Calibration Techniques for a Simons Observatory 90/150 GHz Small Aperture Telescope

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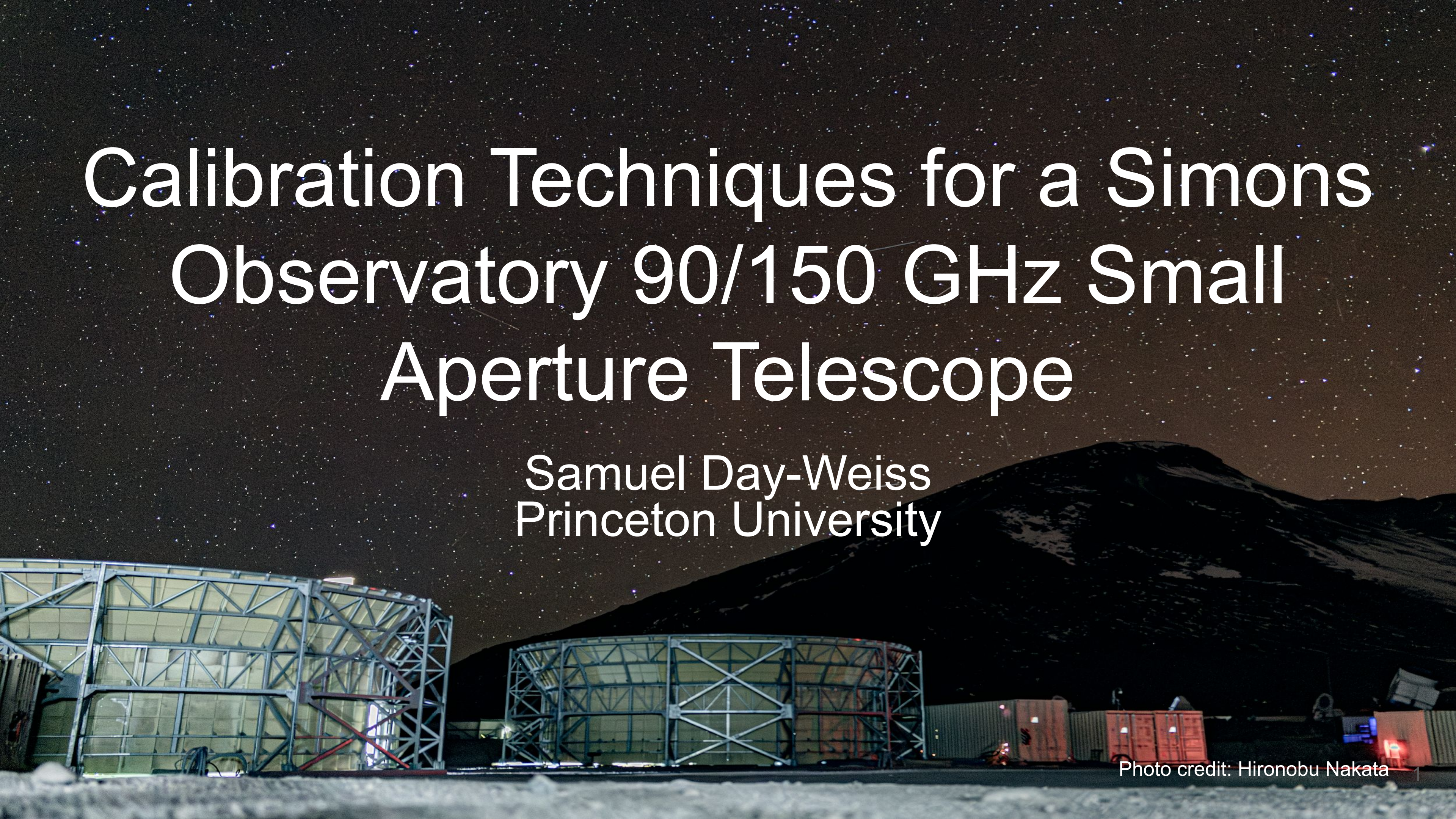


