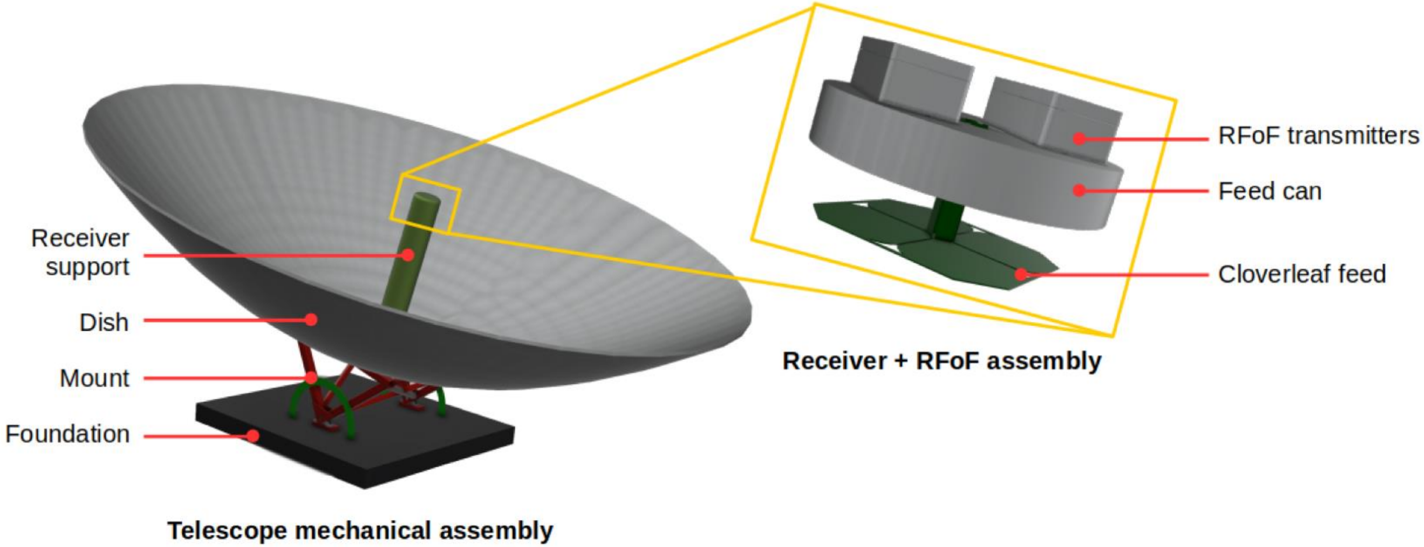

HIRAX Electromagnetic Design
21cm Cosmology Workshop
University of Wisconsin, September 1st 2022
Benjamin Saliwanchik

HIRAX: Who are we? Where are we?

Telescope Mechanical Assembly

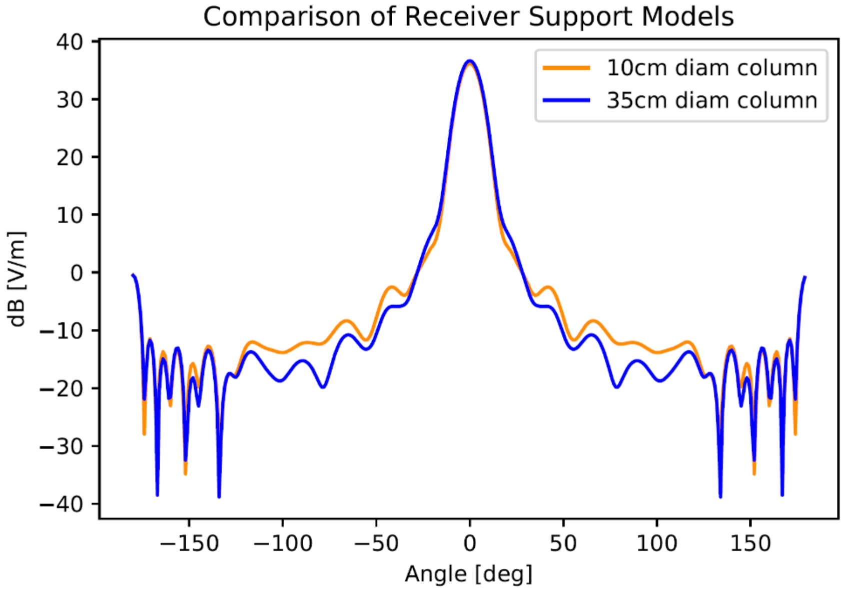
- Low telescope mount improves stability, improves ease of access to feed, reduces cost, still allows necessary +/-30 deg elevation range from zenith
- Simulations say fiberglass receiver column extremely robust: safety factor of 100 and feed displacement <1mm relative to dish under SA record wind speeds
- Easier to position feed, adjust focal point, reduces polarized scattering and beam asymmetry vs feed leg configuration



