Beam characterization for the Simons Observatory Small Aperture telescopes

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On behalf of the Beam, Calibration and Polarization (BCP) Pipeline Working Group (led by Zhilei Xu) of the Simons Observatory Collaboration

Stockholm University

Oskar Klein centre

Vetenskapsrådet

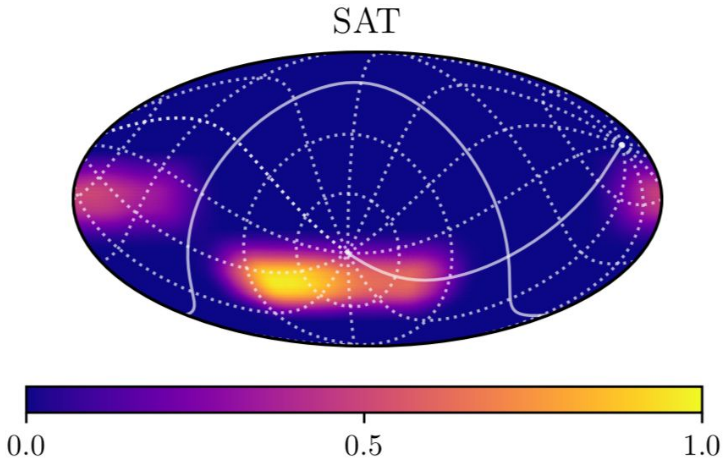
Credit: The Simons Observatory Collaboration

The SO Small Aperture Telescopes (SATs)

- The SATs will constrain the polarized microwave signal in 6 frequency bands centred on 28, 39, 93, 145, 225 and 280 GHz (roughly 20% bandwidth).
- Aim to constraint the tensor-to-scalar ratio, **r,** at a target level of **$\sigma(r) = 0.003$.**

(*The Simons Observatory: Science goals and forecasts, 2019*).

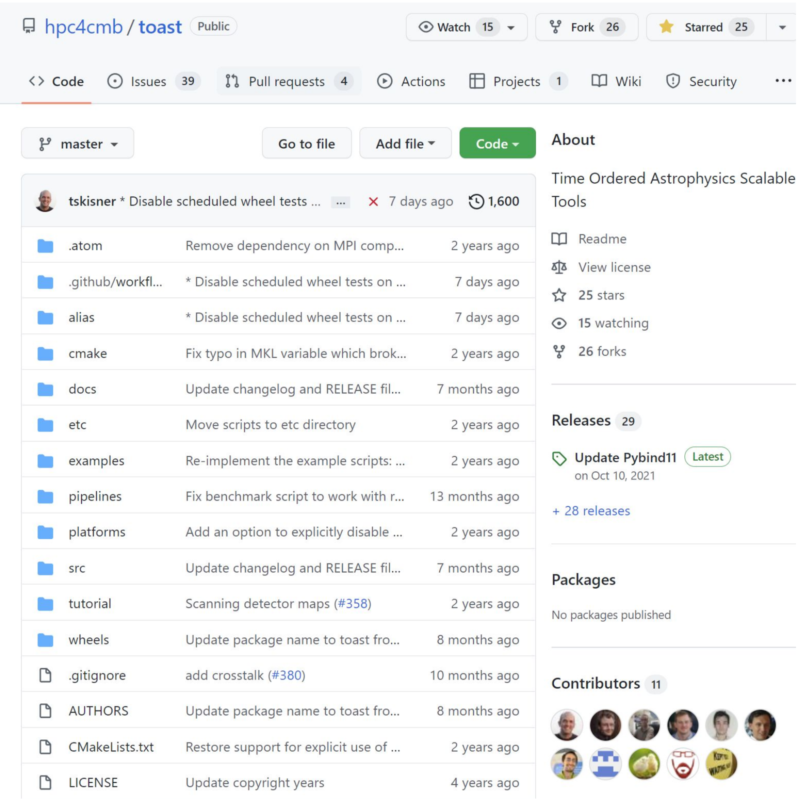
- Each SAT will cover approx. 10% of the full sky, observing from the Atacama Desert in Chile.
- We need to characterize the spatial response (the beams) of these telescopes.



The SATs (left) and the SATs sky coverage shown as hits maps (right).
Credit: The Simons Observatory Collaboration and Hensley et. al, 2021

The signal generation and beam-fitting pipeline

- **TOAST**: Open-source software developed for simulating, gathering and analysing CMB telescope data.
    - Includes the ability to simulate white and correlated detector noise, simulate realistic atmospheric noise, convolve the sky with 2D beam model, etc.
- Sotodlib: Open-source software interfacing with TOAST, adjusted to the Simons Observatory telescopes site and hardware specifications.
    - Includes **point source simulator**, HWP systematics, etc.



