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In-situ Optical Characterization of the Simons Observatory Large-Aperture Telescope Receiver

Claire Lessler

on behalf of the Simons Observatory Collaboration

Photo credit: Hironobu Nakata

Motivation

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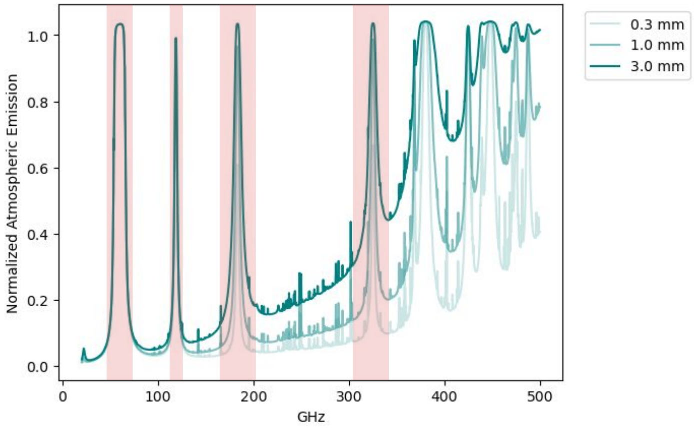
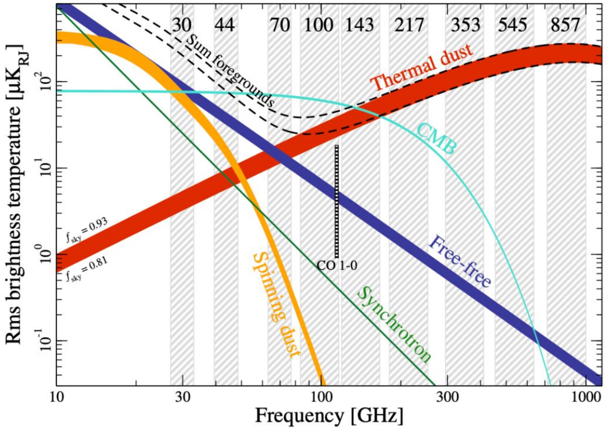
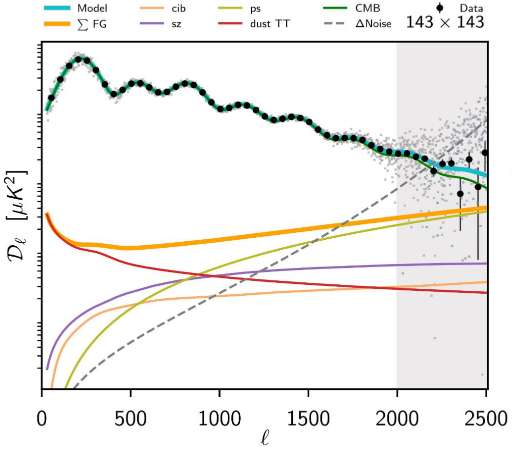
Why should we care about frequency calibration?

Level 1: Avoid atmospheric absorption lines



Level 2: Enable accurate optical component separation





Planck 2018 results. I [1]

Our instrument: the SO LAT

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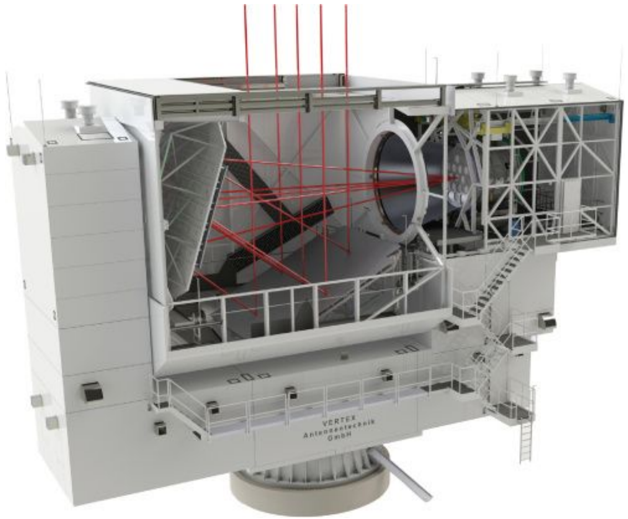
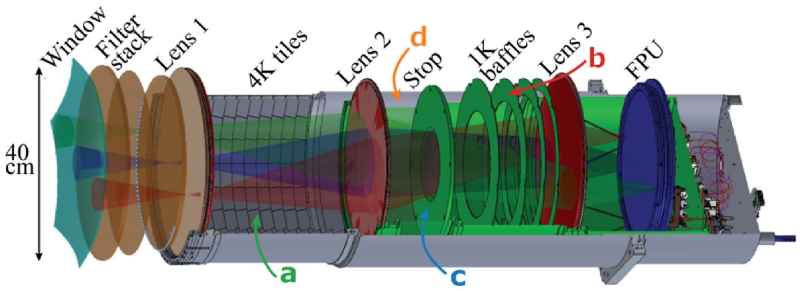


