Calibration Methods for Next-Generation CMB Experiments

Sara M. Simon
she/her
Fermilab
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Photo Credit: Nick Galitzki

The CMB answers fundamental questions

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- CMB constrains dark matter and dark energy through the growth of structure (σ_8), the expansion rate (H_0), and the amounts of dark matter and dark energy
  - Extremely accurate probe of these mysterious dark components
  - Highly complementary to supernovae and large-scale structure studies

Current State of the Field

Temperature Only

BOOMERanG -1998
DASI - 2000
WMAP - 2001
ACT - 2007
SPT - 2007

50k+ detectors

Simons Observatory (SO) ~now
South Pole Observatory ~now

Added Polarization

QUaD - 2005
BICEP - 2006
QUIET - 2008
Planck - 2009
BICEP2 - 2010
Keck Array - 2012
ABS - 2012
ACTPol - 2013
POLARBEAR - 2012
SPT-Pol - 2012
BICEP 3 - 2016
SPIDER - 2015

Stage 3 ($\leq$10 k detectors)

CLASS - 2016
Advanced ACTPol (AdvACT) - 2017
SPT-3G - 2017
POLARBEAR 2 - 2019
Simons Array - 2019
BICEP Array - 2020
SPIDER 2 - 2022

Future

CMB-S4 (500k+ detectors) - 2030s
LiteBIRD - 2030s

Sensitivity Alone is Not Sufficient

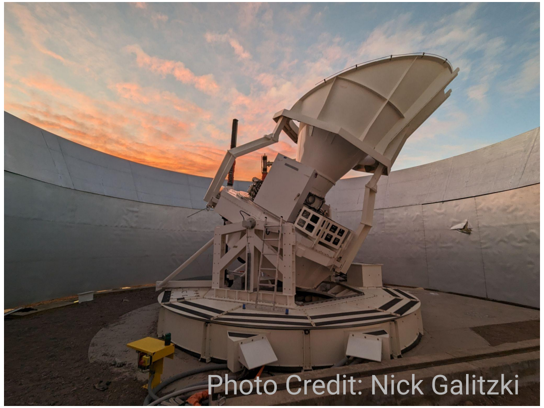
- As sensitivity increases so does our susceptibility to systematic effects
- Science achievable will depend on how well we model and mitigate systematic effects
  - Improved simulations to inform instrument design and removal in analysis
  - Improved calibration to characterize instrument and remove systematic effects

SO's sensitivity is a unique opportunity to develop and demonstrate new calibration methods and technologies for current and future applications

Simons Observatory

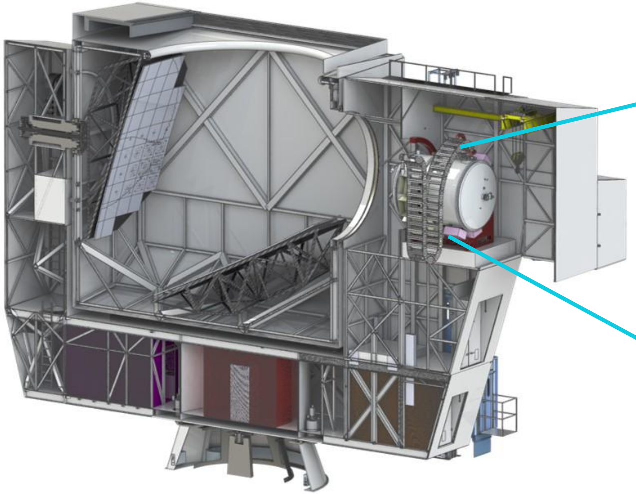
- Located at an elevation of ~5200 m in the Atacama Desert in Chile
- Multichroic cameras 27/39 GHz, 90/150 GHz, 220/280 GHz
- SO Nominal: 60,000+ detectors at ~100 mK
  - Also SO: UK, SO: Japan, and Advanced SO on the horizon→**120k+ detectors**

