New techniques to control instrumental Systematics for CMB experiments

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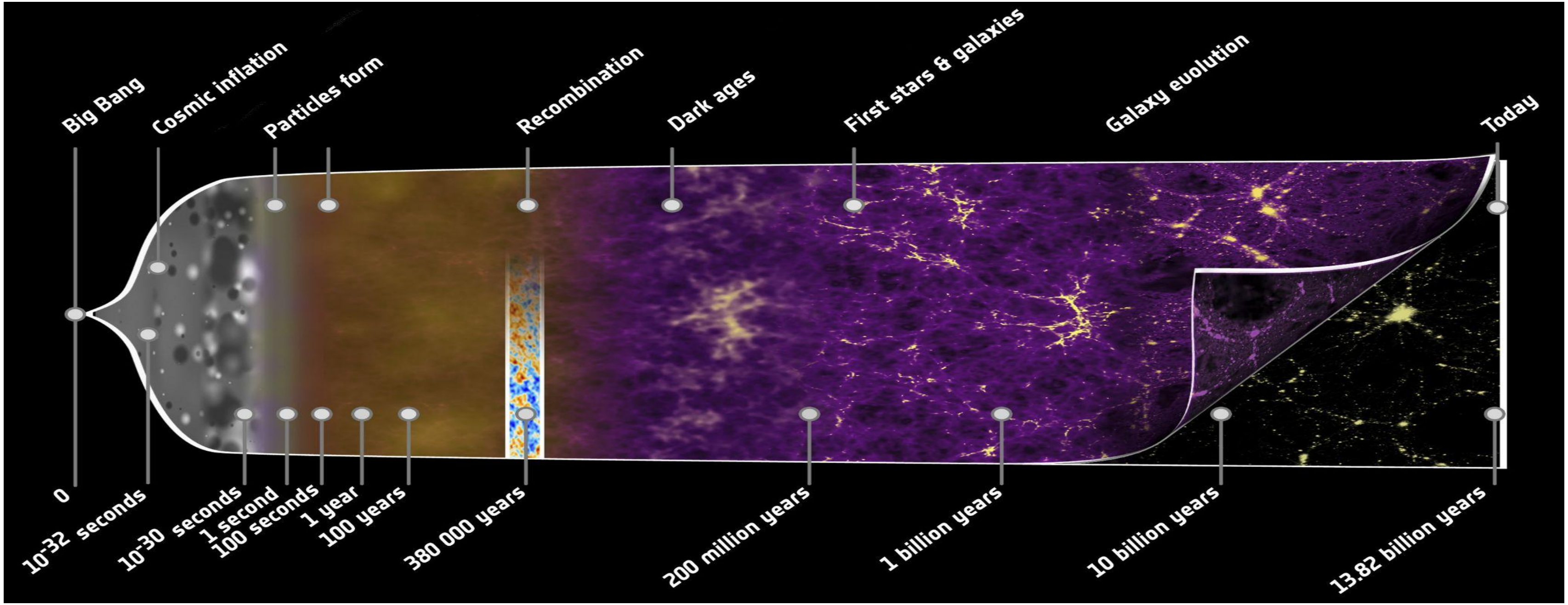
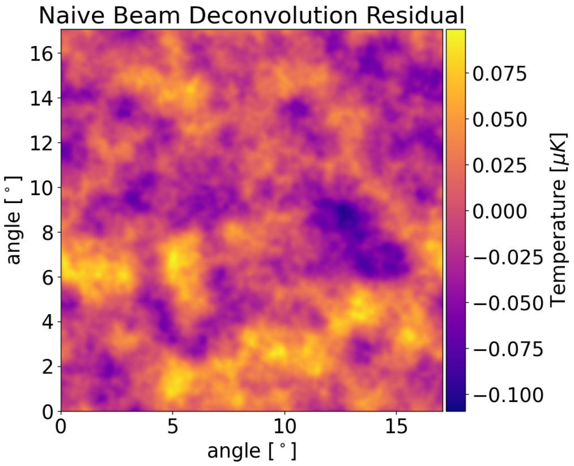
Observing the Universe at mm Wavelength
Grenoble 29/06/2023