- Targets small angular scales
- 7.8 degree FoV at 90 GHz
- Effective f-number: 2.6
- Arcminute angular resolution
  - 1.4 arcmin beam FWHM at 150 GHz



Figures from
Gudmundsson et al. [2]

Our instrument: the SO LAT

Single MF pixel

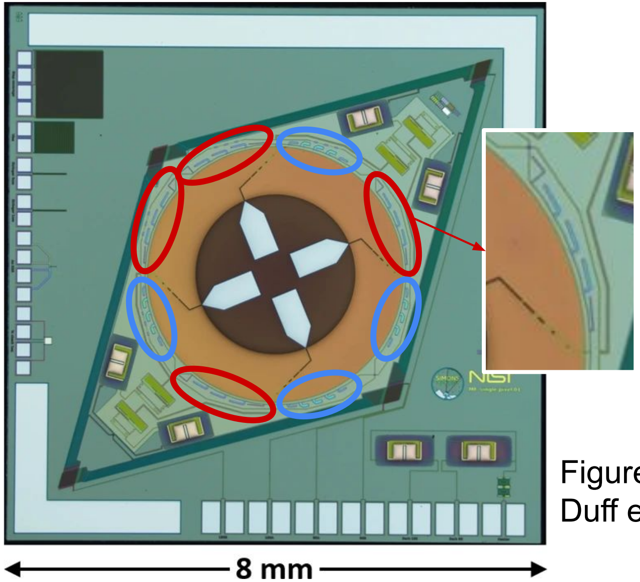


Figure from Duff et al. [3]

MF-1 filters

MF-2 filters

- Bandpasses are defined by on-chip frequency filters.
- A low-pass filter stack below the optics tube window removes excess out-of-band power to decrease loading on the detectors.

Simulated SO bandpasses

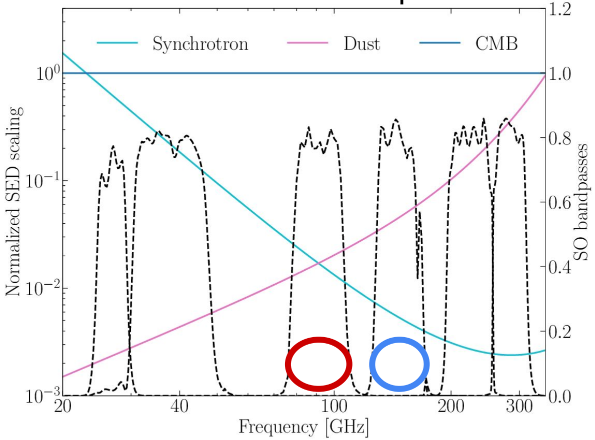


Figure from Abitbol et al. [4]