Receiver Support Structure

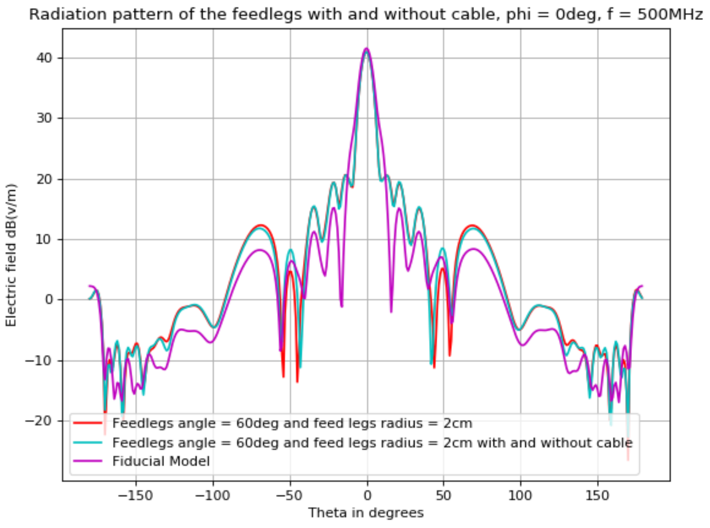
- Different configurations of the receiver support mechanism were simulated, including multiple feed legs, and a central feed column with varying diameter.
- A fiberglass feed column was found to be optimal for RF as well as mechanical criteria.
- Larger diameter feed columns generally have lower loss (less material in forward beam path if diam > feed), sidelobe amp varies with freq but generally lower.

400 MHz

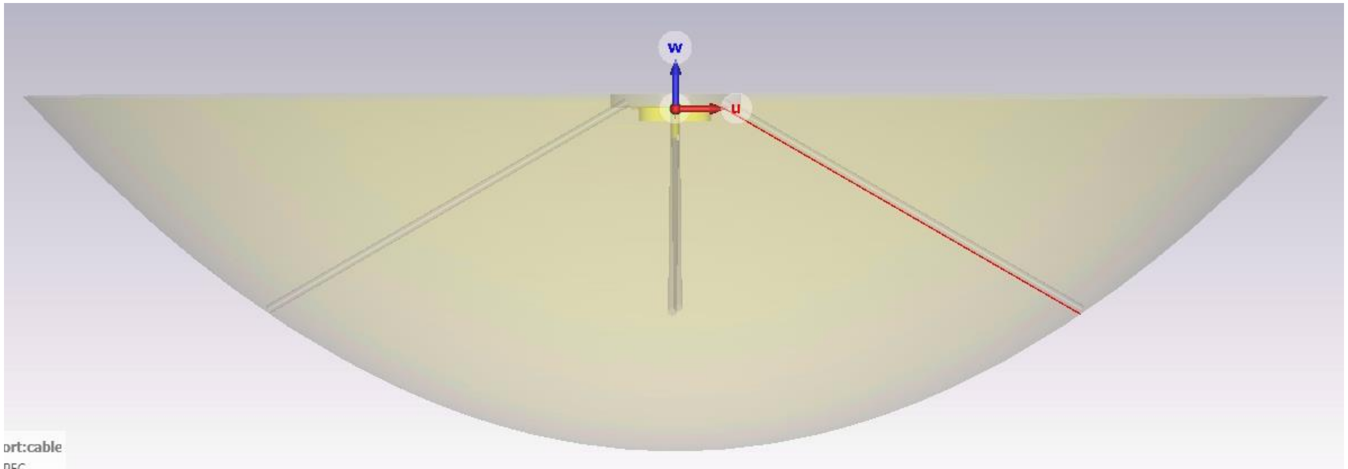


Feed Legs

- However, if you have large feed (possibly Vivaldi) feed legs may be mechanically easier.
- CHORD has selected feed legs, so HIRAX is motivated to use same design for production streamlining.
- Evaluated RF quality of feed leg design: sidelobes several dB worse, but main beam “shelf” eliminated.