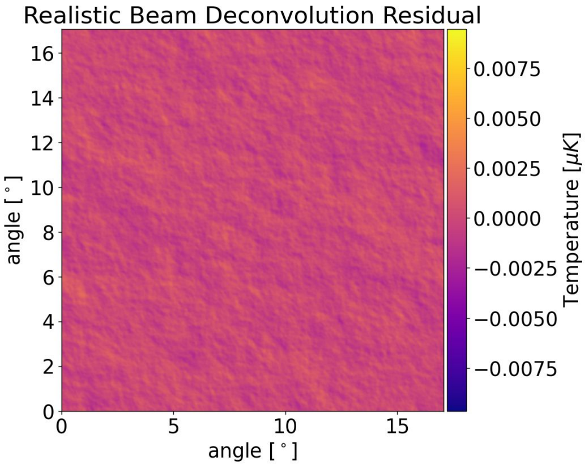
Scientific Background

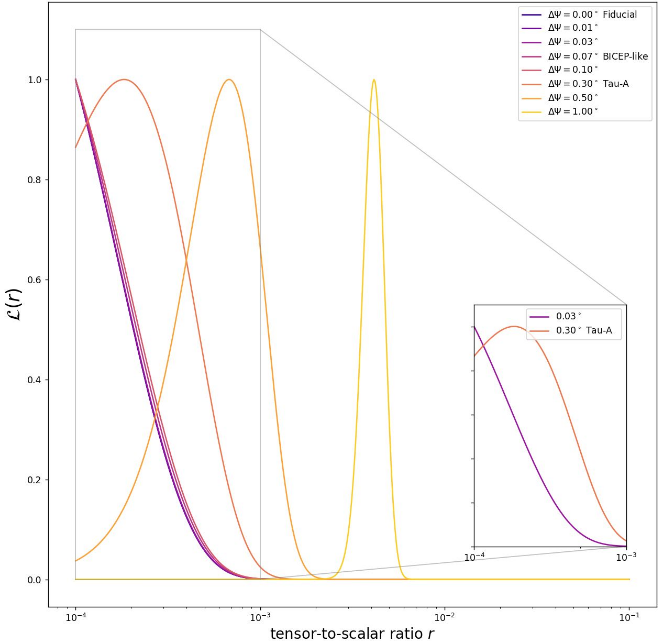


Systematics Effects on B-modes

- Both *Beams* and *Polarization Angle* affects the B-modes signal

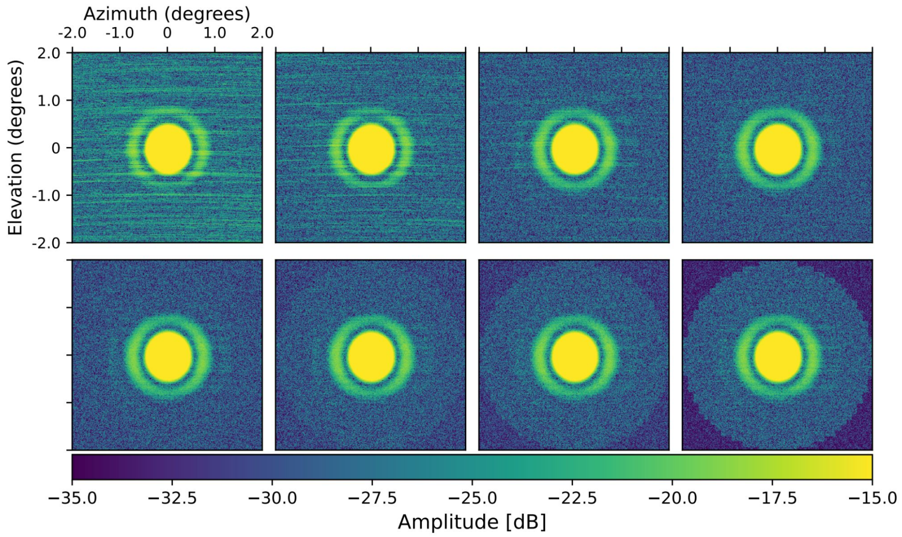


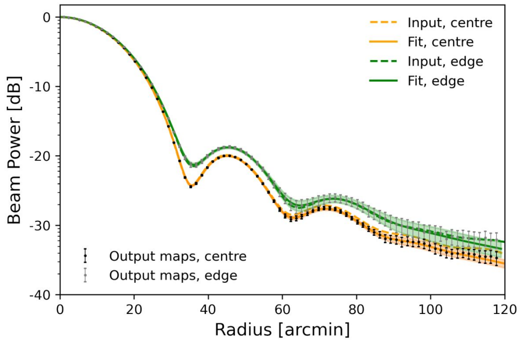




Current Status: Beams

- Planets are the best way to characterize beams
- Simons Observatory developed a code to estimate beams from planets including the effects of correlated modes and pixel location and much more [Dachlythra 2023, arXiv:2304.08995]
- Planets are:
  - Unpolarized
  - Not always visible