Tools for bandpass calibration

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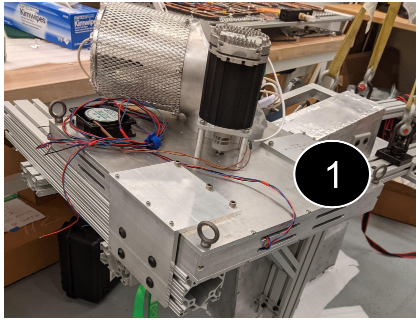
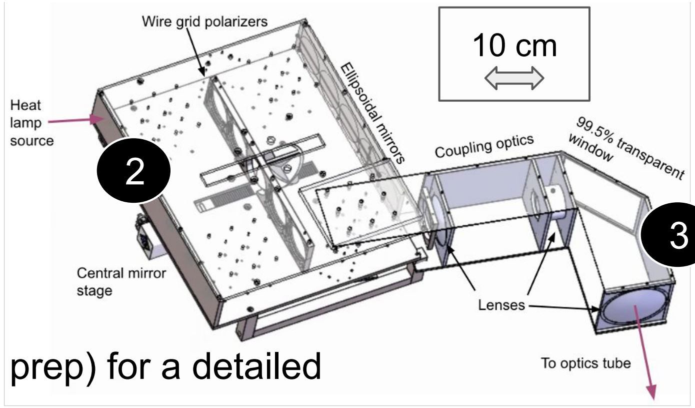
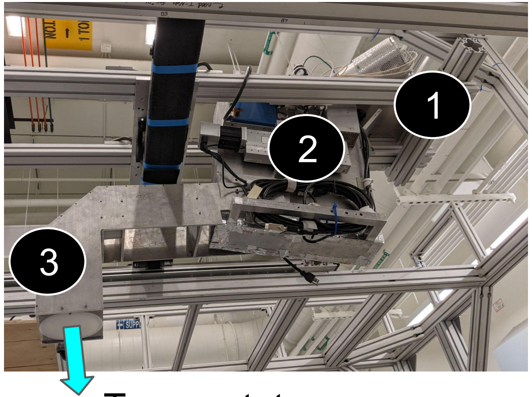
Chopped thermal source ➡ FTS ➡ Coupling optics





See T. Alford, R. Datta et al. (in prep) for a detailed analysis of FTS systematics

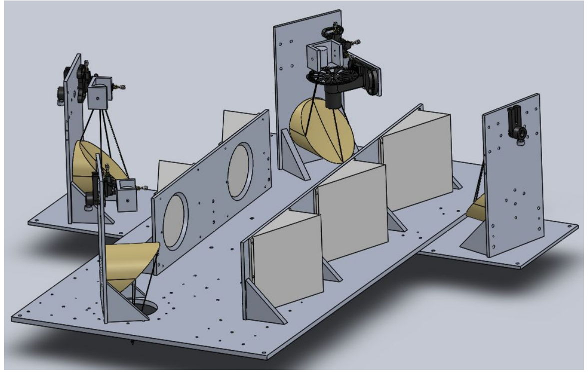
In action!

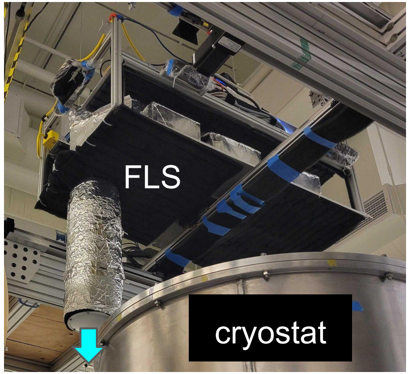


To cryostat

Frequency-Selectable Laser Source (FLS)

See Shreya Sutariya's talk on Thursday at 12 PM!





How an FTS works

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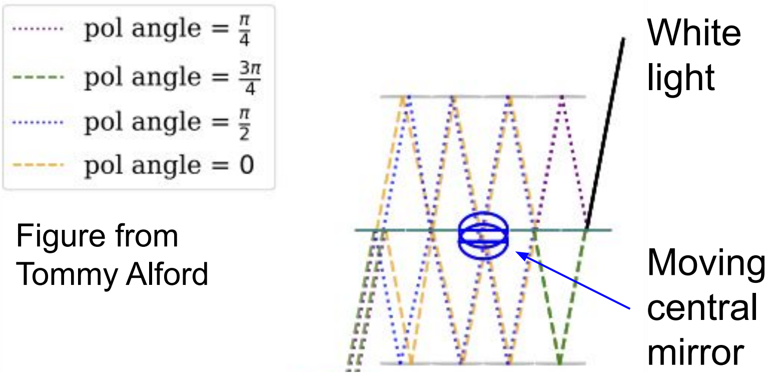
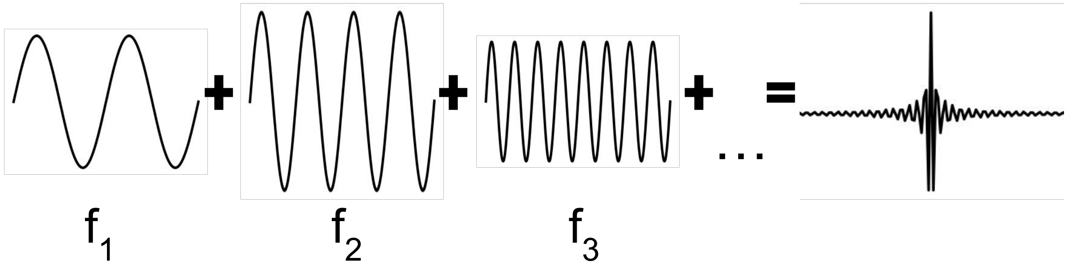
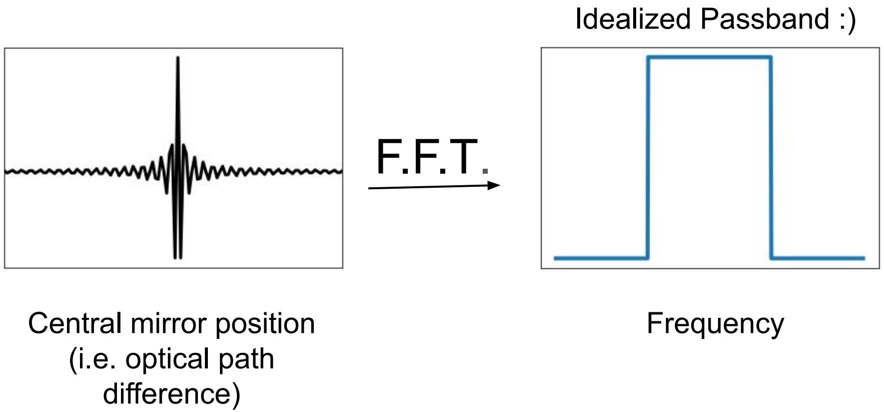


