CMB S4

Calibration Challenges for CMB-S4

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On behalf of the CMB-S4 Collaboration

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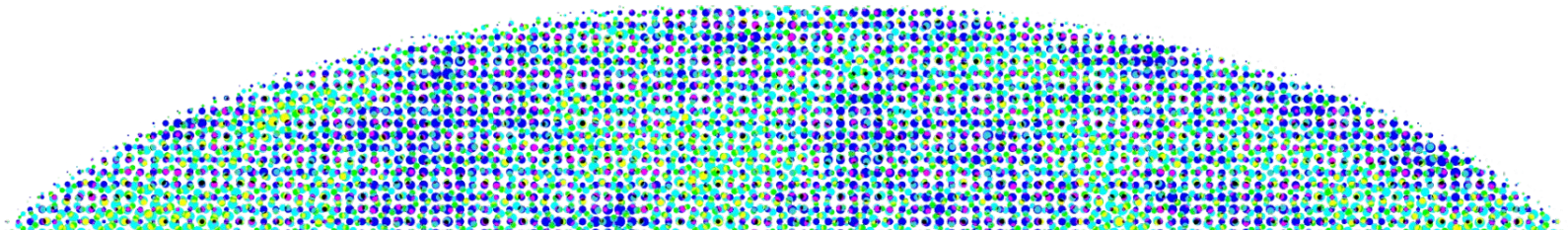
CMB-CAL 2024



CMB-S4 Overview

Next generation ground-based CMB experiment, optimized for 4 driving science goals:

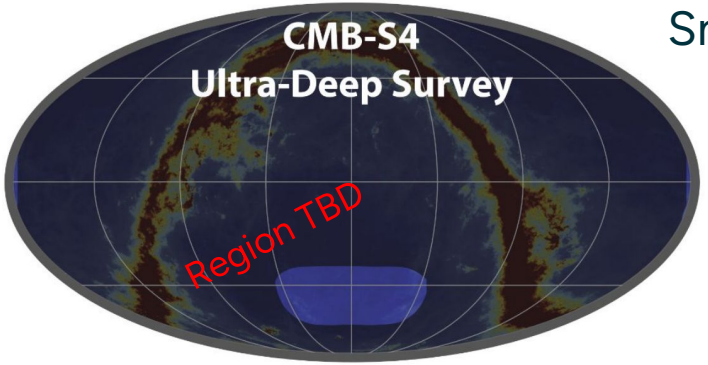
- Search for primordial gravitational waves
  - $> 5\sigma$ detection if $r > 0.003$, else $r \leq 0.001$ at 95% C.L.
- Probe the dark Universe
  - $\Delta N_{eff} \leq 0.06$ at 95% C.L.
- Map matter in the cosmos
  - Detect all $z \geq 1.5$ Galaxy clusters with integrated Compton $Y_{SZ,500} \geq 10^{-12}$ over 50% of the sky and $\geq 10^{-13}$ over 3% of the sky
- Reveal the time-variable mm-wave sky
  - Detect GRB afterglows > 30 mJy over 50% of the sky and > 9 mJy over 5% of the sky at 90 and 150 GHz

Current Status

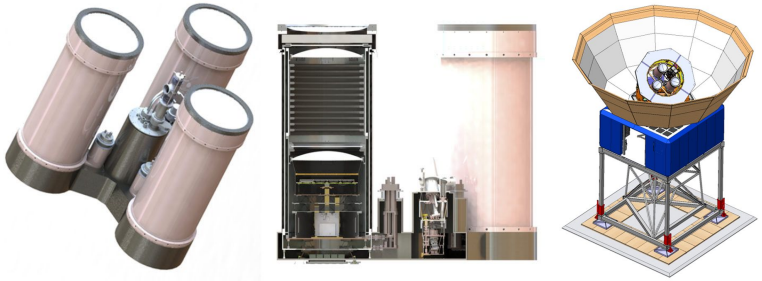
- Received strong support in the Astro 2020 decadal survey and the 2023 P5 report
- Jointly supported by DOE and NSF
  - DOE CD-0 project
  - NSF MSRI-1 design award
- Many potential international partnerships have been identified

- Project is currently re-evaluating the baseline design following the NSF decision not to allow planning for new experiments at the South Pole at this time.