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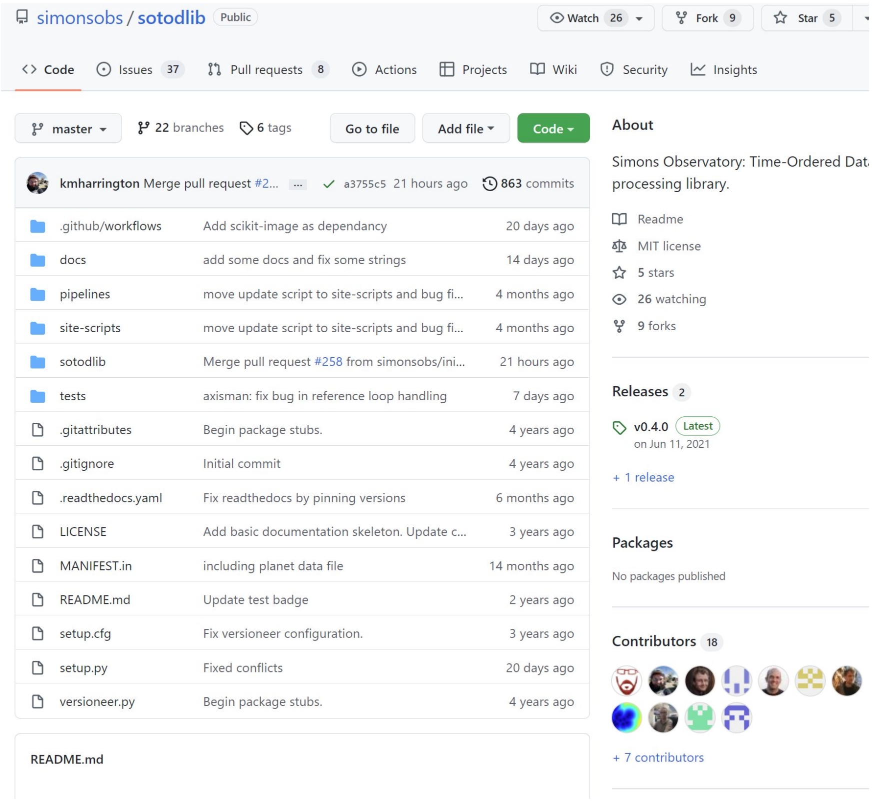
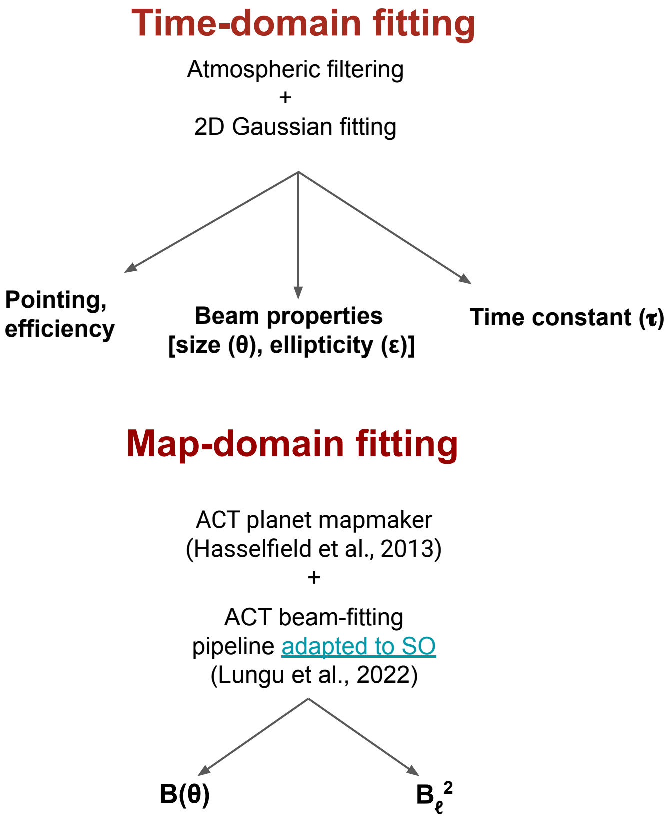


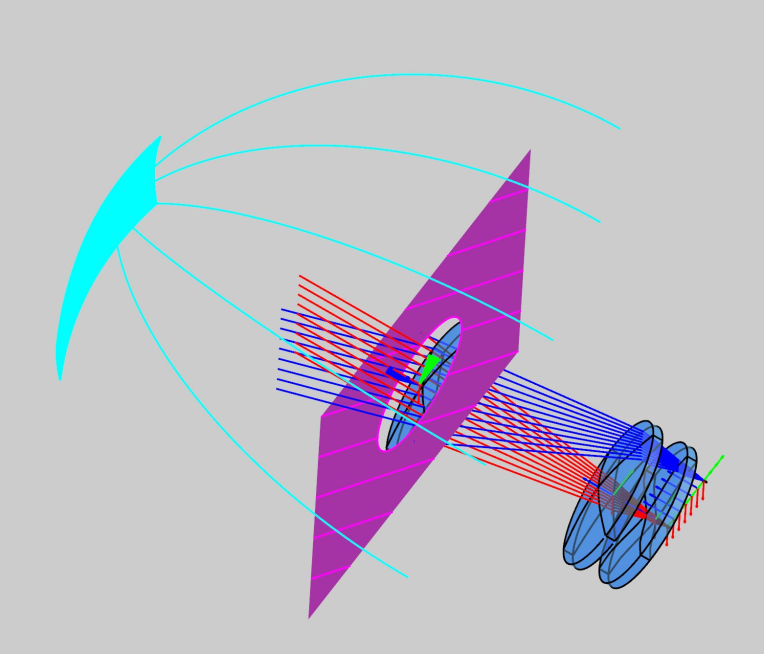
The signal generation and beam-fitting pipeline

- **Calibration source signal** is generated through sampling of (unpolarized) input beam maps scaled with a signal amplitude informed by existing planet brightness models.
- Resultant time streams are then fed to either 1) a time-domain fitting pipeline that is especially attuned to extracting beam centroids, detector time constants, etc; (*Xu et al., in preparation*) or 2) **a map-domain fitting pipeline based on ACT analysis.**



Simulation of the input beam models

- We use **Ticra Tools (**formerly **GRASP)** to generate physical optics simulations of the SAT 3-lens refracting telescope at (so far) four frequency bands: 93, 145, 225 and 280 GHz.
- Generate far-field 2D beam maps for a few pixels in the focal plane going from center to the edge of the field of view.
- Generate both single-and multi-frequency sims.
- The wider beam maps extend to +/- 10 deg.