Figure from Tommy Alford

- Based on the PIXIE design [5]
- Linear movement of central mirror→ change in path difference between orthogonally polarized beams which are recombined at the output
- Fourier transform the detector response as the optical path difference changes→passband

Detector response to individual frequencies as the optical path difference changes:





August 2024 in-situ characterization

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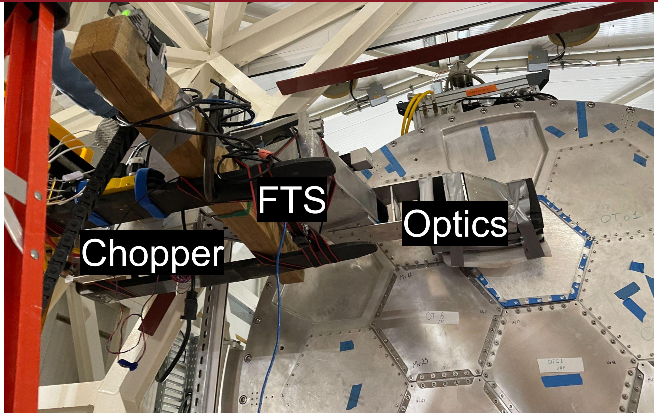
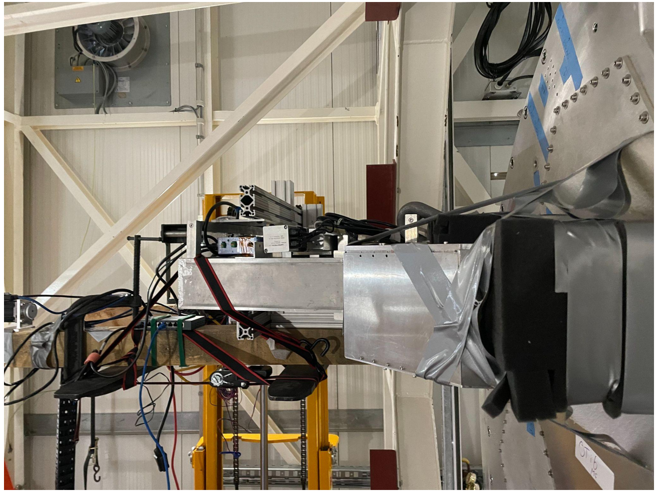