Dachlythra et Al. 2023

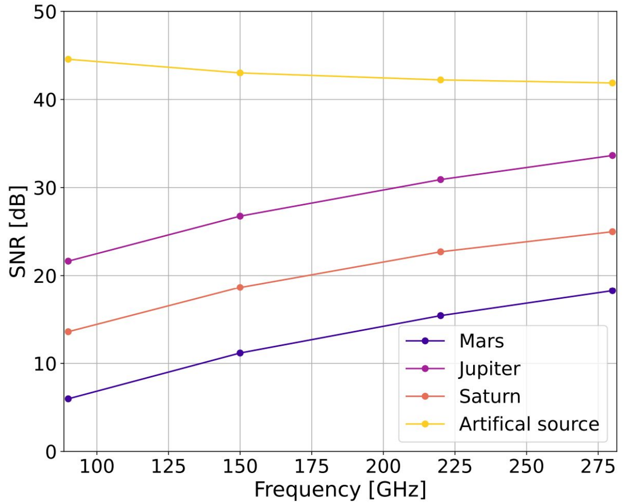
Current Status: Polarization Angle

- The uncertainty in polarization angle for Simons Observatory needs to be lower than 0.2° for the Small Aperture Telescopes in the 90/150 GHz bands to achieve $\Delta r = 2 \times 10^{-4}$ (Abitbol et Al. 2021)
- Best natural calibrator is Tau-A with a polarization angle uncertainty of 0.33° (Aumont et Al. 2019)
- Best artificial calibrator is the one developed for BICEP Array with an uncertainty of 0.07° (Cornelison 2018)
- EB nulling techniques assume zero Cosmic Birefringence, however measurements show a non-zero signal and the effect of Cosmic Birefringence can introduce a systematic in the calibration of Polarization Angle (Minami et Al. 2019)

PROTOCALC

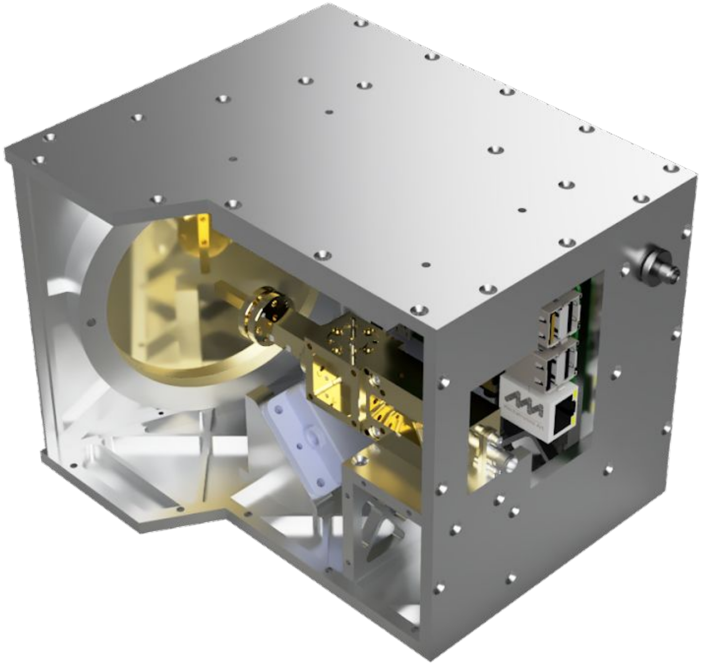
PROTOCALC (PROTOtype CALibrator for Cosmology) is a project funded as a Marie-Curie Fellowship under the Horizon-2020 Program. The goal of the project is to develop a 90 GHz polarization calibrator for CMB Telescopes with the following characteristics:

- <0.1° polarization angle accuracy
- Modularity to be extendable to other frequencies
- Ability to be flown on a commercial drone
- High SNR