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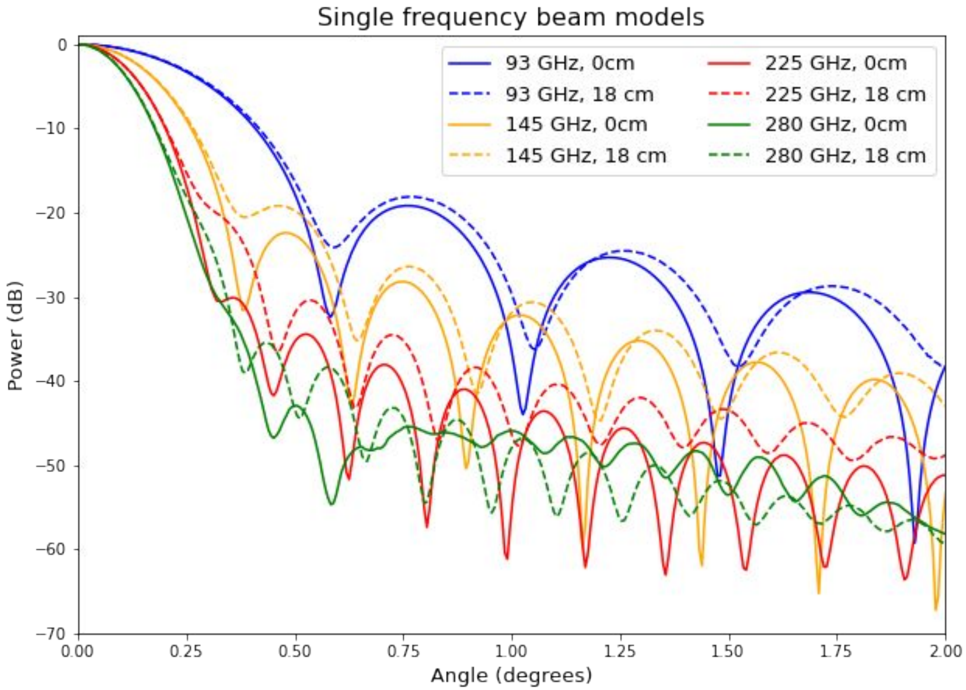

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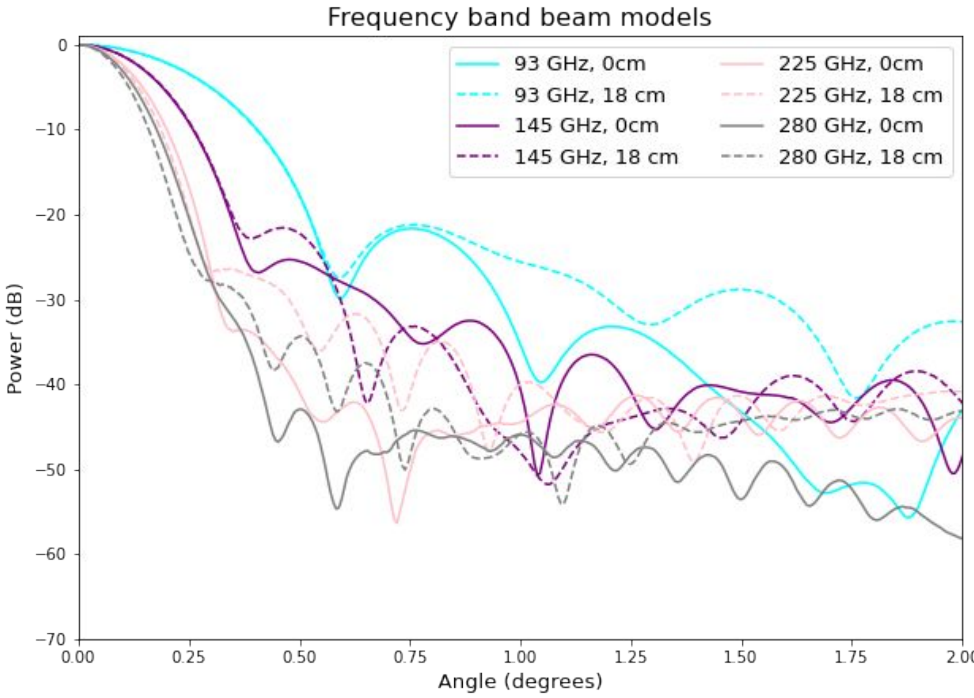

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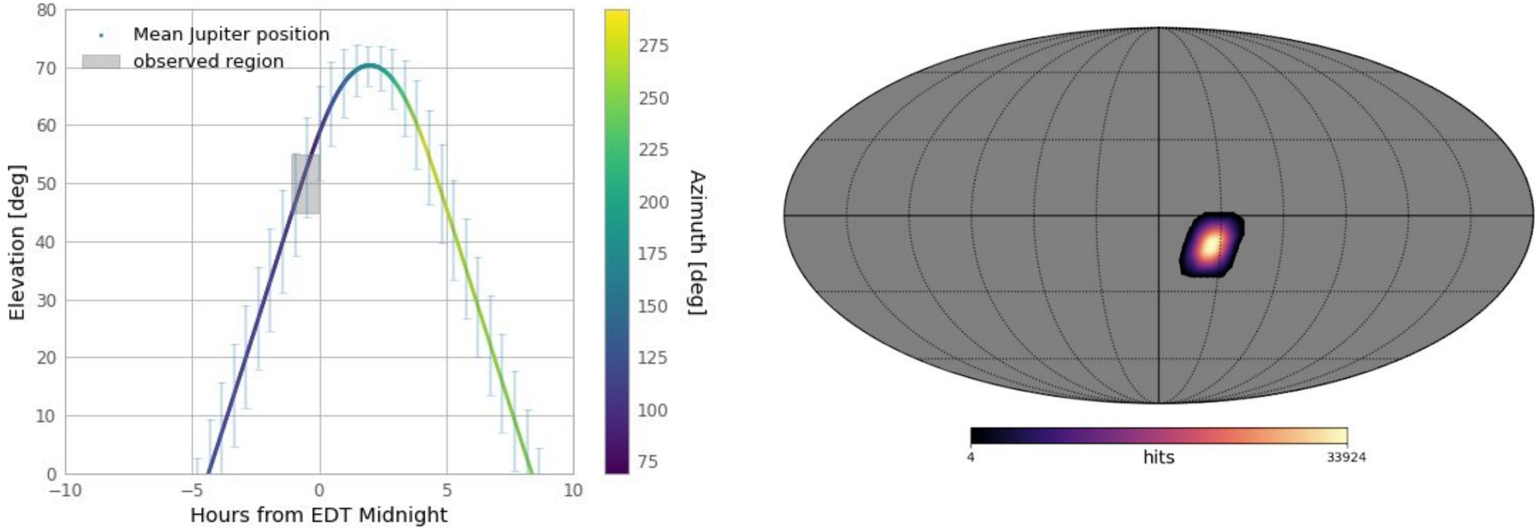
The TOD generation pipeline

