

Empirical Beam Measurements from HIRAX Prototype data



Swiss SKA days
31st Oct to 2nd Sept 2026
HES-SO/HE-Arc - Neuchâtel

AJITH SAMPATH

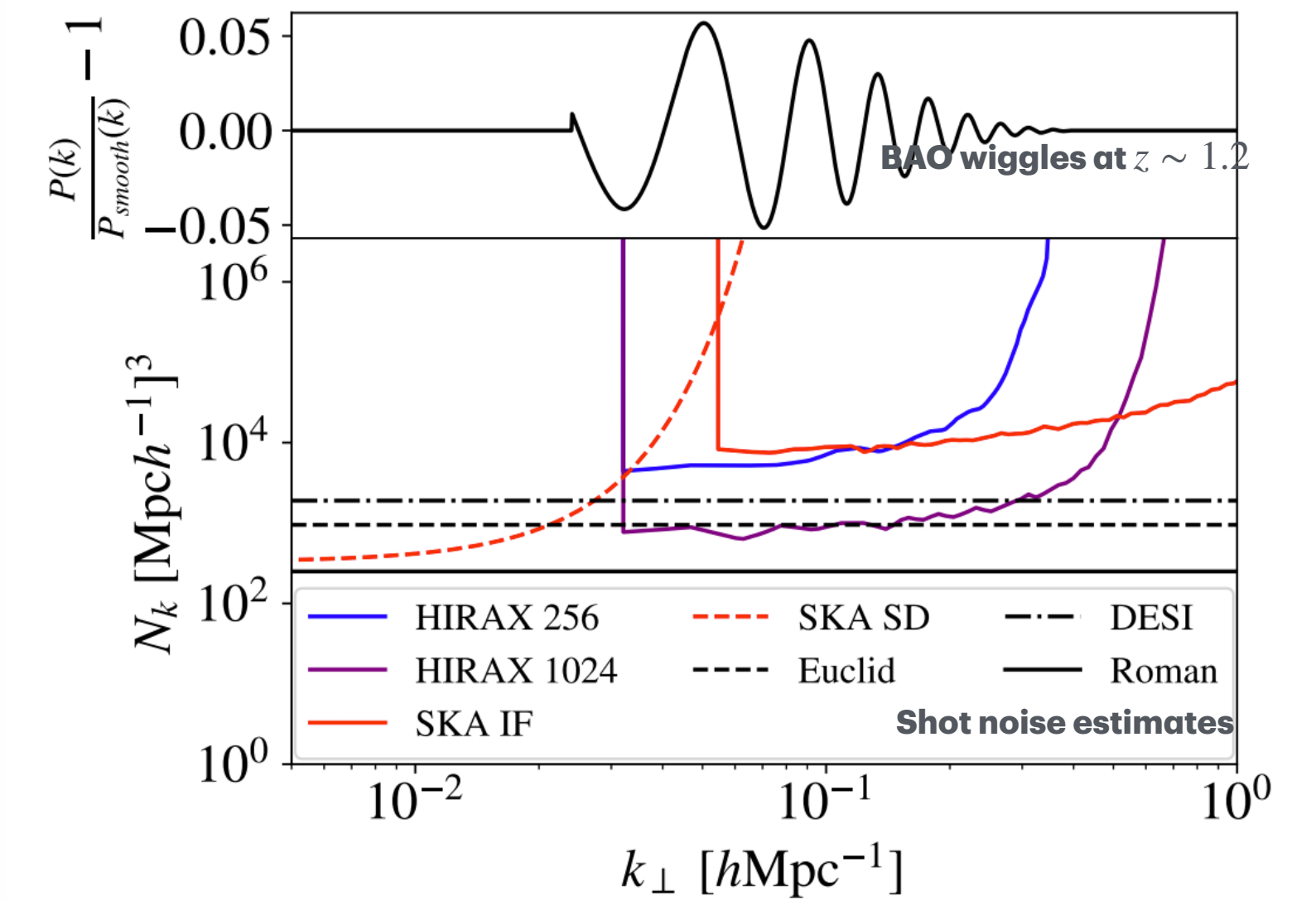
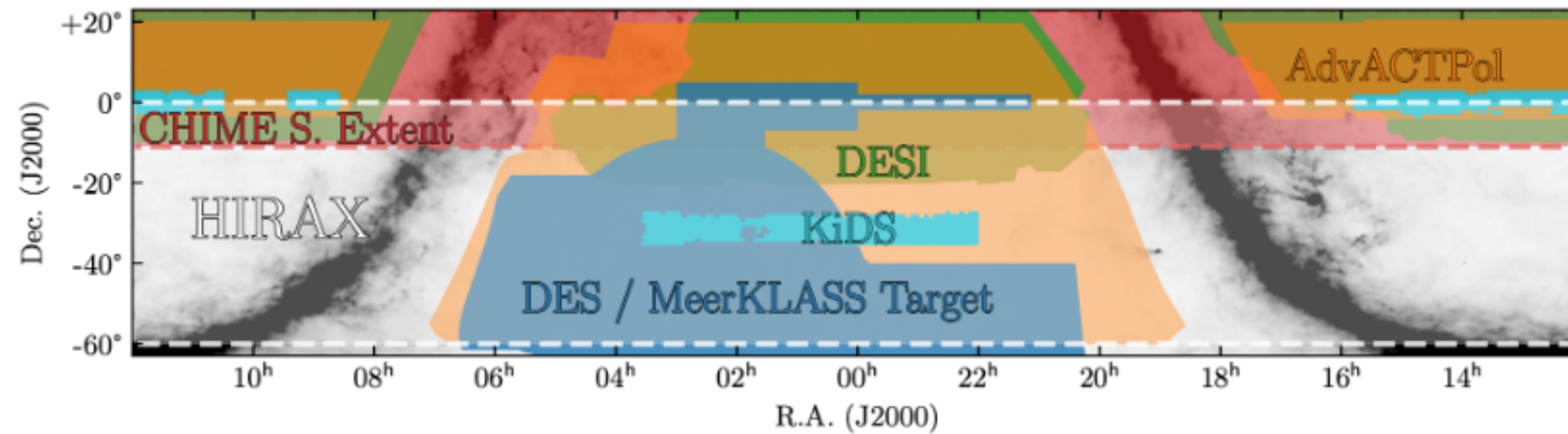
Postdoctoral Fellow
University of Geneva
On behalf of the HIRAX Collaboration
and Swiss-HIRAX team

HIRAX

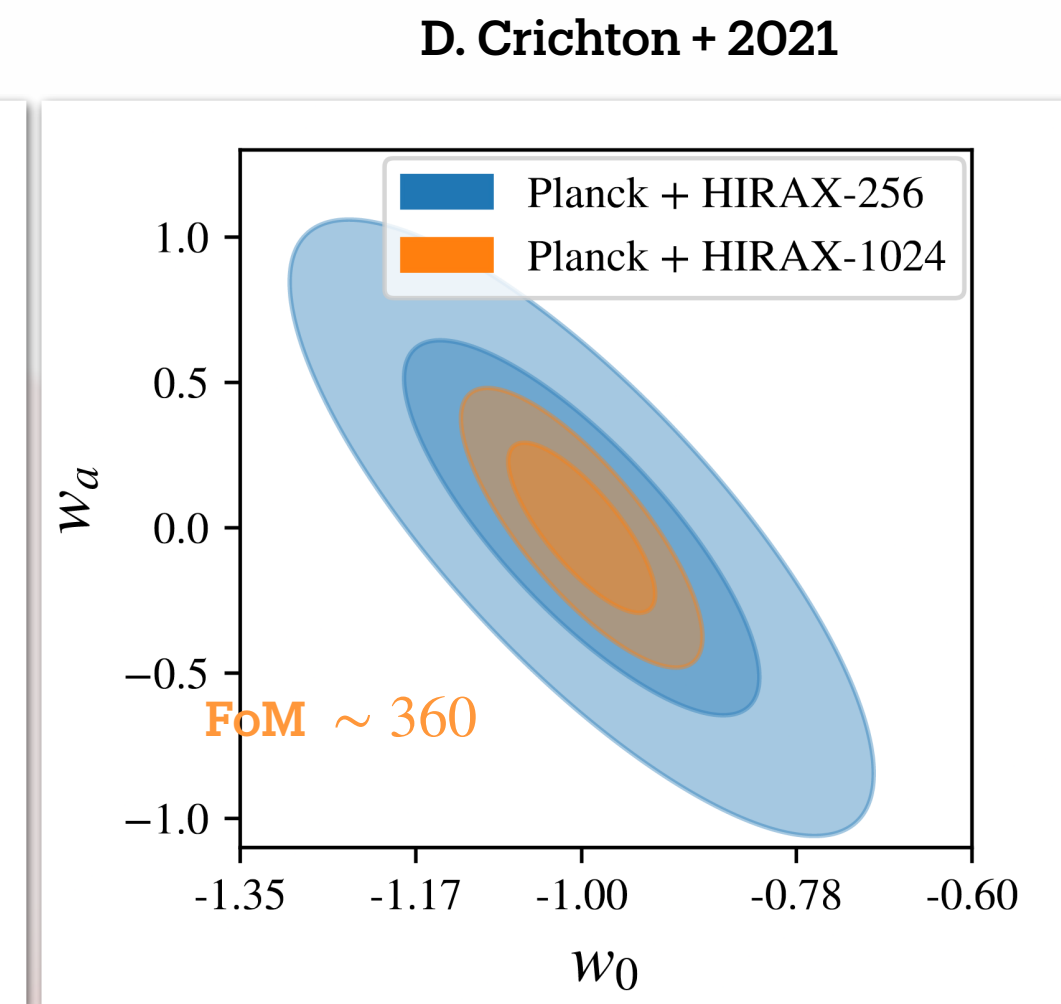
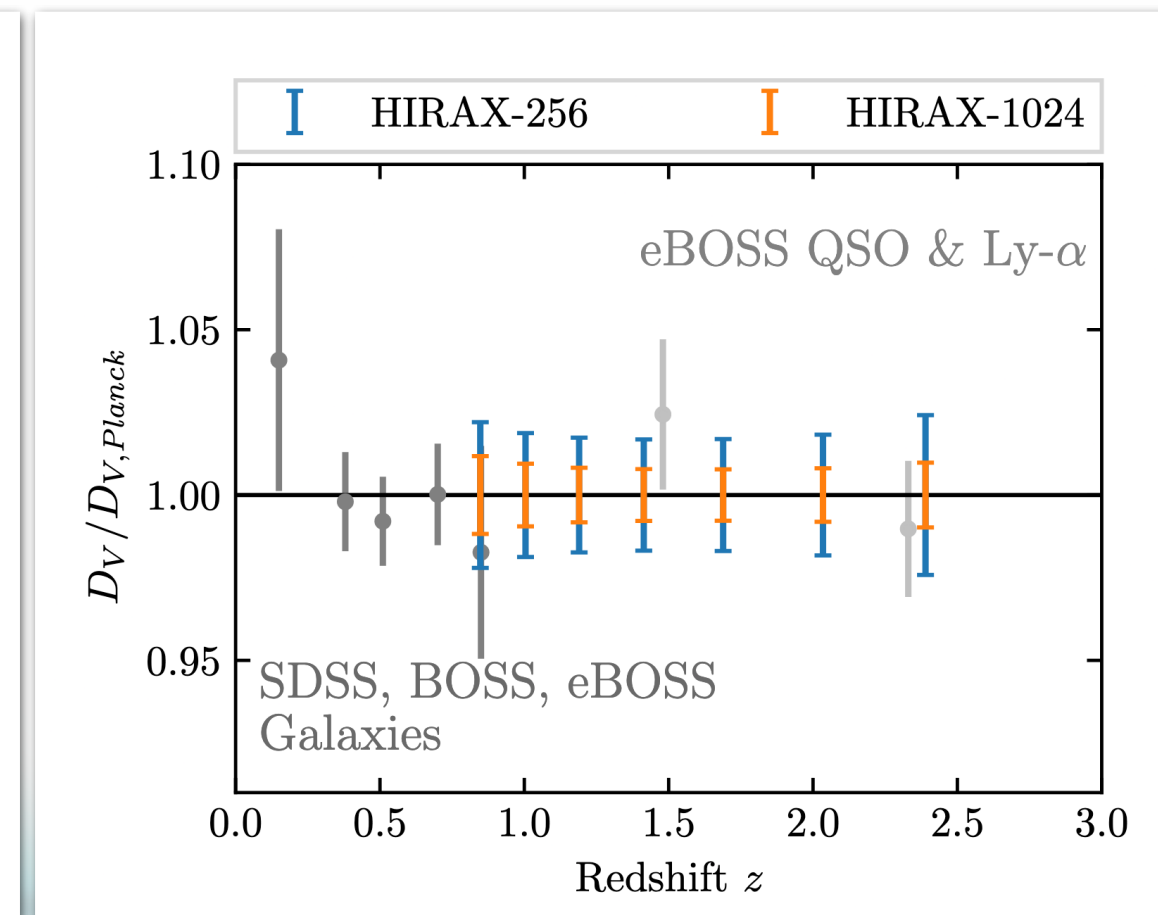
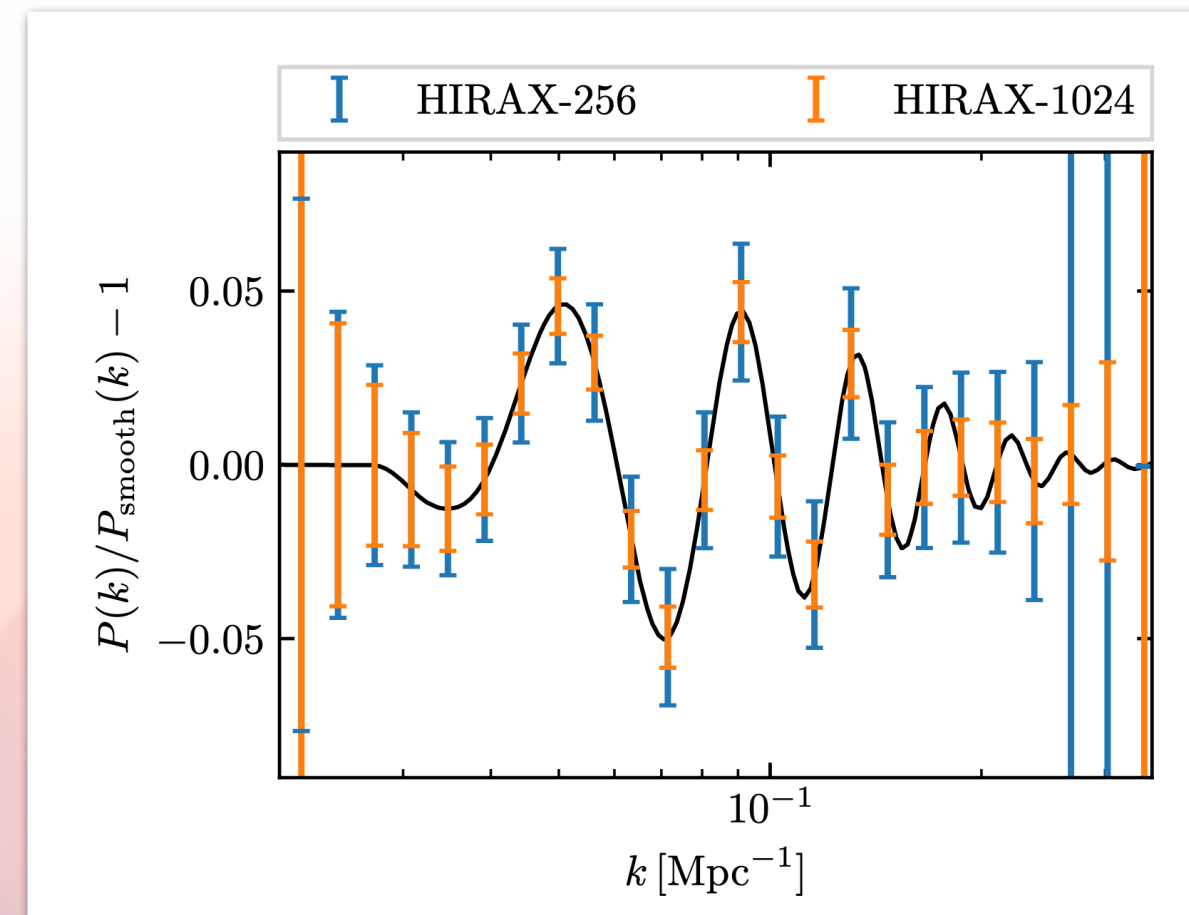
- Hyrax (the rock dassie) is a wild terrestrial mammal found in the bushes of Southern Africa.
- **HIRAX** - Hydrogen Intensity and Real-time Analysis eXperiment - in development and deployment phase in Karoo desert. Guest instrument at the SKA site.
- 1024 element compact, redundant, radio interferometer array in drift-scan mode. Being deployed in phases (first 128)
- 6m Diameter dishes with $f = 0.21$
- $400 - 800\text{MHz} : 0.775 < z < 2.55 : 37.5 - 75\text{cm}$
- Covers ≈ 15000 sq.degrees of Southern sky and scans for 17500 hrs. Manually steerable along declination ($\pm 30^\circ$ in zenith angle)
- Aims to constrain Dark energy equation of state parameters through 21cm intensity mapping. Can also detect pulsars and FRBs as well as can do HI absorber science.



Sensitivity and detection forecasts

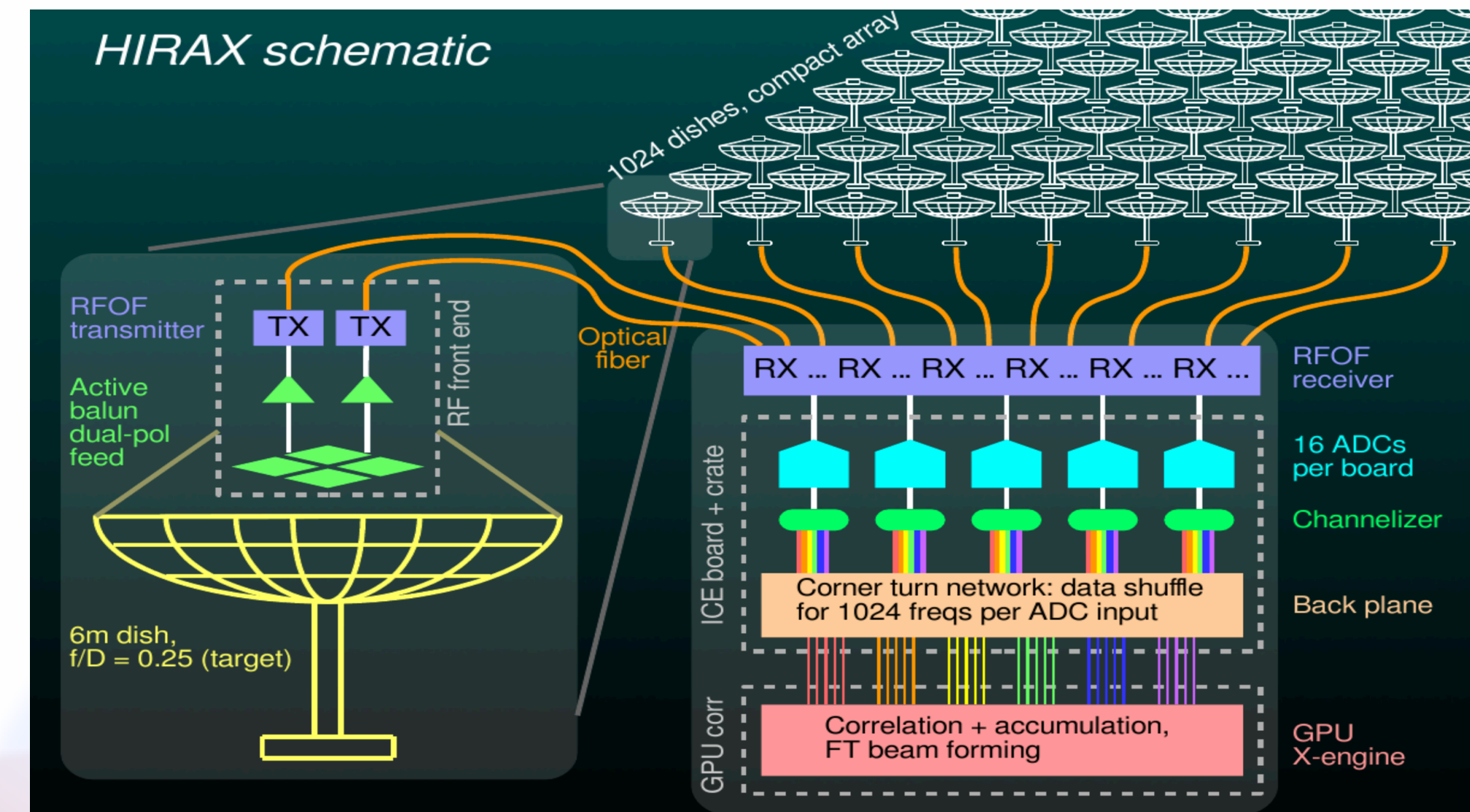
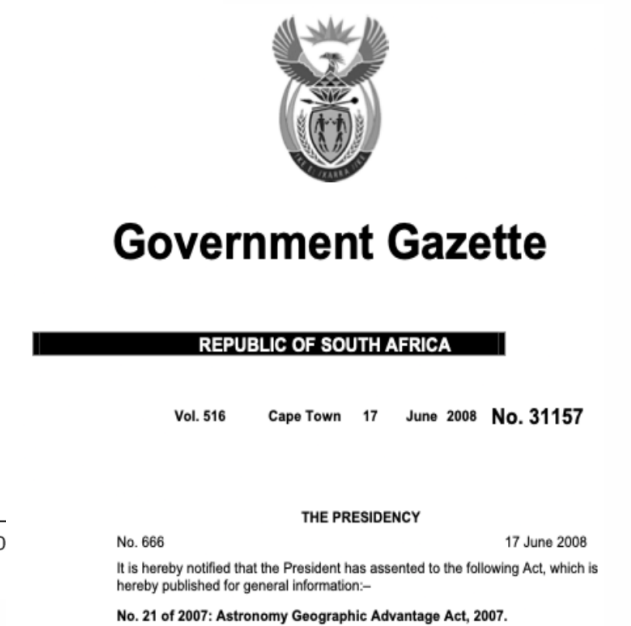
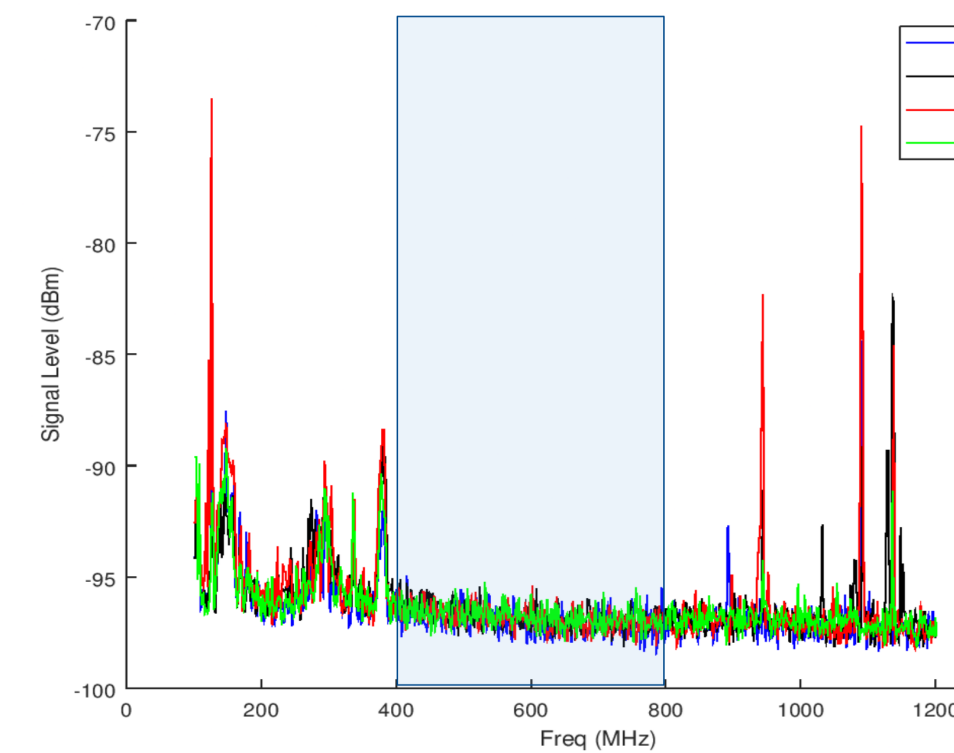


- HIRAX is designed to achieve very high sensitivity at our scales of interest.
 - Comparable to other surveys at high sensitive regions.
- DE FoM : HIRAX-256 ≈ 60 and HIRAX-1024 ≈ 360
- More details on forecasts in an upcoming paper.