Photo credit: Hironobu Nakata

Outline

- SAT calibration status
  - Bringing together all of SO's calibration development efforts
  - A focus on data from "SATP3"
  - Optical design overview
- Beam calibration
  - Intensity beam: preliminary profiles with Jupiter
  - Polarization beam: new challenges and analysis plan
- Absolute polarization angle calibration
  - Preliminary observations of Tau A (Crab Nebula)
- Summary

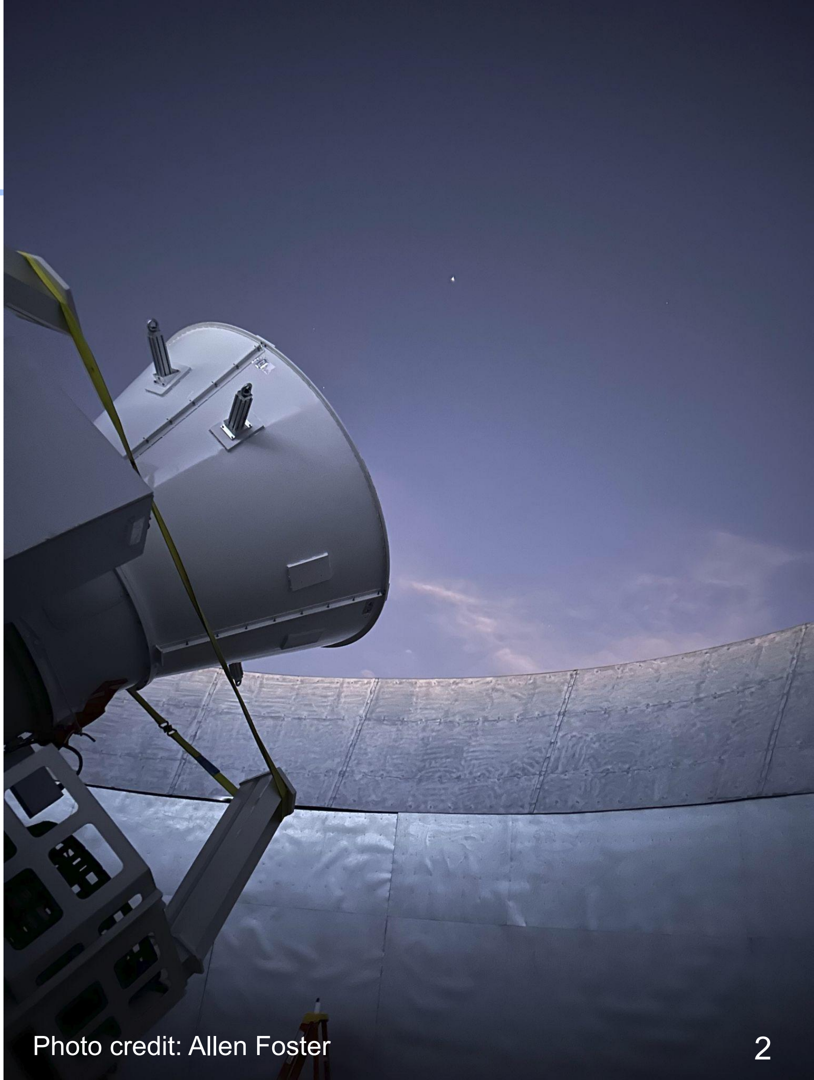


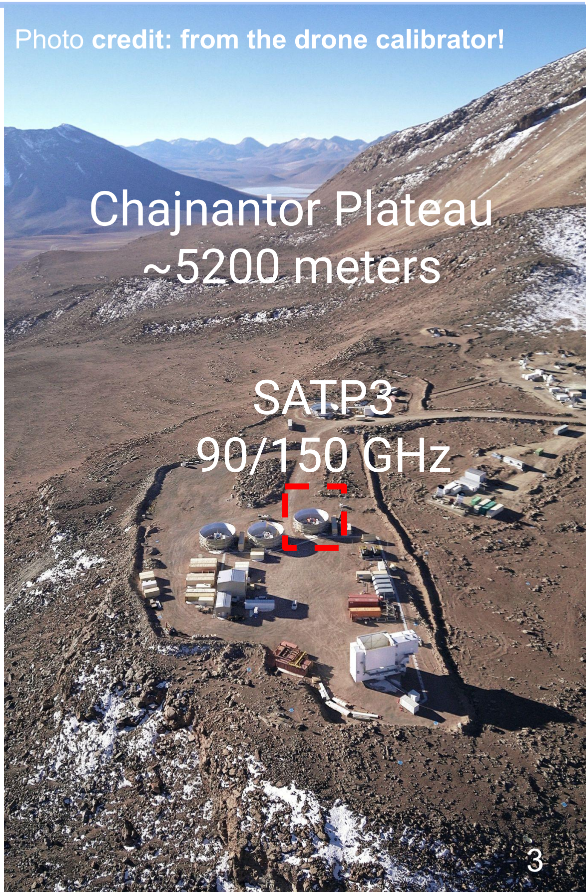
Photo credit: Allen Foster

The Simons Observatory (SO) SATs: SATP3

- In-field integration began: Oct 2023
- First Jupiter/CMB observations: December 2023
- 3 distinct observing periods marked by instrument upgrades to improve systematics
- ~2000 hours of CMB observations