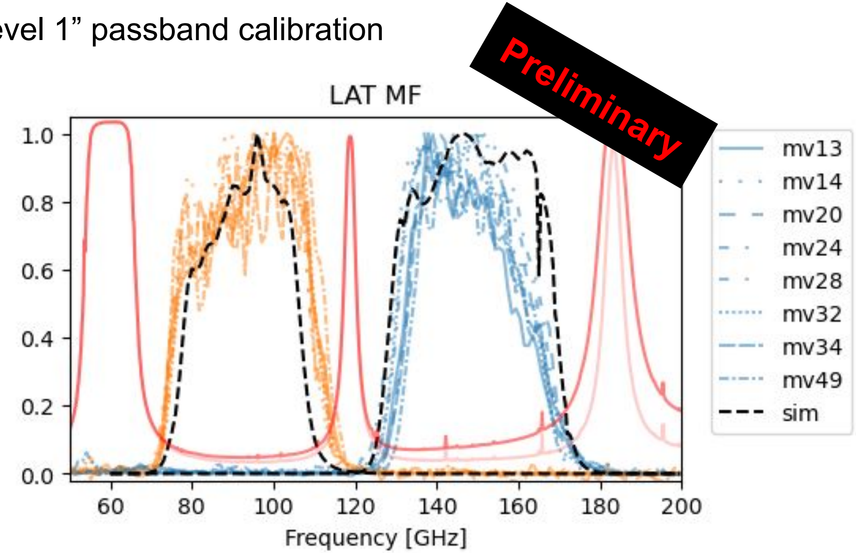


August 2024 in-situ characterization

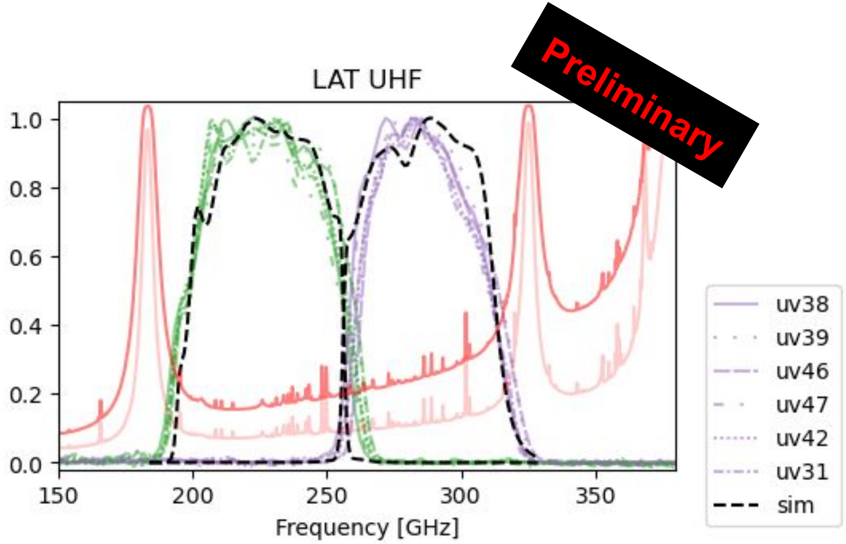
1. Place NDF over array
2. Park FTS & coupling optics over array
3. Stream data with FTS on white-light fringe
4. Make sure enough detectors see a signal (~100 per observation)
5. Set FTS parameters (i.e. mirror step size & throw) according to the frequency range of the array
6. Stream data while changing the FTS central mirror position
7. Fourier-transform the TODs to produce bandpasses for each detector
8. Average all bandpasses per array with weights proportional to each detector’s SNR^2

~1700 detectors (14 arrays) measured!