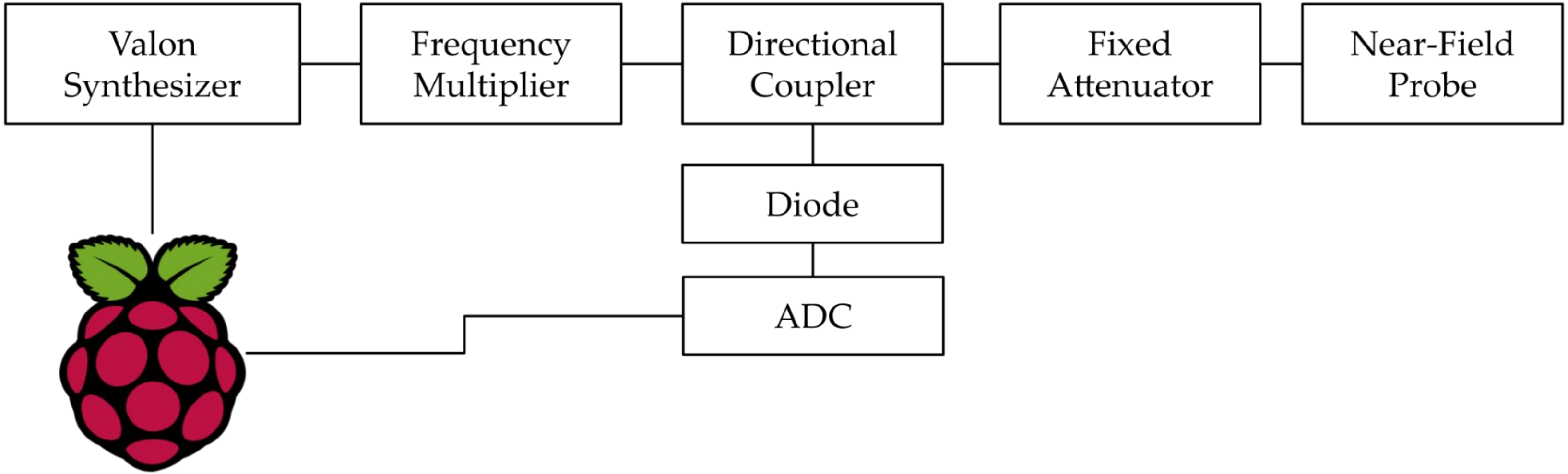
Technical Specifications

- Weight: <1.8 Kg
- Dimensions: 165x130x130 mm
- Power Consumption ~17W
- Controlled by Raspberry Pi
- W-Band Output:
  - Output Power: -18dBm
  - Output Beam: 115x65 deg
- Attitude System:
  - Sony RX0 M2 for Photogrammetry
  - Inclinometer
  - GPS-RTK based on Ublox system



RF Configuration

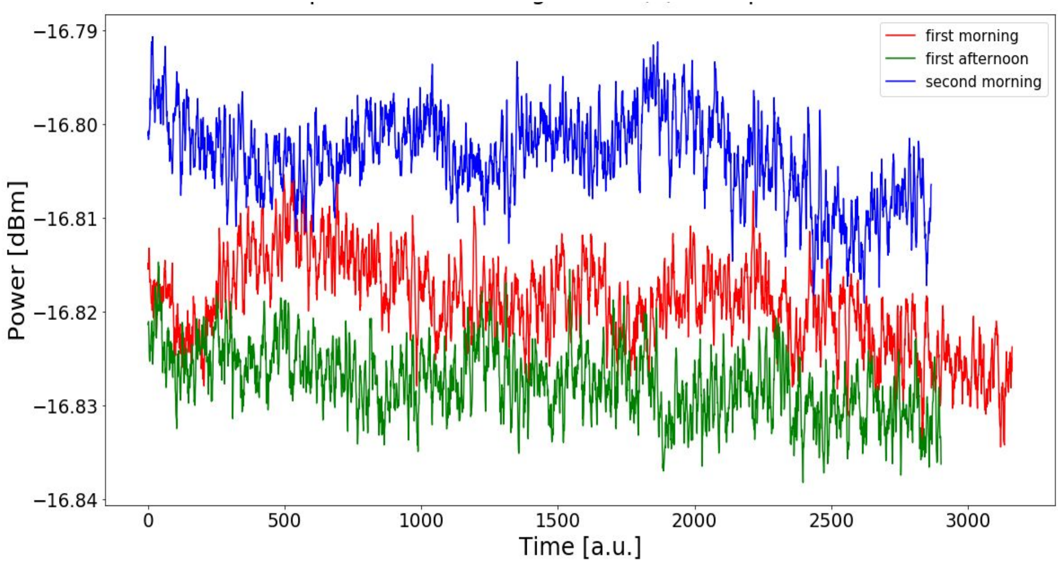
- Frequency generated by a Valon and then Multiplied
- Presence of a Directional Coupler to split the radiation and read it with a diode



In-Lab Calibration: Source

Several tests to calibrate the source in the laboratory

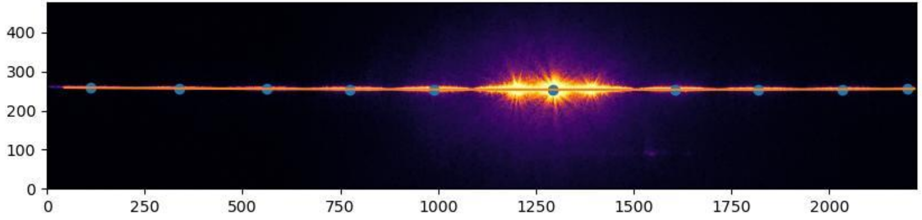
- Frequency Stability of the Source: ~10 kHz @ 90GHz
- Power Stability:
  - Single run ~ 0.01 dBm with a power output of -17dBm
  - Different days ~ 0.03 dBm
- Components characterization at the VNA
- Responsivity of the Diode
- Measure of the Antenna Beam