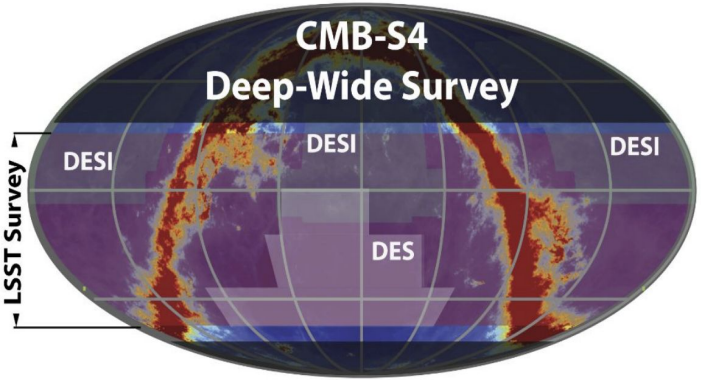
CMB-S4 Instrument



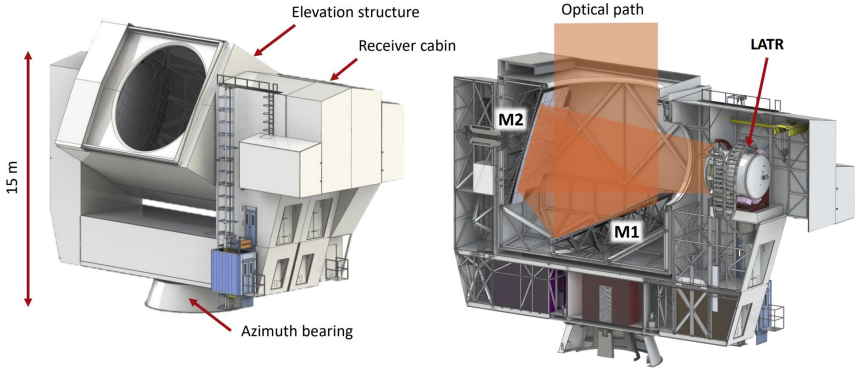
Small Aperture + Delensing Large Aperture Telescopes



\+ TBD LAT design

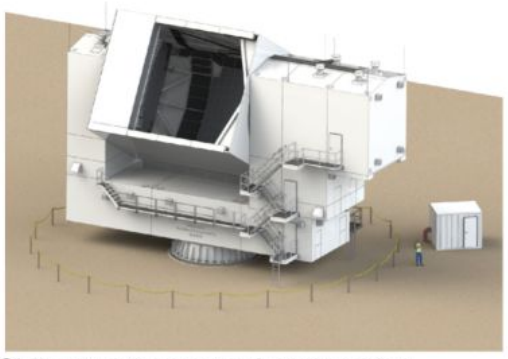


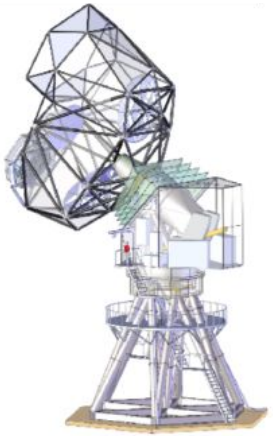
Crossed-Dragone Large Aperture Telescopes

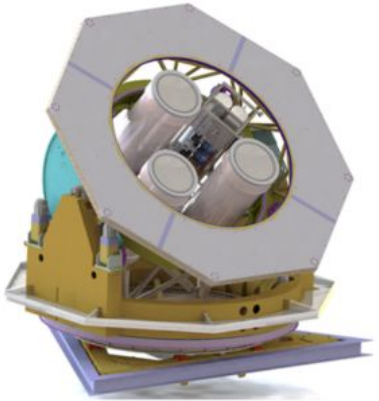


CMB-S4's Former Baseline Design

The Chile-only configuration will not require fewer telescopes or detector modules
(It may require more)