"Level 1" passband calibration



8 MF arrays measured



6 UHF arrays measured

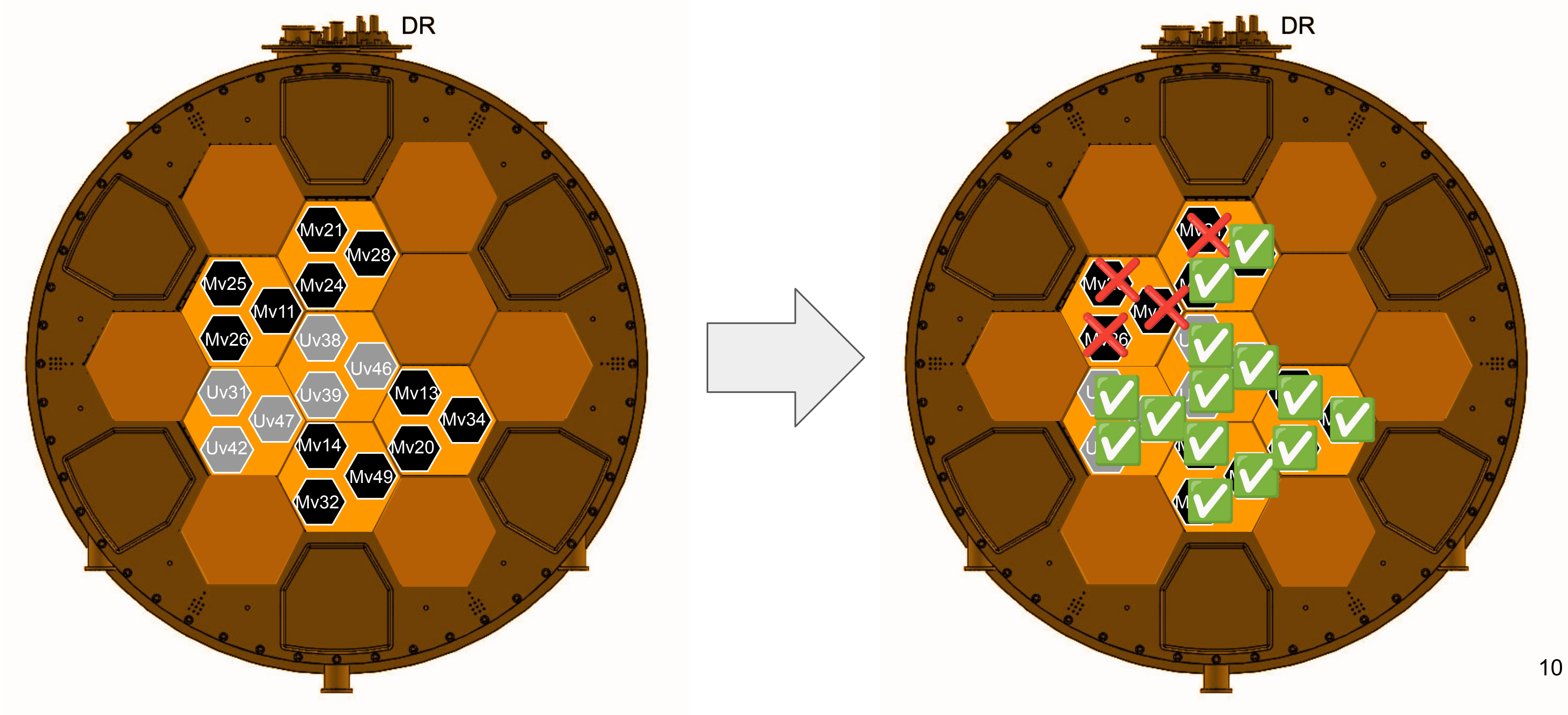
Red: normalized emission at 1mm, 3mm PWV

Dotted: simulated passband

- Bands mostly match simulations.
- The edge of the MF-1 (90 GHz) band appears shifted, but both bands remain within spec and negligibly affect the LAT's mapping speed.
- Finer "level 2" passband analysis will require repeat calibration without NDFs.

~1700 detectors (14 arrays) measured!

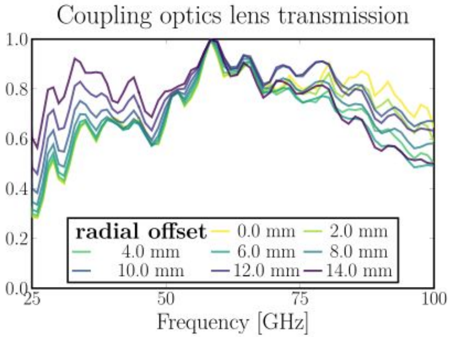
"Level 1" passband calibration



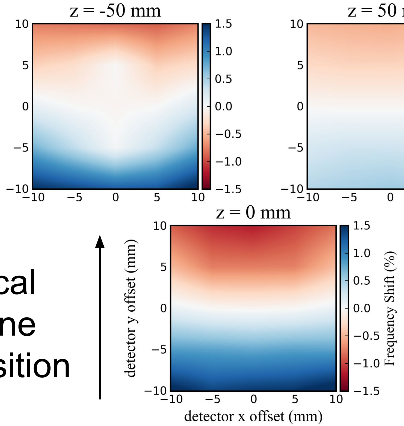
Future improvements

"Level 2" passband calibration

- HDPE lenses in coupling optics introduce standing-wave interference effects → spectral shifts depending on detector position on focal plane



- Current in-situ characterization requires manually moving the FTS between arrays & estimating the focus → limits the number of detectors we can measure