- ~460 hours of calibration observations (source scans primarily)

This talk:

- Calibration observations since July 31 2024
- 32 observations of Jupiter
- 25 observations of Tau A

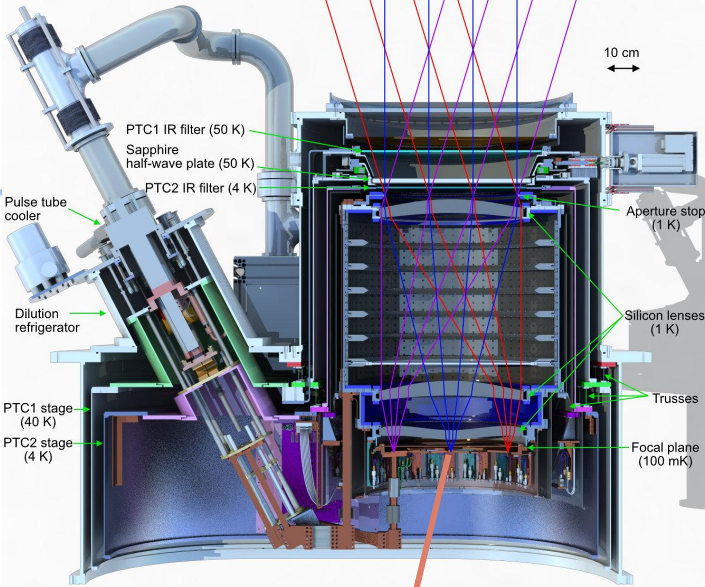


Optical design

(see Galitzki et al., 2024 for more details on the cryostat itself)

- UHMWPE window
- 40K IR filter stack
- CHWP
  - Pancharatnam-style 3-layer sapphire stack
  - 2 layers of meta-material AR coating (alumina)
  - Superconducting magnetic bearing (see Yamada et al., 2024, similar to PB-2b design)
- 4K meta-material AR coated alumina filter
- 1K aperture stop
- 3 refractive lenses
- 1K LPE filters
- ~12,000 optically coupled TESes
  - Feedhorn-OMT coupled
  - Target ~70-80% (PWV dependent) yield successfully going into current CMB maps

Yamada et al. (2024)