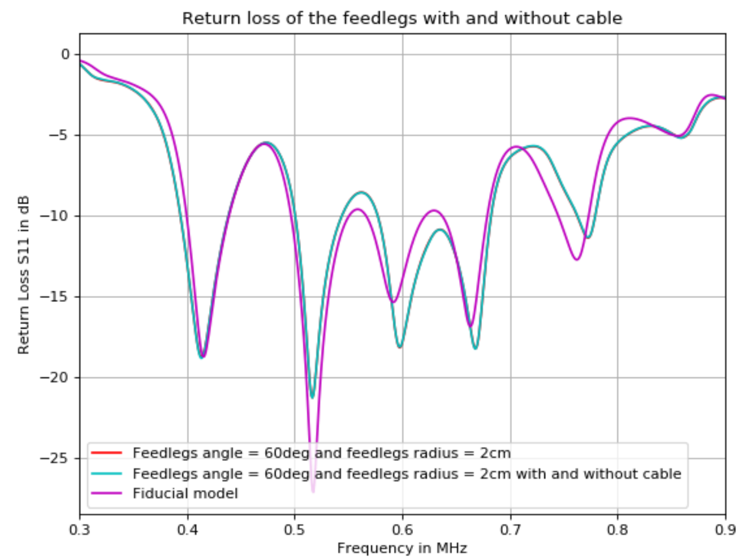


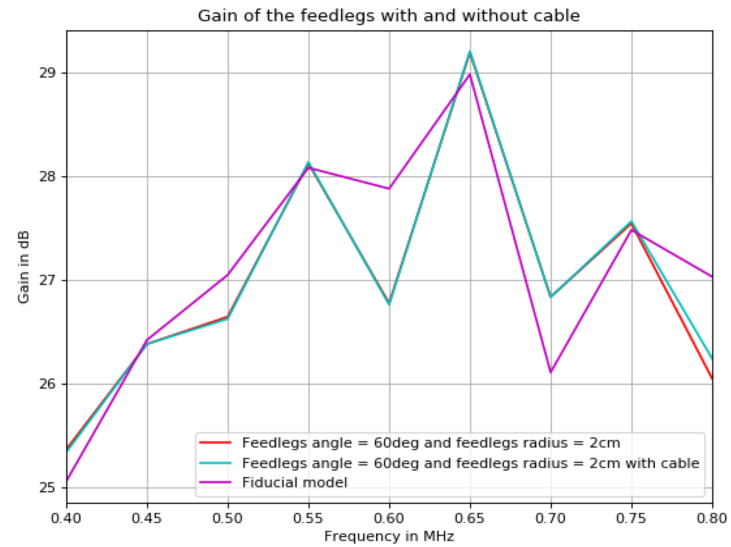
Feed leg sims by Sindhu Gaddam (UKZN)



Feed Legs

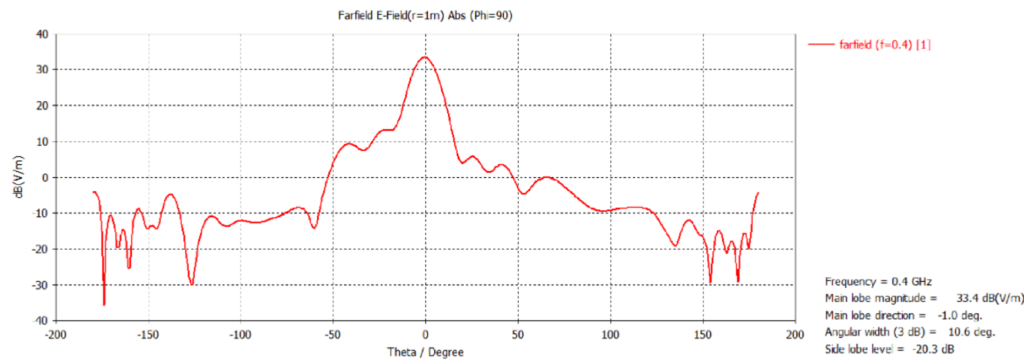
- S11 with feed legs comparable to feed column. ~2dB worse at 550 MHz, ~2dB better at 650 MHz.
- Gain varies across band, but lower for legs on average. Lower by 1dB at 600 MHz and 800Mhz, and higher by <1dB at 700 MHz.
- Most likely HIRAX will follow CHORD design for cost reduction of using existing mechanical design, and of knowledge transfer to SA manufacturer.

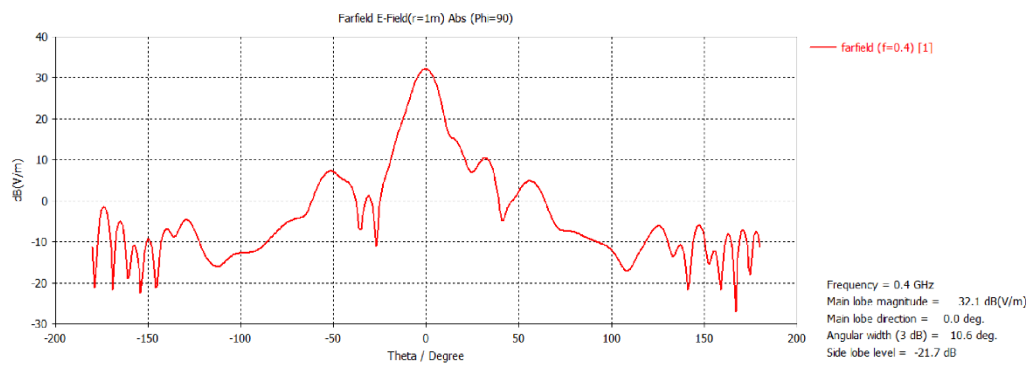


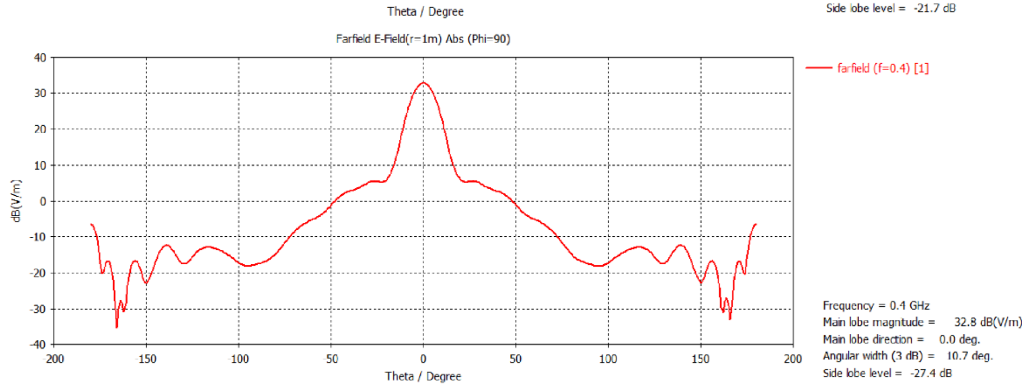


Symmetrizing Cables

- Feed power cabling was found to be a significant source of potential asymmetry in the beam, even for small diam wire.
- Data is on RFoF, not relevant.
- Plots show beams at 400MHz with 15 AWG wire (1.5mm diam) running [top] from feed to dish edge, [middle] from feed to dish vertex 18cm offset from boresight (at column diam), and [bottom] along feed boresight to dish vertex
- Less mechanically convenient with feed legs. Still potential to align cable with vertex, possibly small conduit for protection. Updated EM sims underway to assess impact.