2x CDs 1x TMA

85 optics tubes / receiver
1 detector module / tube

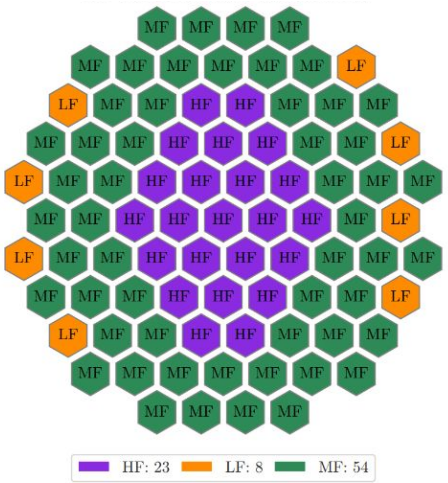
3x SATs

3 optics tubes / mount
12 detector module / tube

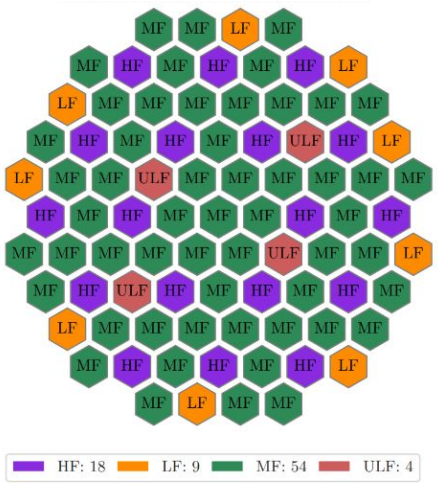
Frequency Band Distribution (Former Baseline)

LATs

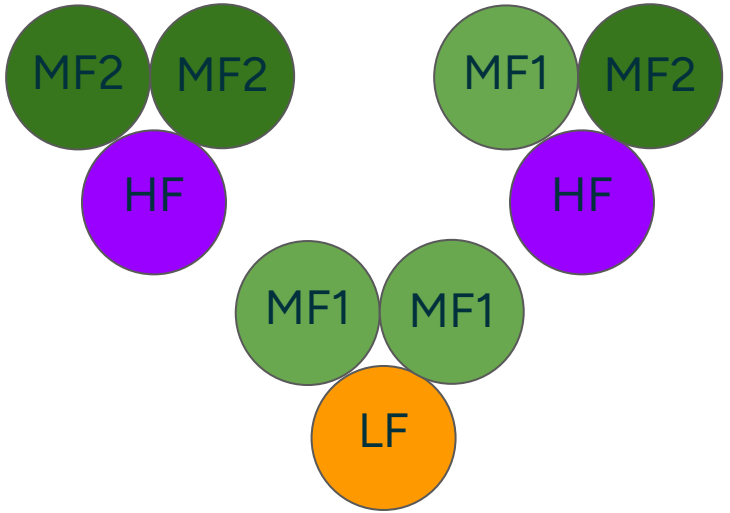
CD



TMA



SATs



Property	ULF	LF		MF		HF	
Center frequency (GHz)	20	25	37	92	149	227	286
Fractional bandwidth	0.25	0.26	0.47	0.32	0.28	0.26	0.21
$N_{\text{detectors}}$ per optics tube	54	96	96	860	860	934	934

Property	LF		MF1		MF2		HF	
Center frequency (GHz)	25	37	85	145	95	155	227	286
Fractional bandwidth	0.26	0.47	0.24	0.22	0.24	0.22	0.26	0.21
N_{det} per optics tube	288	288	3480	3480	4008	4008	11208	11208

Gallardo et al, 2406.13854

CMB-S4's Challenges

Overall

- Sensitivity
  - > 500,000 detectors observing for 7 years
  - Efficient instrument and survey strategy
- Systematics
  - Careful instrument design and calibration
- Galactic foregrounds
  - Many frequency bands from 20 - 280 GHz