Practical challenges

- RFI - Radio Frequency Interference
- Foregrounds – strong, magnitudes higher than HI (upto 6 orders)
 - Extragalactic Point sources, Galactic synchrotron and Faraday-rotated polarised FGs
- Instrumental systematics
 - Primary beam (chromaticity - mode mixing, surface deformities, mutual coupling, standing waves, etc.,)
 - Non-redundancy - array layout errors, dish to dish changes, non-uniform beam responses.
 - Thermal noise / Sensitivity, Polarization leakage and Cable reflections
- Data volume and computation
 - The 1024 (256) element array will produce a very large daily dataset: 150 (9) TB / day [220 (14) PB for full 4 year survey]

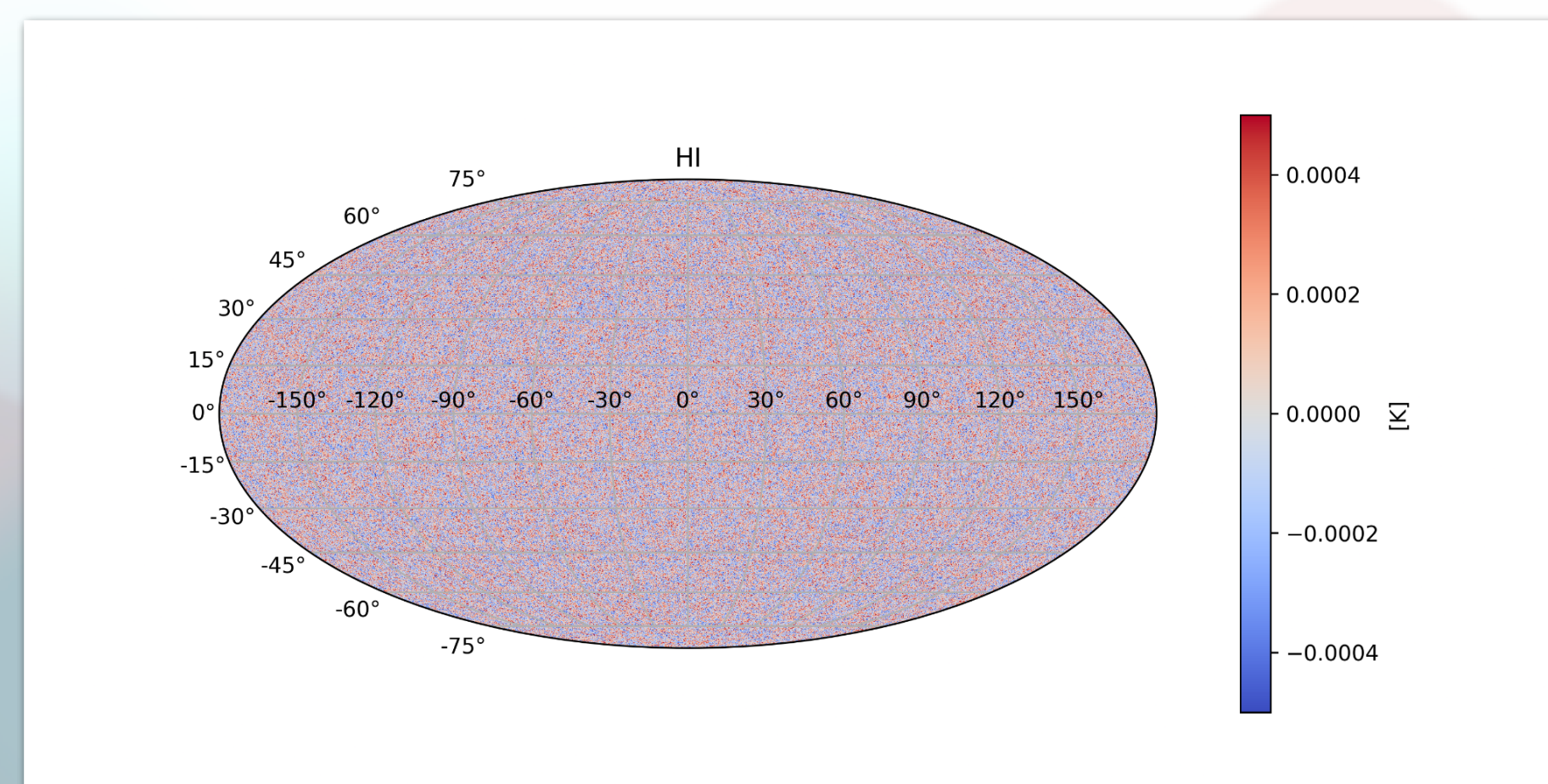
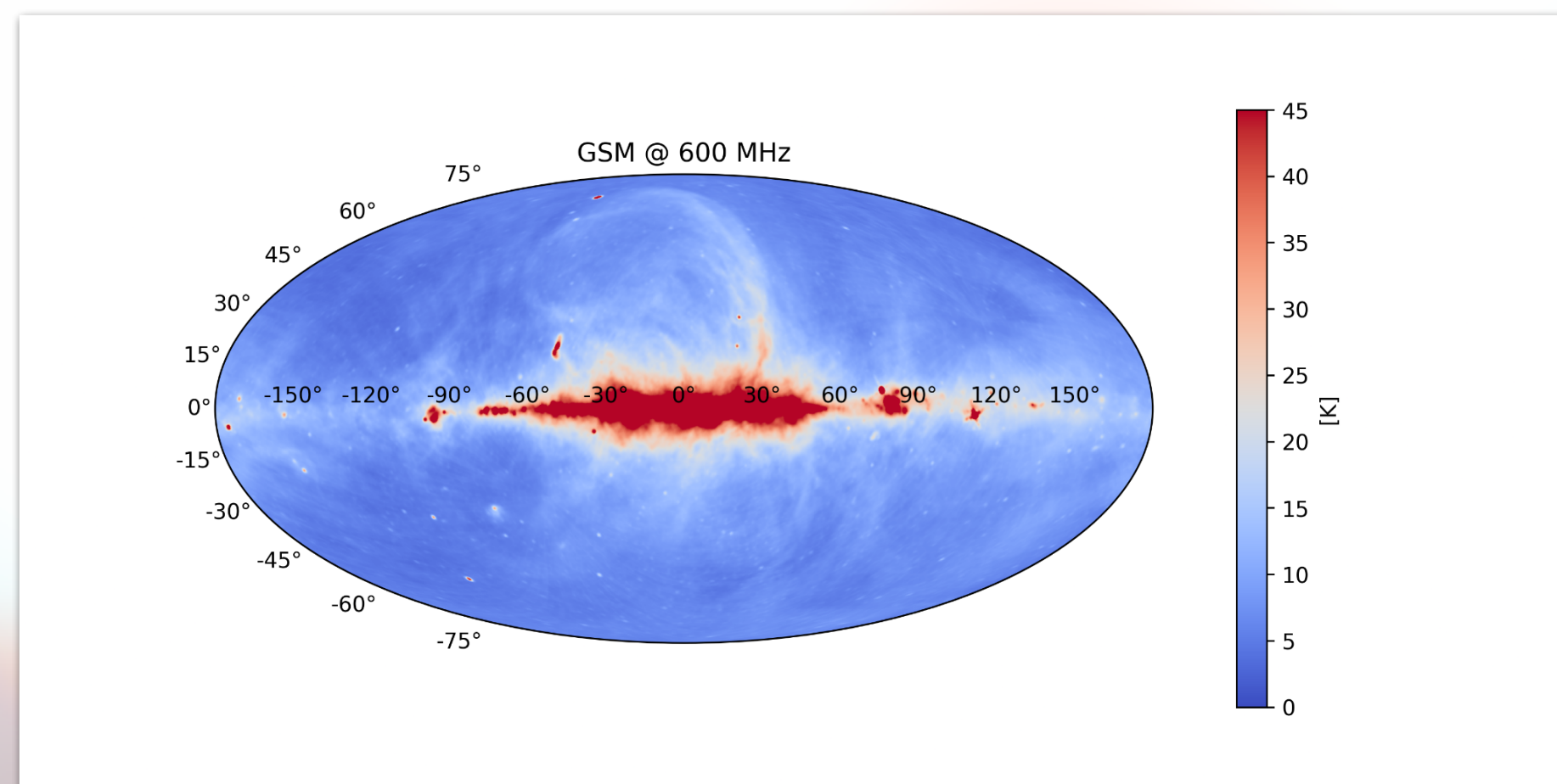
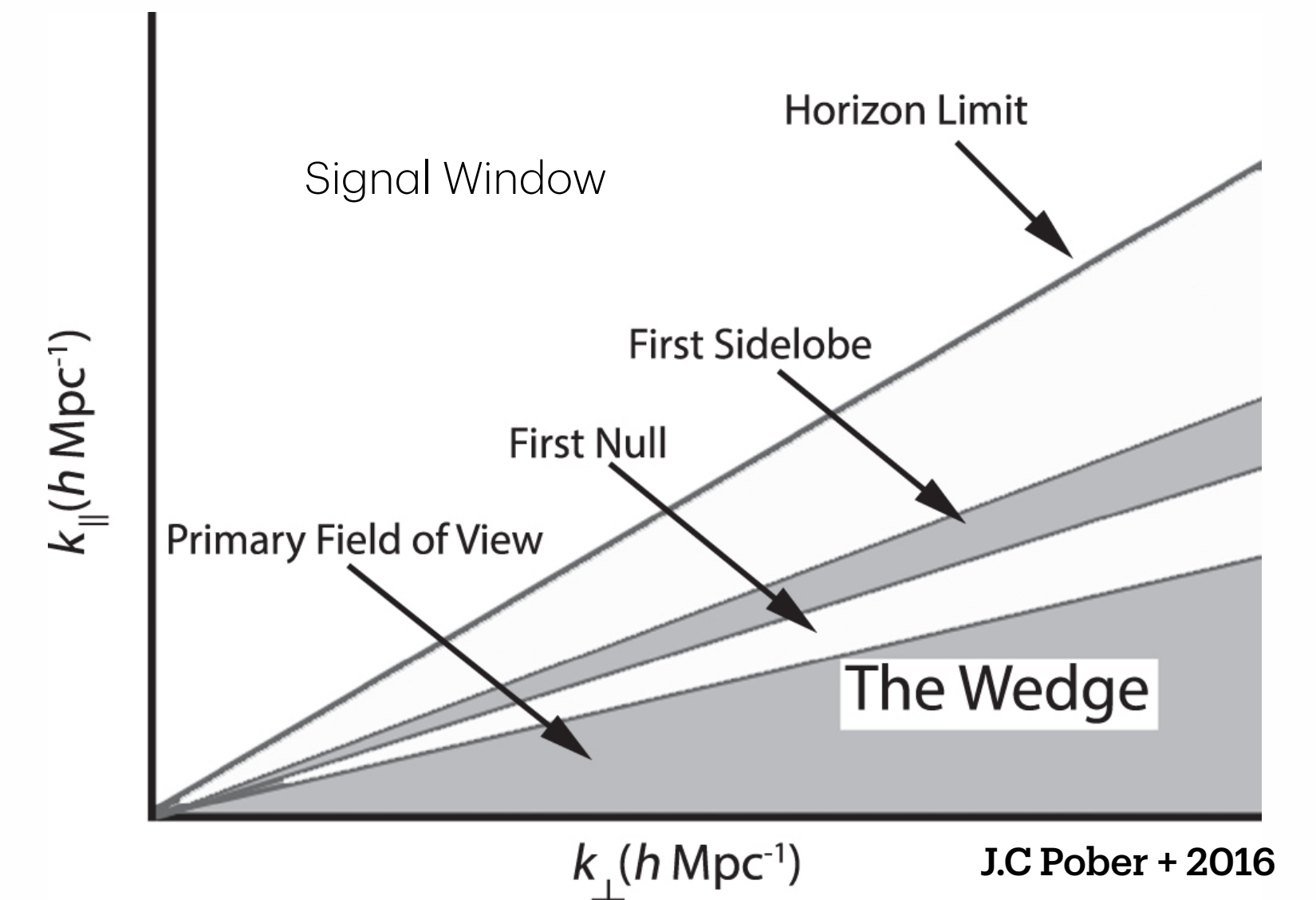


Foregrounds Instrumental systematics

- RIME - Radio Interferometer Measurement Equation:

$$V^{i,j}(\nu) = \int B_i B_j^*(\hat{\theta}, \nu) I(\hat{\theta}, \nu) \exp[-2\pi i \mathbf{u}_{i-j} \cdot \hat{\theta}] d\Omega$$

- Foregrounds are orders of magnitude brighter than the HI signal but almost spectrally smooth (confined to the wedge shaped region in cylindrical power spectrum). Whereas HI signal is highly varying in frequency. So the signal is isolated in a clean FG-free window.
- But the spectral structure imparted by the instrument - particularly the primary beam pattern- can mix these modes, and cause foreground leakage - shrinking the window.

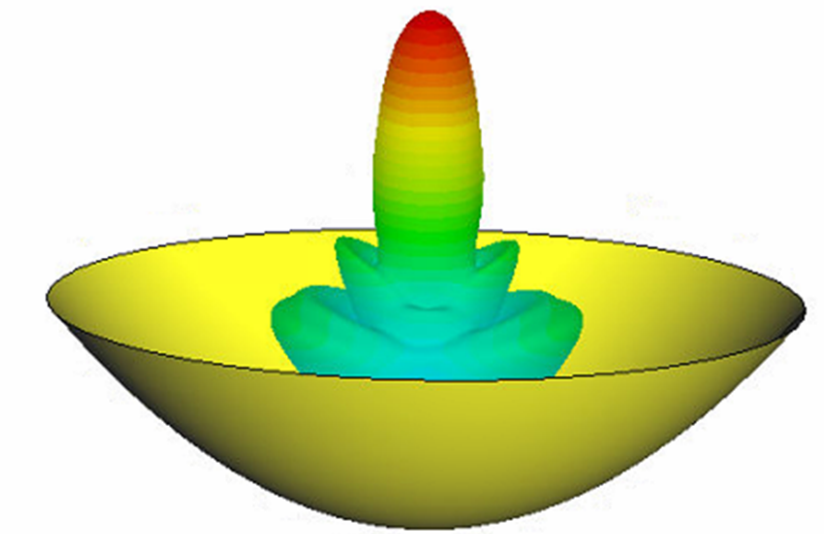


Primary beam

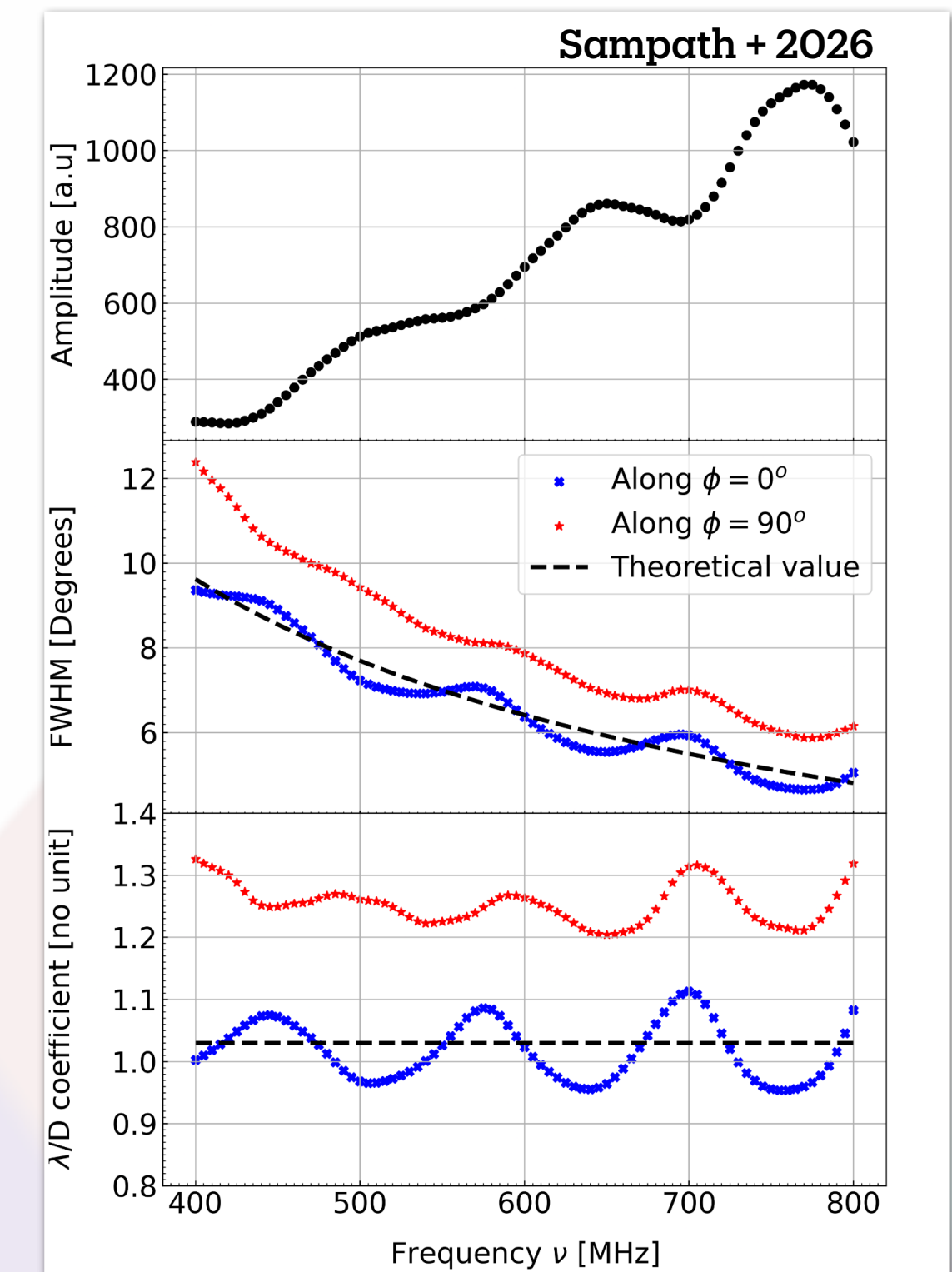
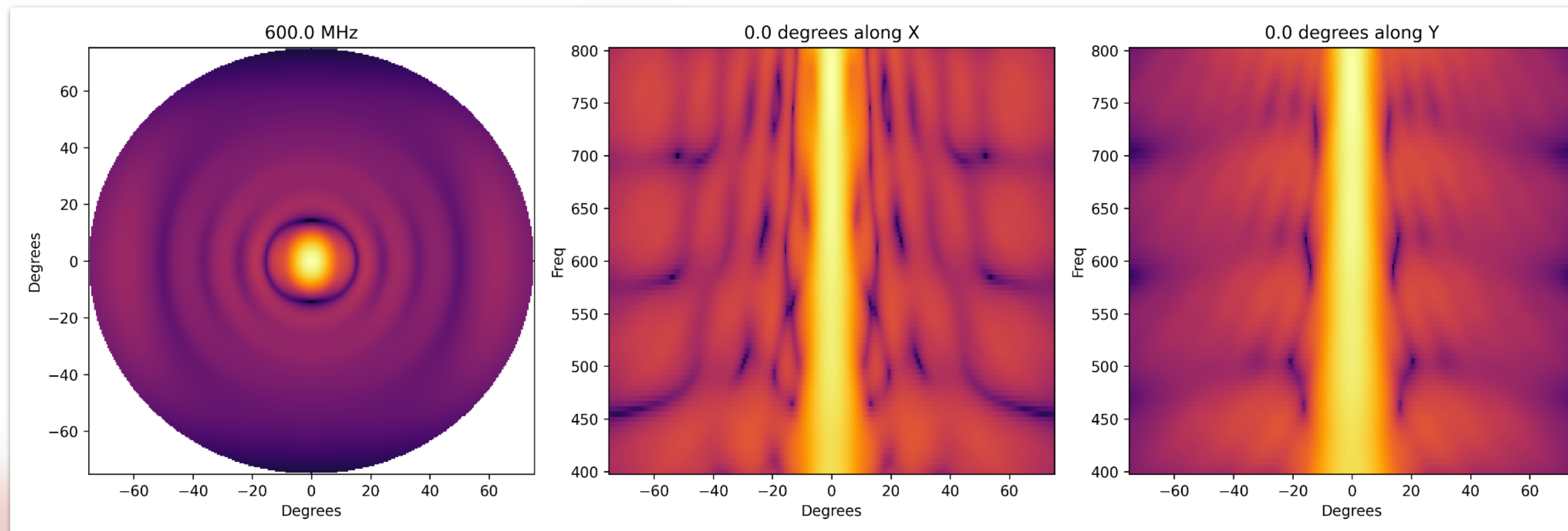
- The radiation pattern/primary beam is the reception pattern of an individual antenna. It is the directivity of an antenna - i.e., the direction in which the antenna is more sensitive.
- This pattern is decided by the way the hardware system is designed - such as how the feed (at focus) designed and positioned, the dish surface smoothness, the supporting legs, etc.,
- It is a function of both angular directions and operating frequency : $B : B(\theta, \phi, \nu)$
- The beam width (FWHM) decides the most power received by the antenna (mainlobe) - but the less receptive structures (sidelobes) can also mix signals due to its sensitivity to directions away from pointing.