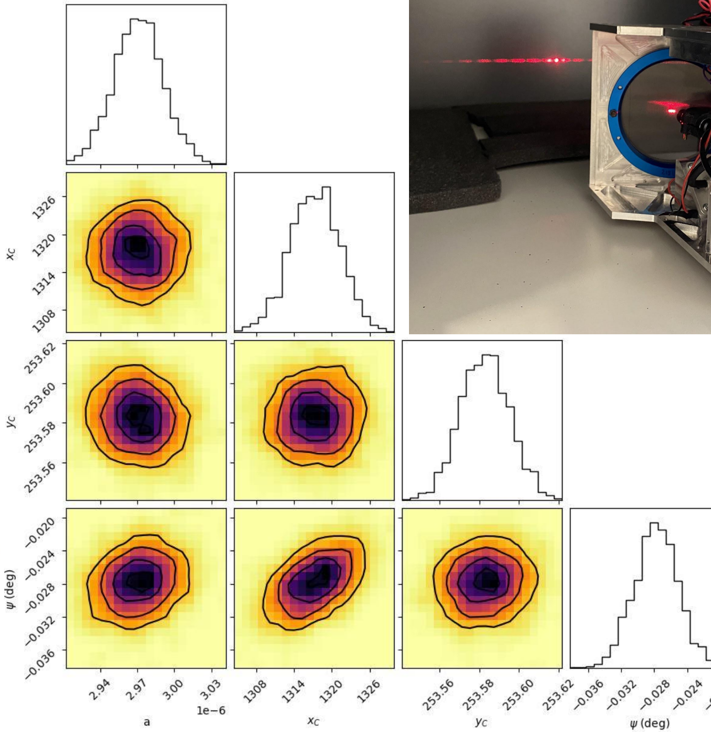


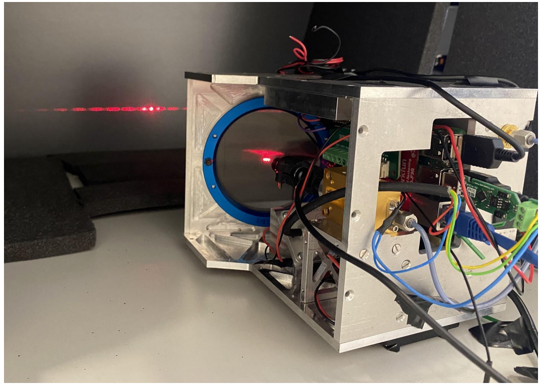
Credits to Giulia Conenna

In-Lab Calibration: Alignment

- Use of a Laser to align the polarization grid with the camera and the inclinometer
- Alignment accuracy <0.02° between the Camera and the Grid