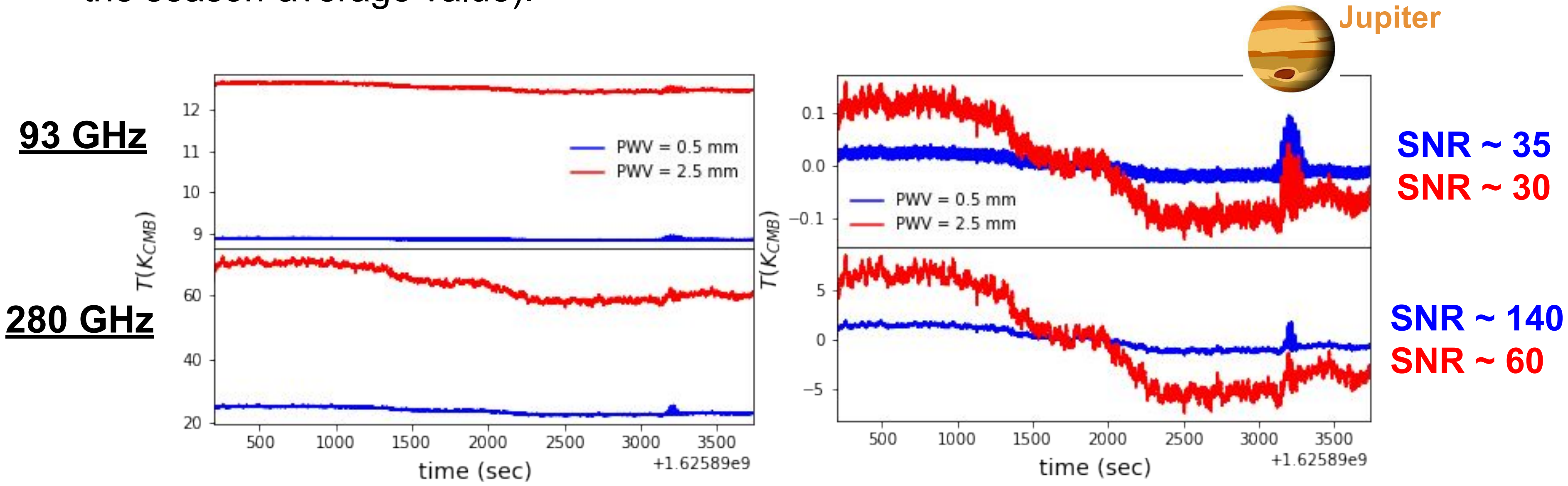
- We focus on simulating Constant Elevation Scans (CES) of Jupiter over a 2-month period using **TOAST** and **sotodlib**.
- Simulating 4 frequency bands: **MF1**, **MF2**, **UHF1** and **UHF2** (93, 145, 225 and 280 GHz).
- Analytic detector noise (including 1/f - noise) with realistic NET and atmospheric emission of fixed brightness.



Average Jupiter position over a month's period (left) and the hits map produced from a single observation of a narrow patch around Jupiter projected in equatorial coordinates (right).

The atmospheric emission in the time domain

- In the results presented today, we fix Precipitable Water Vapor (PWV) to 1 mm (roughly the season-average value).

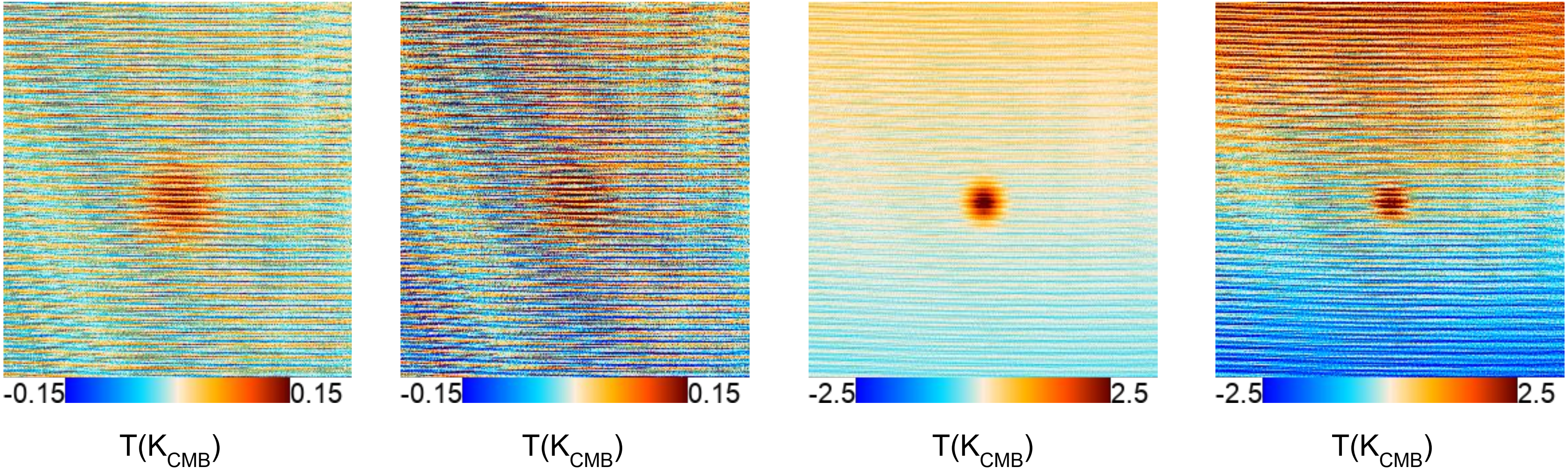


(Left) Simulated time-ordered data of a single detector including atmospheric emission of PWV=0.5 and 2.5 mm at 93 and 280 GHz. (Right) Same after subtracting the data mean for better visualization. The simulations refer to single frequency input beam models.