Credits : Keshav Bechoo

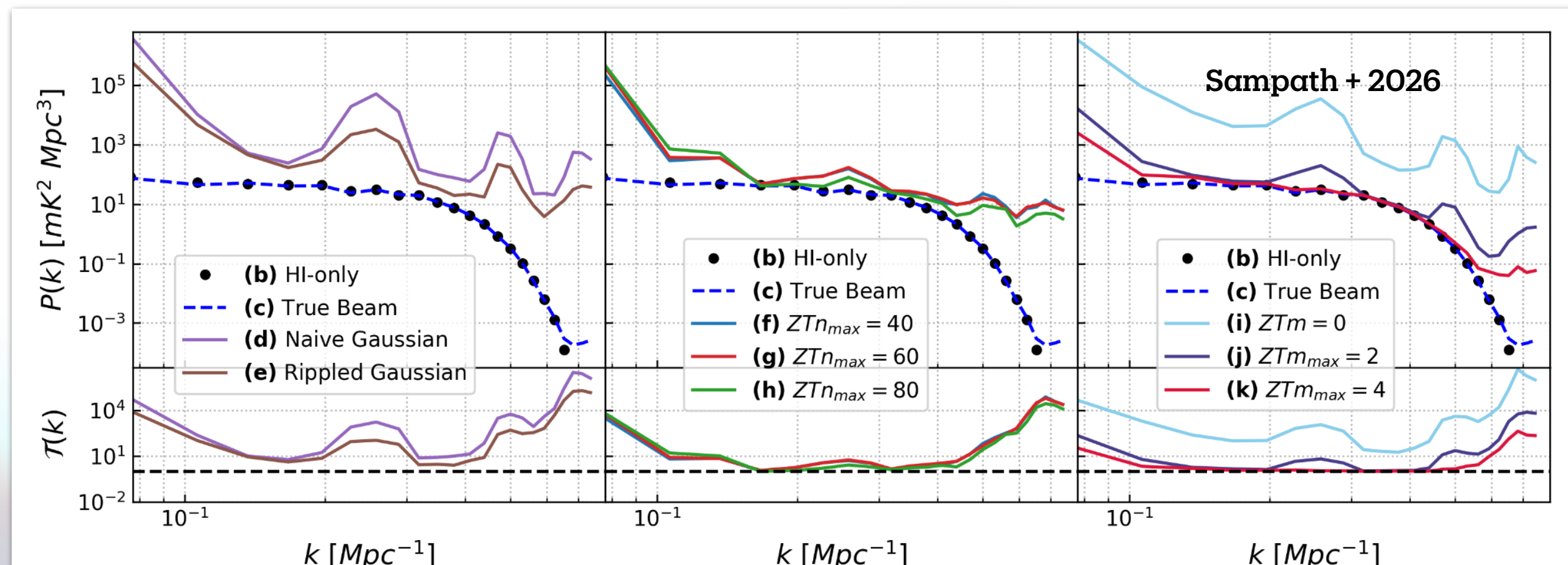
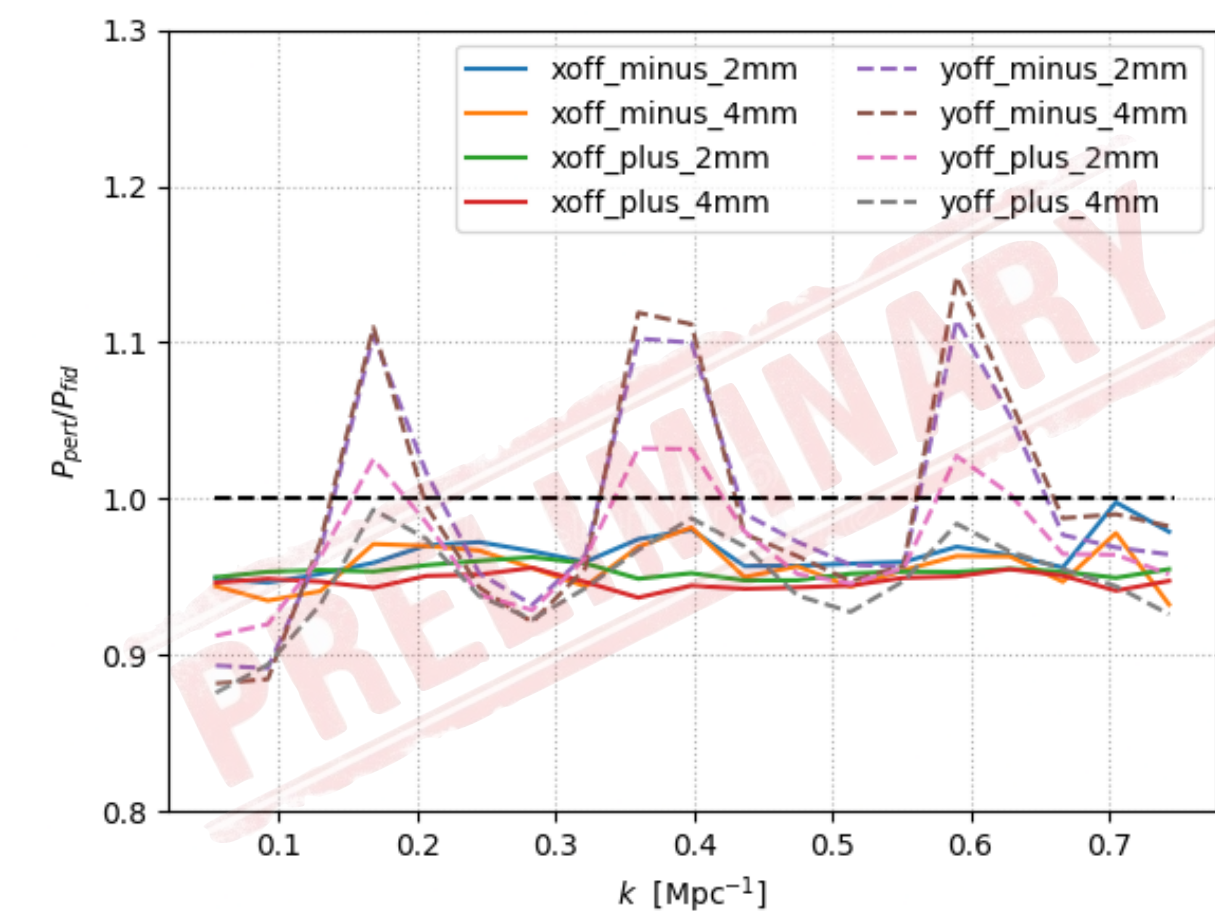
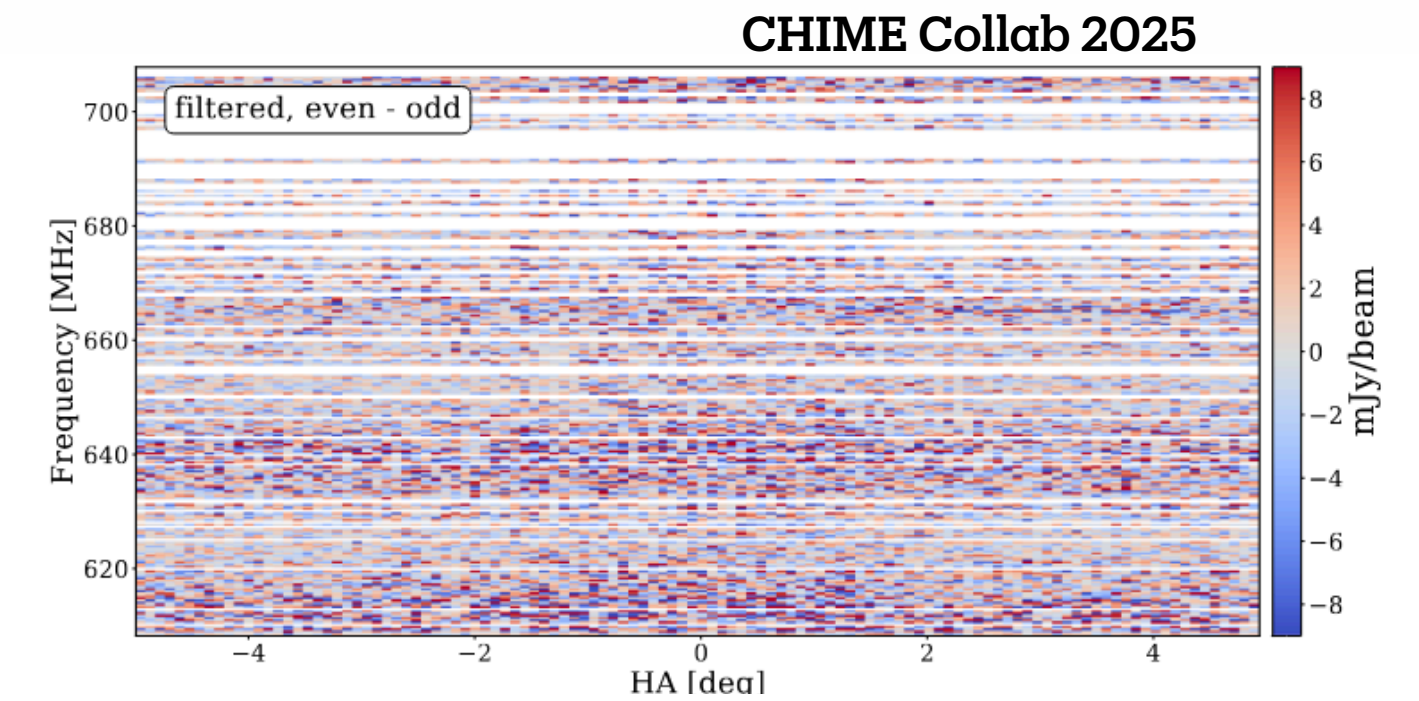


Credits : Aditya Karigiri



Primary beam — Impact in $P(k)$

- An individual antenna's chromaticity is modeled and the impact of it in HI signal recovery in the presence of diffuse foreground emission is shown in our past paper - Sampath + 2026.
- The primary beam chromaticity when uncompensated in foreground cleaning, imparts a ripple in the power spectrum - also reported in CHIME data (CHIME Collaboration + 2025).
- A simple positional offset (in the order of mm) in the feed of the antenna relative to the reflector creates spectral structures too.



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OPEN ACCESS

Primary Beam Chromaticity in HIRAX. I. Characterization from Simulations and Power Spectrum Implications

Ajith Sampath, Devin Crichton, Kavilan Moodley, H. Cynthia Chiang, Eloy De Lera Acedo, Simthembile Dlamini, Sindhu Gaddam, Kit M. Gerodias, Quentin Gueuning, N. Gupta

▼ Show full author list

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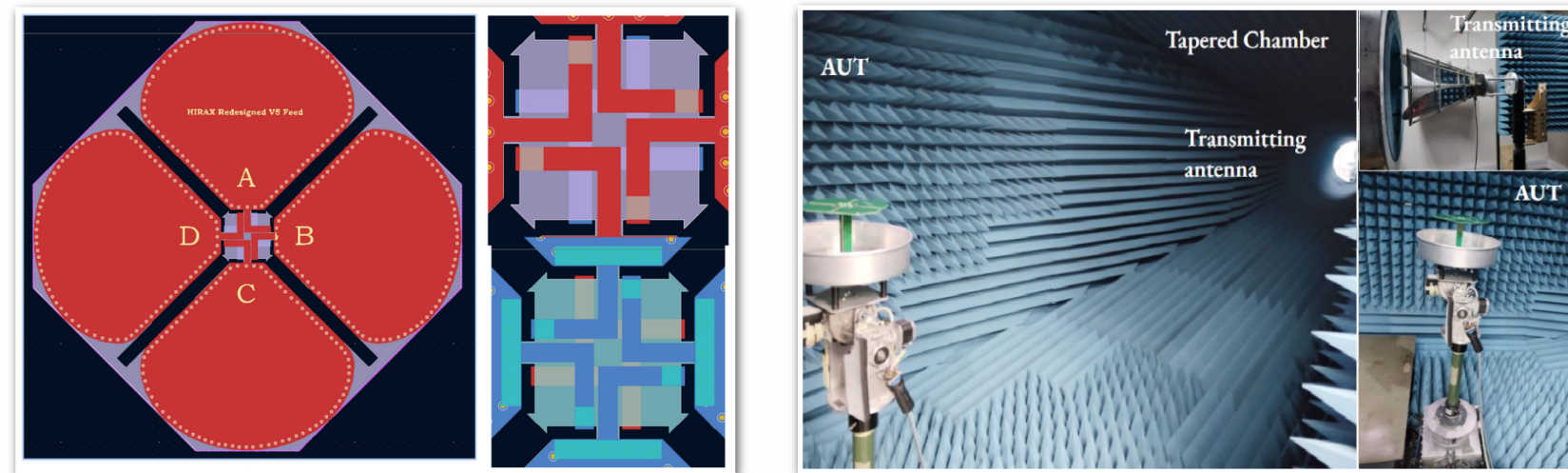


How to tackle this?

How to tackle this?

Hardware - Improving feed and characterizing dish surface

New Feed development and testing



Credits : Sindhu Gaddam

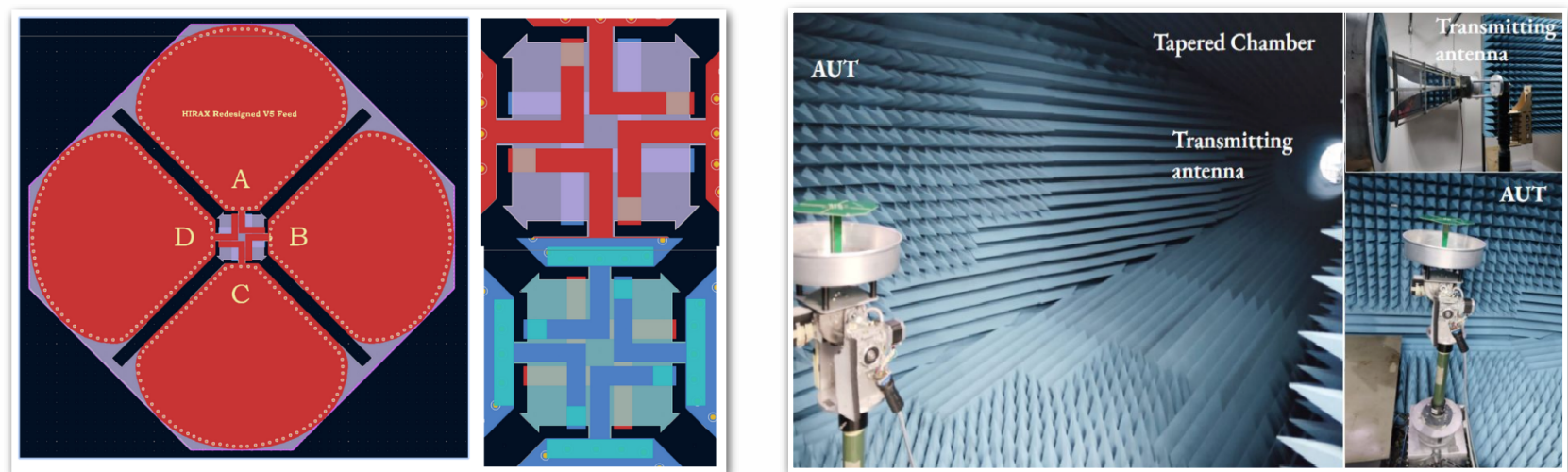
Dish metrology



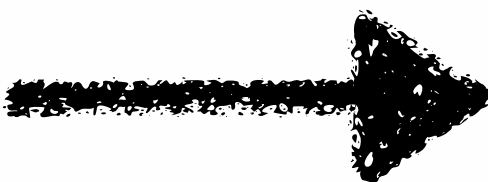
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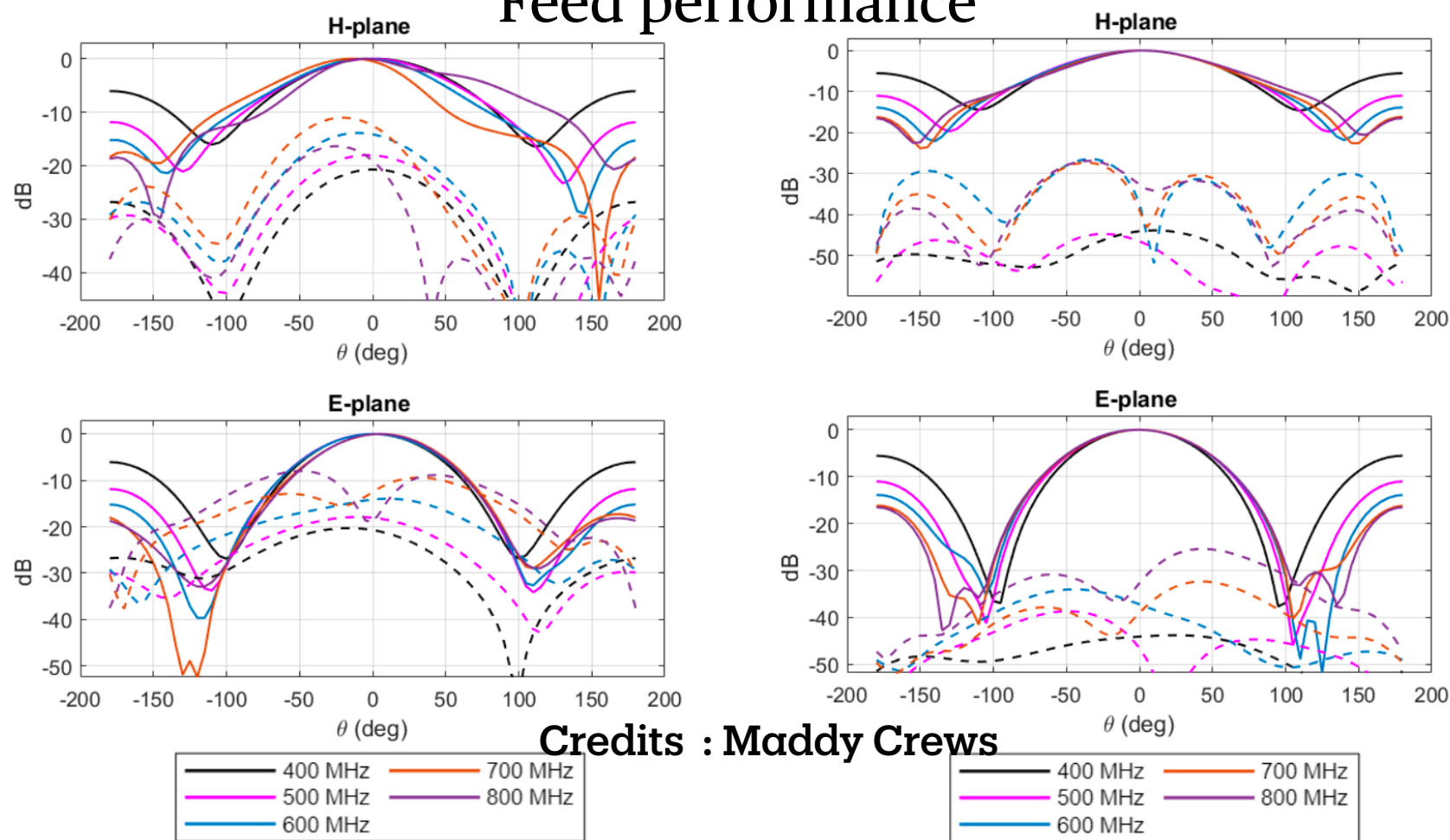
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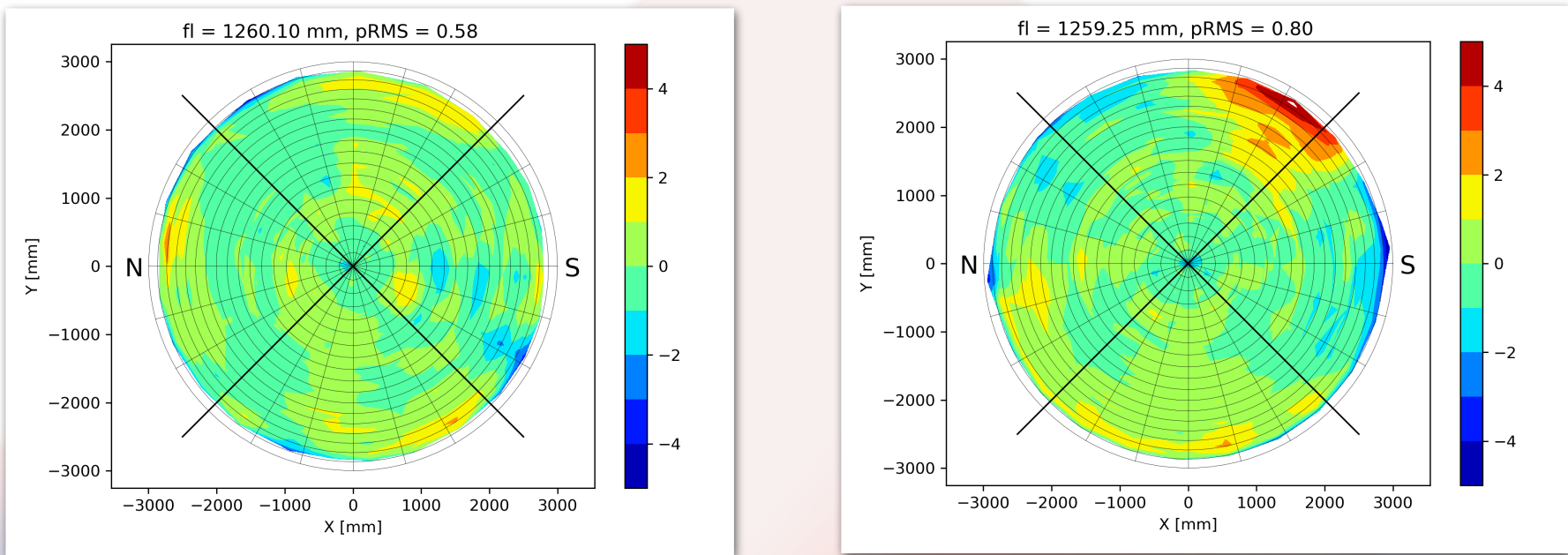


Feed performance



Credits : Maddy Crews

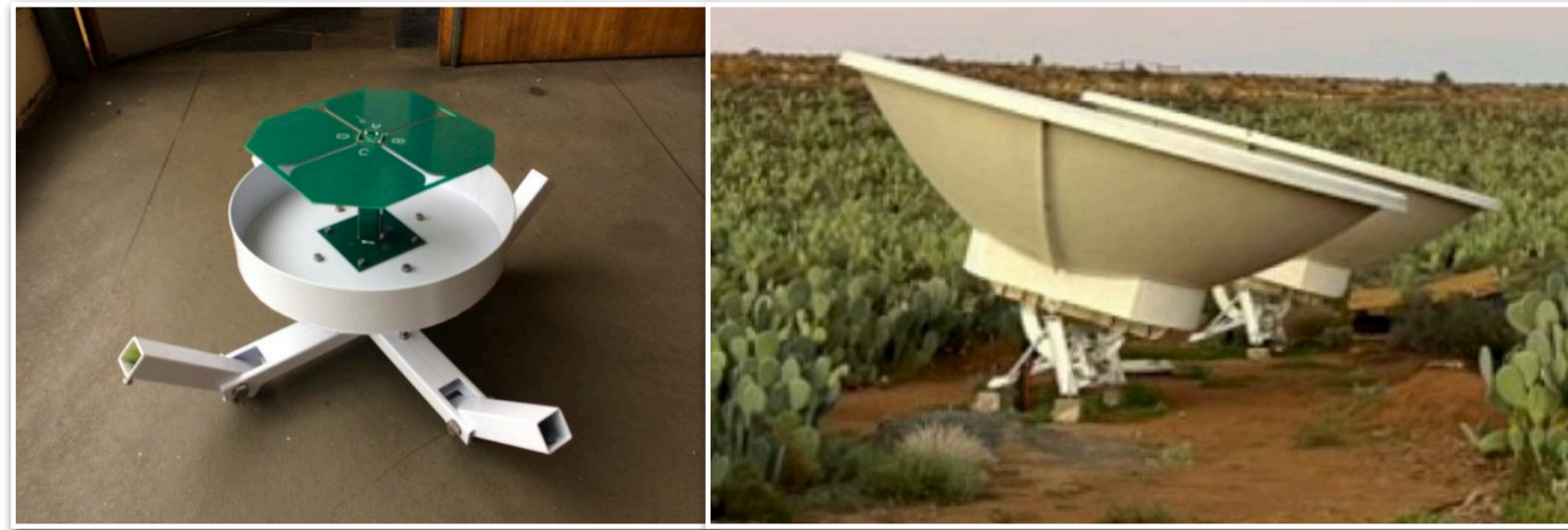
Dish metrology



Credits : Jennifer Studer

How to tackle this?