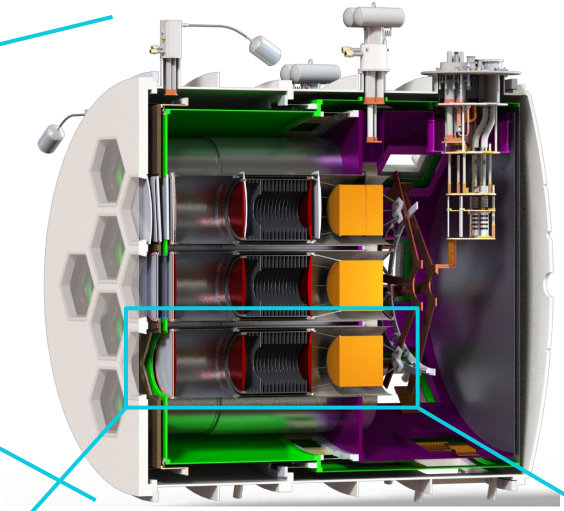
Small Aperture Telescopes (SATs):
- Three ~0.5 m refractive telescopes
- Measure/constrain primordial B-mode



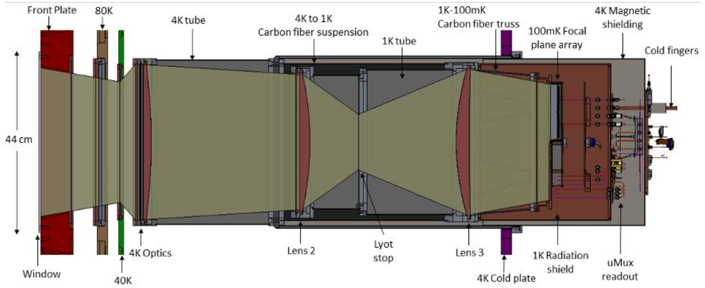
Large Aperture Telescope (LAT):
- One ~6 m crossed-Dragone telescope with 7 optics tubes
- Small angular scale science

Large Aperture Telescope

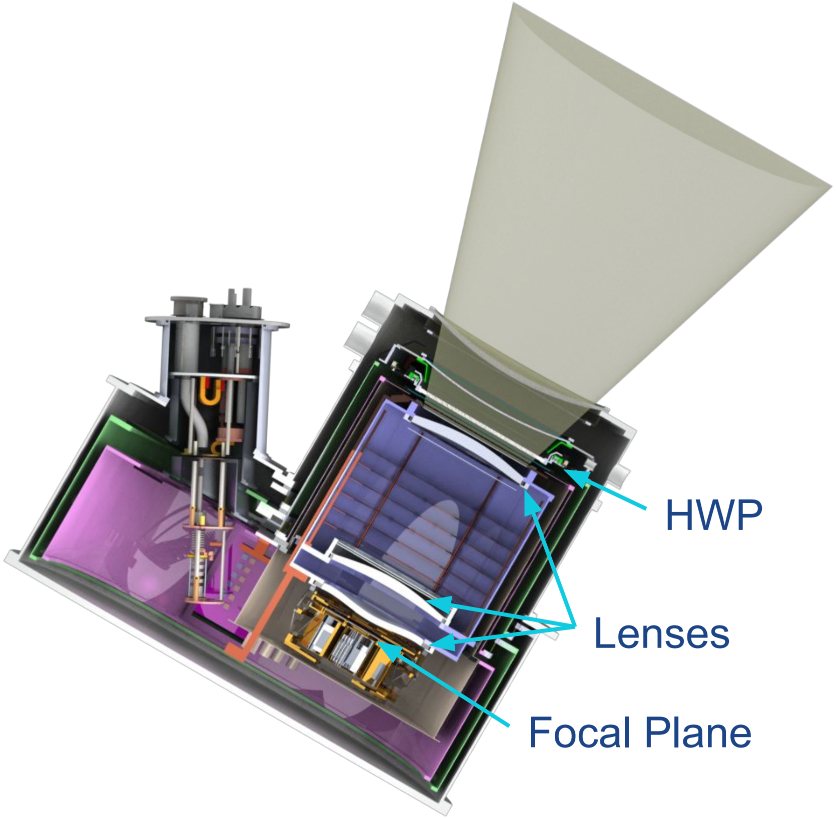




- 6 m Crossed-Dragone
- 1.4 arcmin beam full width at half maximum (FWHM) at 150 GHz
- 1.3˚ field of view (FOV) per optics tube, 7.8˚ FOV total