The atmospheric emission in the map domain

- In the map domain, the atmospheric emission appears as a stripy pattern which becomes more pronounced with increasing frequency and PWV value.

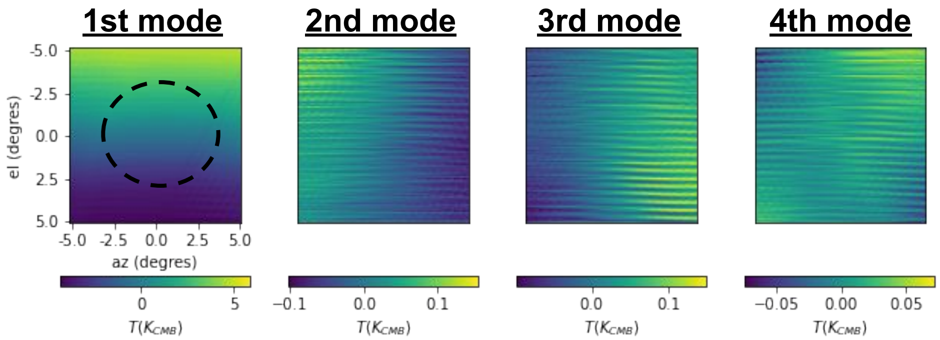
93 GHz, PWV=0.5 mm | **93 GHz, PWV=2.5 mm** | **280 GHz, PWV=0.5 mm** | **280 GHz, PWV=2.5 mm**

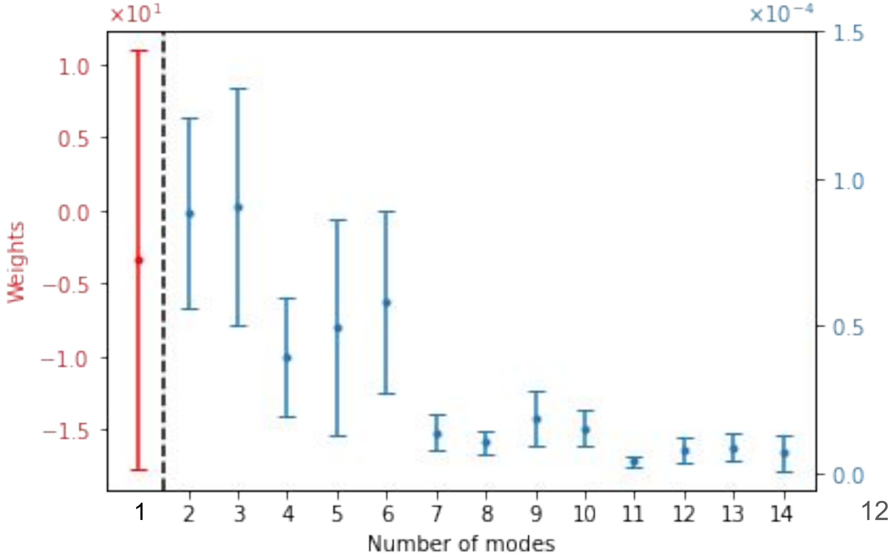


From left to right: Maps of a single Jupiter observation at 93 GHz for PWV values of 0.5 and 2.5 mm plotted together with the corresponding cases for the 280 GHz frequency band. The simulations refer to single frequency input beam models.

The implemented map-maker

- The ACT map-maker (Hasselfield et. al, 2013; Lungu et. al, 2021) attempts to mitigate correlated/atmospheric noise through PCA analysis.
- The selection of the mask radius (θ_{mask}) is important:
  - Narrow masks risk removing significant amount of beam power.
  - Wide masks risk not capturing properly the noise properties.
- The selection of the number of modes that are removed is important:
  - Fine balance between removing noise and eliminating beam power.
  - A single mode seems to capture the correlated atmospheric noise sufficiently in most cases.

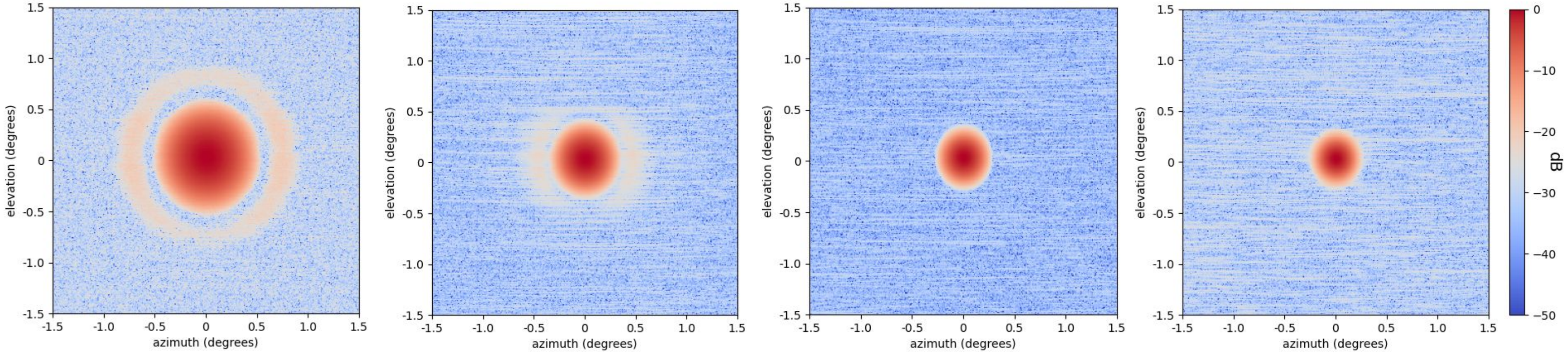




Planet maps

- Wafer-averaged (stacked) planet maps of a single observation (1 hour of data) run with a frequency band input beam model for a centre pixel with N=10 modes removed in the PCA analysis.
- A region of radius ~1-2 degrees (fluctuating value based on the beam size) was masked around the source for the noise levels estimation (input beam model extends to ~ 4 degrees) .
- Striping is more apparent at higher frequencies.