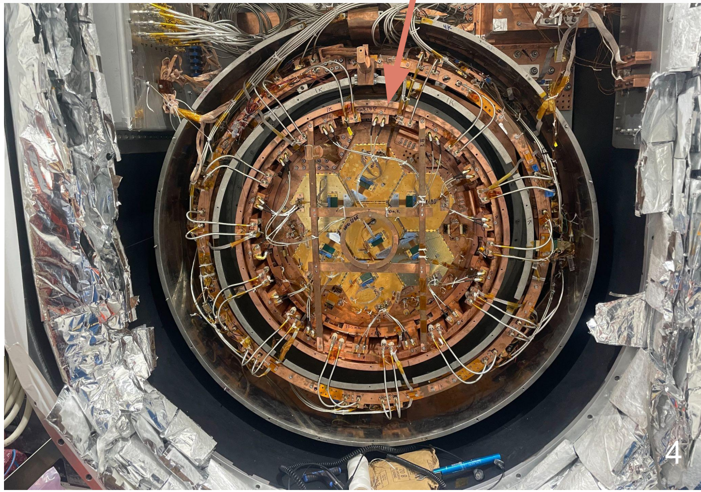


On Sky

ws4

ws3 ws0 ws5

ws2 ws1 ws6



Beam calibration: Intensity

preliminary

Why Jupiter?

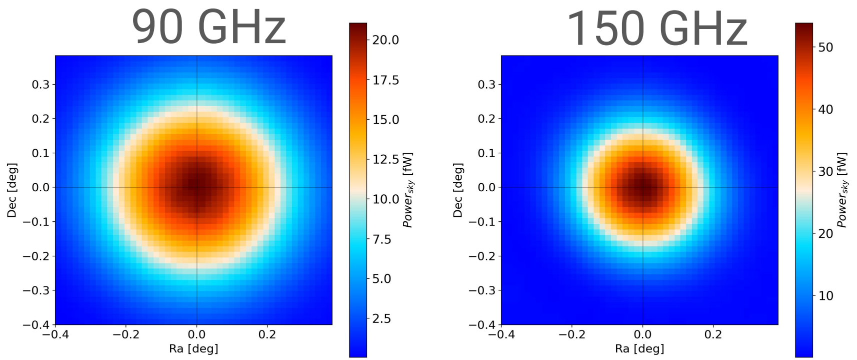
- High S/N at our observing frequencies
- Essential for measuring solid angle
  - Jup solid angle varied from 0.02 - 0.03 usr
    - ~72, 36 usr beams (point source!)
  - Already 2-3% constraint on solid angle
- Can be used as an independent pW → T_cmb calibrator

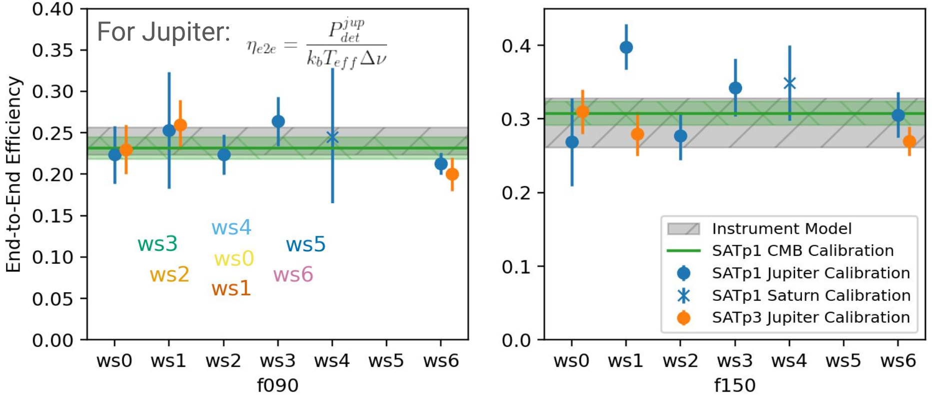
Map Making

- Inverse-variance weighted filter-binned map
- Planet mask + polynomial interpolation
- PCA calculation and mode subtraction

Challenges

- Source availability/coverage with wide focal plane
- 32 obs split between wafers (one at at time)





All estimates using simulated bandpasses (errors shown driven by this and the solid angle)