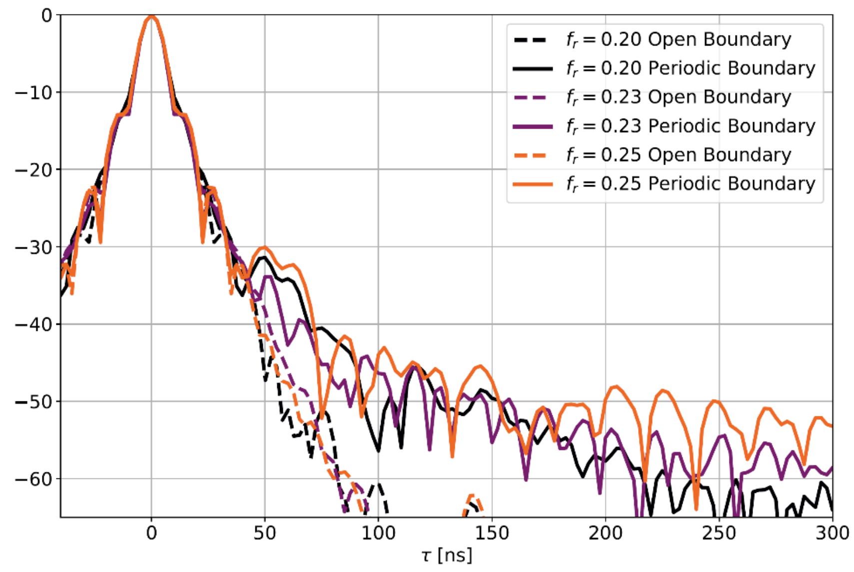






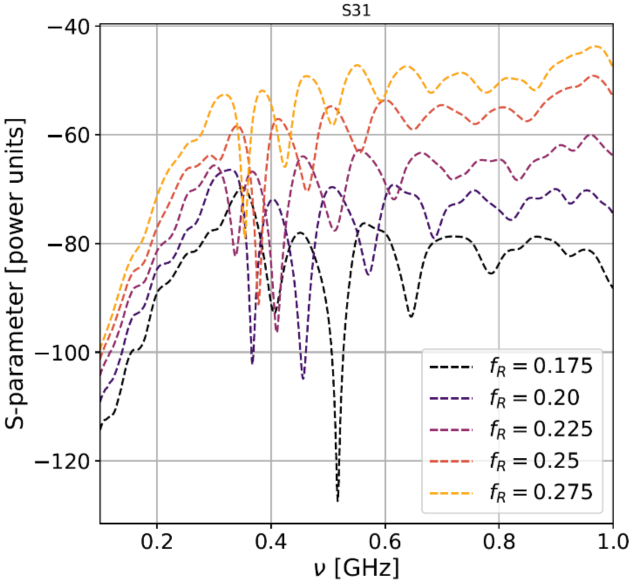
Optimizing Focal Ratio

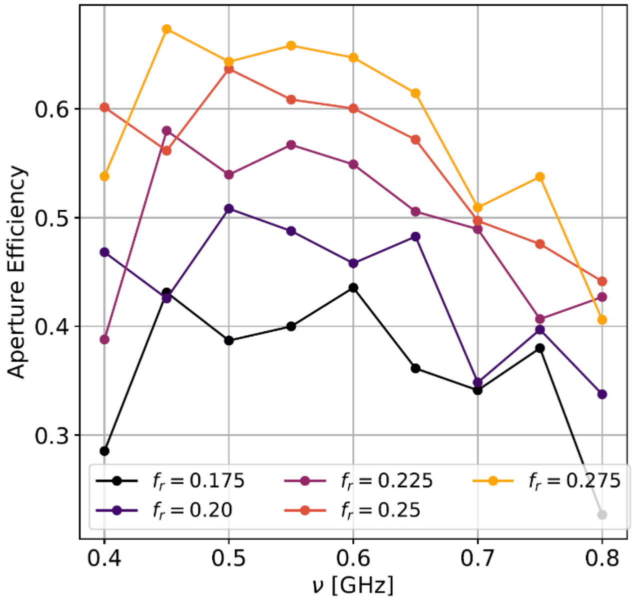
- Also examined dish f-number.
- The instrument delay kernel shows how foregrounds leak from small Fourier modes into large, cosmologically interesting, modes. Want to minimize width.
- Dashed lines show shallower dishes better for single dish, because reduces internal scattering.
- However, in array configuration deeper is better, because it reduces intra-dish scatter.