93 GHz **145 GHz** **225 GHz** **280 GHz**



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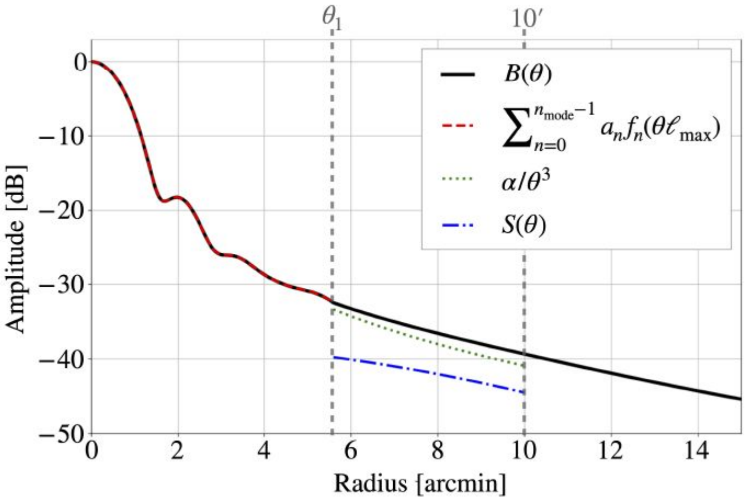
The beam fitting code

- ACT beam fitting code (Lungu et al., 2022).
- Corrects for bias induced by PCA mode removal and stitches a sidelobe to the beam at the θ_1 core/wing transition.
- Fits the core beam employing Bessel functions of the first kind.
- Varies the beam wing scale and the maximum multipole number of the fit.
- Best-fit model found using Akaike Information Criterion (AIC).

$$B(\theta) = \begin{cases} \sum_{n=0}^{n_{\rm mode}-1} a_n f_n(\theta \ell_{\max}) & \text{for } \theta \leq \theta_1 \\ \alpha/\theta^3 + S(\theta) & \text{for } \theta_1 < \theta \,. \end{cases}$$

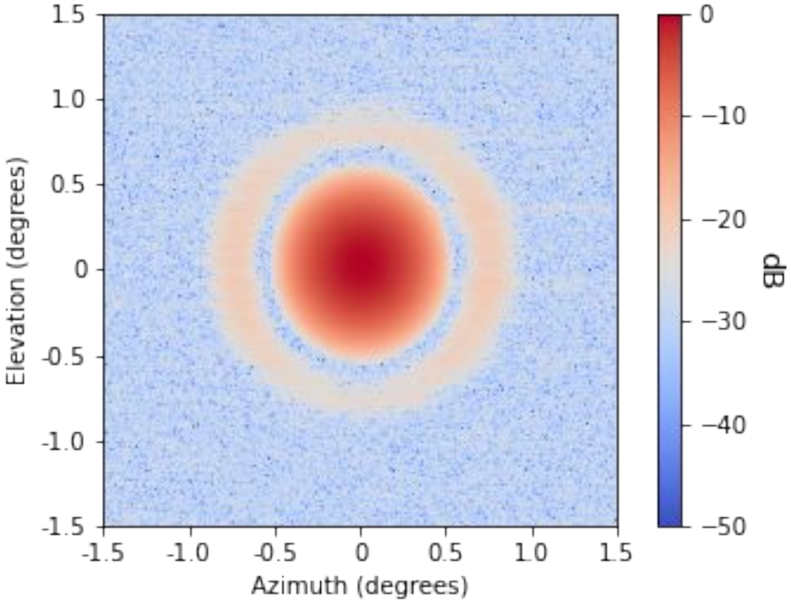
$$f_n(\theta \ell_{\max}) = \frac{J_{2n+1}(\theta \ell_{\max})}{\theta \ell_{\max}}$$