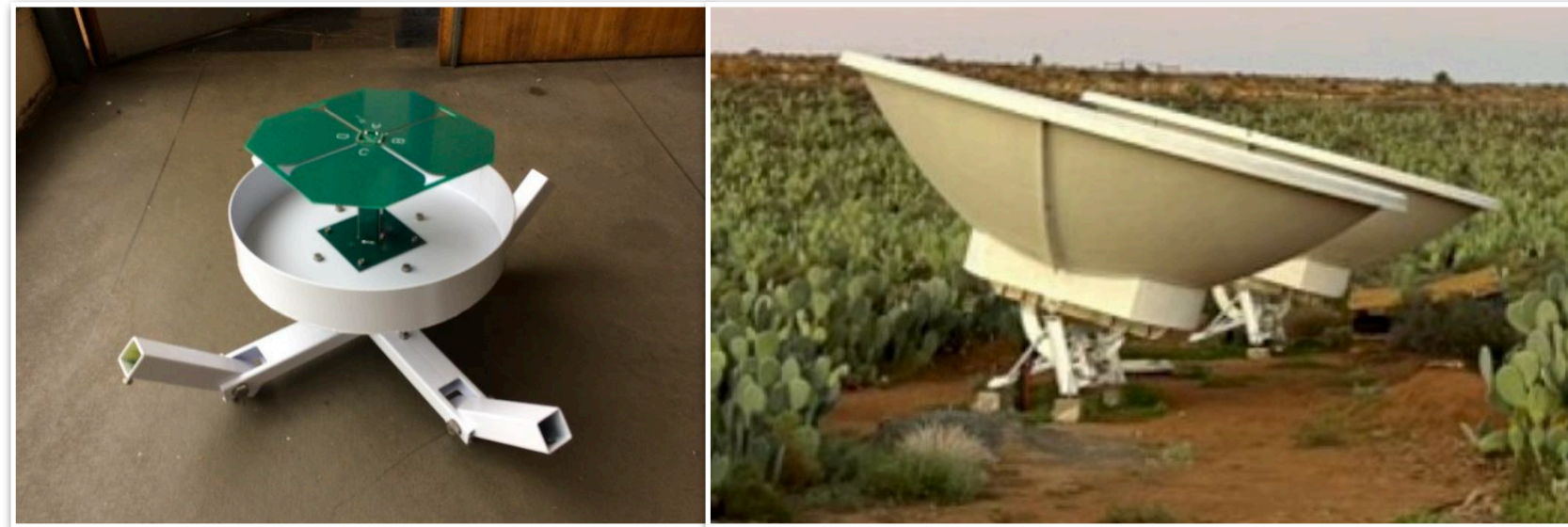
Simulate - EM radiation pattern



Real Feed and Dish

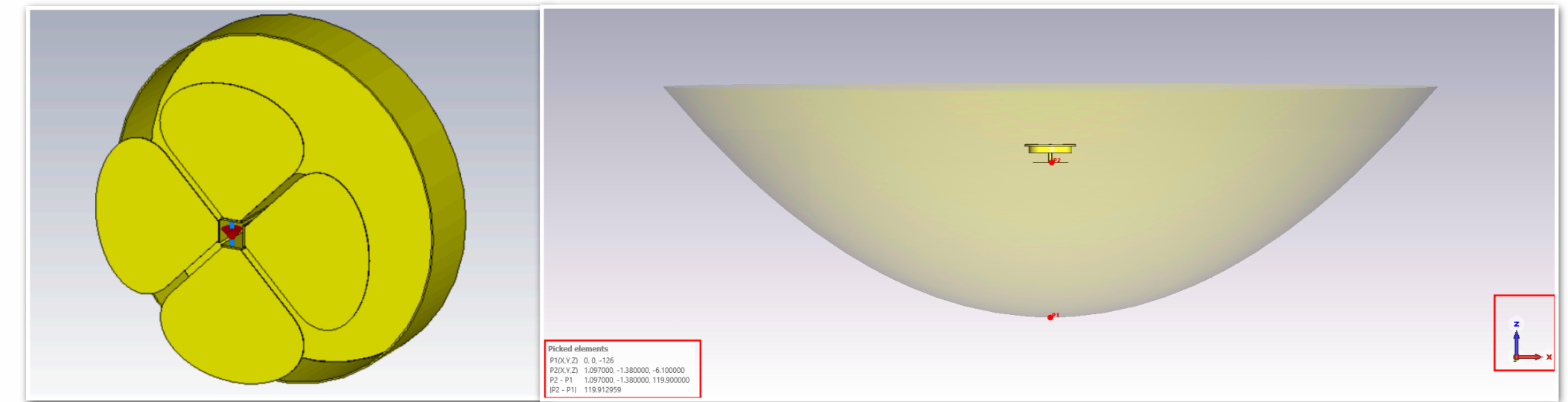
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Real Feed and Dish

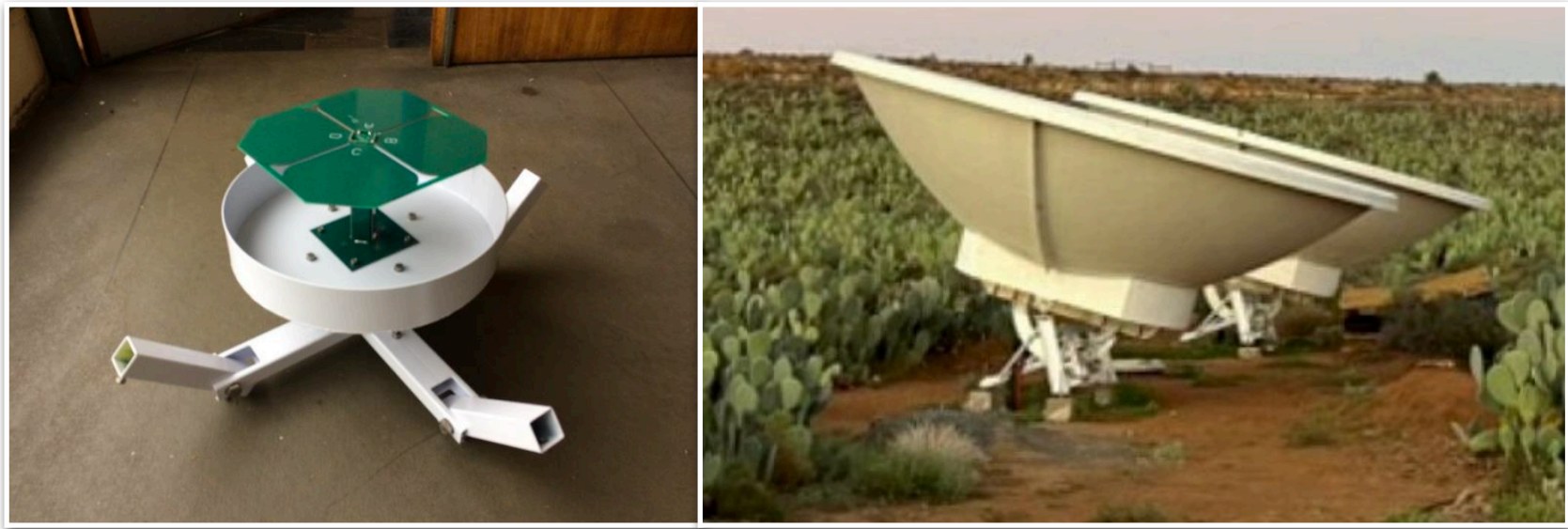
CAD 3D model



Feed and Dish models

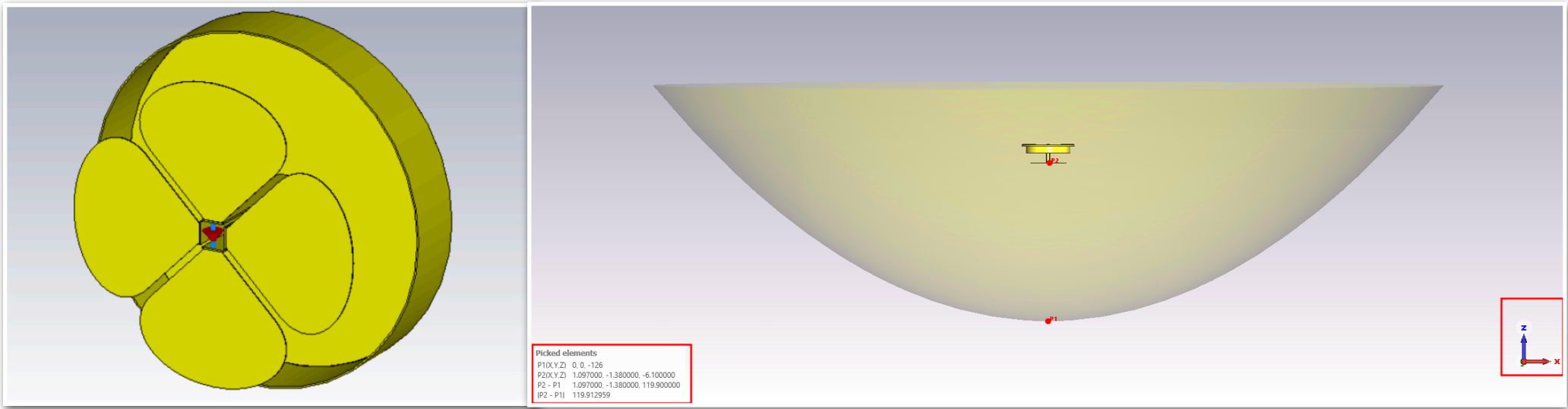
How to tackle this?

Simulate - EM radiation pattern

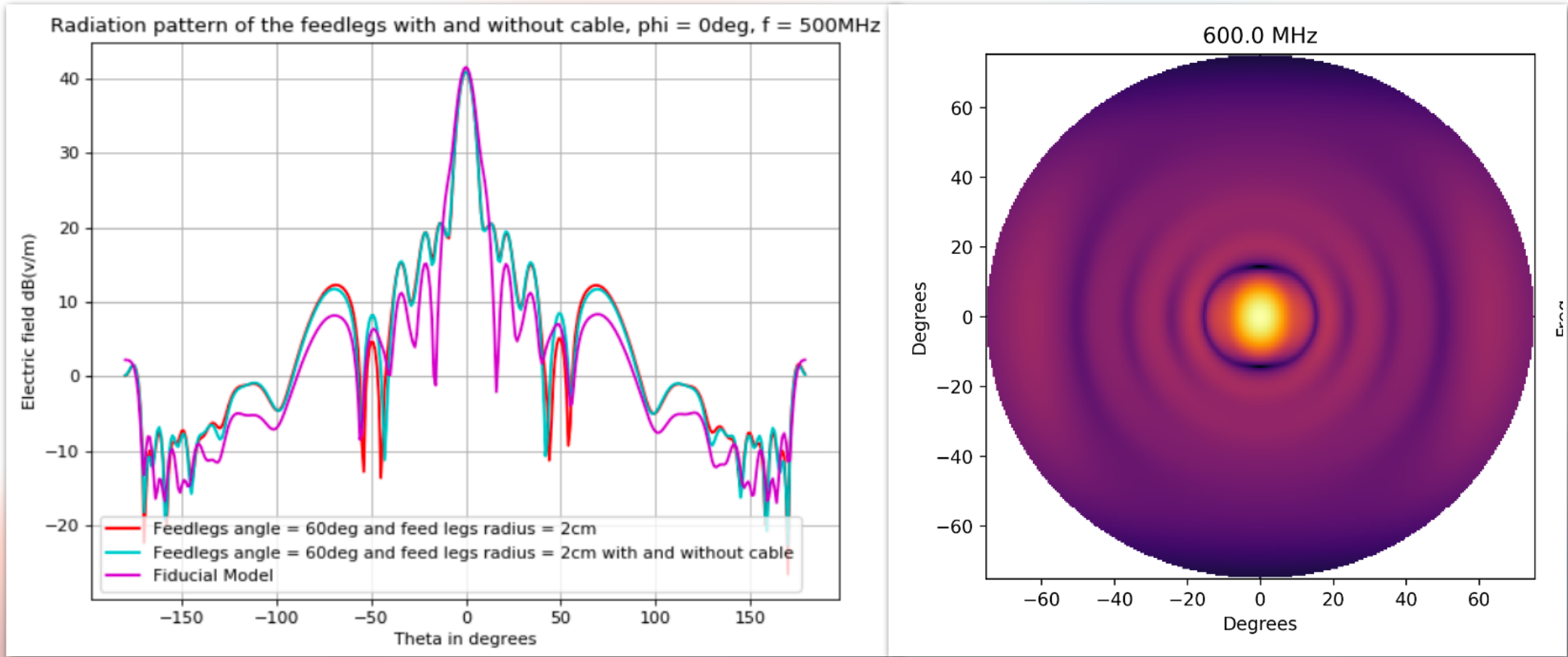


Real Feed and Dish

CAD 3D model



Feed and Dish models



EM solvers like
CST Studio Suite

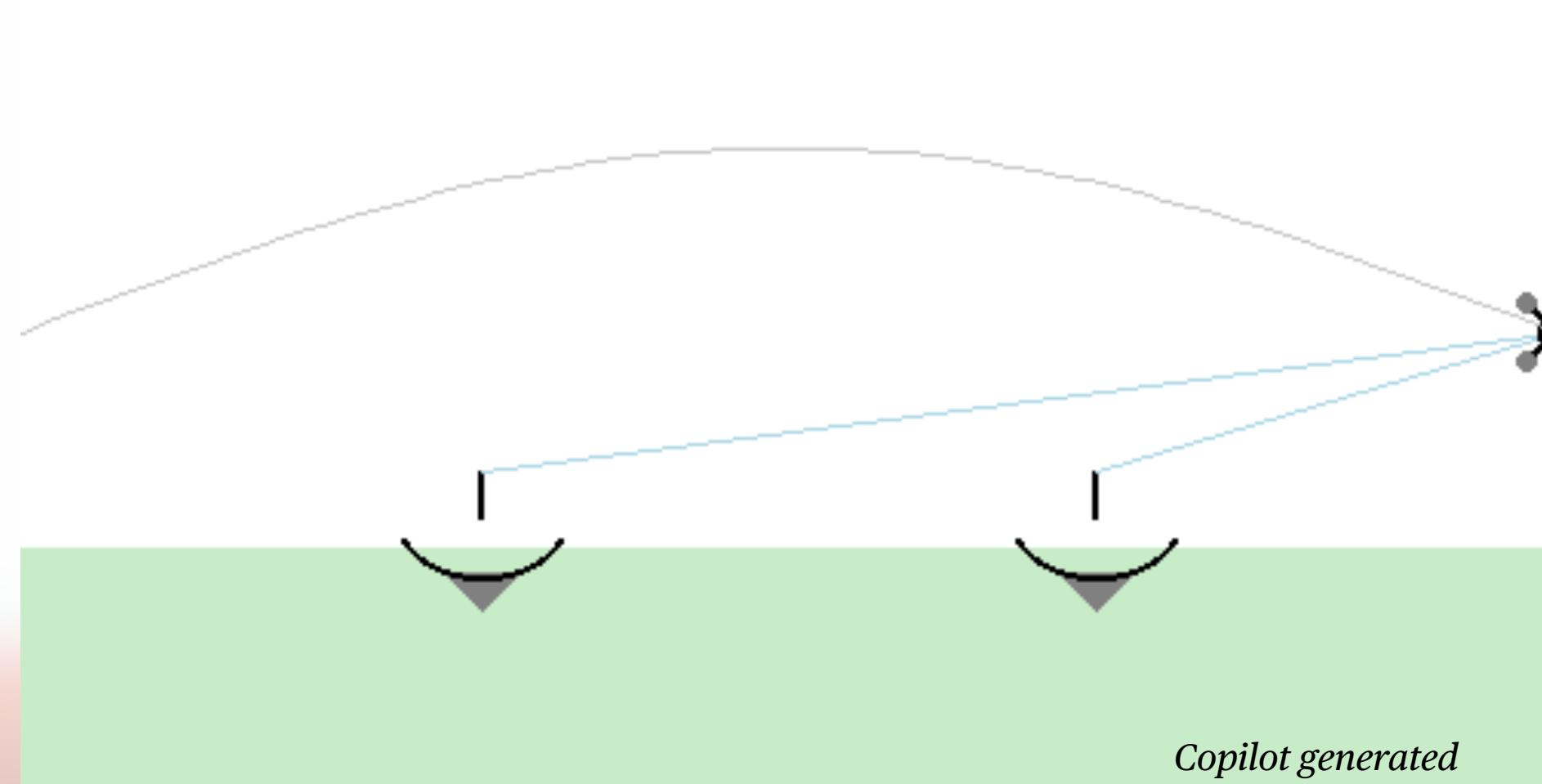
How to tackle this?

Measure using Drone flights

- Using a transmitter fitted to a drone, and fly it over the dishes at the far field,

$$\text{Far field distance } d_{ff} = \frac{2D^2}{\lambda}$$

- Sample as densely as possible to measure the beam angular features accurately.



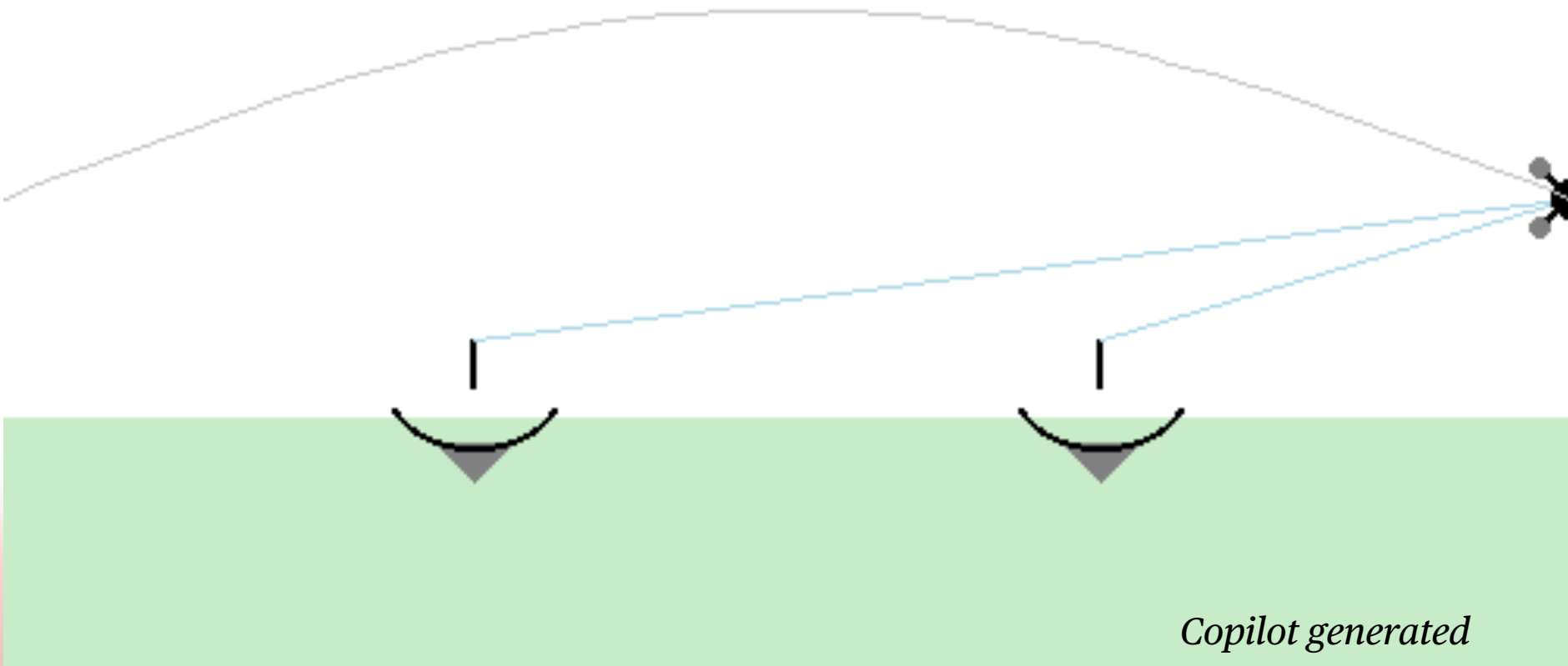
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Measure using Drone flights