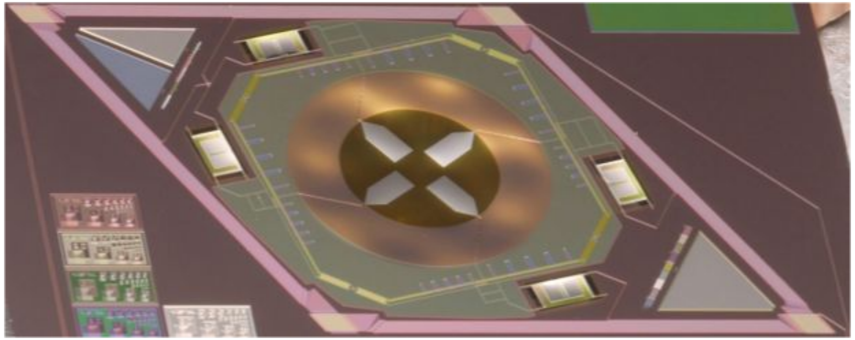
Small Aperture Telescopes

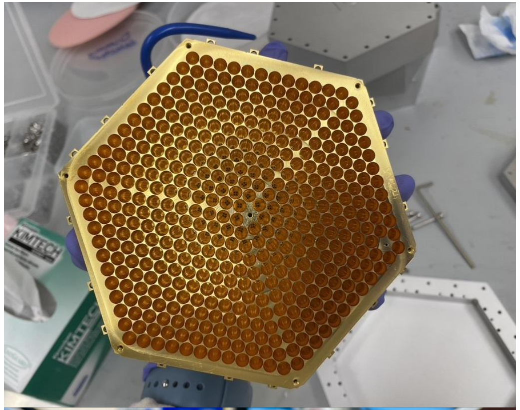


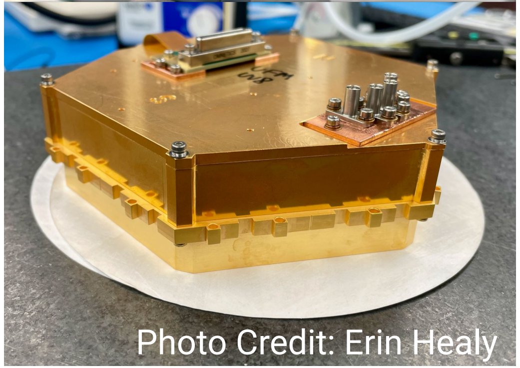
- 3-lens refractive design
- 17 arcmin FWHM at 150 GHz
- FOV=35°
- Polarization modulation with a continuously rotating, cryogenic half-wave plate (HWP)
    - Polarization modulation mitigates atmospheric noise, systematic effects, and instrumental polarization leakage
    - Can be used to calibrate and characterize instrument→ time constants, data selection, monitor gain

Detector Modules

- Feedhorn-coupled orthomode transducers (OMTs) for most modules → beam defined by feedhorn
- Transition-edge sensors (TESes) with ~160 mK transition
- 4 detectors/pixel: 2 orthogonal polarizations for 2 bands
- Read out with μMUX ~1000 detectors/line







SO Nominal Science Forecasts

Parameter	Current Best	SO Baseline	Method
$\sigma(r)$	0.03	0.003	BB + ext delens
$\sigma(N_{eff})$	0.2	0.07	TT/TE/EE + $\kappa\kappa$
$\sigma(\sum m_\nu)$	0.1 eV	0.04 eV	$\kappa\kappa$ + DESI-BAO
$\sigma(H_0)$	0.5	0.4	TT/TE/EE + $\kappa\kappa$
$\sigma(\sigma_8)$ (%)	7%	2%	$\kappa\kappa$ + LSST-LSS + DESI-BAO

Plus: 20,000+ galaxy clusters

The Simons Observatory Collaboration, 2018

Key Calibration Challenges

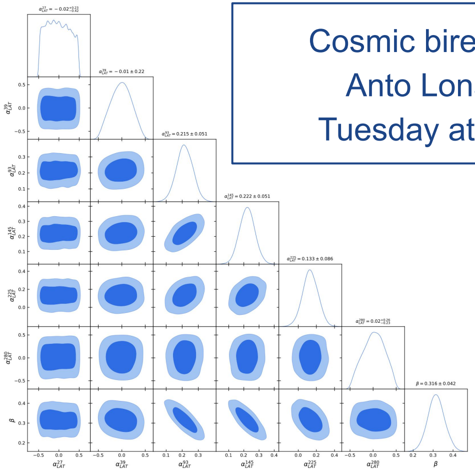
- Unprecedented sensitivity → higher susceptibility to systematic effects
- Different calibration requirements and methods between LAT and SATs
- 60k+ detectors→ variability
- Balancing calibration time with observation time
- Feedback loop with analysis and calibration observations