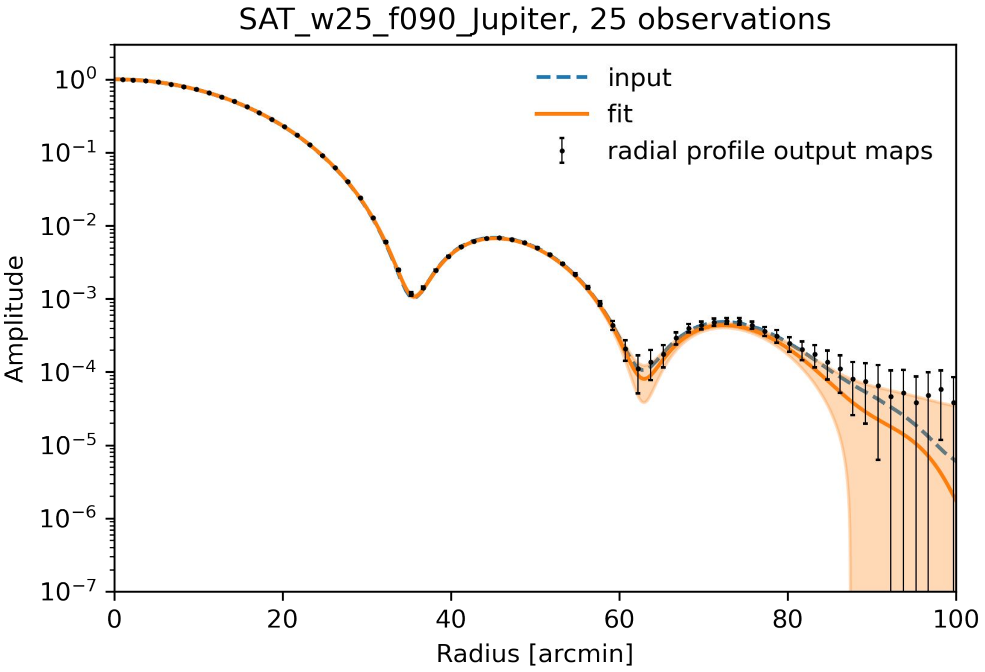


Credit: Lungu et al., '22

Logarithmic profile of 93 GHz beam, simulated for frequency band

- The reconstructed beam wing from the data deviates from a $1/\theta^3$ function.
- Good agreement of input and reconstructed profile up to ~3 times the beam size.





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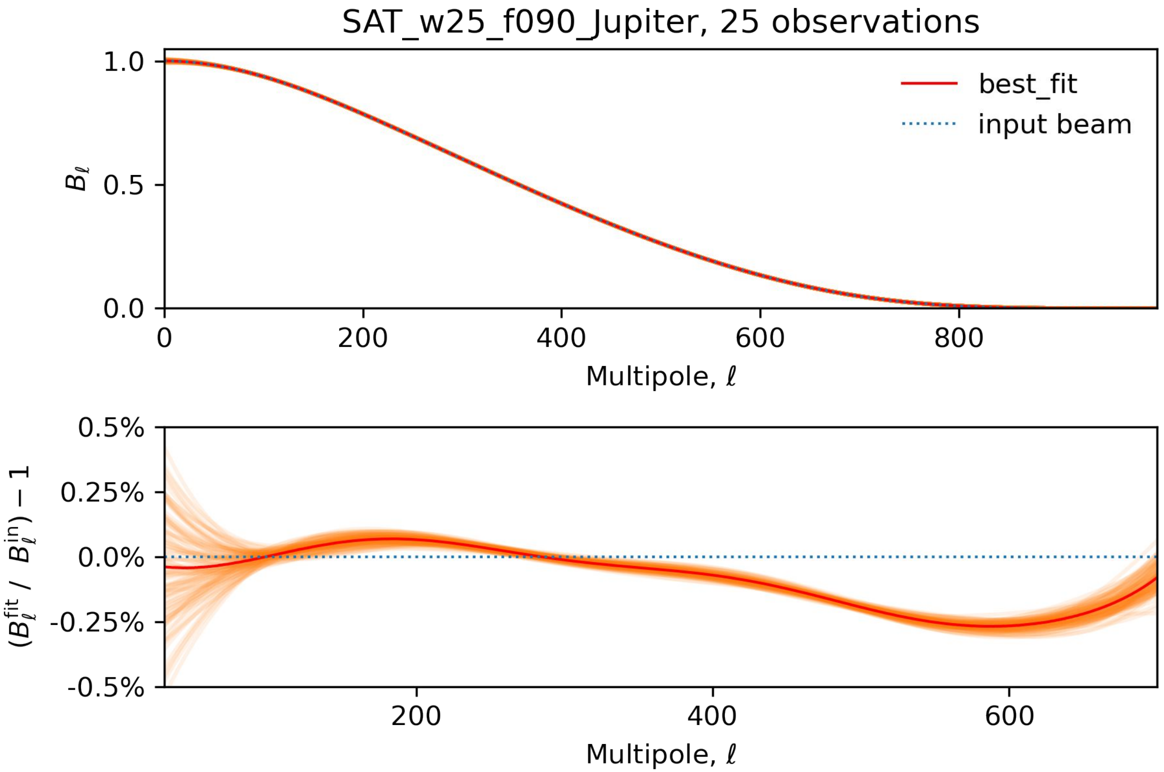
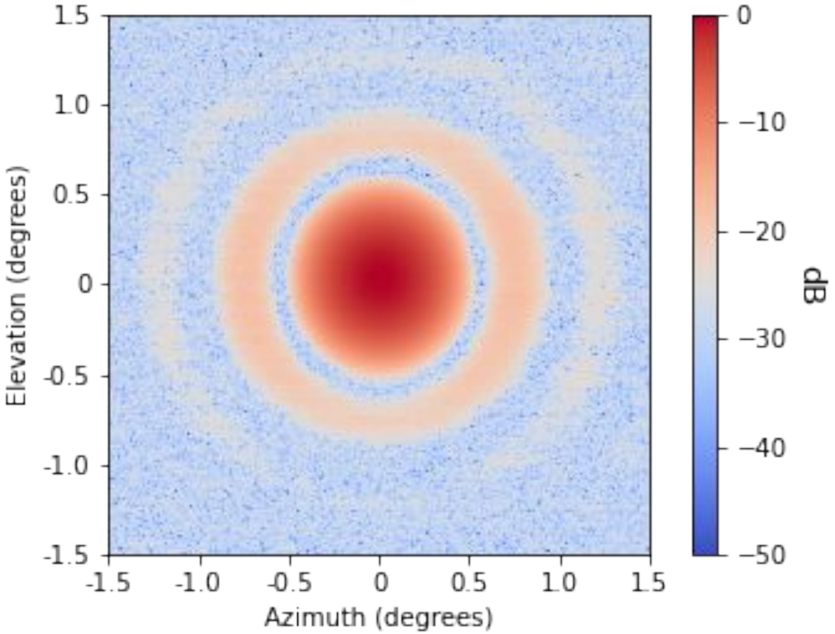
Window function of 93 GHz beam, simulated for frequency band