Optimizing Focal Ratio

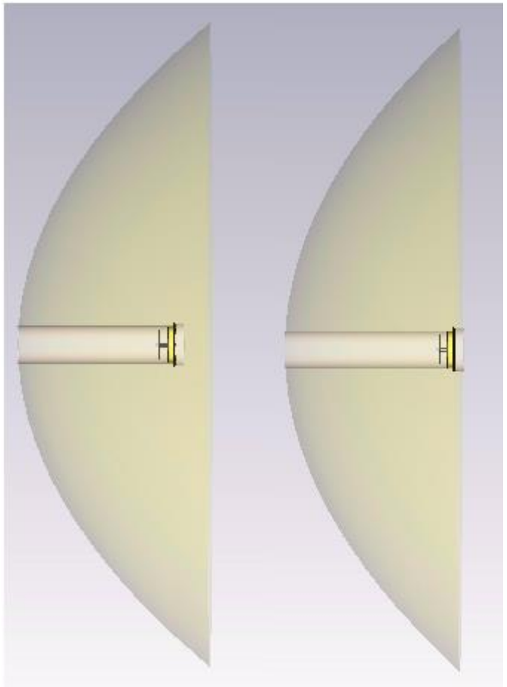
- Crosstalk amplitude (S31) reduced in array with deeper dishes, but aperture efficiency also reduced.
- Lower f/D ratios are also increasingly difficult to mechanically support
- Initially selected f/D = 0.23, which reduces S31 by ~10dB relative to the prior 0.25 design, while only reducing efficiency by ~5%. However, now considering 0.21, which would reduce S31 by ~20dB and efficiency by ~10%. (Some efficiency may be recoverable by feed illumination changes.)



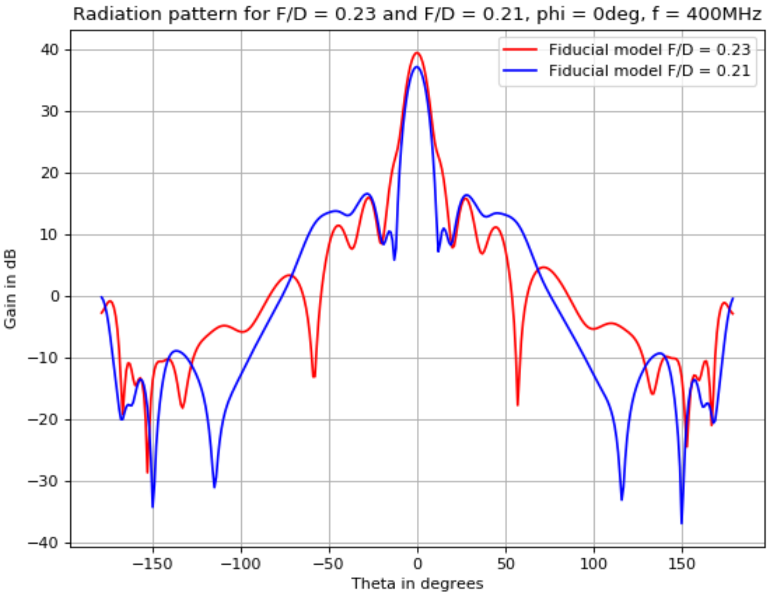


Optimizing Focal Ratio

- With f/D=0.21 entire feed+can structure sits well below dish rim. Significantly reduces crosstalk.
- Gain is also reduced on average, and sidelobes potentially increased.



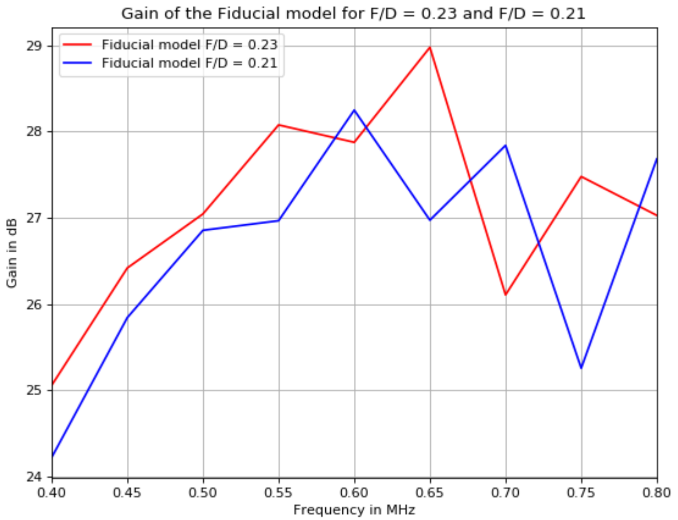
focal ratio 0.21 focal ratio 0.23

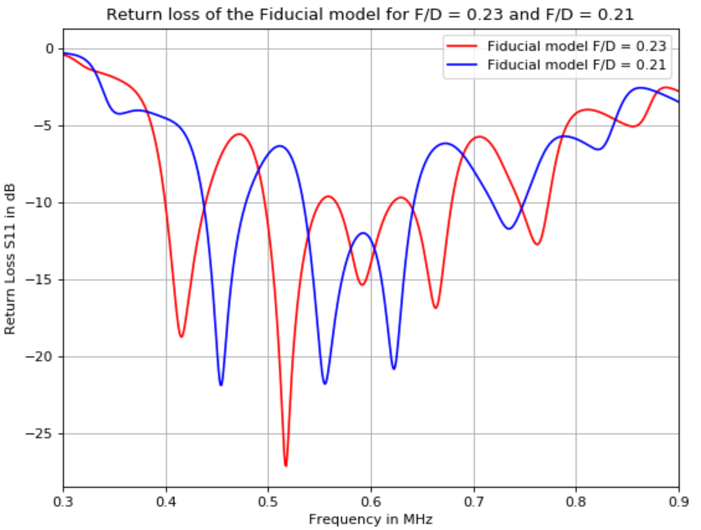


Focal ratio sims by Sindhu Gaddam (UKZN)