Focal plane position

In focus

- **Frequency shifts** due to path-length variations in the beam through the FTS
- These depend on:
  - Quality of focus
  - Position of detector relative to FTS central pointing position

See T. Alford, R. Datta et al. (in prep) for more detail

Future improvements

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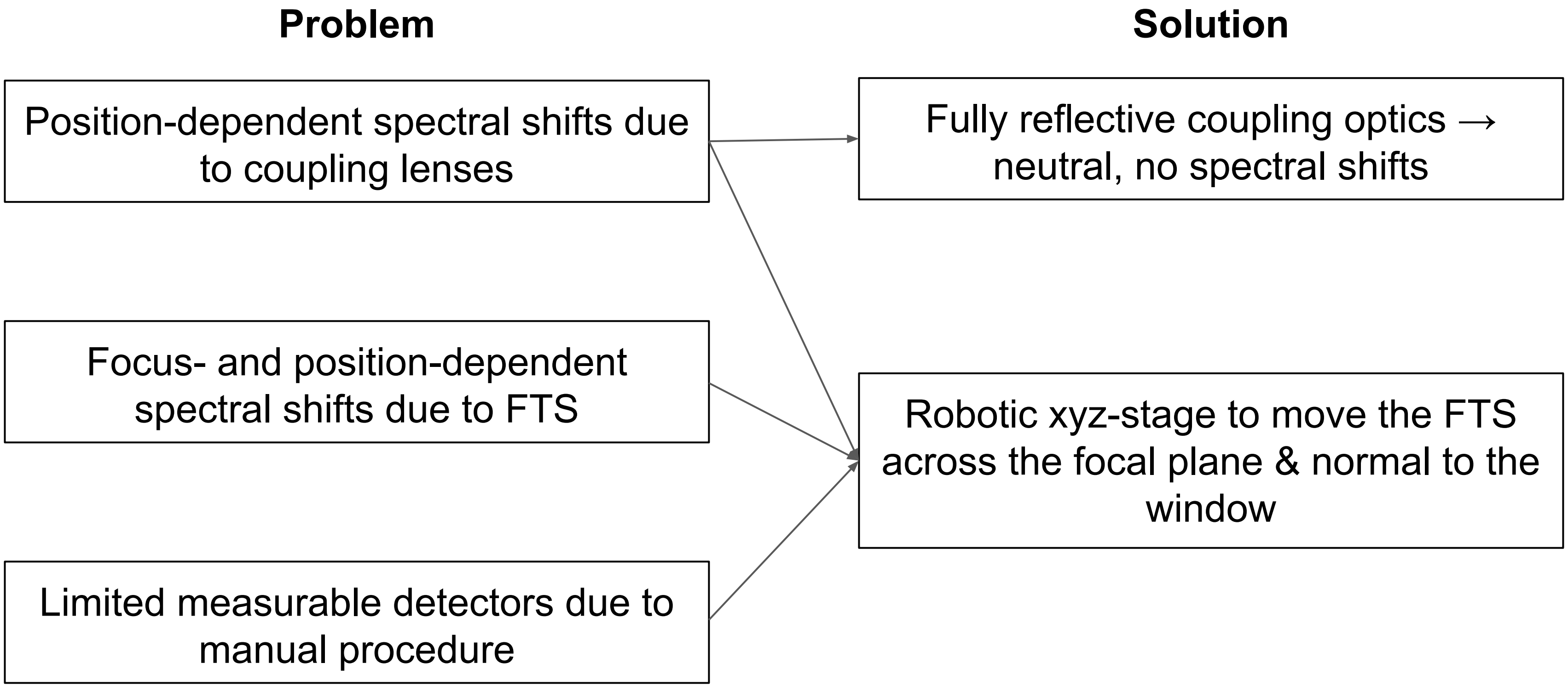
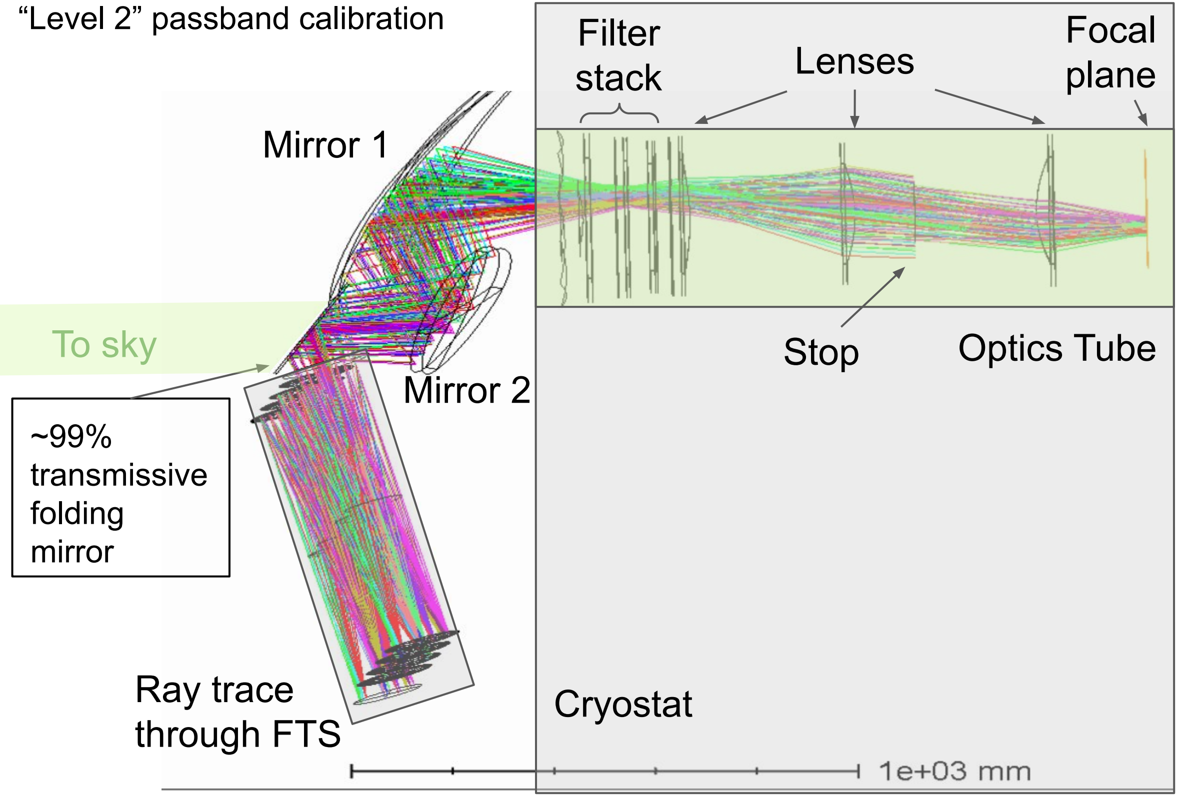
"Level 2" passband calibration