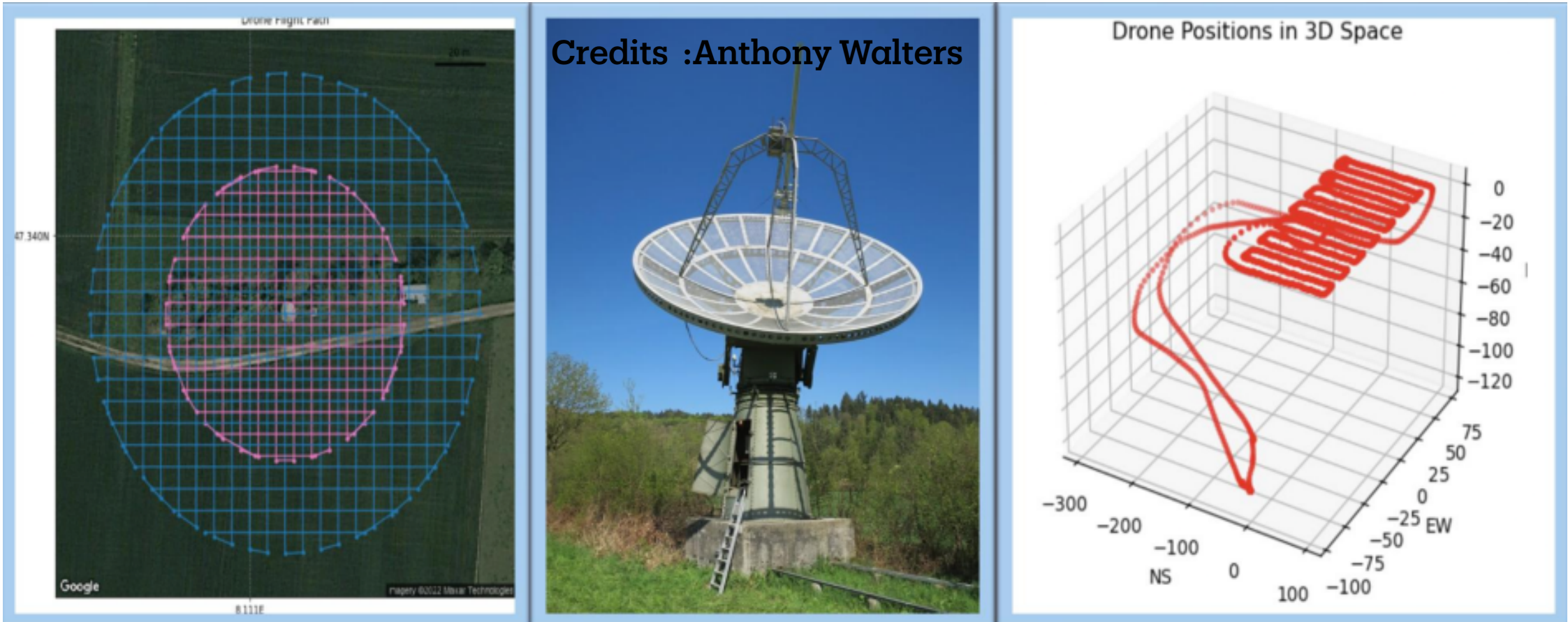
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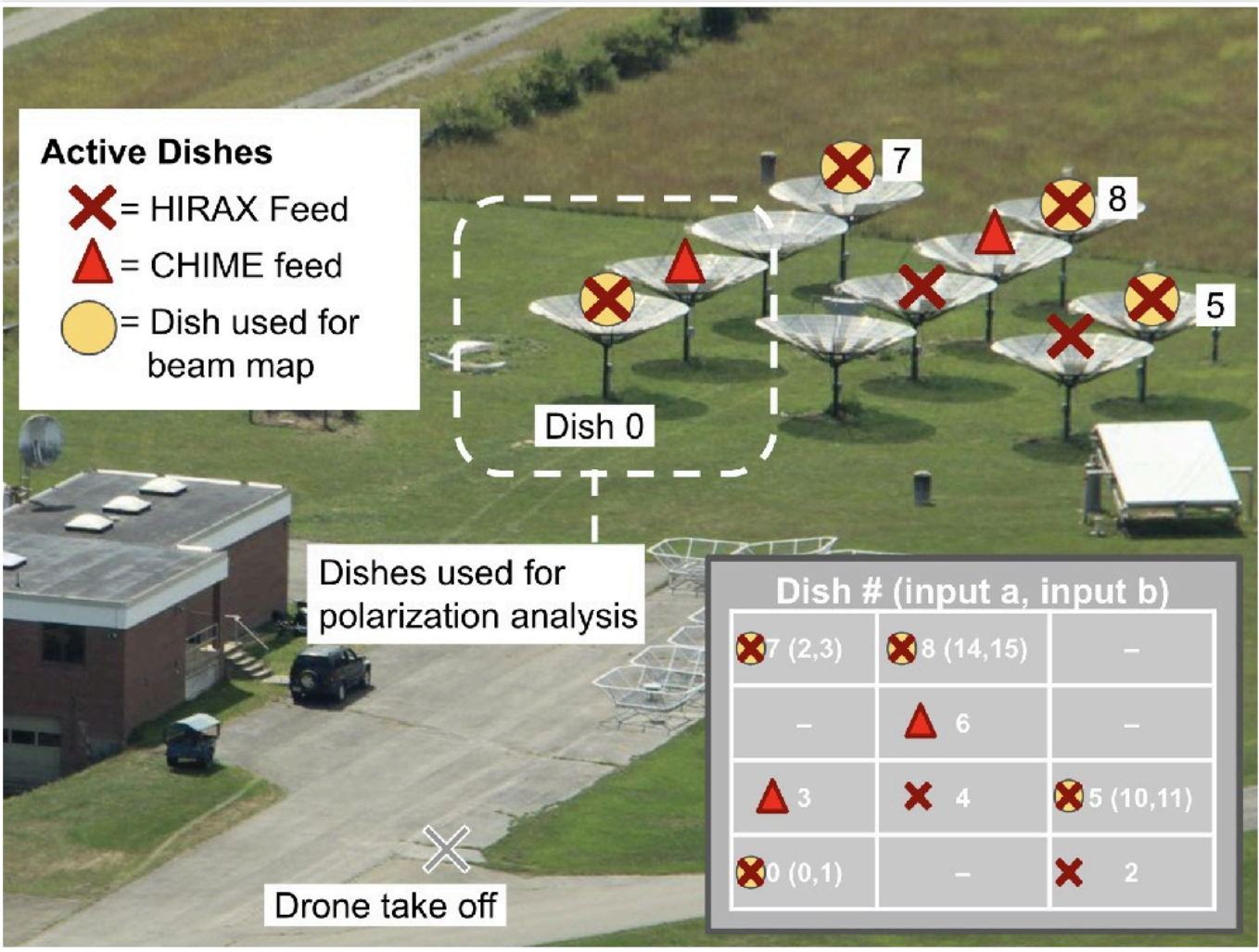
- Sample as densely as possible to measure the beam angular features accurately.
- Tested at Bleien in the past.
- Drone flight campaign - planning is underway - subject to approval from SKA/MeerKAT.



Bleien Tests 2023



TONE array @ GBO



E.Kuhn + 2025

South Africa Drone

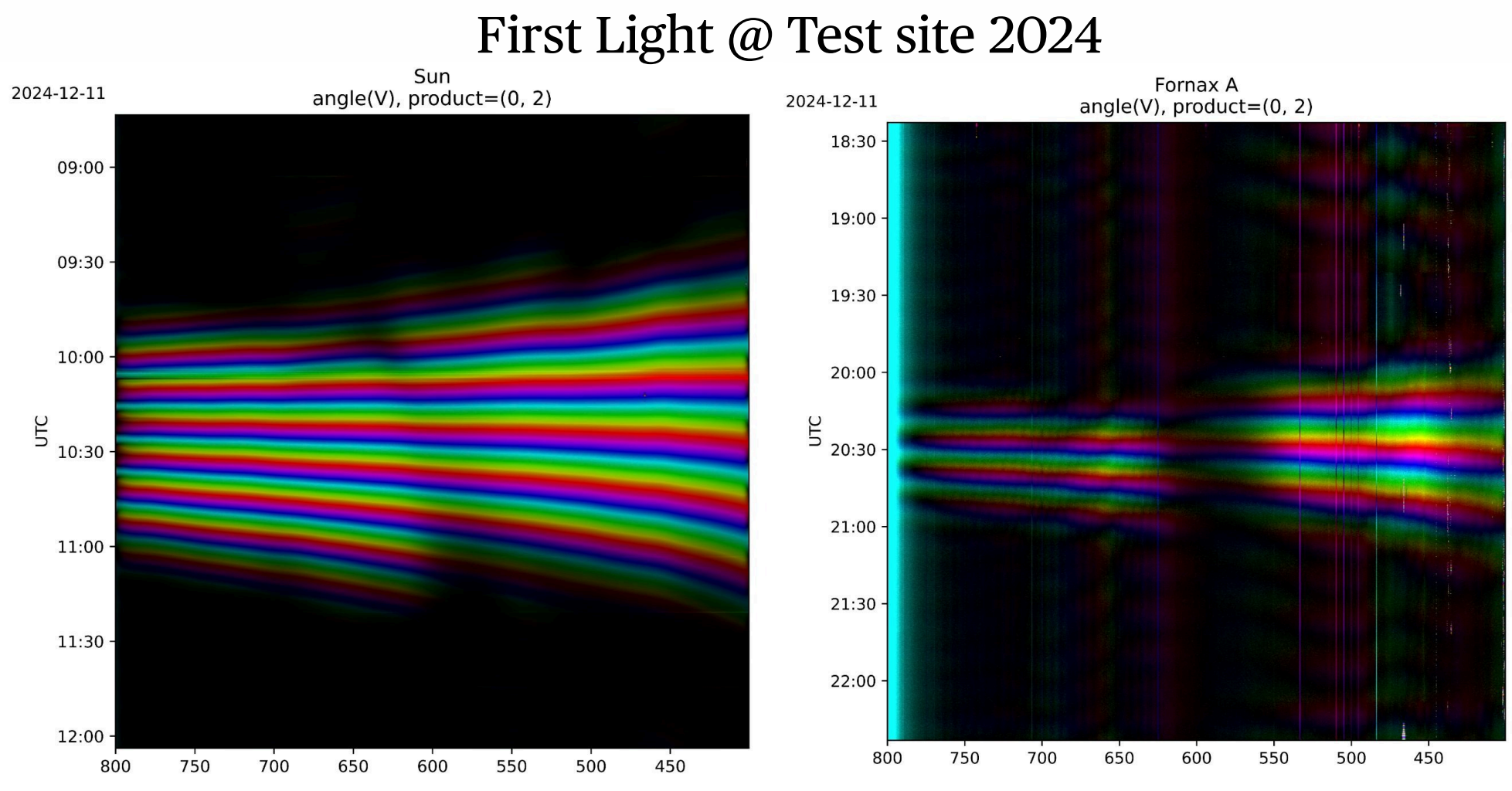
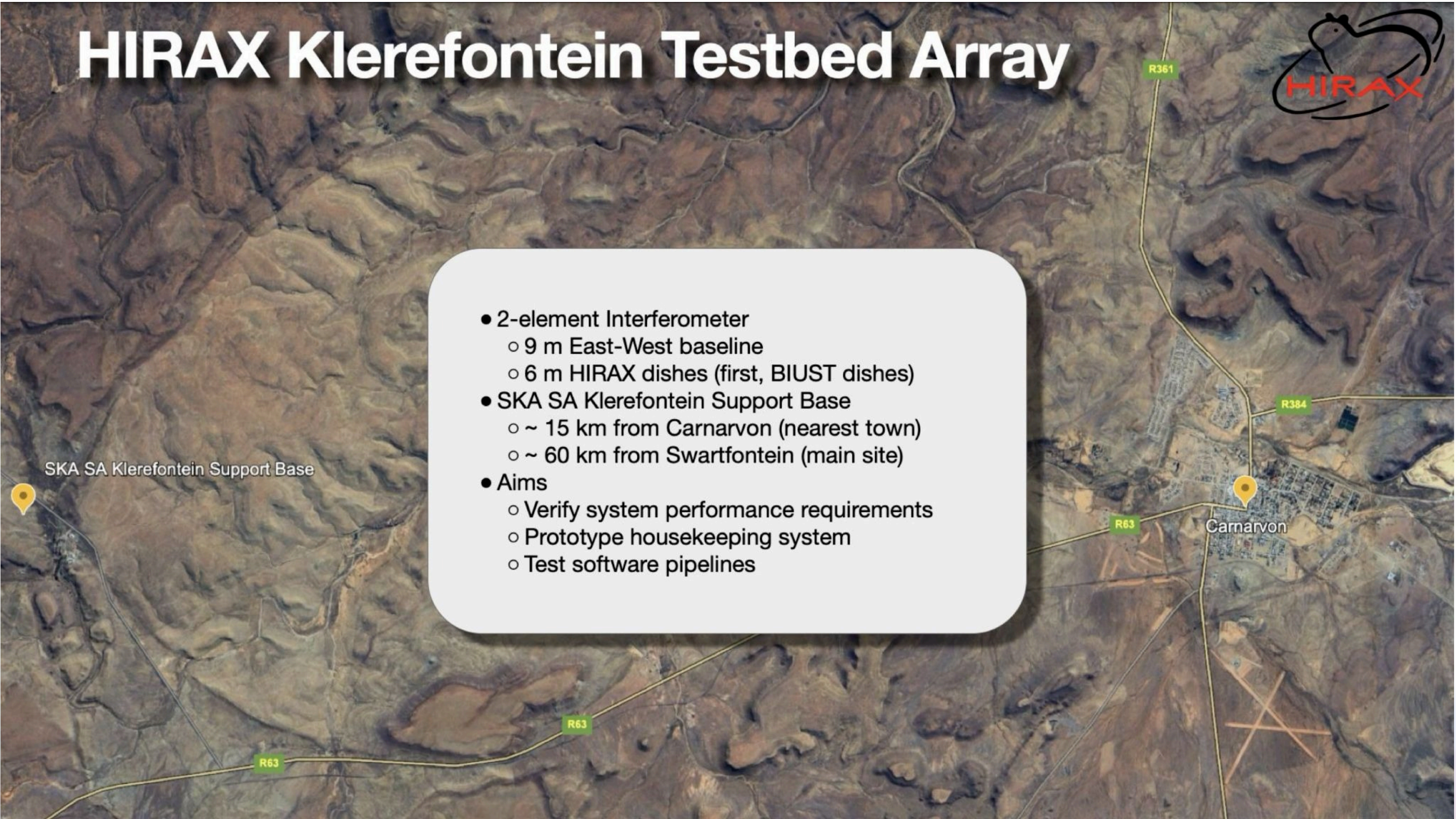


Yale Drone



How to tackle this?

Measure using observations

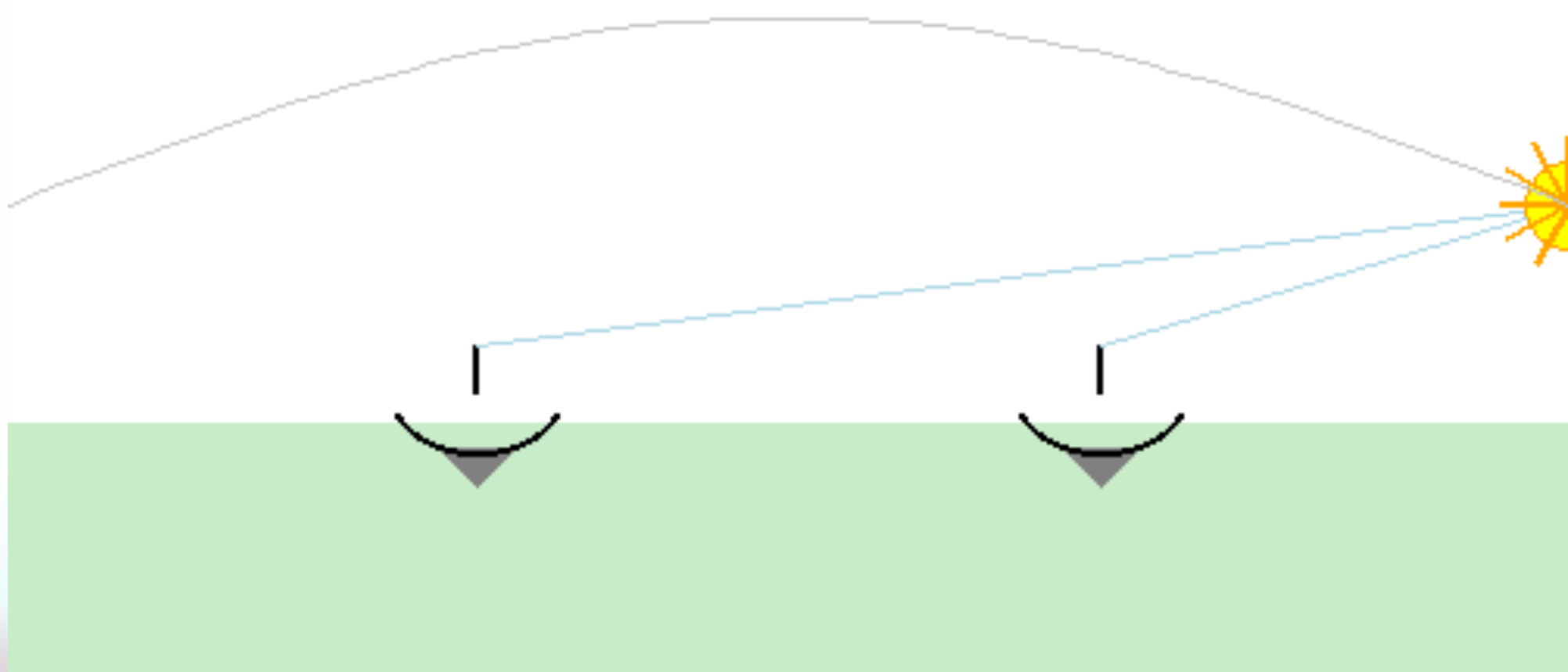


Credits : Anthony Walters

Solar transit to map the beam

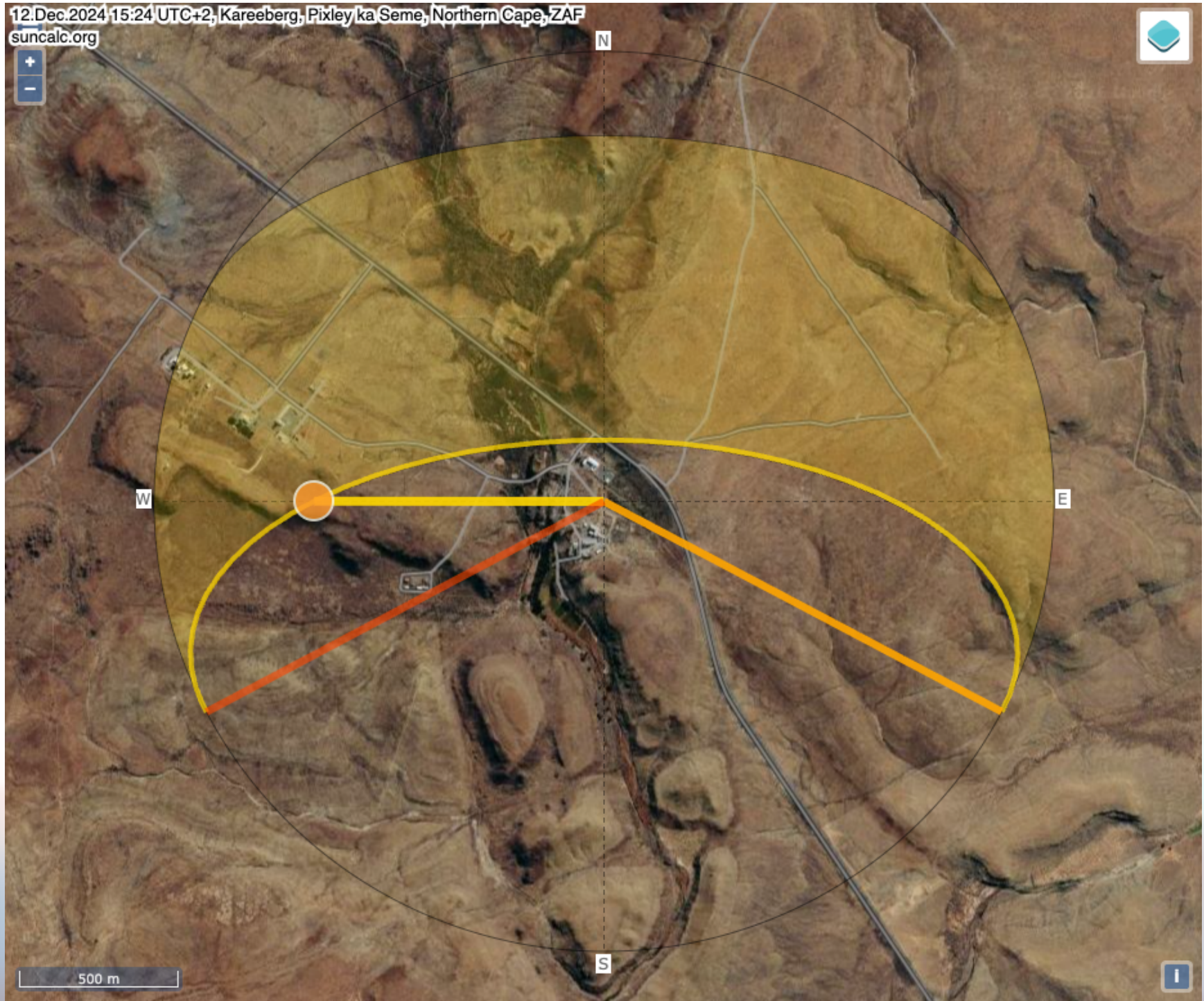
Dec 2024 Transits at test-bed site

- Using astronomical point source transits, we can map the primary beam response at some angles, corresponding to the path of the source in the celestial sphere.
- Sun is one such source - really bright - but not exactly a point source.