SO is developing and using detailed simulations to understand calibration requirements

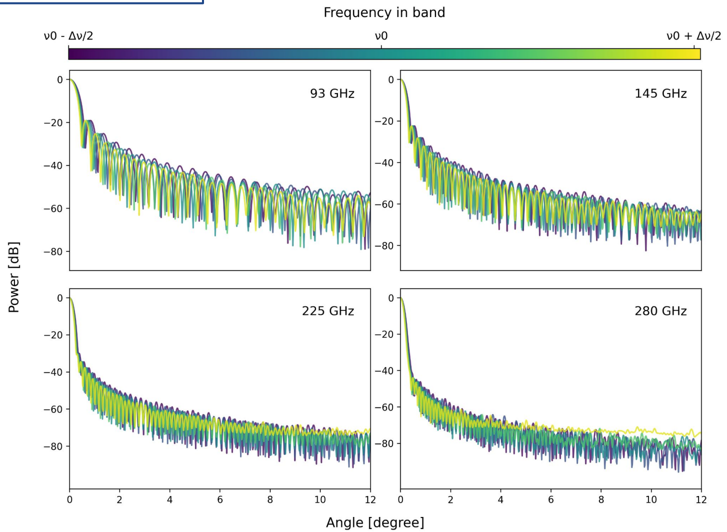
SO uses a conservative calibration approach with multiple methods to reduce risk

SO is developing novel techniques in tandem with demonstrated methods

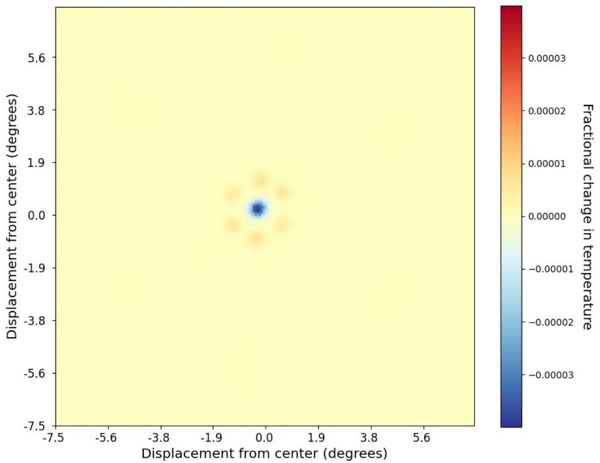
Simulation Development



Cosmic birefringence
Anto Lonappan:
Tuesday at 5:30 pm



Beam chromaticity
Nadia Dachlythra: Wednesday at 11:40 pm



Crosstalk simulations
Toby Satterthwaite:
Thursday at 12:40 pm

Bandpasses

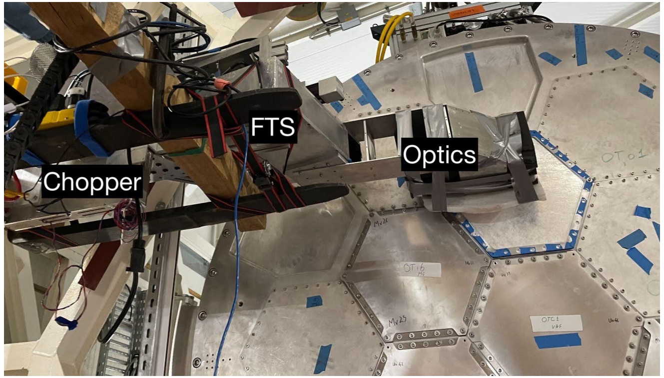
Requirements

- Center frequency requirement on order ~0.5-1% for 90/150 GHz with less stringent constraints once marginalized (Abitbol, et al., 2021, Giardiello, et al., 2024)
- Expect that Sunyaev Zel'dovich (SZ) cluster science case requirements may be more stringent → detailed studies underway (S. Sutariya)