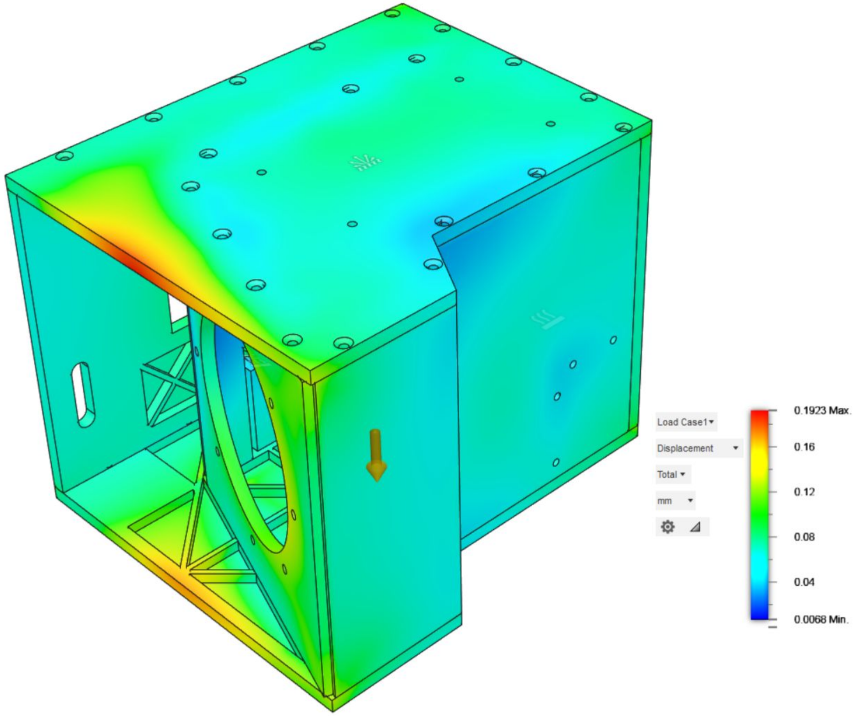






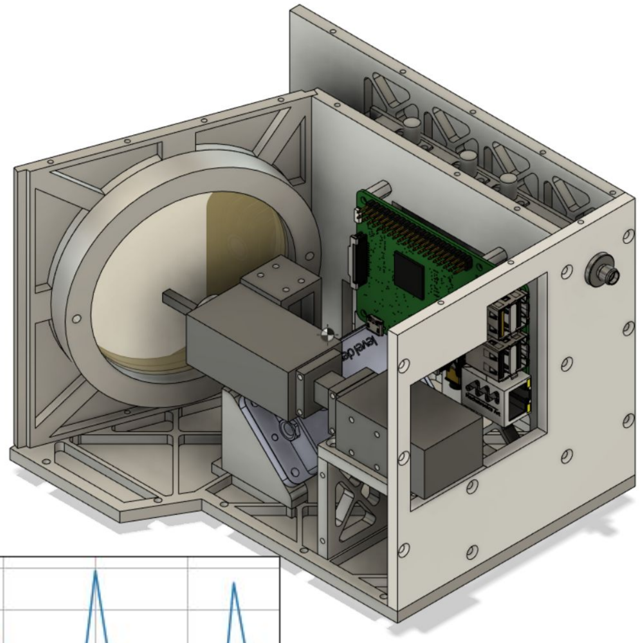
Thermal Simulation

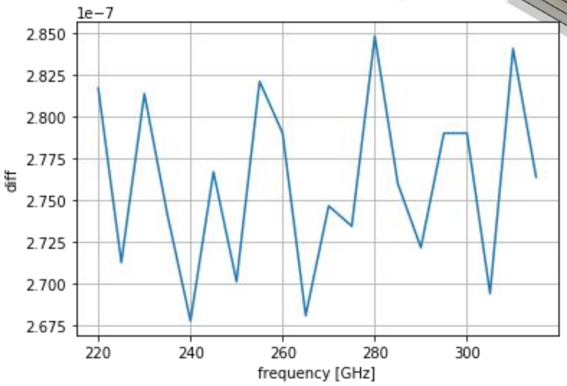
- Verify the effect of thermal contraction on the grid to camera and inclinometer alignment
- Lab conditions: 20 C and 1 atm
- Site Condition: 0 C and 0.5 atm
- Relative movements for both < 50μm
- Average Temperature at the Site ~12C, due to the heating coming from the multiplier, the RPi and the Valon



Modularity

- Simply changing the Multiplier Support and the RF chain after the Valon we can extend the frequency capability
- We are collaborating with Josquin Errard at APC to integrate a 225 to 325 GHz source on Board.
- We already performed the in lab source characterization