Copilot generated

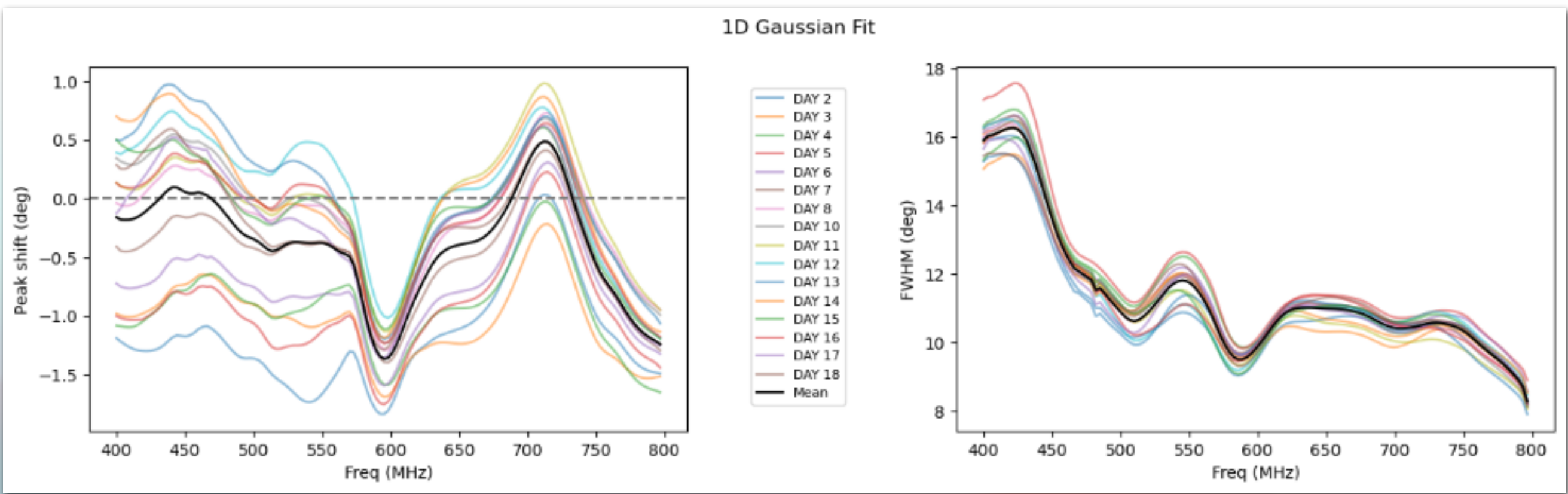
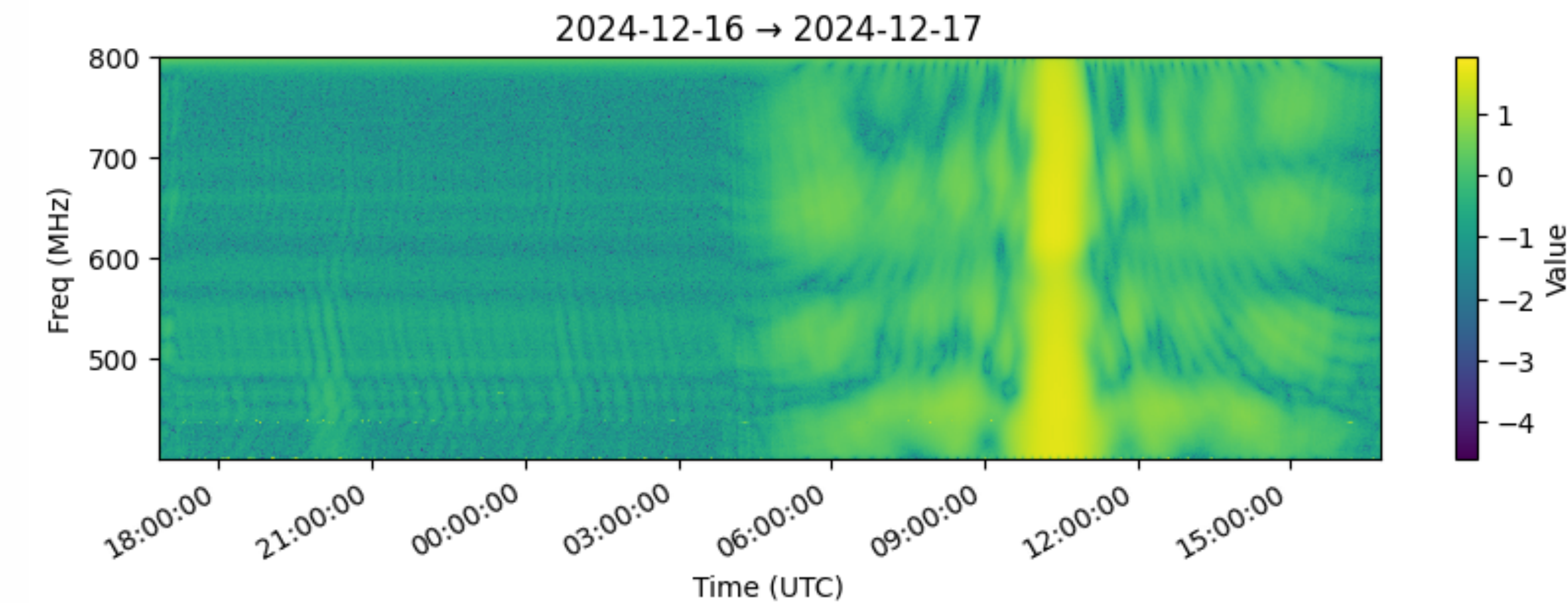
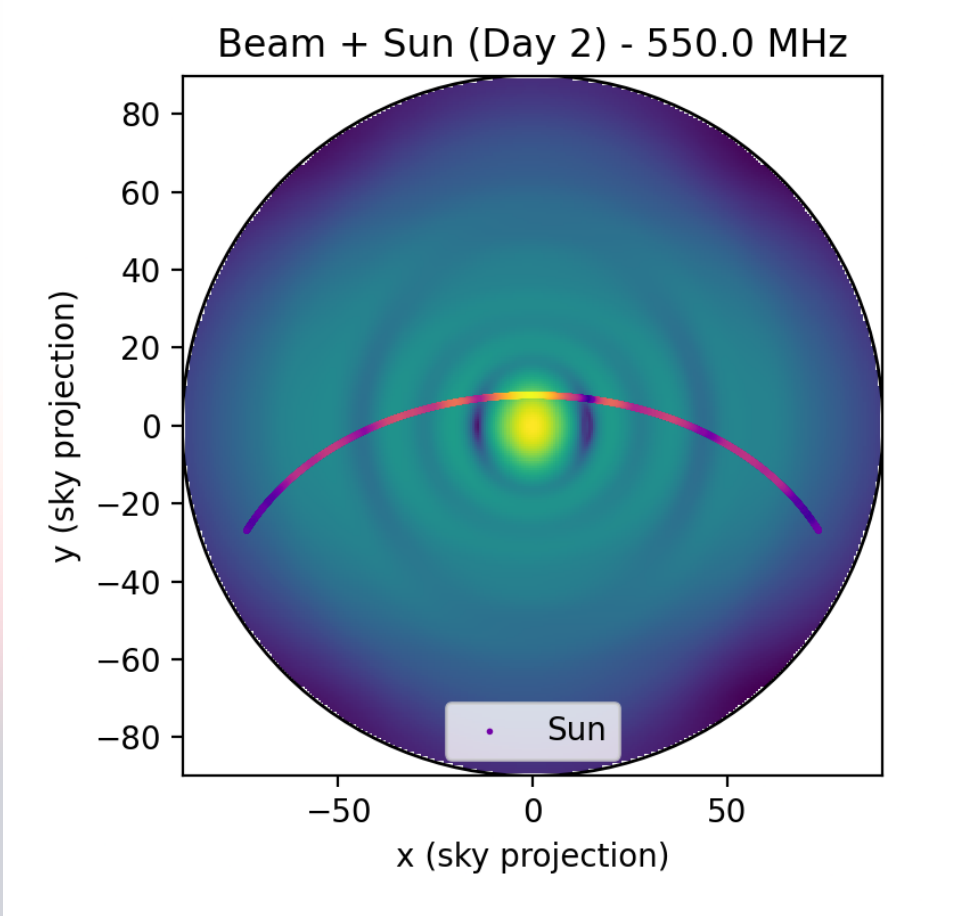
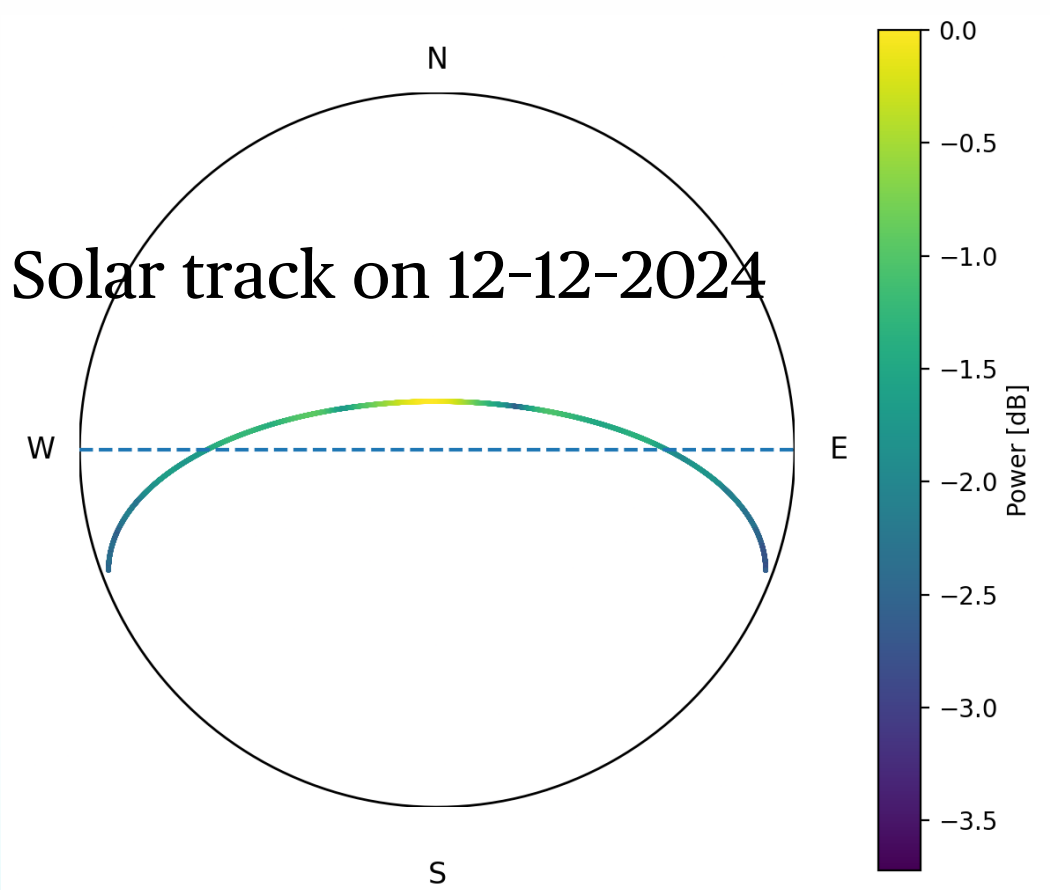
Dishes	2
Pointing	Zenith
Baseline length	~ 9m
Baseline Orientation	East-West
Freq Channels	1024 (binned to 81)
Obs. Start	11-12-2024
Obs. End	29-12-2024
No. of full observing days	17
No. of Vis products	10
Analysed Vis product	(1,3) Inter-dish Copol



Solar transit to map the beam

Beam squint and width

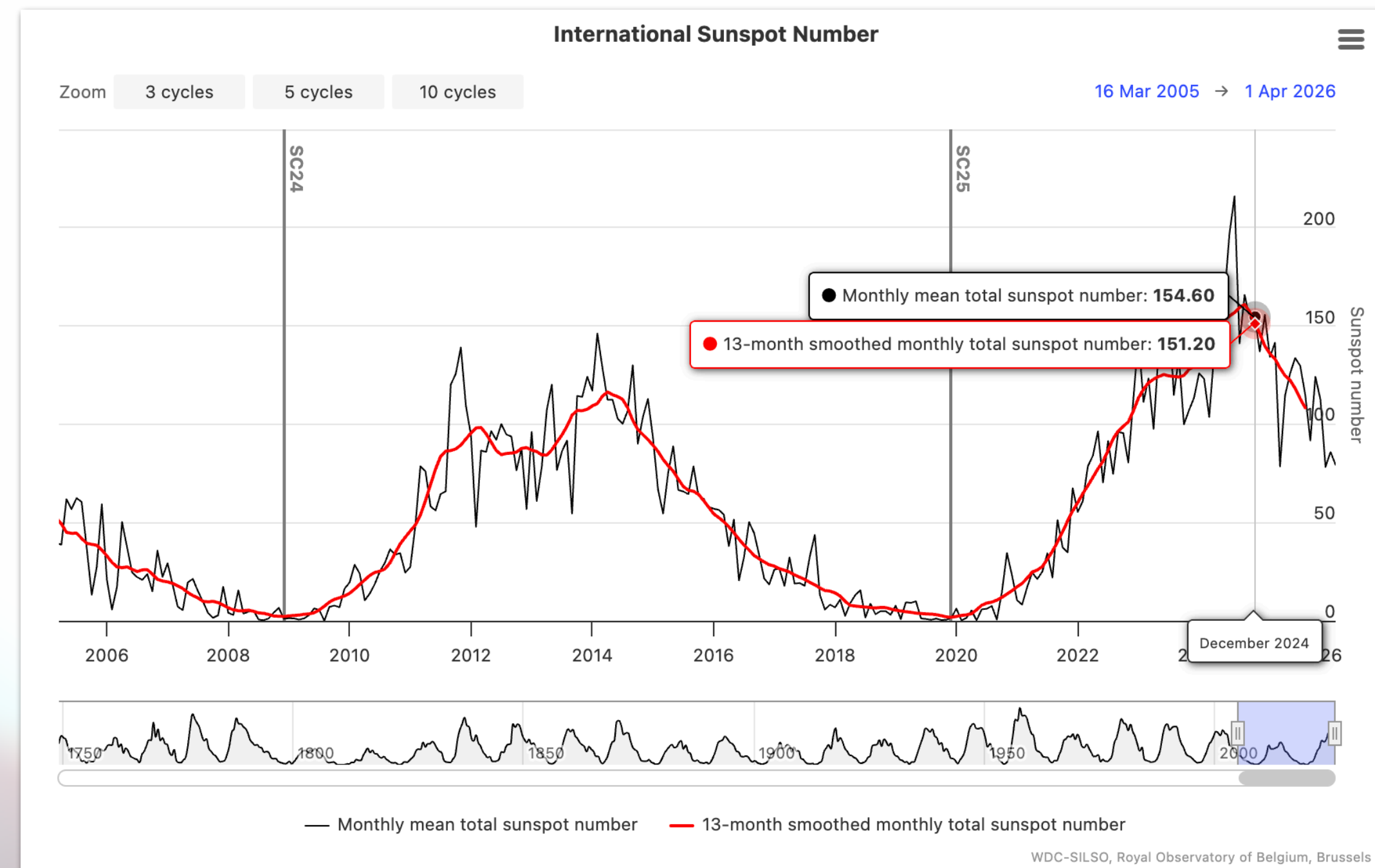
- Based on the solar path relative to the telescope location and pointing, we can map the positions to the beam angular coordinates.
- And get some basic instrumental properties out of it.



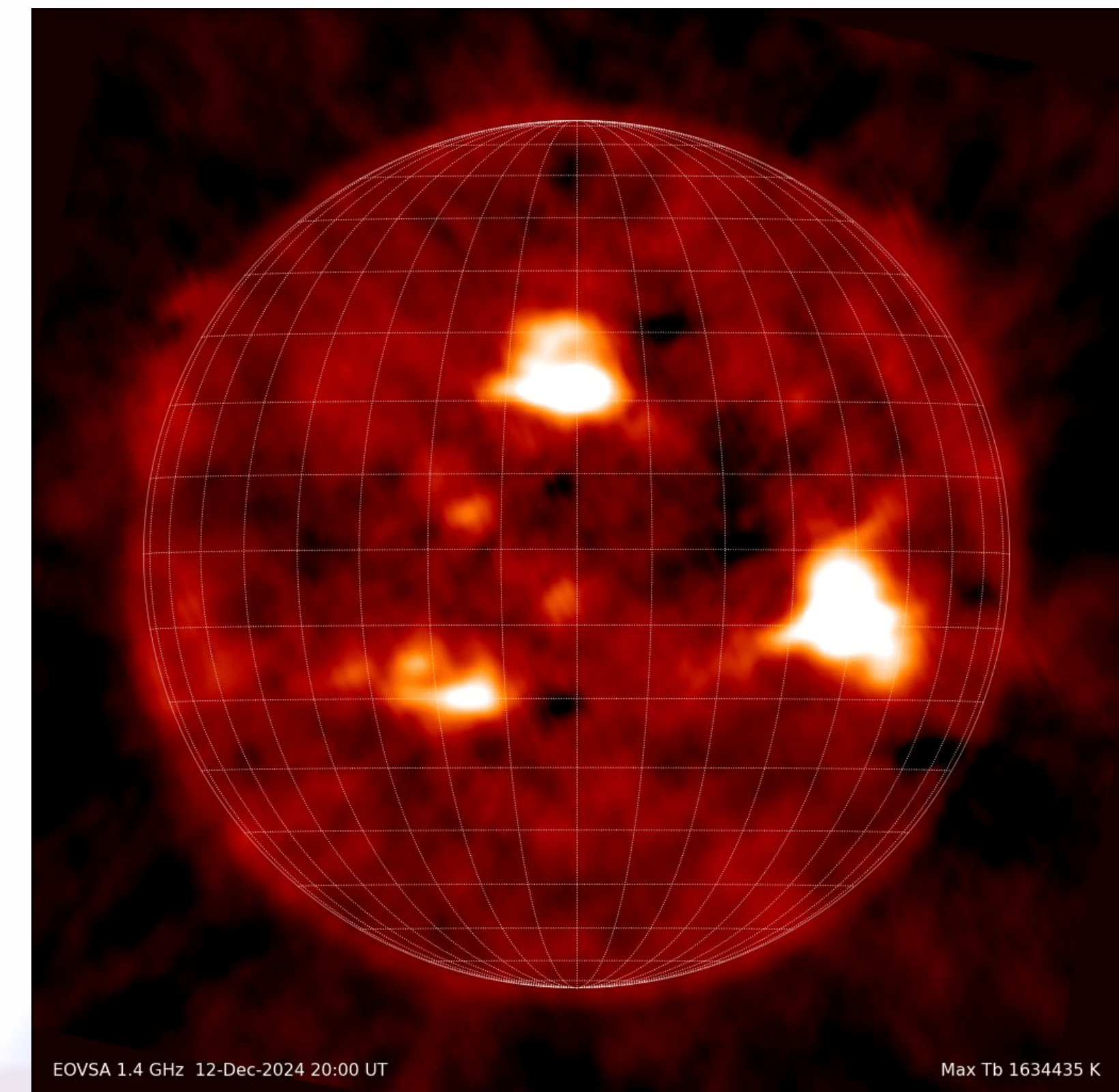
Solar transit to map the beam

Solar activity during Dec 2024

- But active radio emissions which are non-thermal in nature, during solar high can be utilized for this - they act almost as a point source.
- Our few (good) observations happened to be on the time when the solar activity is at its peak.