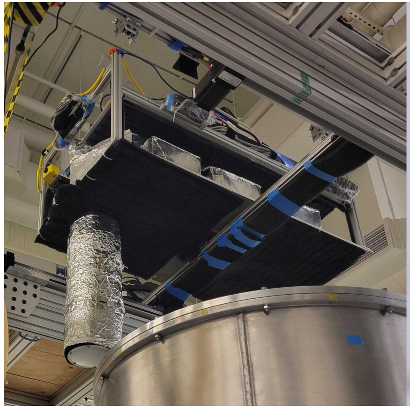
Key Challenges: Reaching required limit with hardware + number of detectors

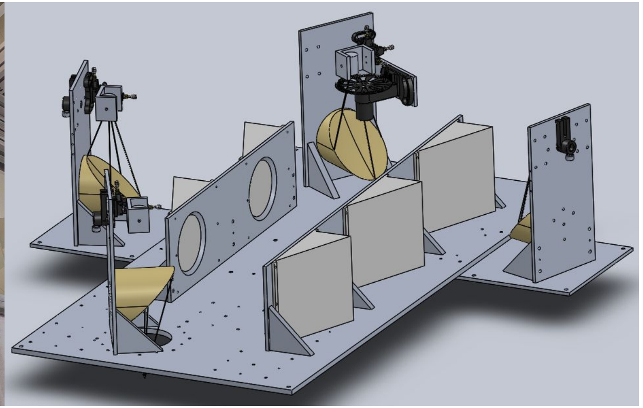
Bandpass Calibration

- Dedicated campaigns with Fourier Transform Spectrometer (FTS) → move to fully reflective optics to further reduce uncertainty to required level
  - During season with poor observing conditions
- Radiometer and weather station (continuous) → characterize atmospheric effects
- Developing new technology with frequency-selectable laser source (FLS) → higher frequency resolution, more direct measurement



FTS and future calibrators
Claire Lessler:
Tuesday at 5:50 pm





FLS measurements, Shreya Sutariya: Thursday at 12 pm

Polarization Angle

Requirements

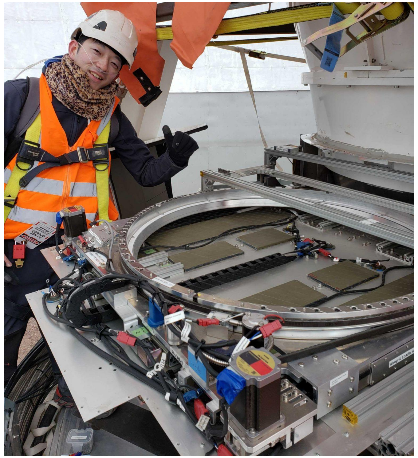
- SATs: 0.4° for 90/150 GHz (Abitbol, et al., 2021)
    - When using half-wave plates (HWPs), time constant uncertainties contribute to polarization angle uncertainty
- LAT: 0.25° sufficient (Giardiello, et al., 2024)

Key Challenges: Reaching required hardware levels for SAT + combining methods + few available celestial sources

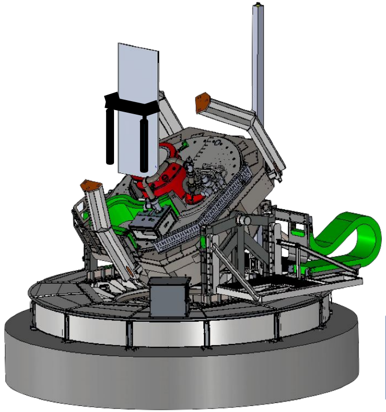
(Tau A only known to ~0.27°, varies by band [J. Aumont, et al., 2020])

Polarization Angle Calibration

- SATs
  - Time Constants
    - Electrical time constants via bias steps ~hourly
    - Correlate electrical time constants with ~weekly time constant measurements with wire grid
  - Wire grid calibrations ~weekly
  - ~Weekly Tau A observations
  - Annual drone calibration
  - Plate calibrator
  - Self-calibration is an option but sacrifices limits on cosmic birefringence
- LAT
  - ~Weekly Tau A observations
  - Cross-correlation with SATs → developing new technique
  - Exploring new method with polarized starlight (B. Hensley)