Optimizing Focal Ratio

- Gain degraded by 0.55dB on average, 14% reduction in power.
- May be able to recover some sensitivity by changing feed can to illuminate dish better. Sims underway.
- S11comparable. Maybe better in middle of band, ~550-650 MHz.
- Less structure to S11, which might be beneficial.



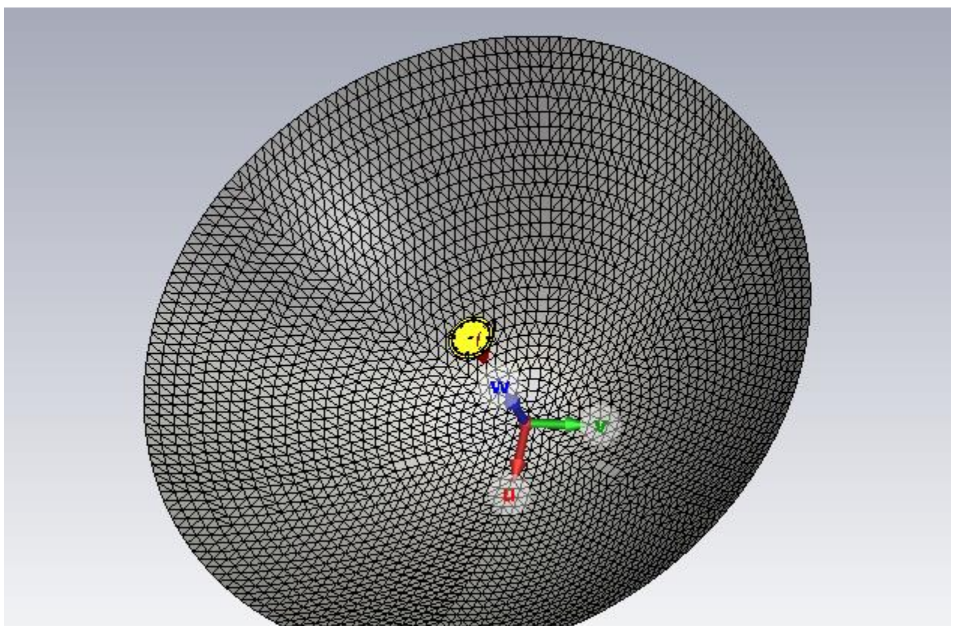


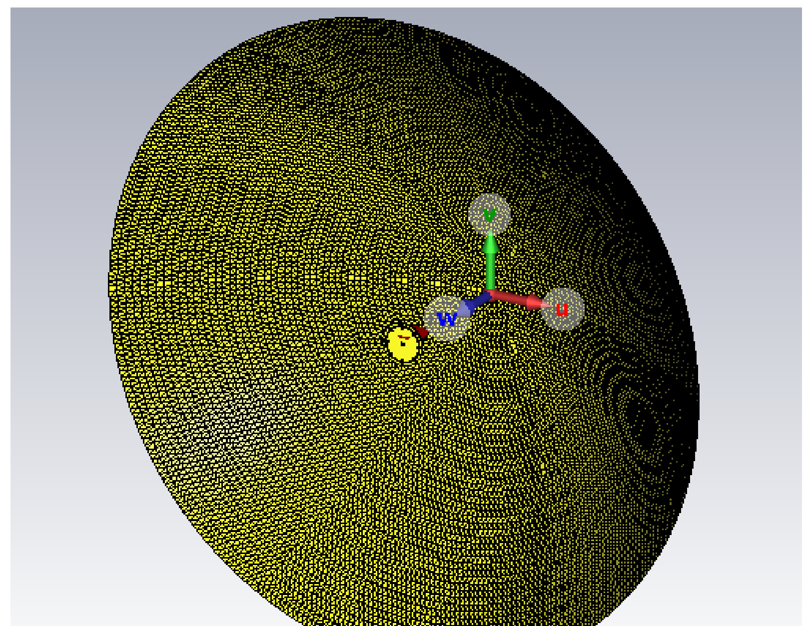
Array Crosstalk Sims with CCA

- Working on new method of simulating crosstalk for full array with Leslie Greengard and staff at the Simons Foundation CCA/CCM.
- Idea is to compute scattering matrix for single array element: response to all possible input waveforms, modeled as planewaves from all directions on sky. Or, at least O(10,000) directions on sky.
- Scattering matrices can be summed “trivially” to get response of whole array.
- Computationally intensive, but we believe tractable.