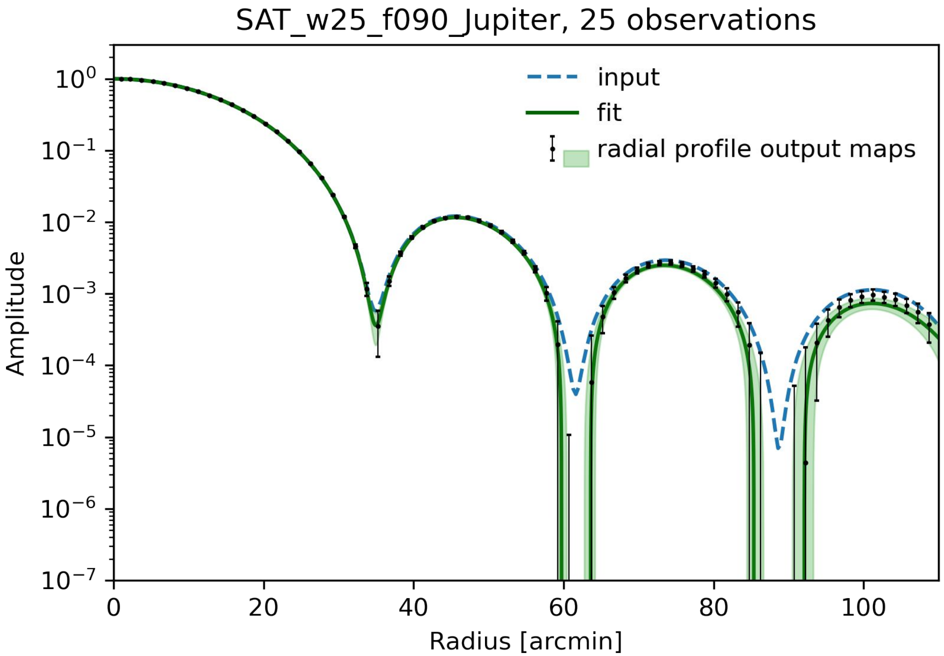
- The beam window function bias is ≤ 0.5 % for multipoles 30-700.
- This remaining bias will be further investigated.



Logarithmic profile of single frequency 93 GHz beam

- The reconstructed beam wing from the data deviates from a $1/\theta^3$ function.
- Good agreement of input and reconstructed profile up to ~3 times the beam size.





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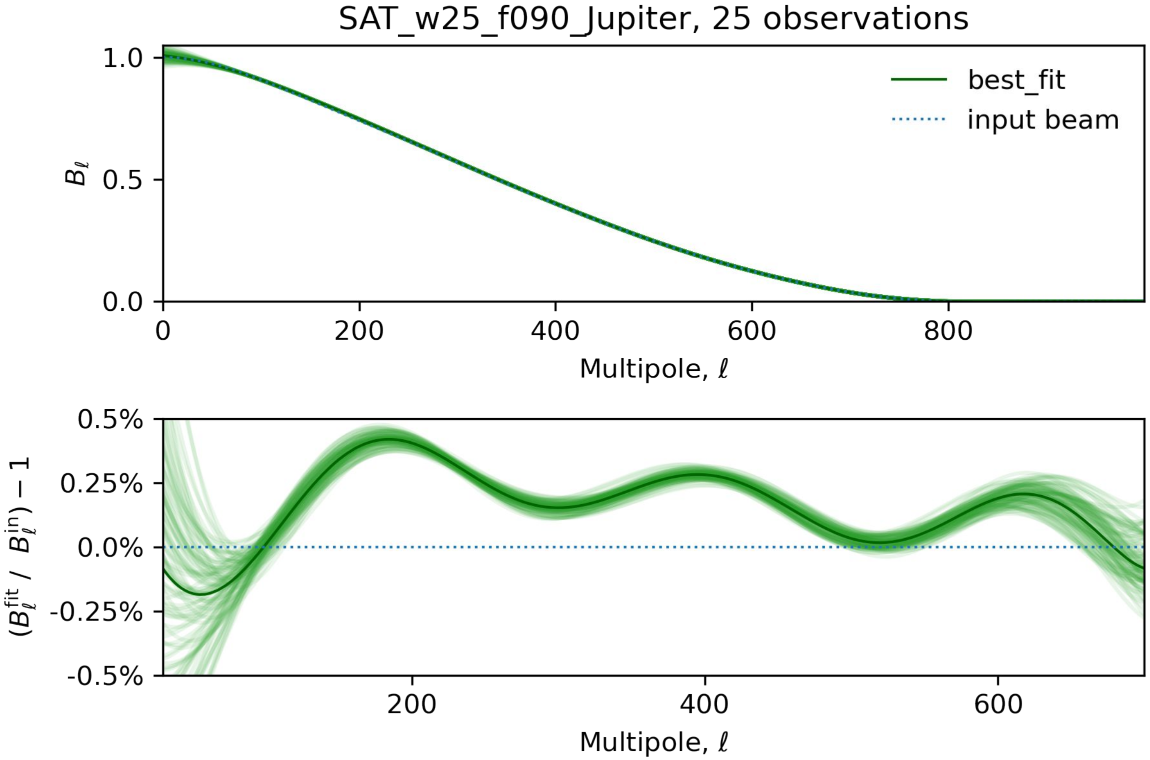
Window function of single frequency 93 GHz beam

- The beam window function bias is ≤ 0.5 % for multipoles 30-700 but is higher than in the case of the beam simulated for the frequency band.
- Single beam maps have higher SNR and we should extend our beam models further away.



Future prospects : Calibrating with artificial sources

(***Gabriele Coppi, Rolando Dünner, Nicholas Galitzki ++***)

- Astrophysical sources are not always available and thus might require extended periods of observations to achieve sufficiently high Signal-to-Noise ratio (SNR).
- Artificial sources (drones) can be tuned to achieve a higher SNR as compared to planets.
- Drones offer a particularly promising way to calibrate the polarization response of our instruments.

  (See ***Dünner et al, 2020***)
- Stay tuned for Nicholas Galitzki's and Gabriele Coppi's talks tomorrow morning.

Credit: Gabriele Coppi