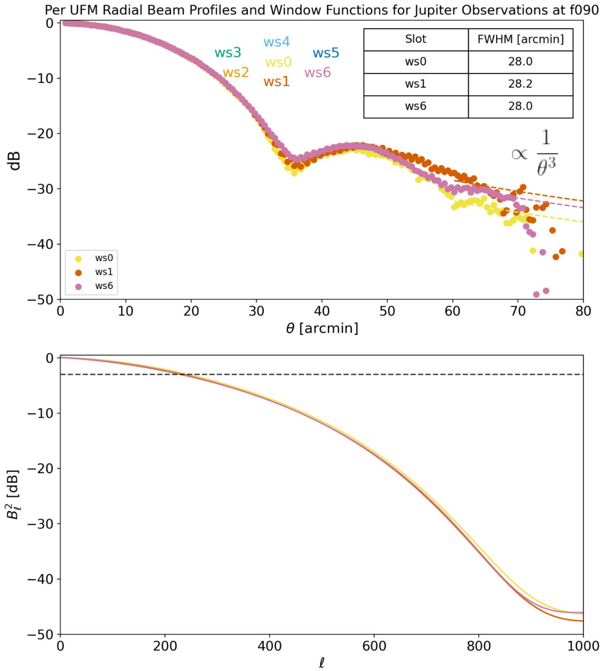
Beam calibration: Intensity

90 GHz, mask: 1°
N = 40

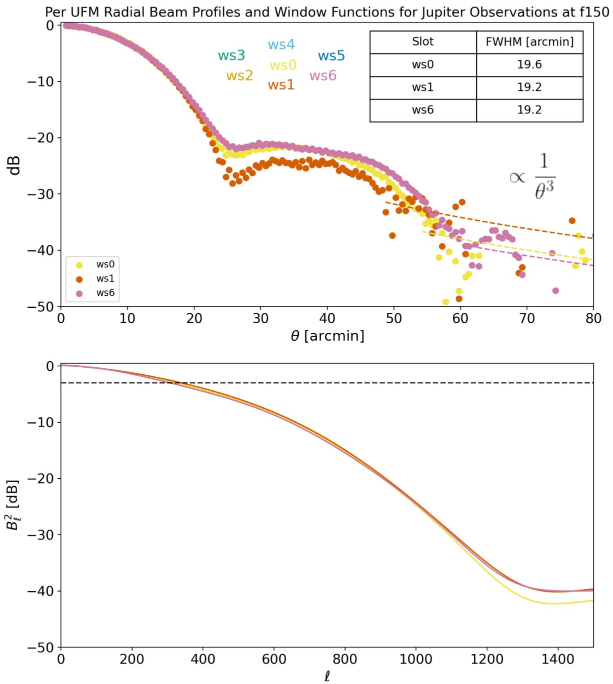
preliminary

150 GHz, mask: 1°
N = 40

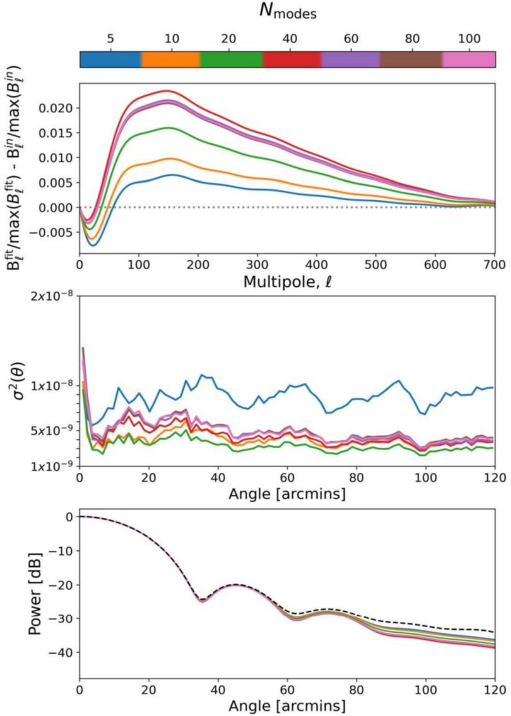
90 GHz bias from sims, mask: 2.5°



Slot	FWHM [arcmin]
ws0	28.0
ws1	28.2
ws6	28.0



Slot	FWHM [arcmin]
ws0	19.6
ws1	19.2
ws6	19.2

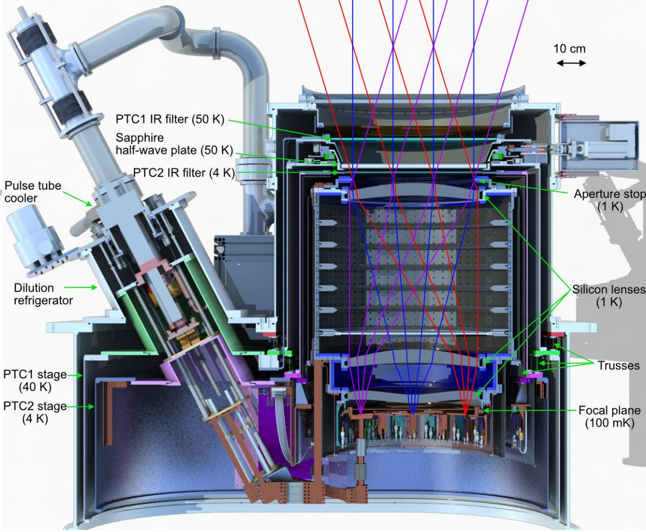


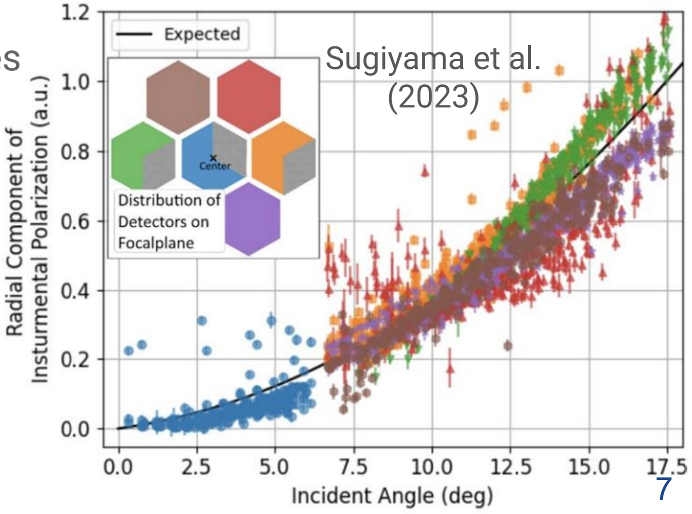
Future work to follow Dachlythra et al. (2024) and Lungu et al. (2022)

Dachlythra et al. (2024)

Beam calibration: Polarization

- Beams
  - Drone measurements
  - Tau A (far side lobes not accessible)
- Monopole leakage
  - From HWP synchronous signal
  - Quadratic radial increase expected (Essinger-Hileman et al, 2016)
- Jupiter
  - Higher order leakage terms
  - Extrapolation of synchrotron emission from lower frequencies puts linear pol fraction < 0.2% (Weiland et al. (2011))
  - Expansion in Gauss-Hermite functions (ABS did monopole, dipole, quadrupole terms, motivated by the HWP model)
- Challenges
  - Components above the HWP
    - PB-2B dominated by monopole of primary mirror
    - ABS HWP first optical element
  - New anti-reflective coating
    - Ongoing work to improve the ABS model for SO





Sugiyama et al. (2023)