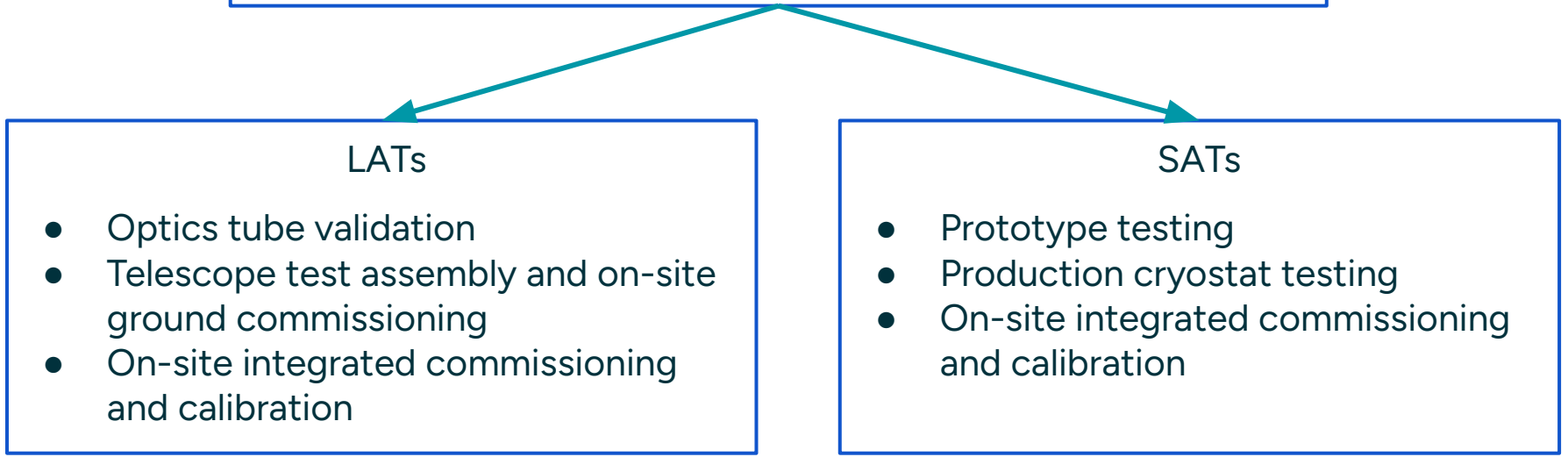
Calibration

- Number of detectors
- Time or sensitivity needed to calibrate them to CMB-S4's science requirements

Testing and Calibration Plan

Detector modules tested individually to qualify for deployment

- Same tests for both LAT and SAT modules
- Starts early in the project



Detector Module Testing

Goal: Qualify for deployment

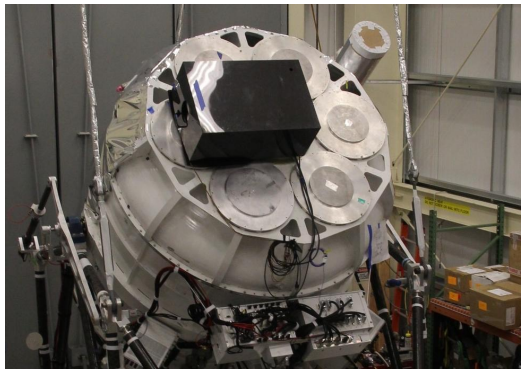
Measurement All wafers Spot checks	**Test Equipment**
Detector parameters	Cold load
NET and detector stability	Cold load
Time constants	Chopped source
Observing bandpasses	Fourier Transform Spectrometer (FTS)
Out-of-band leakage	Fourier Transform Spectrometer (FTS) (alt: grill filters)
Polarization response	Chopped polarized source
Beam shape	Beam mapper
Magnetic pickup	Magnetic field generator
RF pickup	RF source