Credits to Sofia Savorgnano

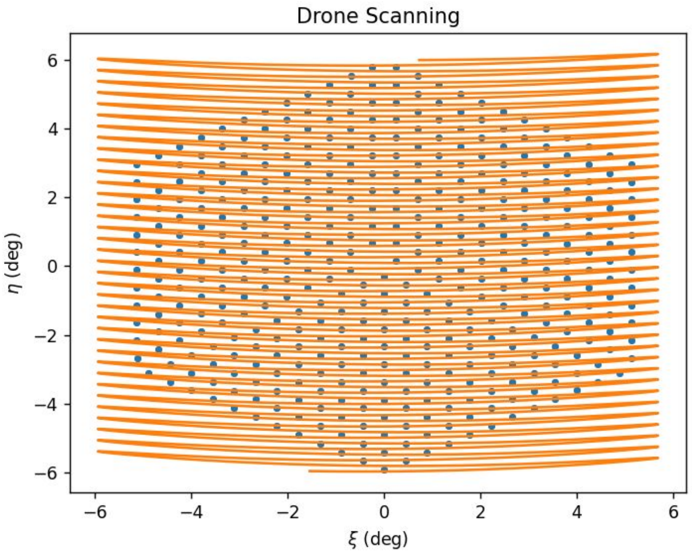
Simulation on Simons Observatory

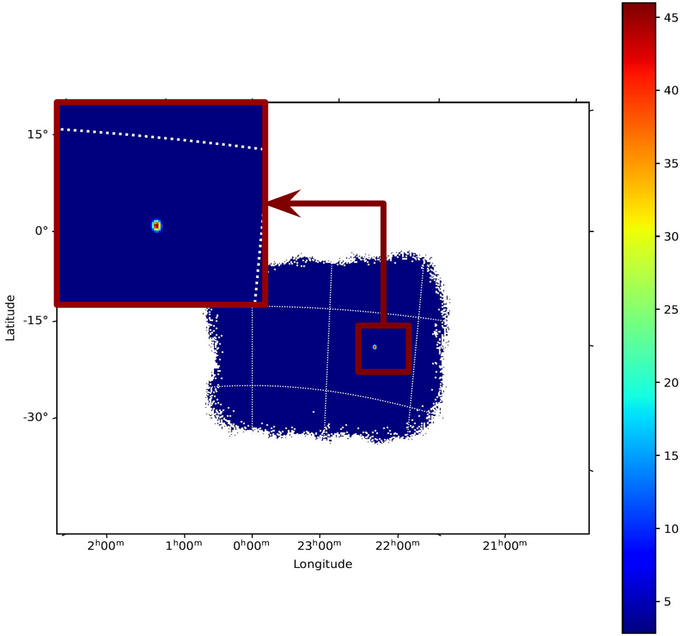
Developed an operator for TOAST 3 (currently part of the Simons Observatory repo *sotodlib*)

- Simulate drone movements
  - Initial position of the drone can be given in Azimuth and Elevation
  - Different Scanning of the drone available
  - Includes sources of error (Position error, wind gusts)
- Simulate the source emission
  - Possibility to use a Top-Hat beam or a Gaussian beam
  - Includes random gaussian noise based on the lab measurements
  - Designed to simulate other sources other than the 90 GHz

Simulation Results

- Drone scan of 7 min on the central array for the SAT (90 GHz channel)
- Telescope scans in Azimuth and Drone in Elevation





Deployment Environment

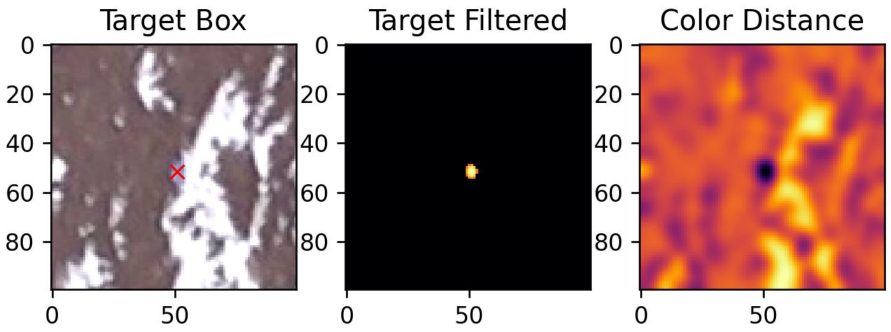
- The calibrator source is installed on a DJI Ronin MX Gimbal
- The Gimbal is installed on a DJI Matrice 600 Pro
- Cerro Toco Site at 5200m
- Environment Temperature ~ 2 C
- Average wind conditions
- Tested at the same time of the 150 GHz source
- Two Campaigns: Apr 22/Feb 23

Flights Information

- Max Altitude: 350m with respect to the starting point
- Max Flight Duration: 12min30s
- Max of 11 Flights in a day (6 with the 150 GHz source and 5 with the 90 GHz)
  - 150 GHz: HoverCal developed by **PUC** in Santiago
  - 90 GHz: PROTOCALC
- Multiple Telescopes Observed the source at the same time
- Multiple Scanning Strategies Tested
  - Raster Scan of the drone (all Telescopes just observing)
  - Drone moving along a meridian on a Sphere centered on CLASS (CLASS moving in Azimuth)
- Source Chopped at 47Hz and kept always on