Absolute pol. angle calibration: Tau A

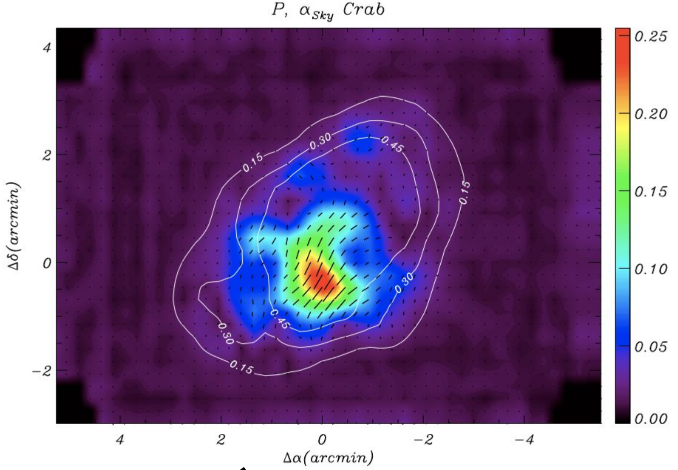
- ~ 6' x 4' extended source
  - J083.627 + 022.021
  - Supernova remnant
  - Synchrotron emission from central pulsar interacting with surrounding gas

- Polarization angle known to ~ 0.27° (J. Aumont et al, 2020)
  - This assumes no correlated systematic errors between frequencies
  - Can have frequency dependence
  - SAT req. 0.4 deg
  - Combine with wire grid and drone measurements