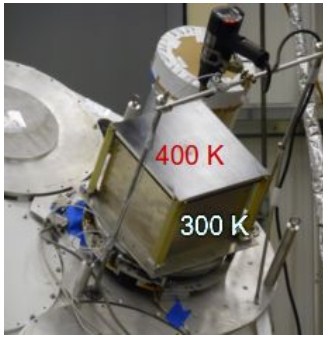
LATs:
Pre-deployment Optics Tube Validation

All measurements will be done on the high-T_c transitions

Measurement	Equipment
Band properties	FTS or alternative
Pol. angle and effic.	Chopped polarized source
Optical efficiency	Beam-filling thermal loads
Beam maps at window	Thermal beam mapper
Scattering maps	Scattering mapper

Examples from SPIDER
See talk by E. Shaw





LAT Telescope Commissioning

Telescope-only tests before the receiver is installed

Measurement	Equipment
Individual mirror surface	Laser tracker or photogrammetry
Multi-mirror alignment	Holography setup (tower-mounted source, receiver)
Pointing	Star camera

Example from SPT

On-Site Integrated Commissioning

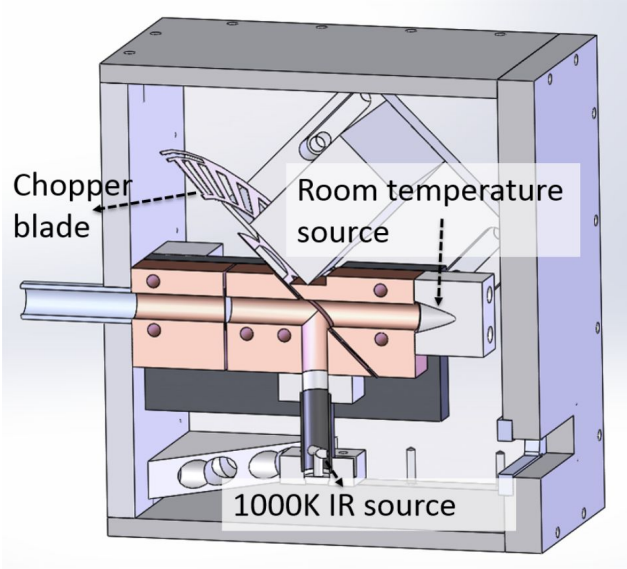
Measurements on the fully integrated telescope + receiver

Measurement	Equipment
Time constants / Gain	Chopped source coupled through hole in mirror
Band properties	FTS (spot checks, receiver only)
Beam sidelobes	Bright sources

On-Sky Measurements

- Beams
- Pol. Angle
- Elevation Nods

Example from SPT



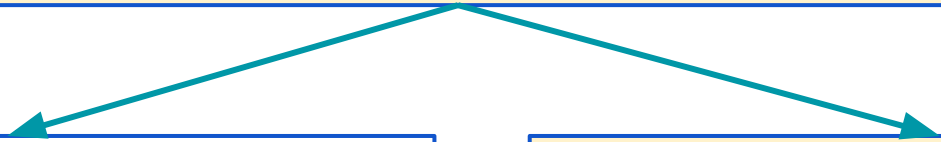
Pan et al, 1805.03219

SAT Calibration Plan

Info from Kirit Karkare, SAT calibration L3 lead, on behalf of the SAT WG

Detector modules tested individually to qualify for deployment

- Same tests for both LAT and SAT modules
- Starts early in the project



LATs

- Optics tube validation
- Telescope test assembly and on-site ground commissioning
- On-site integrated commissioning and calibration

SATs

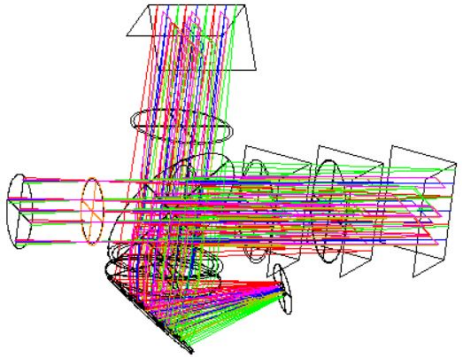
- Prototype testing
- Production cryostat testing
- On-site integrated commissioning and calibration