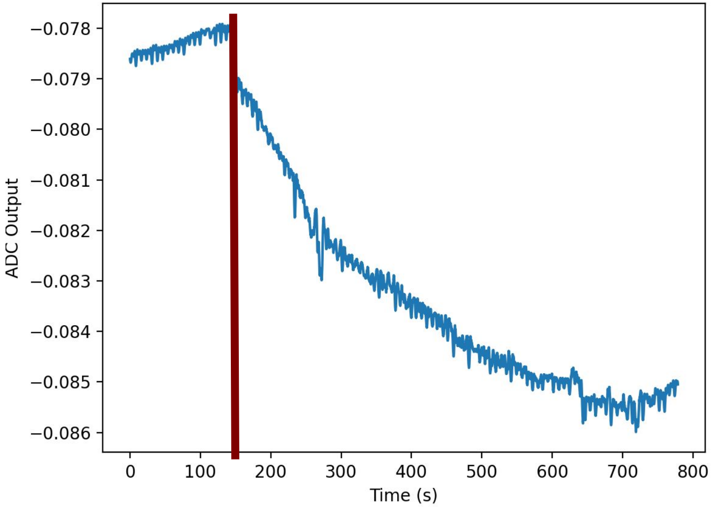
Attitude Determination

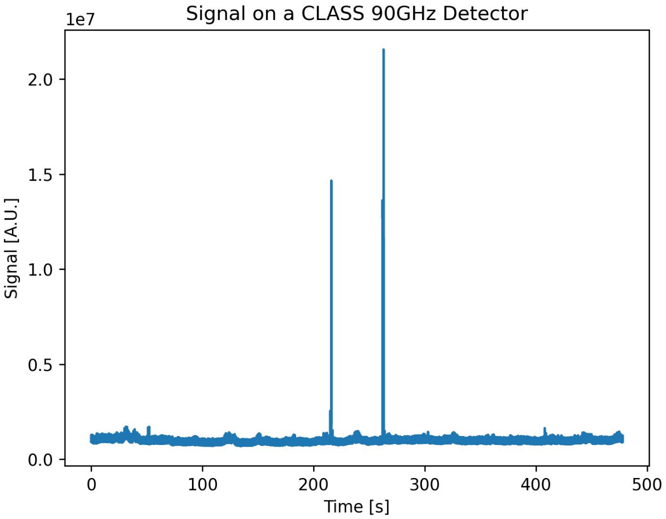
- Using Photogrammetry and GPS
  - 4K video at 30fps
  - Automatic Target Recognition using ΔE color distance
- Inclinometer as backup system (integration in progress)



Real Time data

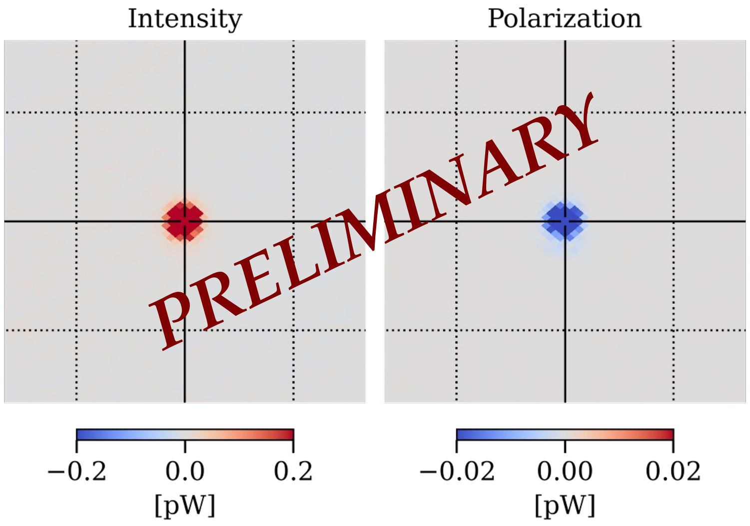
- CLASS observation of the source during the April 22 flight
- Very High SNR (~40 dB)
- Source Affected by a thermal drift





CLASS Analysis April 22

- 150 GHz Channel (HoverCal source)
- Co-Added Detector Maps
- Polarization Value:
  - Expected: 0.091 pW
  - Measured: 0.086 pW
- Drone Angular Size:
  - Measured: 0.0461 deg
- HoverCal Funding Grants:
  - *ANID grand FONDEF IDeA ID21I10236*
  - *ANID grant BASAL CATA FB210003*



Credits to CLASS and R.Dunner

Future Steps

- Analyze current data
- Based on the experience from previous flights, we will have:
  - Integrate a high sampling rate inclinometer (>200 Hz)
  - Integrate the drone RTK solution with the payload RTK solution
  - Remove additional weight to extend the flight time
    - Currently studying the eventual switch from Aluminum to 3D printed plastic (possible loss of some modularity)

Conclusions

This project is still ongoing but:

- The source has been developed and tested. We developed a suite of calibration tests that we performed in laboratory that can easily be replicated
- The source flew in April 2022 and February 2023 and we are currently analyzing the data
- We have a clear path forward to improve the source and achieve the final goal of the absolute polarization angle accuracy required

THANKS !!

Scientific Background: B-modes

- CMB radiation is partially polarized:
  - E-modes: divergence-free
  - B-modes: curl-free
- B-modes are created by tensor perturbations, so by a passage of gravitational waves generated during the inflationary era
- B-modes have never been measured as of today