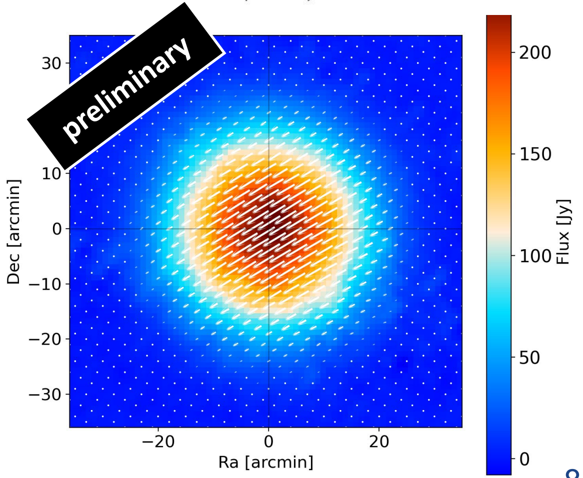
Top: P [K, antenna] with pol angles

Bottom: T [Jy] with pol angles

J. Aumont et al., (2010) for XPOL at 90 GHz w/ 27" resolution



SATP3 ws6 at 90 GHz w/ ~28' resolution

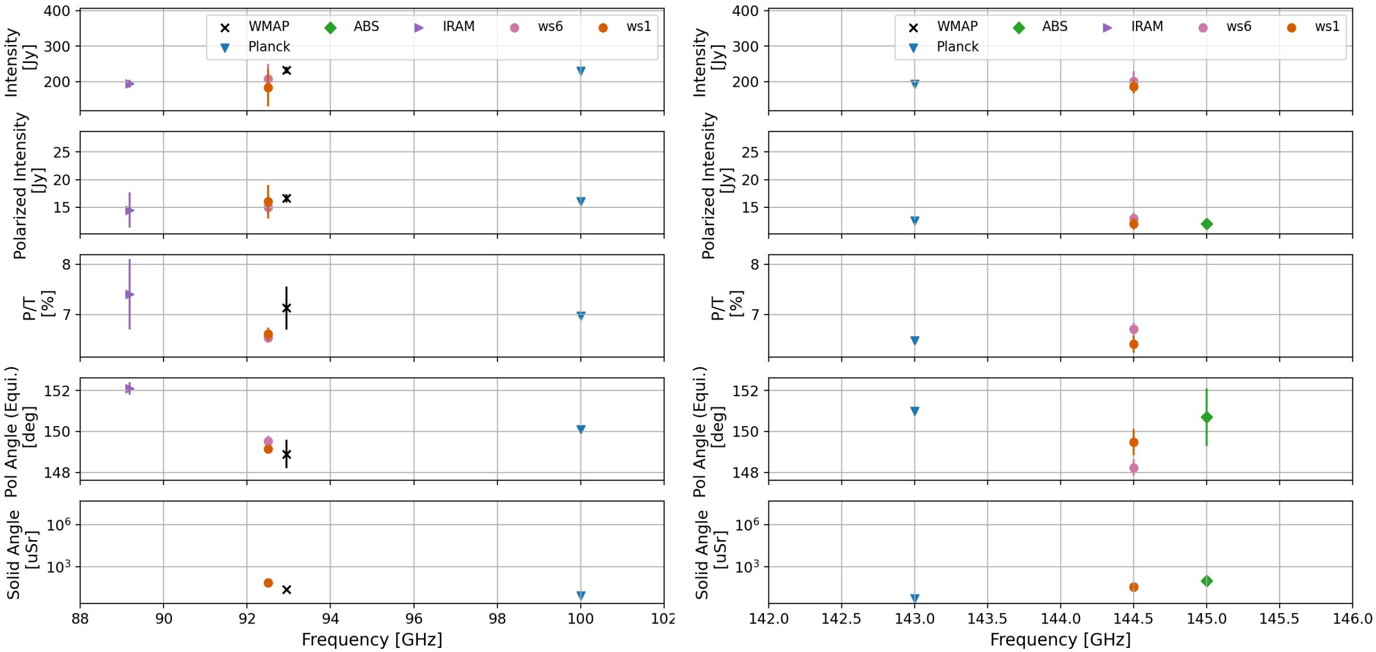


Absolute pol. angle calibration: Tau A

- 25 observations between both wafers
- Statistical uncertainties in pol angle:
  - ~0.3 deg at 90 GHz
  - ~0.4 deg at 150 GHz
- 1 sigma bound on polarization efficiency > 78% (using pol. intensity)
  - Far tighter constraints from calibration to the CMB

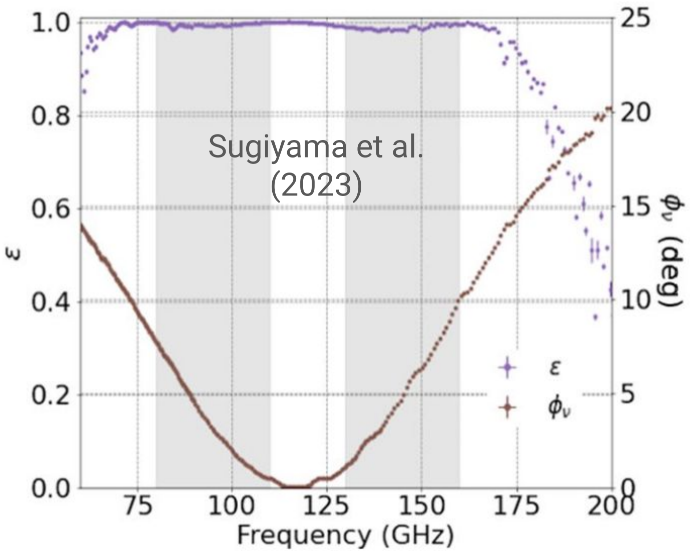
preliminary

Pol Angle assumes a 1.52 deg band averaged phase offset from 90→150 GHz



Absolute pol. angle calibration: Tau A

- A possible source of pol. angle systematic uncertainty: **band center uncertainty**
- Planned:
  - FTS campaign with linearly polarized source
  - Measure HWP polarization modulation properties as well as the band centers



Simulated SAT Band Centers
f090: 92.7 GHz
f150: 144.4 GHz

Summary

- New and exciting data as the SATs exit the initial commissioning phase!

- Jupiter is an optimal source for intensity and leakage beam mapping
  - Already important confirmations of our pointing, gain calibration, and beam mapping methods
  - Optimizing coverage is difficult

- Tau A will serve as a reliable source for absolute polarization angle calibration
  - Constraints on angle likely worse than the SAT requirement
  - Will have to combine with wire grid and drone measurements

Thank You