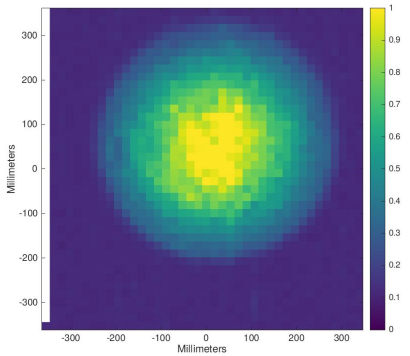
SAT North American Testing (Prototype + Production)

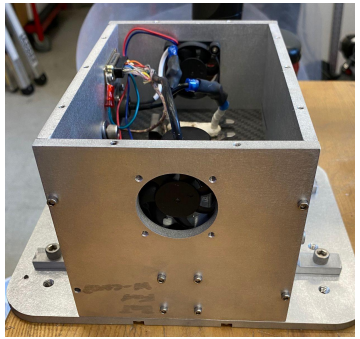
- Developing CMB-S4's equipment designs based on experience with current generation SATs
  - Optical efficiency → Aperture-filling thermal load
  - Beam shape → Near-field beam mapper
  - Bandpasses → Fourier Transform Spectrometer
  - Polarization response → Near-field polarization calibrator
  - Magnetic pickup → Helmholtz coil

Beam mapper tested on BICEP Array

On-going FTS design study



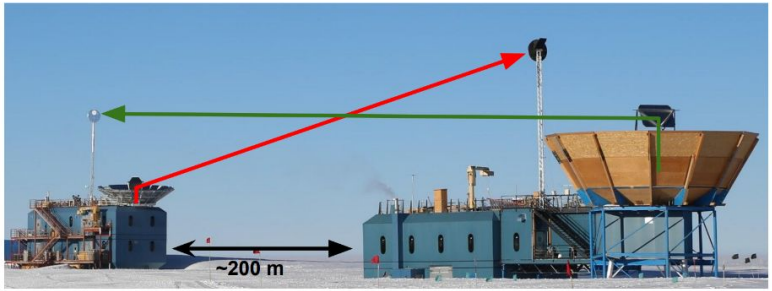


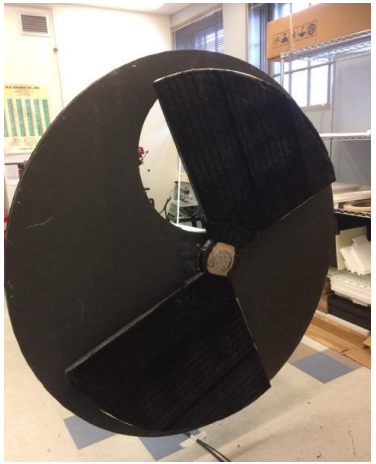


On-Site SAT Calibrations

- Equipment informed by North American measurements and previous generation SATs as much as possible
- Need all equipment from previous slide plus
  - Calibration mast
  - Far-field thermal chopper
  - Far-field flat mirror
  - Amplified microwave source
  - RF sources and monitoring
  - Star camera
- Equipment design will be optimized once Chilean SAT design is finalized
  - HWPs likely to be added to telescope design

Example from BK





Meeting CMB-S4's Calibration Challenges

- Much work still to be done on requirements flowdown, hardware prototyping, and systematics trade offs for different calibration equipment designs
- Similarities between types of measurements for the modules, LATs, and SATs
  - Different measurement requirements
  - Different optical coupling
- Performing calibrations in a timely manner will likely require many copies of hardware
  - Could be optimized by frequency band in some cases if desired.
- Calibrate in North America as much as possible, but still lots needed on site
  - Prototype measurements are important

Summary

- CMB-S4 faces unprecedented calibration challenges
  - Number of detectors
  - Sensitivity required for science goals
- Calibration plan is currently being developed as instrument design is being optimized
- Guided by experience from previous CMB experiments

Questions?

CMB-S4 Meeting, Summer 2024