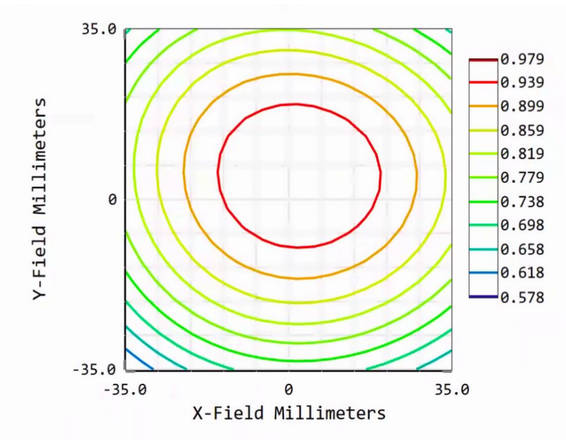


LAT coupling optics

“Level 2” passband calibration



Strehl Ratio Field Map



Thank you

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科研費 KAKENHI

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References

1. Planck collaboration, *Planck 2018 results. I. Overview and the cosmological legacy of Planck*, A&A 641 (2020) A1 [arXiv:1807.06205]
2. Gudmundsson et al., "The Simons Observatory: modeling optical systematics in the Large Aperture Telescope," Appl. Opt. 60, 823-837 (2021)
3. Duff, S.M., Austermann, J., Beall, J.A. et al., “The Simons Observatory: Production-Level Fabrication of the Mid- and Ultra-High-Frequency Wafers,” *J Low Temp Phys* **216**, 135–143 (2024)
4. Maximilian H. Abitbol et al., “The Simons Observatory: gain, bandpass and polarization-angle calibration requirements for B-mode searches,” JCAP05 (2021) 032
5. A. Kogut et al., “The Primordial Inflation Explorer (PIXIE): a nulling polarimeter for cosmic microwave background observations,” JCAP07 (2011) 025