Simulating Dish Deformations

- Working on procedure for simulating dish deformations in CST.
- Can import dish measurements from photogrammetry, etc. and create dish model including real deformations to assess beams and cosmology impact.
- Working to assess how many facets are necessary.
- Below: 5.6k vs 22.6k triangular equal area facets.

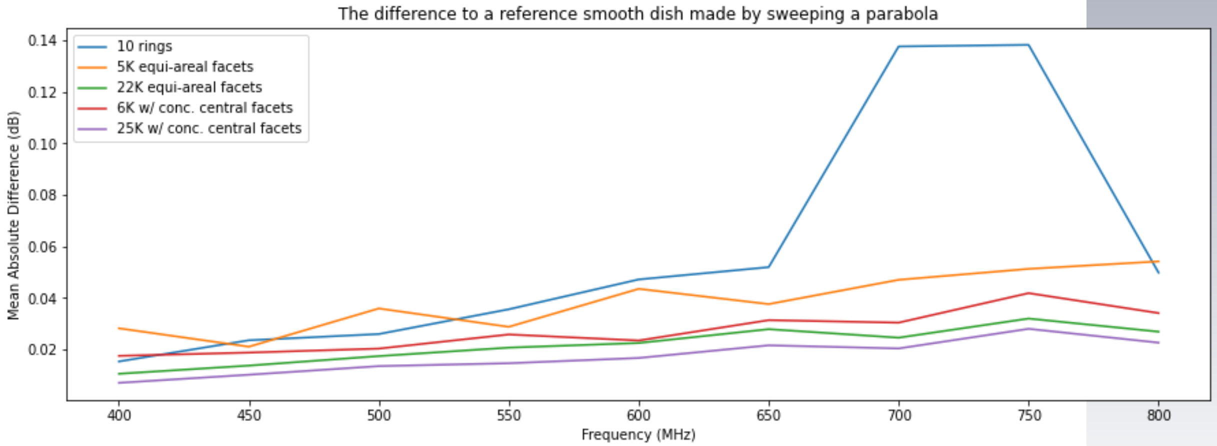


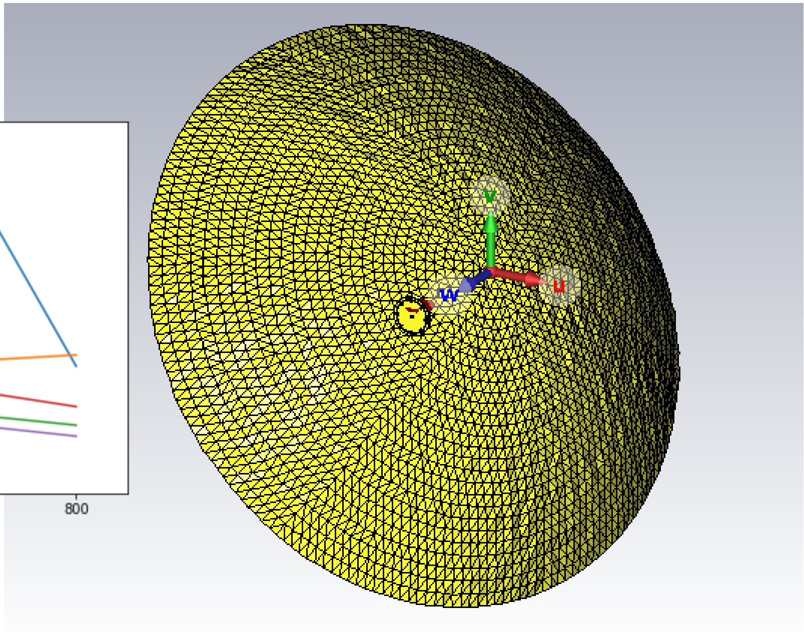


Deformed dish sims by Kit Gerodias (McGill)

Simulating Dish Deformations

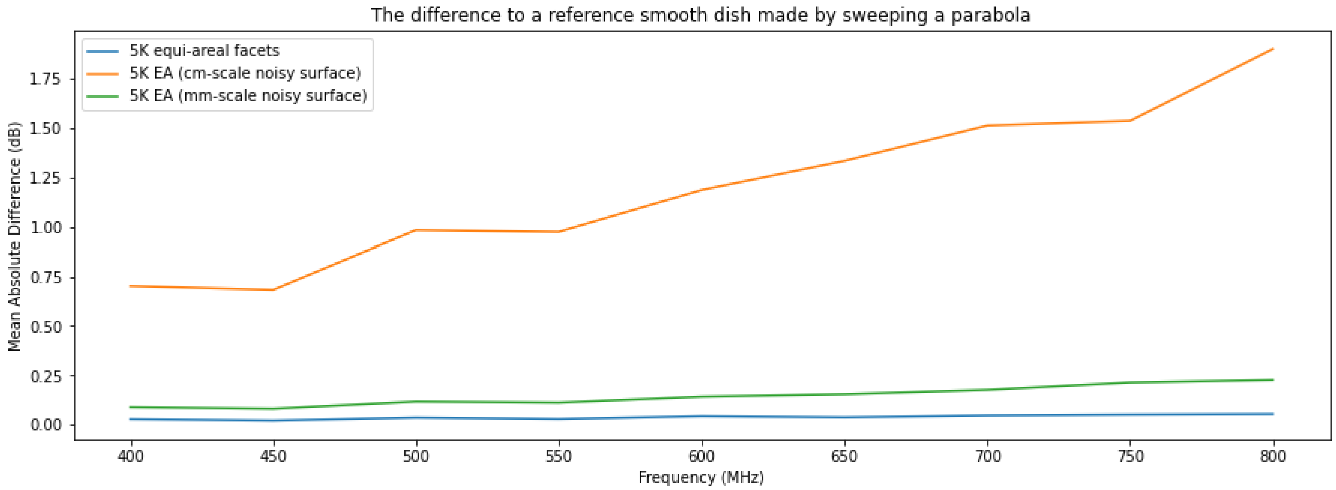
- 5k facets produces beams that differ from the perfect paraboloid by 0.05dB at highest frequencies, averaged across the beam.
- Increasing to 22k facets reduces error to 0.02dB average.
- We can then perturb the dish surface and examine the resulting beams.
- Below is a dish with the w-axis (distance up from vertex) perturbed with RMS 1.5cm. This is very large compared to realistic deformations.