Wire grid calibrator
Hironobu Nakata:
Tuesday at 12:40 pm



HoverCal + POLOCALC
Rolando Dünner:
Tuesday at 11:40 am

Plate calibrator - Erin Healy

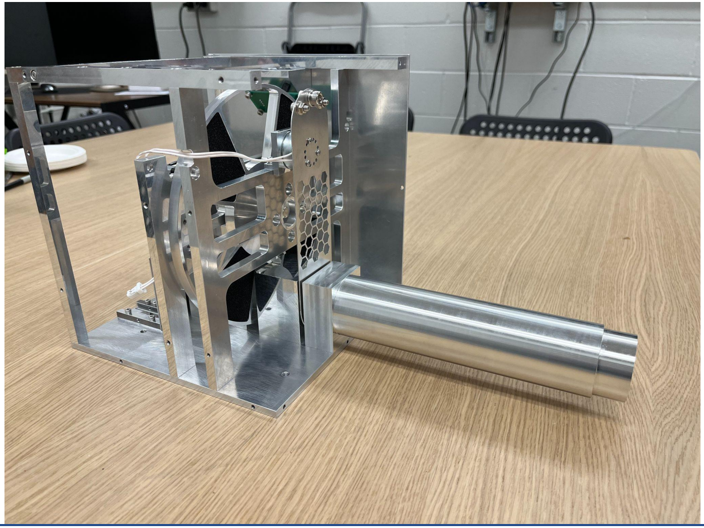
LAT Time Constant Calibration

Requirements

- Requirements depend on time constant → faster detectors can have higher uncertainty
- Power spectrum constraints set requirement at <10% for target SO time constants (S.M. Simon & E. Calabrese)

Key Challenge: Understanding uncertainties from correlation of electrical/optical time constants

~Hourly electrical time constants via bias steps correlated with optical time constants from stimulator every few hours when rebiasing



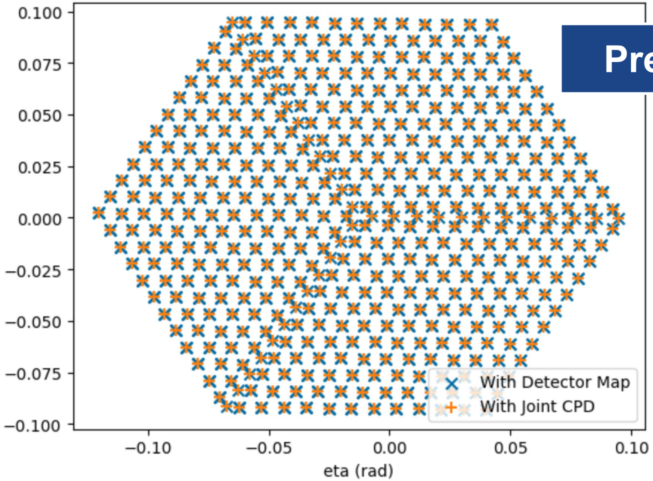
Stimulator calibrator
Yudai Seino: Tuesday at 10:10 am

Pointing Calibration

Requirements
- LAT: <15 arcsec offset pointing
- SATs: <20 arcsec RMS (G. Teply & J. Didier)

Key Challenges: Availability of sources early in project + getting pointing observations at the same azimuths and elevation as observations

- SATs
  - Moon observations
  - Planet observations
  - Star camera (as needed)
- LAT
  - Point sources
  - Planet observations