Solar activity from 11-12-2024 to 29-12-2024 at 1.4GHz

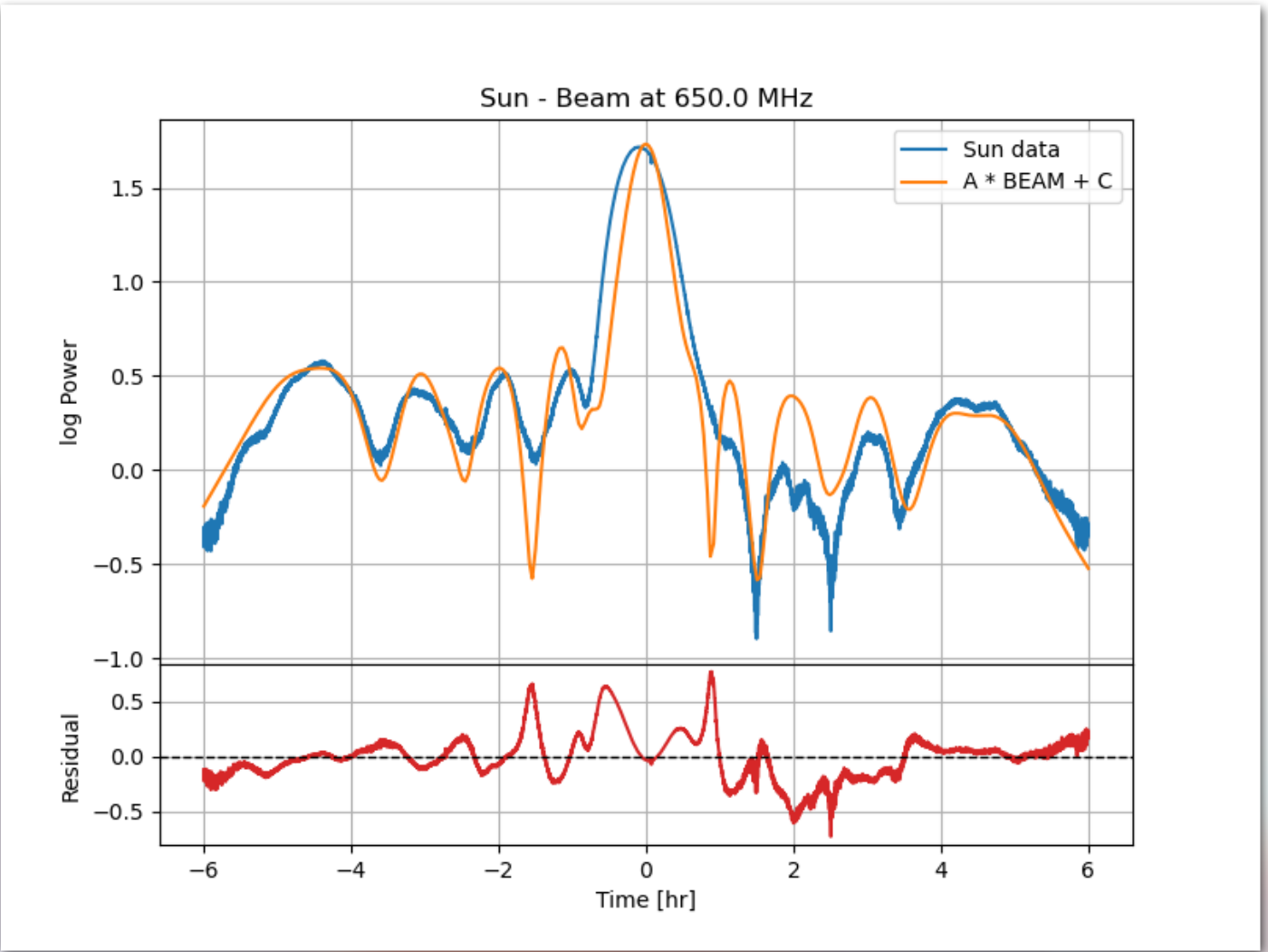
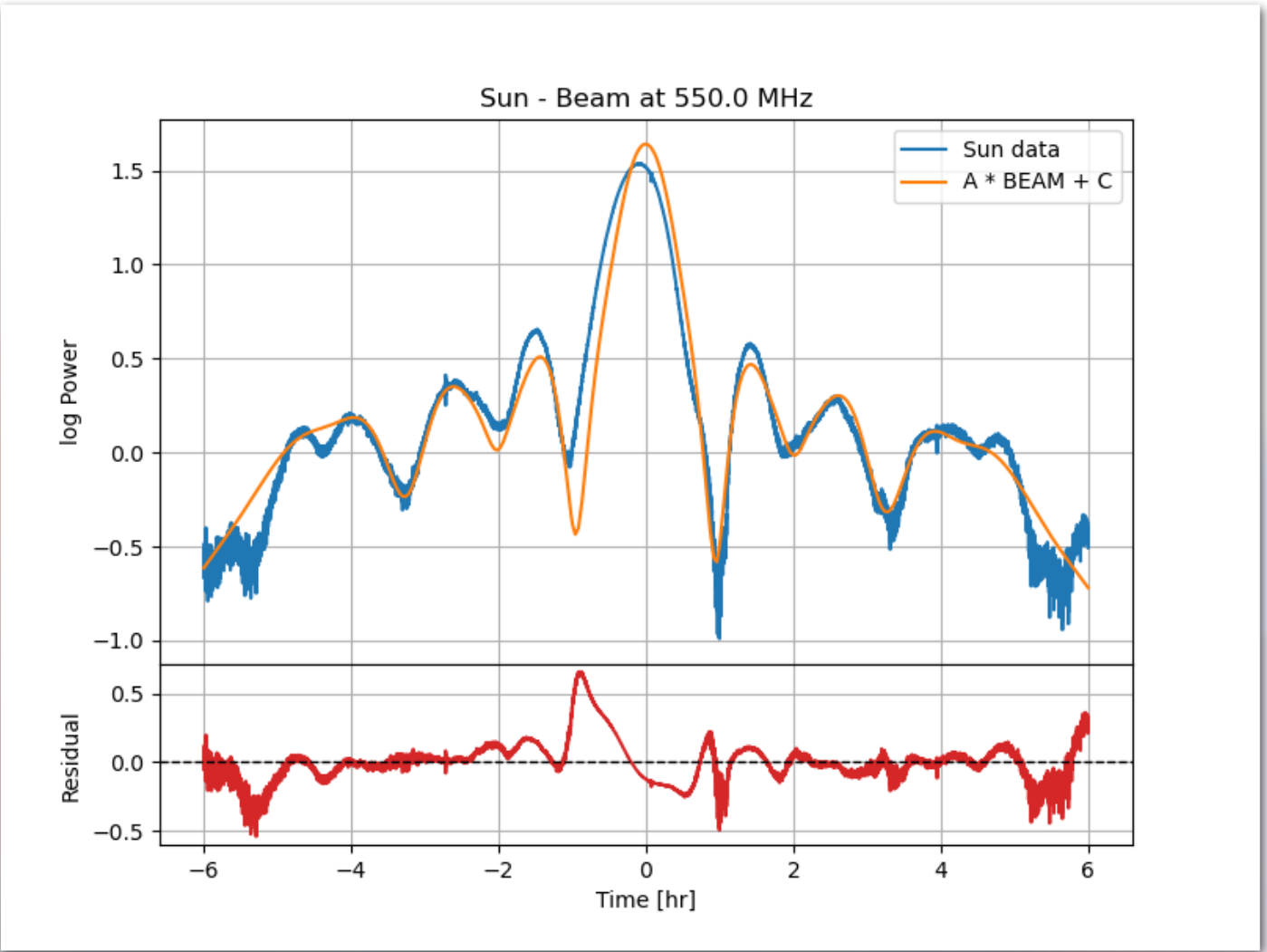
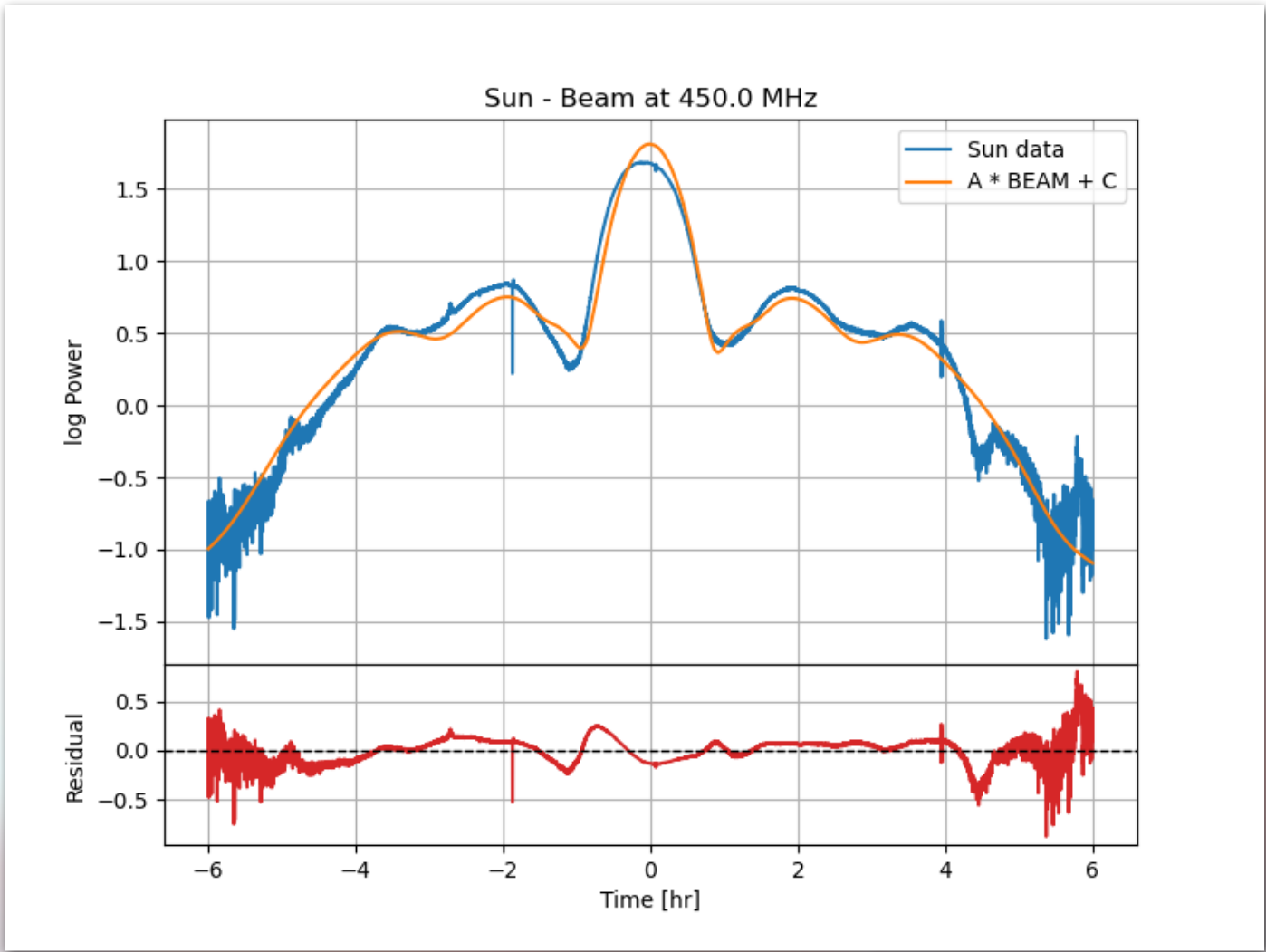
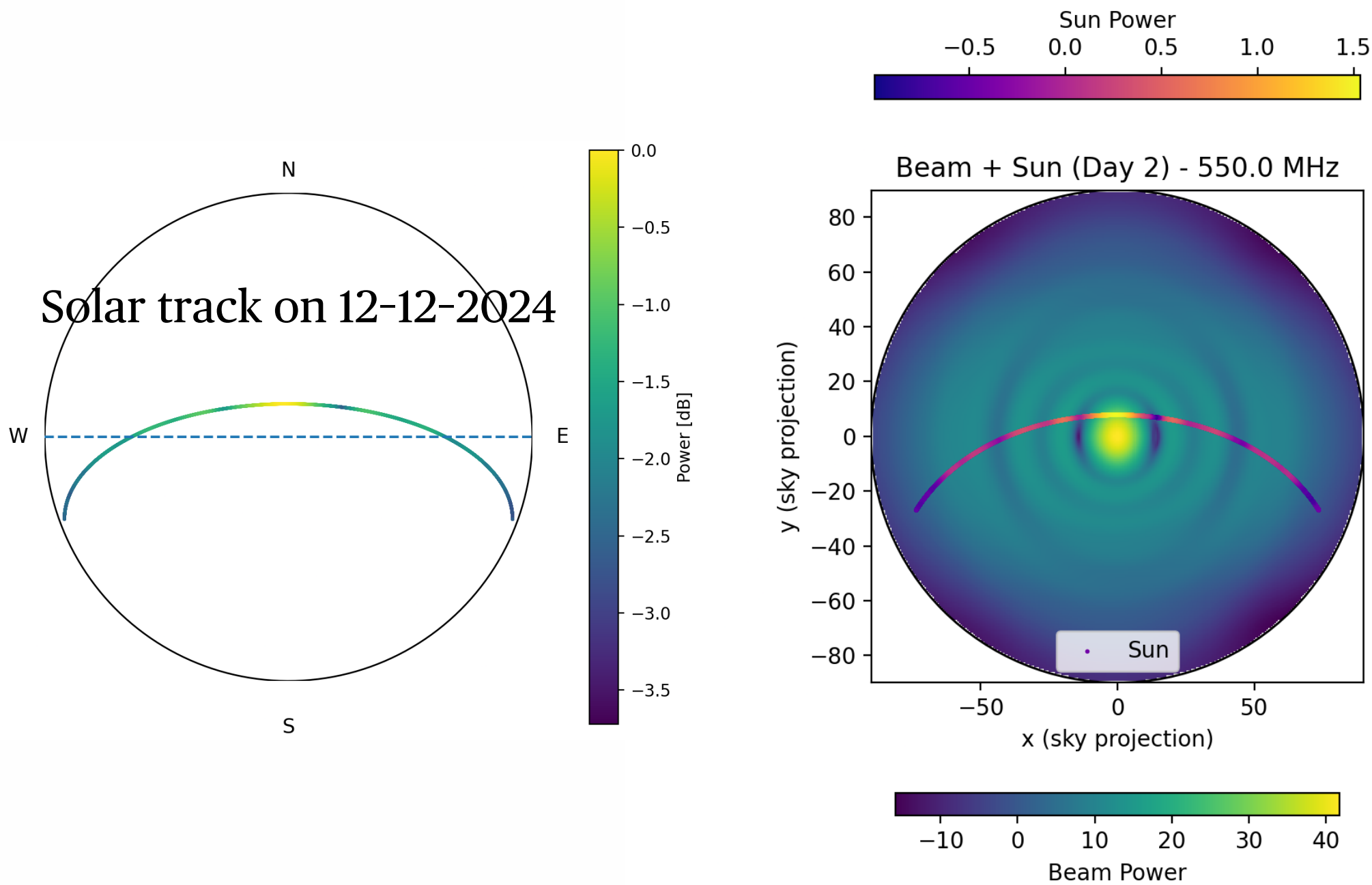


Solar transit to map the beam

Comparison to CST simulated beam

- A simple linear template of simulated beam model (from CST Studio Suite) fitted with the solar track, shows really nice agreement **even for a single day observation**.

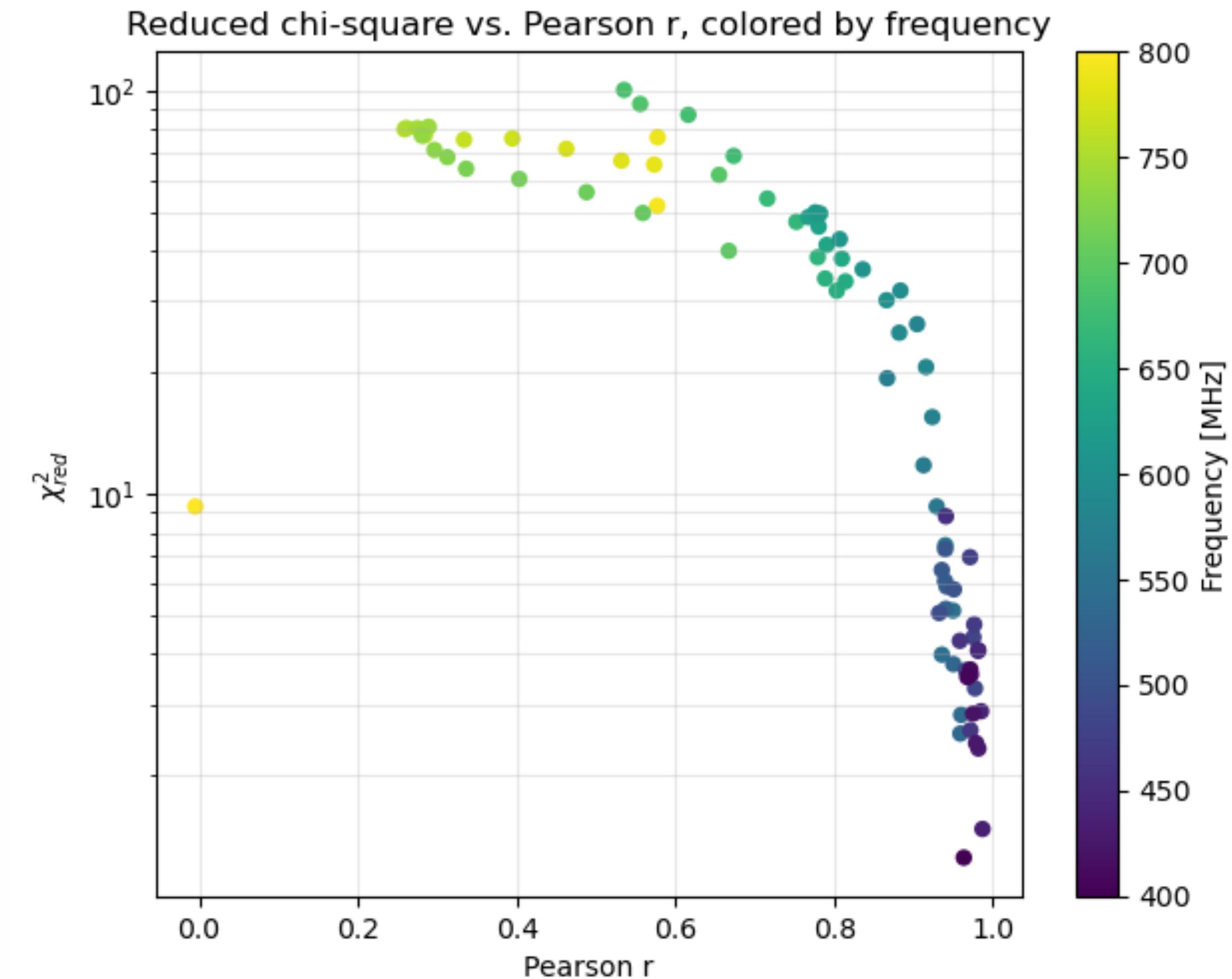
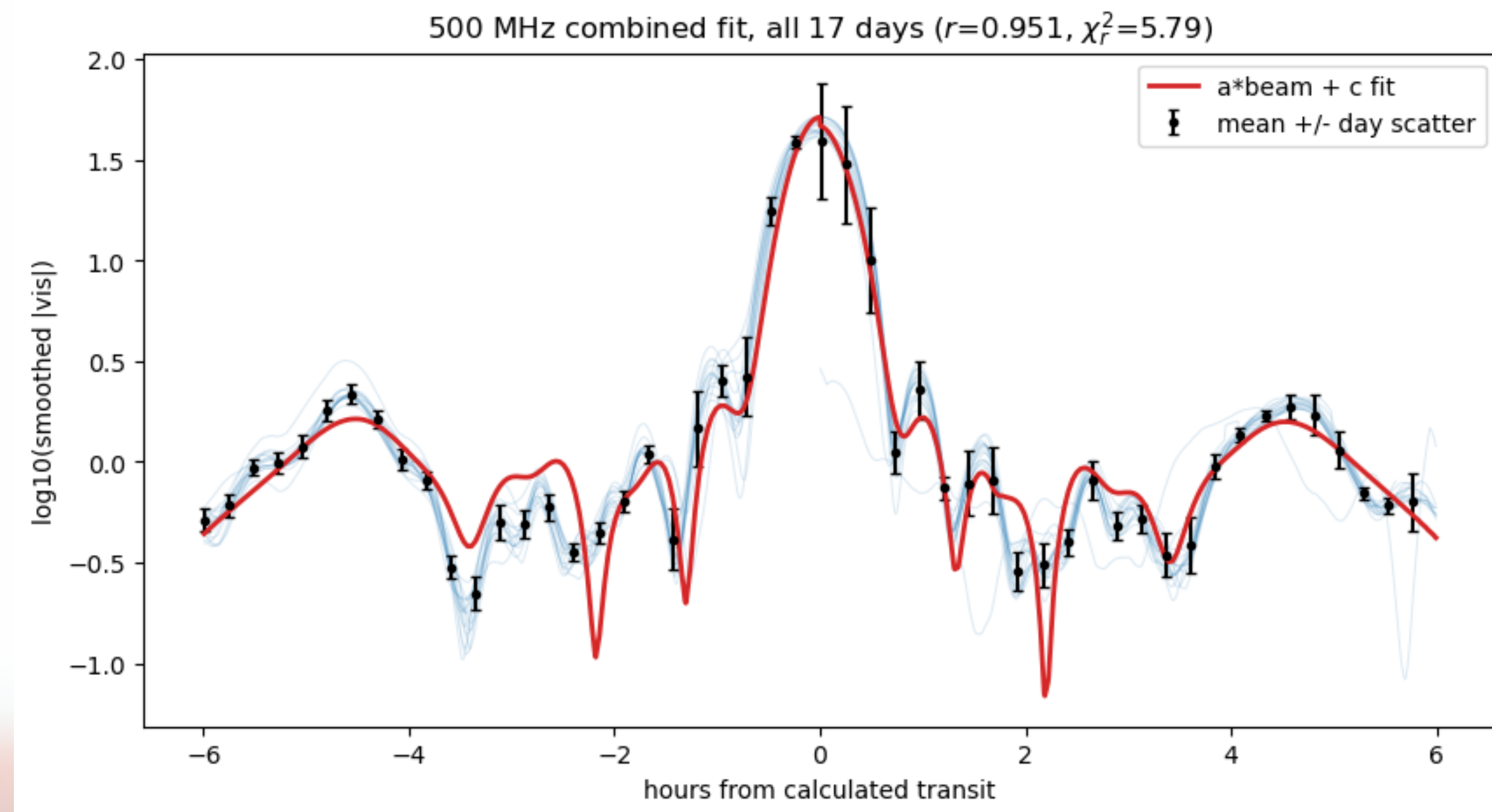
$$B_{\text{sun}} = a * B_{\text{cst}} + c$$



