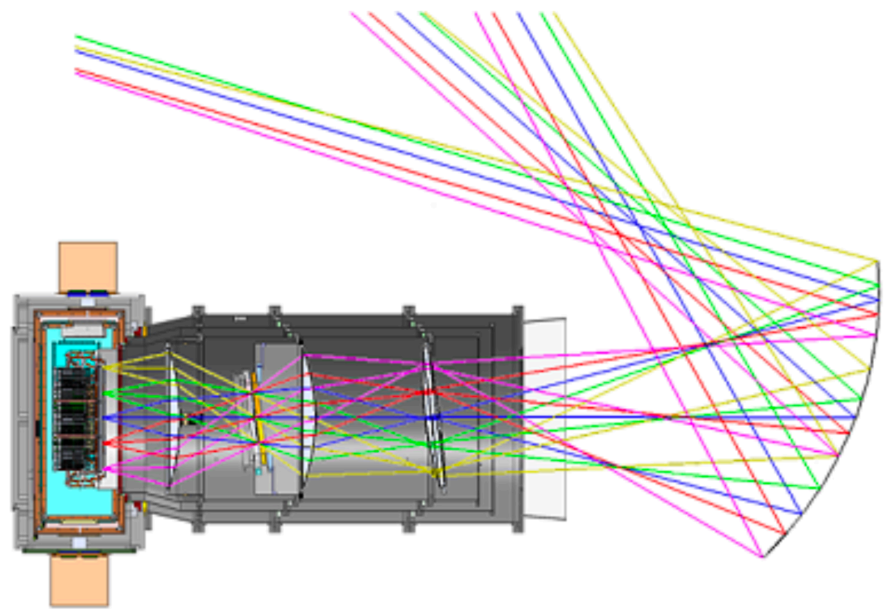
- Simple two-lens objective/field lens design with a stop just behind the objective.
- The lenses and stop are cooled to 4 K.
- Single-frequency band per telescope
- Lenses are HDPE plastic (BICEP2/Keck Array) or alumina (BICEP3)
- Design employs a comoving absorptive conical baffle above of the telescope cryostat, and fixed reflective ground shields.
- Polarization modulation using stepped boresight rotation of the entire telescope.
- Spider uses a 4K HWP rotated twice per sidereal day to modulate polarization.



CMB-S4 Technology Book, https://arxiv.org/abs/1706.02464

Polarbear-2/Simons Array/SPT-3G

- Off-axis Gregorian telescopes
- Alumina refractive reimaging optics:
  - 4K Lyot Stop
  - Telecentric (flat) focal plane
- Multichroic (2 or 3 band) focal planes.
- PB2/SA will have a continuously rotating HWP for polarization modulation.
- Co-moving baffles and prime focus/primary shields. No fixed ground shield



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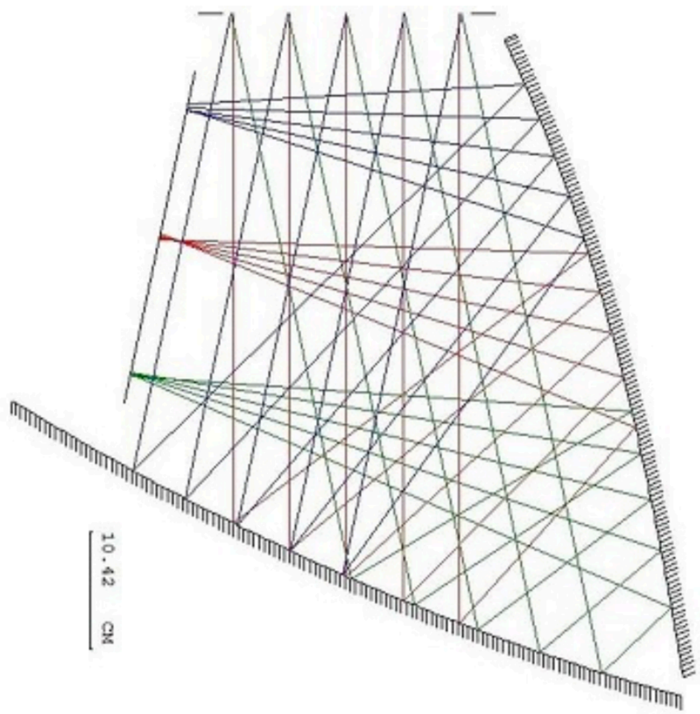
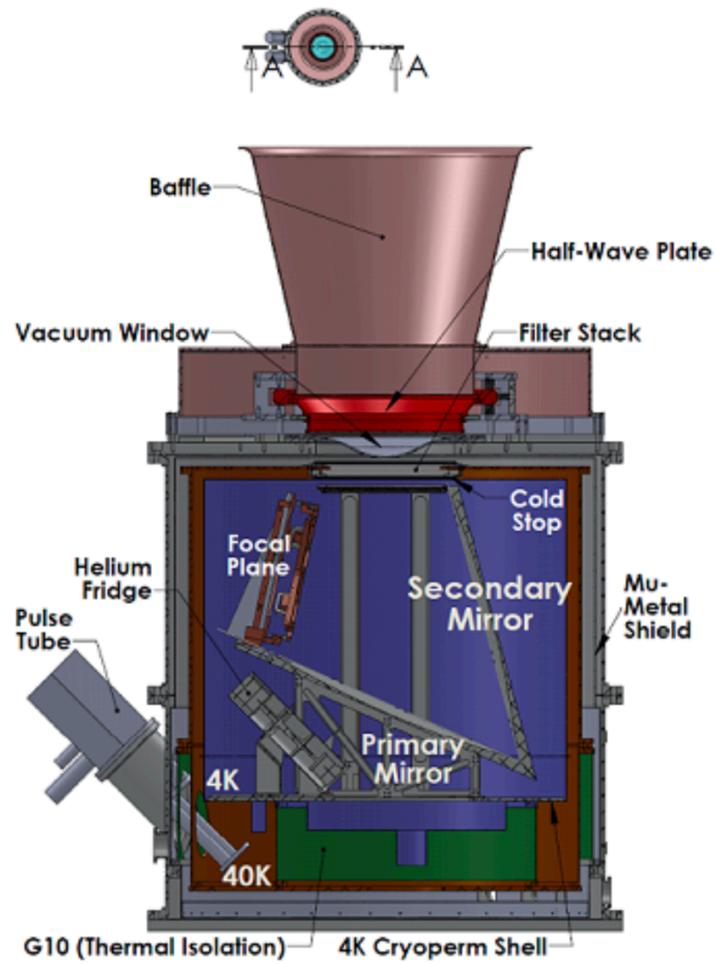
ABS





- 60-cm cryogenic (4K) crossed-Dragone
- 4K 25-cm aperture stop
- Ambient-temperature, 33-cm-diameter continuously-rotating HWP is placed at the entrance aperture of the receiver
- Reflective baffle and a co-moving ground shield

CMB-S4 Technology Book, https://arxiv.org/abs/1706.02464

Summary

- Heritage and conservative evolution of space-based experiments has been very successful.
- Higher sensitivity requirements increase the complexity of the experiment.
- Ground-based experiments are pathfinders for technology and techniques that can be used in the next-generation space experiment.
- However, the sensivitivy and control of systematics required to measure r = 0.001 is unprecedented.
- Careful studies are needed to control systematics and calibrate the instrument to the needed accuracy and precision.