Preliminary

Pointing model
Saianeesh Harridas:
Thursday at 9:30 am

Responsivity

Requirements

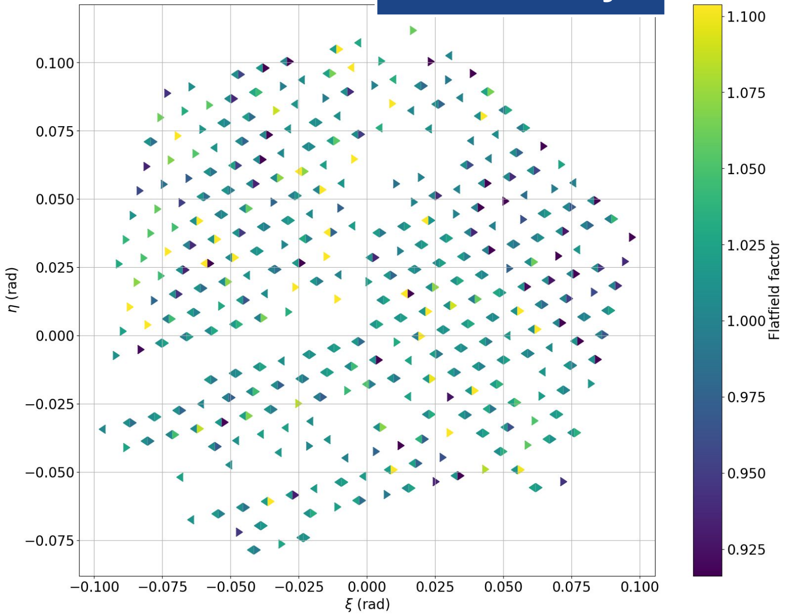
- SATs: 2.8% for 90/150 GHz (Abitbol, et al., 2021)
- LAT: 1% gain uncertainty has a non-negligible effect, marginalization can help reduce requirement (Giardiello, et al., 2024)

Key Challenge: Reaching levels required for LAT science

Responsivity Calibration

- SATs
  - Jupiter, Venus, and Saturn observations
  - Second harmonic of the half-wave plate (HWP)
  - Relative responsivity from wire grid
  - Calibration with Planck/WMAP
- LAT
  - ~Hourly measurements with stimulator
  - Uranus observations
  - Calibration with Planck/WMAP

Preliminary



Gain calibration
Kevin Crowley : Tuesday at 9:50 am

Beams

Requirements

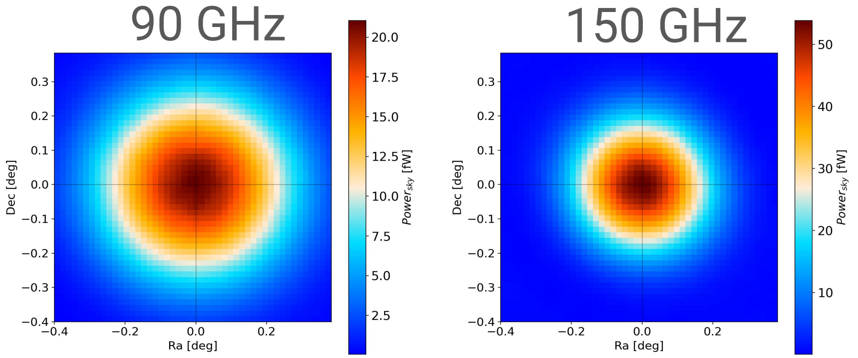
- Depend on potential variations in beam (e.g. day/night, azimuth/elevation dependence)
- LAT: Primarily set by uncertainty in window function of beams
- SATs: Polarized beam is critically important→ detailed studies underway on polarized beams (L. Saunders) and frequency-dependence (N. Dachlythra)

Key Challenges: Effectively tracking and building up a beam model over time + Understanding variation + Combining different observations to fully characterize beam + Limited source availability (SAT) + Balancing CMB field priorities

Beam Calibration

- SATs
  - Jupiter, Venus, and Saturn observations
  - Annual drone measurements (polarized beam)
  - Hybrid Moon (<41˚)/Sun (>41˚) far sidelobe observation campaign
- LAT
  - Uranus and Neptune for the main beam
  - Saturn, Jupiter, and Venus for the mid-range beam
  - Moon/Sun for far sidelobes

Preliminary



SAT calibration measurements
Samuel Day-Weiss: Thursday at 9:50 am

Summary

- Calibration and systematic mitigation will determine experiment performance in current and future generations of CMB experiments
- SO is using both novel simulations and instrumentation to improve calibration and systematic mitigation
- SO commissioning and observations are now underway → Beginning to test full calibration plan and new calibration techniques
- The coming years will include new and exciting results on the performance of these new calibration technologies and methods in addition to SO science results

SO will serve as a key testbed for calibration methods and technologies in the coming years → Critically important for future CMB projects like CMB-S4

Thank You

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