Solar transit to map the beam

Agreement with simulations

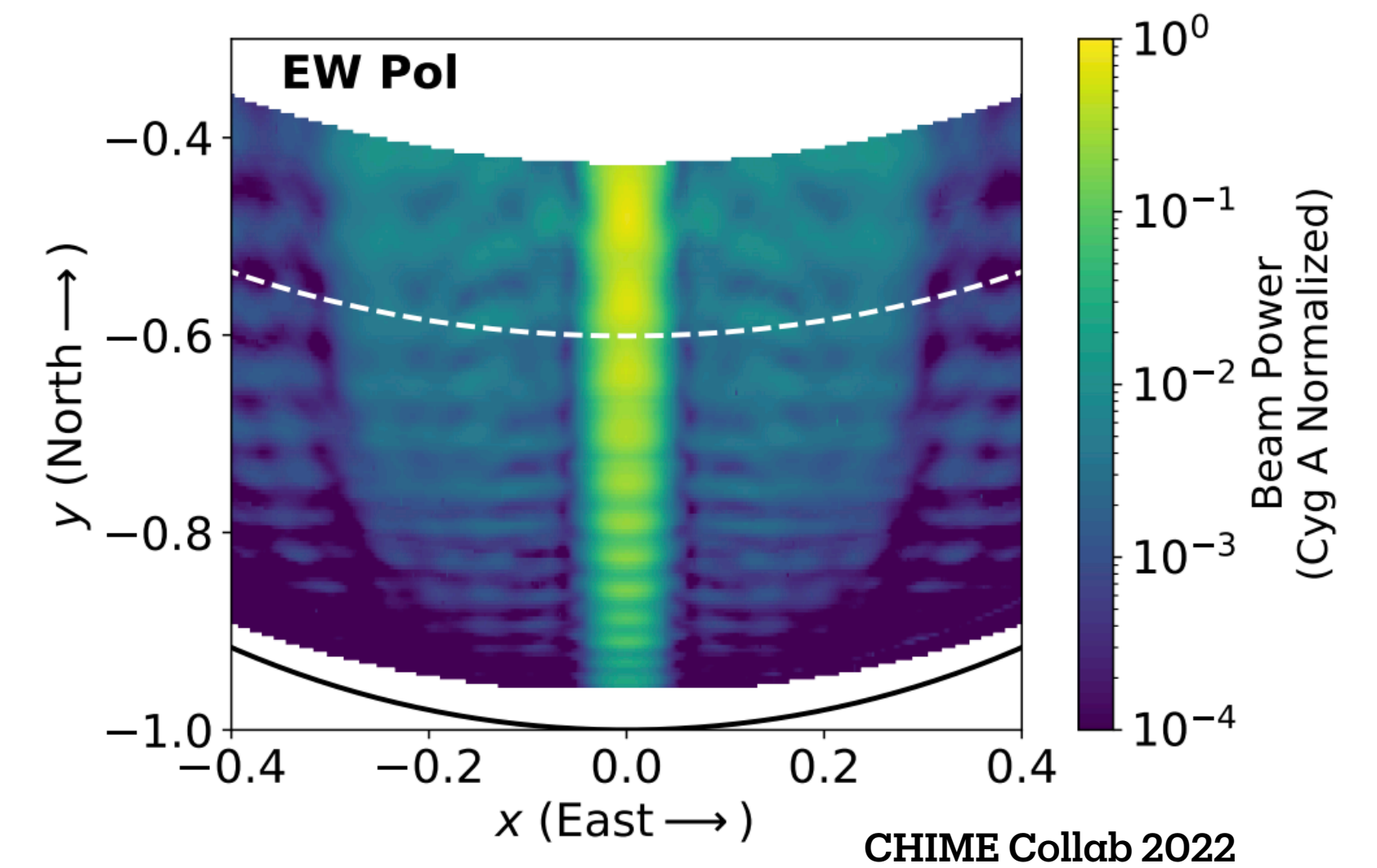
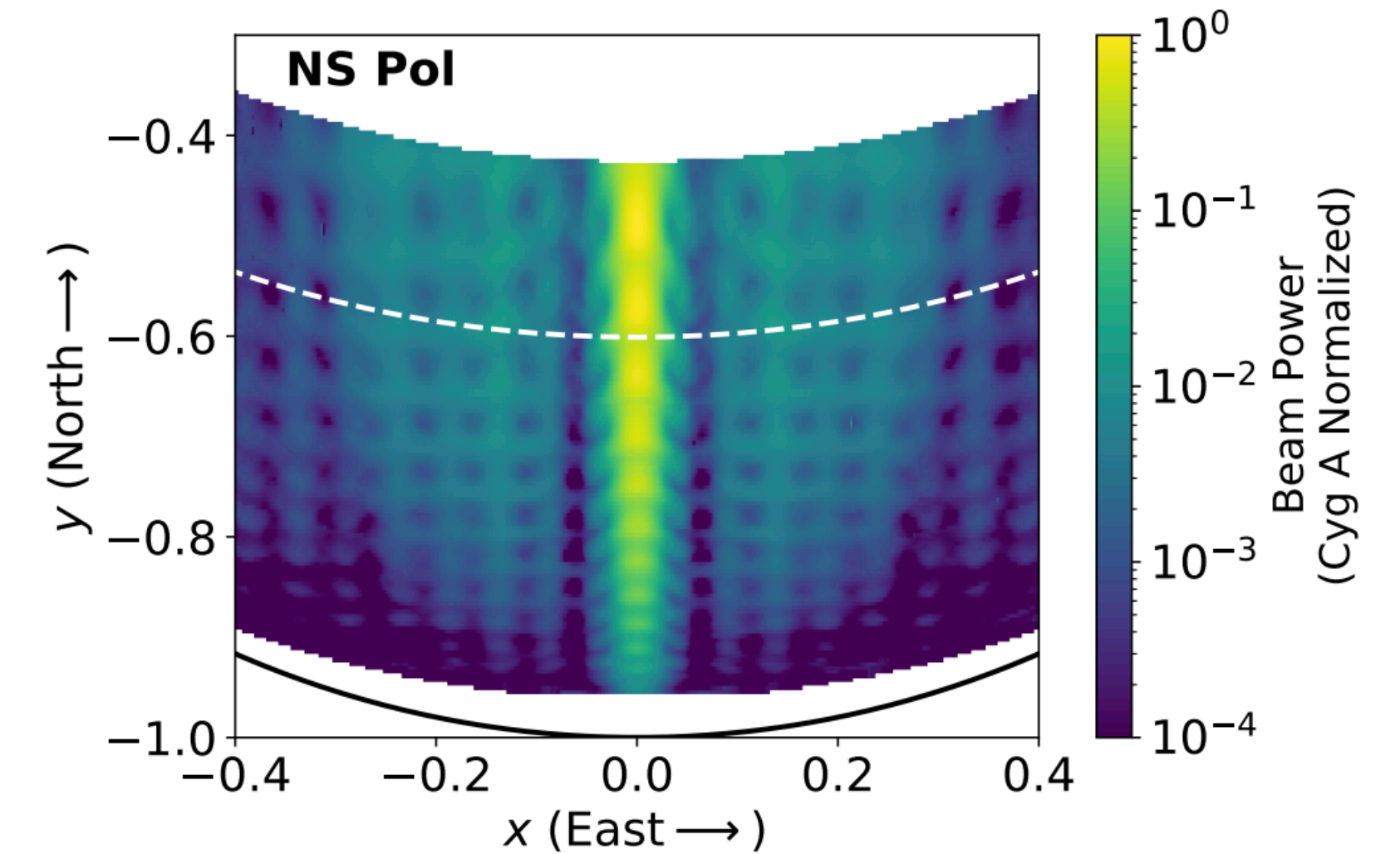
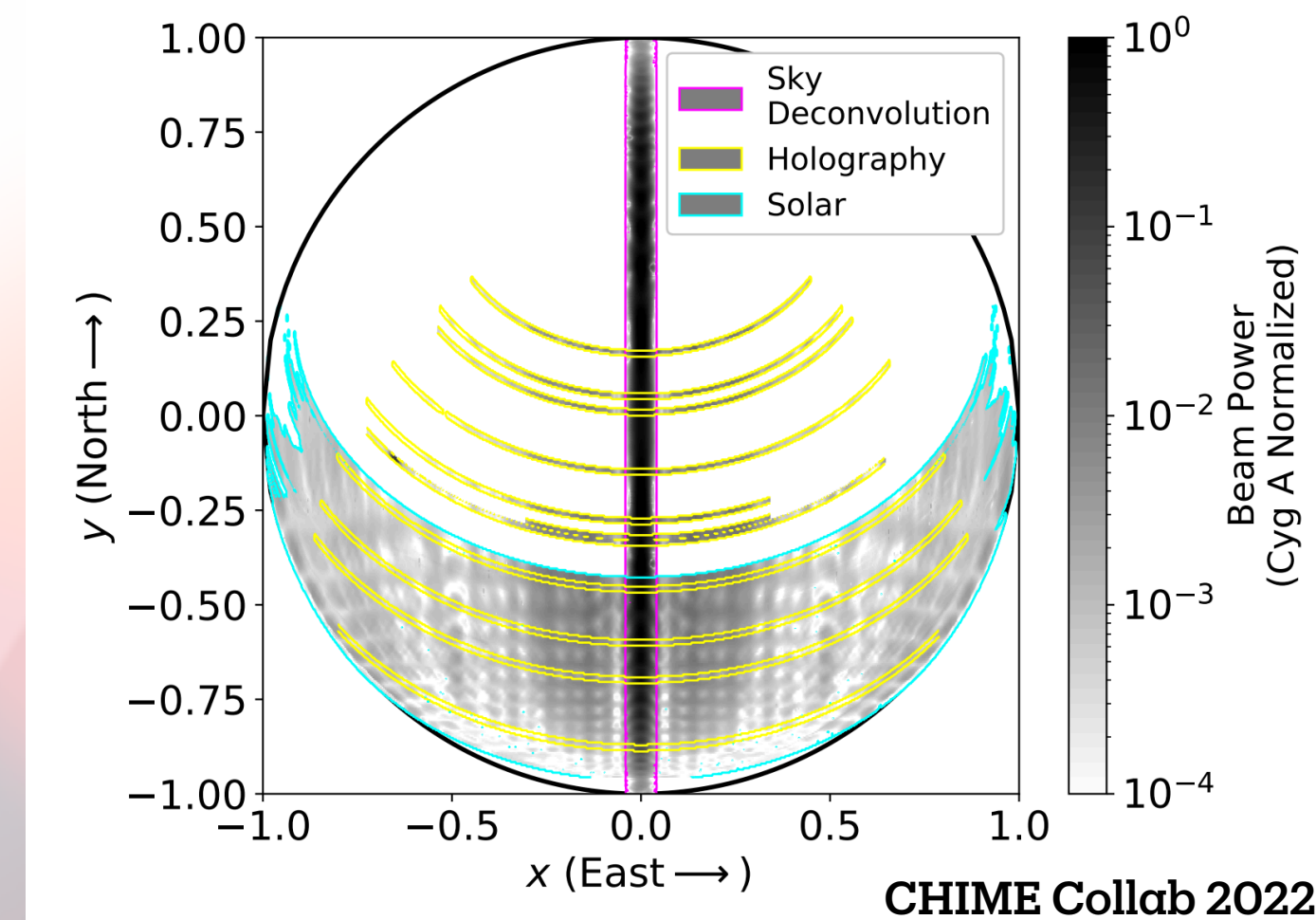
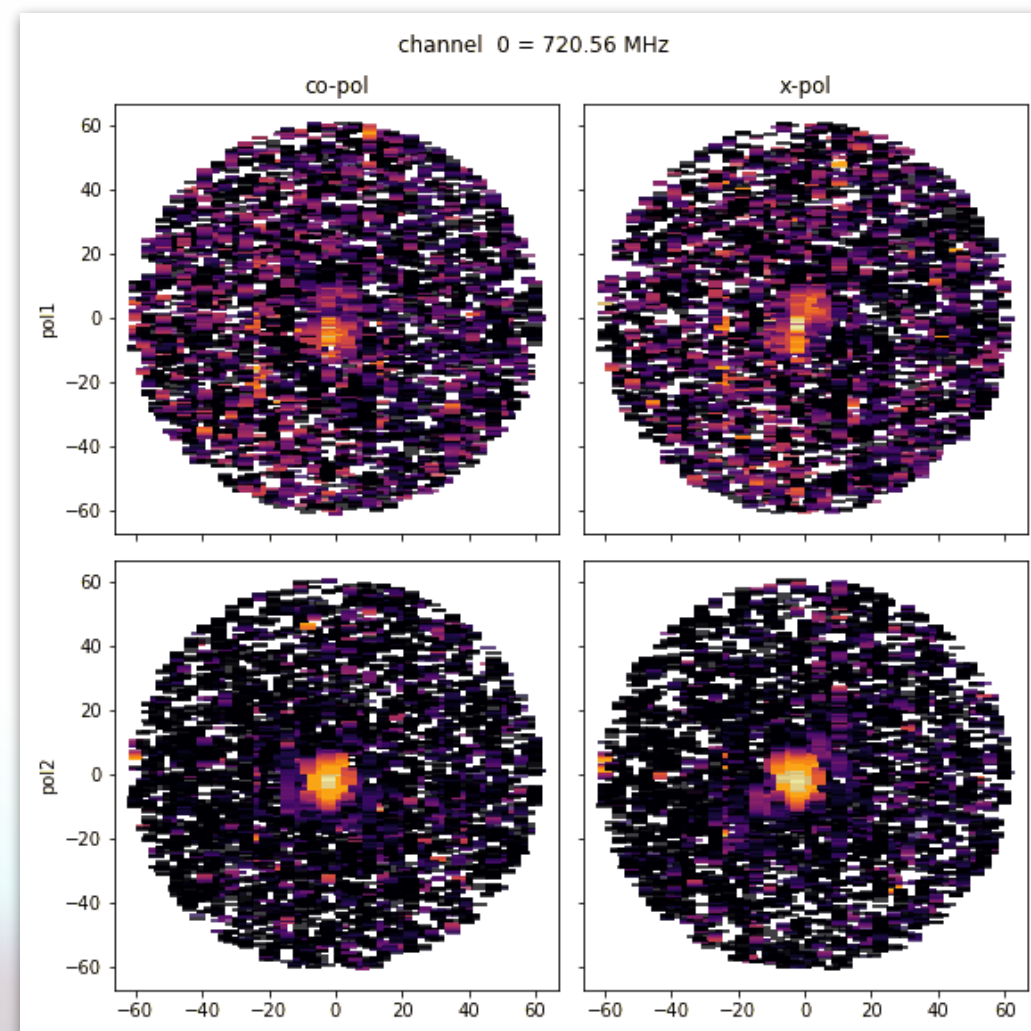
- A combined analysis of all available days of observations are used to build a robust instrument model of the test bed dishes.
- However, the simulated beam model deviates from measured data at higher frequencies.



Solar transit to map the beam

2D beam mapping next

- To build the 2-dimensional model we would need these slices observed over several months.
- A comprehensive primary beam model can be constructed with all the these on-sky, and drone measurements and validated with simulated ones - once the planned drone and observation campaigns are over.

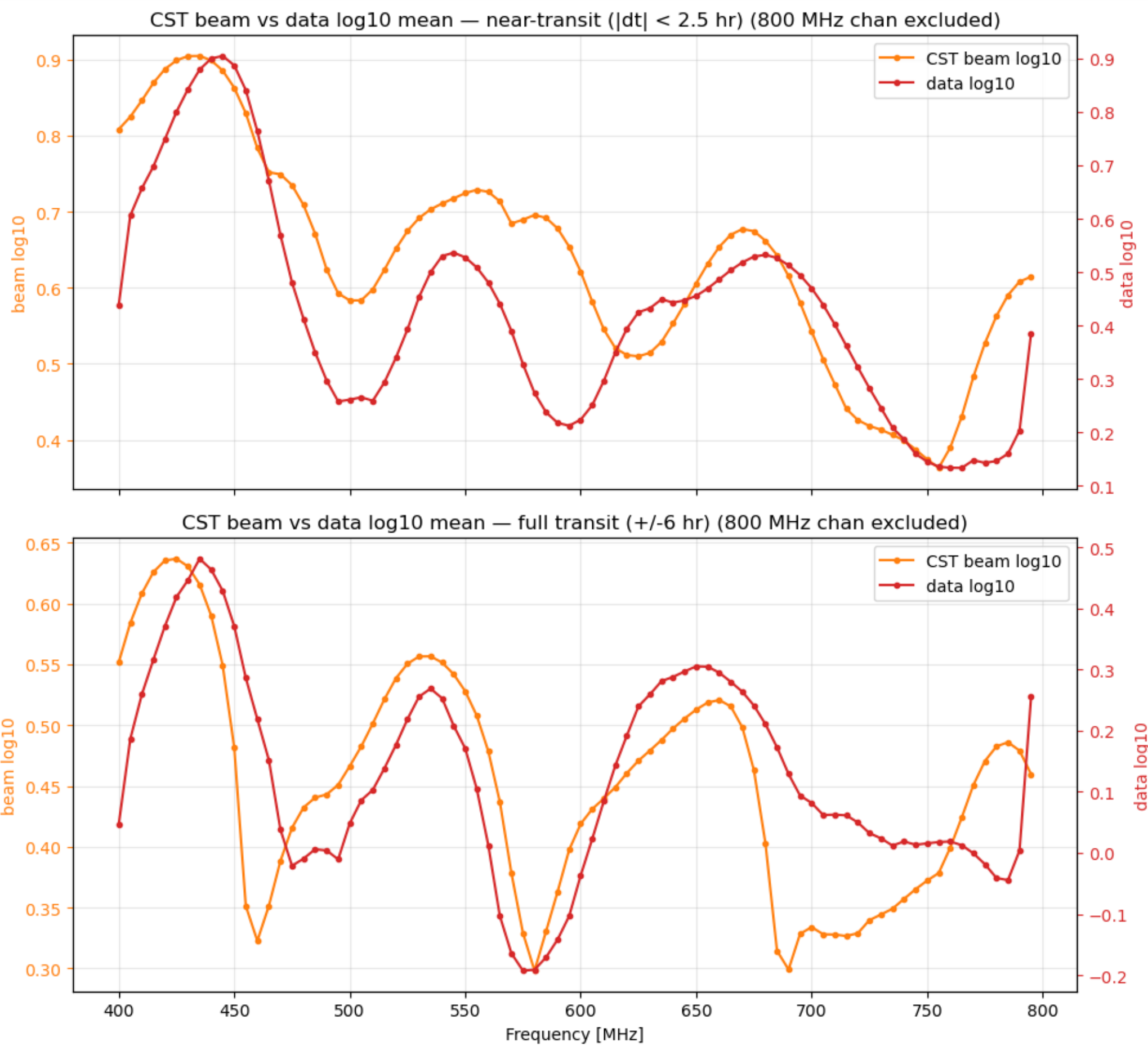
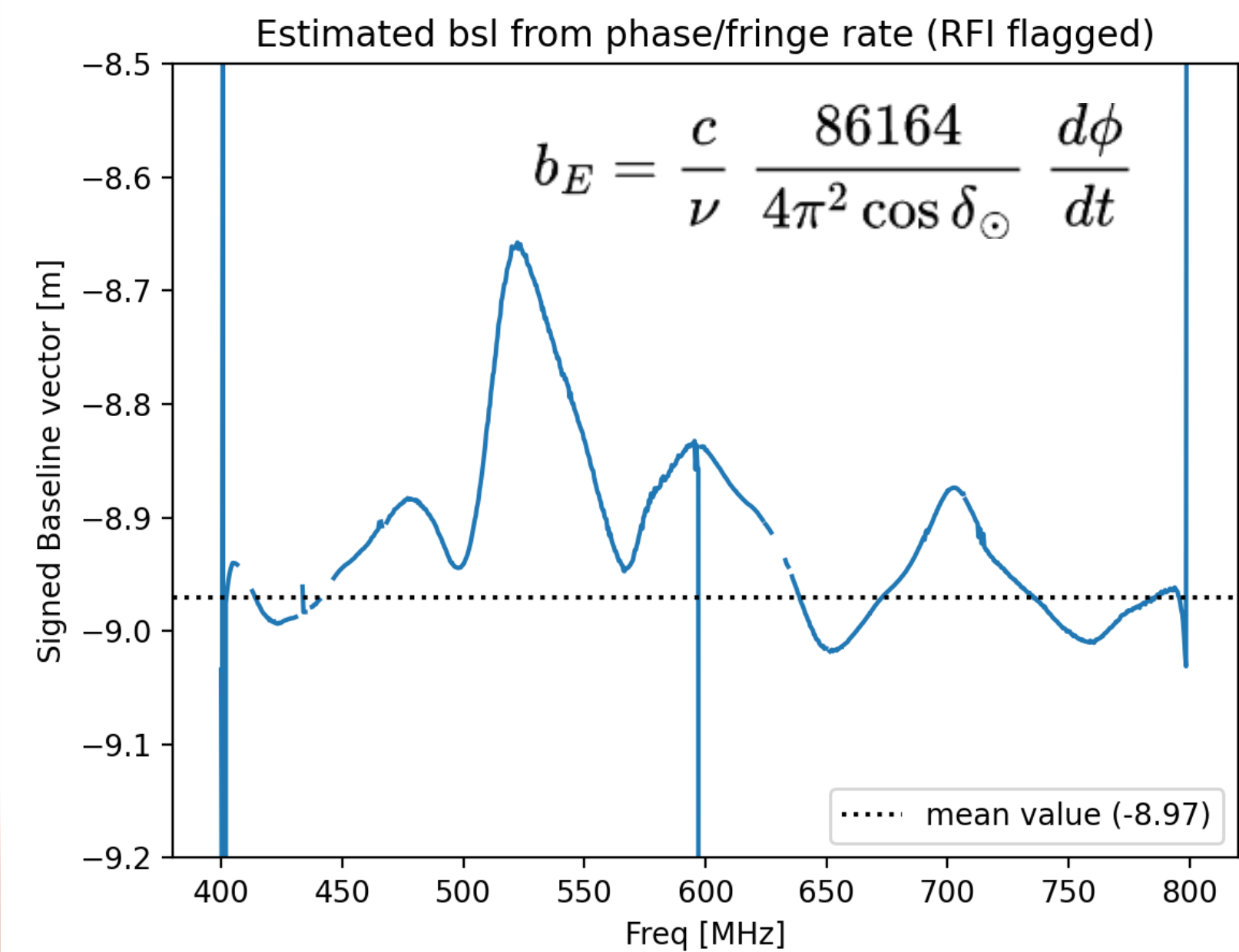


CHIME Cylinder beams mapped with one year of solar transits

Solar transit - other inferences

Direction independent chromaticity

- Apart from mapping the beam, these observations show clear consistencies with simulations on direction independent estimates too.
- A time-average also shows a pattern well matched with simulations for both full data/track and around transit time.
- A baseline estimate shows absorbed chromaticity (evaluated during transit time)



HIRAX - Current Status

Deployment phase

- 32 element core is now deployed - with 5 other elements in the outskirts of the planned Phase I deployment (128 element array)
- Only 2 of them are instrumented through a "suitcase interferometer" for first tests.



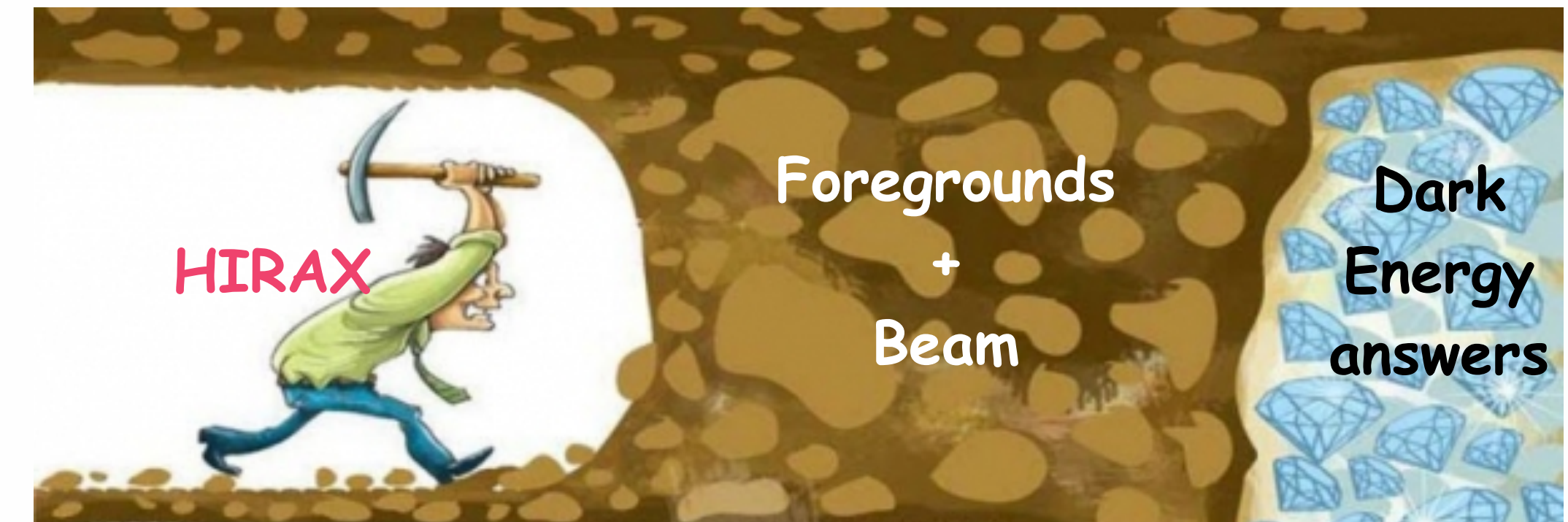
Suitcase Interferometer

A1 (D0003)	B1 (D0012)	C1 (D0007)	D1 (D0011)	E1 (D0013)	F1 (D0014)	G1 (D0016)	H1 (D0023)	I1 (D0024)	J1	K1	L1	M1	N1	O1	P1 (D0004)
A2 (D0025)	B2 (D0021)	C2 (D0020)	D2 (D0017)	E2 (D0015)	F2 (D0018)	G2 (D0008)	H2 (D0019)	I2	J2	K2	L2	M2	N2	O2	P2
A3 (D0022)	B3 (D0026)	C3 (D0028)	D3 (D0030)	E3 (D0032)	F3 (0034)	G3 (0037)	H3 (0039)	I3	J3	K3	L3	M3	N3	O3	P3
A4 (D0010)	B4 (D0027)	C4 (D0031)	D4 (D0029)	E4 (D0033)	F4 (0035)	G4 (0038)	H4 (0036)	I4	J4	K4	L4	M4	N4	O4	P4
A5	B5	C5	D5	E5	F5	G5	H5	I5	J5	K5	L5	M5	N5	O5	P5
A6	B6	C6	D6	E6	F6	G6	H6	I6	J6	K6	L6	M6	N6	O6	P6
A7	B7	C7	D7	E7	F7	G7	H7	I7	J7	K7	L7	M7	N7	O7	P7
A8 (D0005)	B8	C8	D8	E8	F8	G8	H8	I8	J8	K8 (D0009)	L8	M8	N8	O8	P8 (D0006)



Summary and future

- 21cm Intensity Mapping with HIRAX looks really promising in solving the Dark Energy mystery.
- But the instrumental systematics coupled with the powerful Foregrounds are in the way.
- We need to control, characterize and disentangle the systematics to recover the valuable HI signal.
- EM simulations, hardware optimizations, Drone beam mapping and Solar beam mapping can reveal the reality of the beams.
- End-to-end propagation of these beam models are underway - along with site development and deployment of the array.
- Lot to look forward to!





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 [ajithsampath](https://github.com/ajithsampath)

 <https://ajithsampath.github.io/>



Thanks for listening!