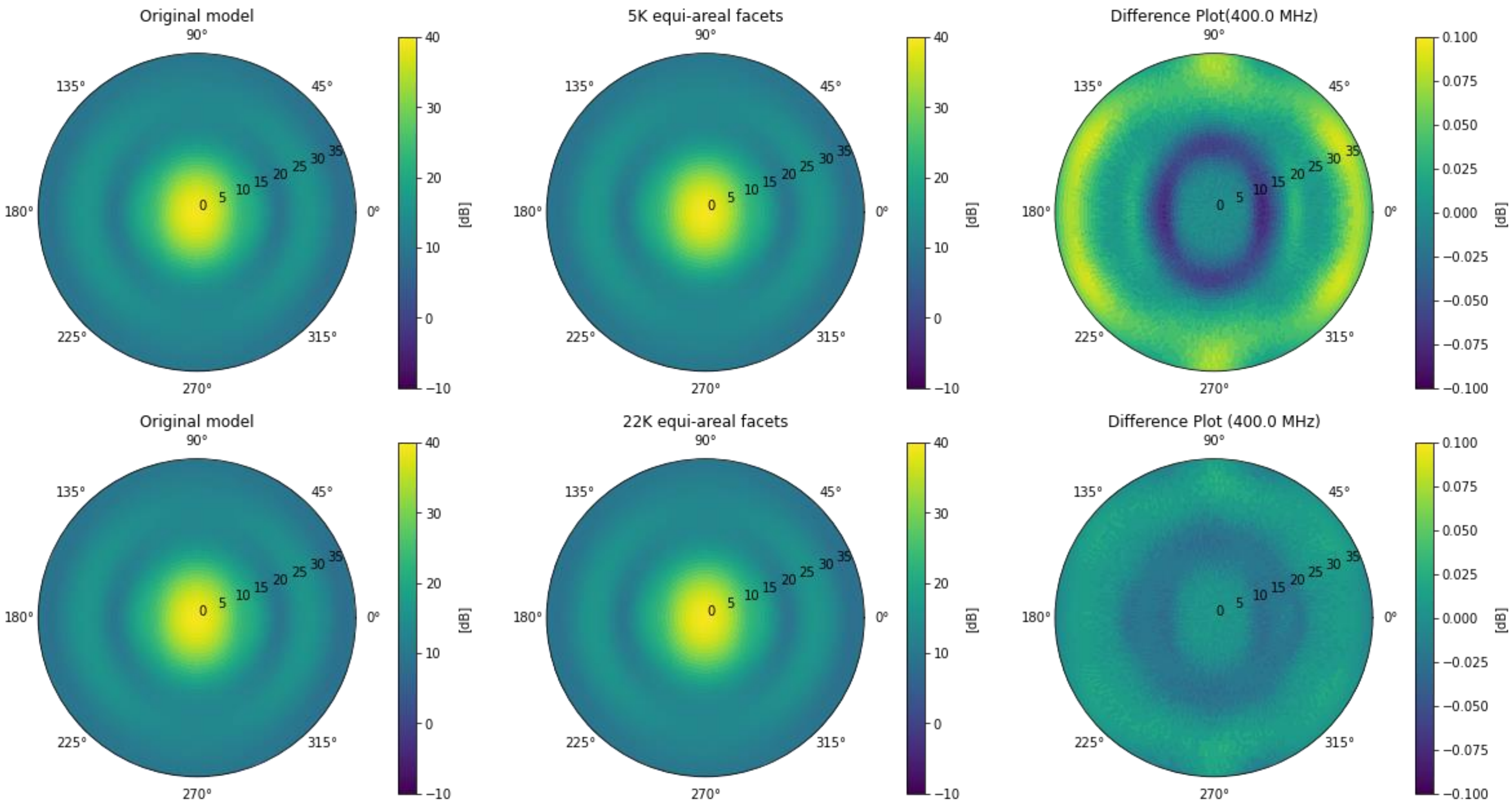


Simulating Dish Deformations

- Effects of deformations can be easily seen in mean difference between beams (below), and in induced spatial structure of beams (following slides).



Faceted Dish vs Perfect Paraboloid



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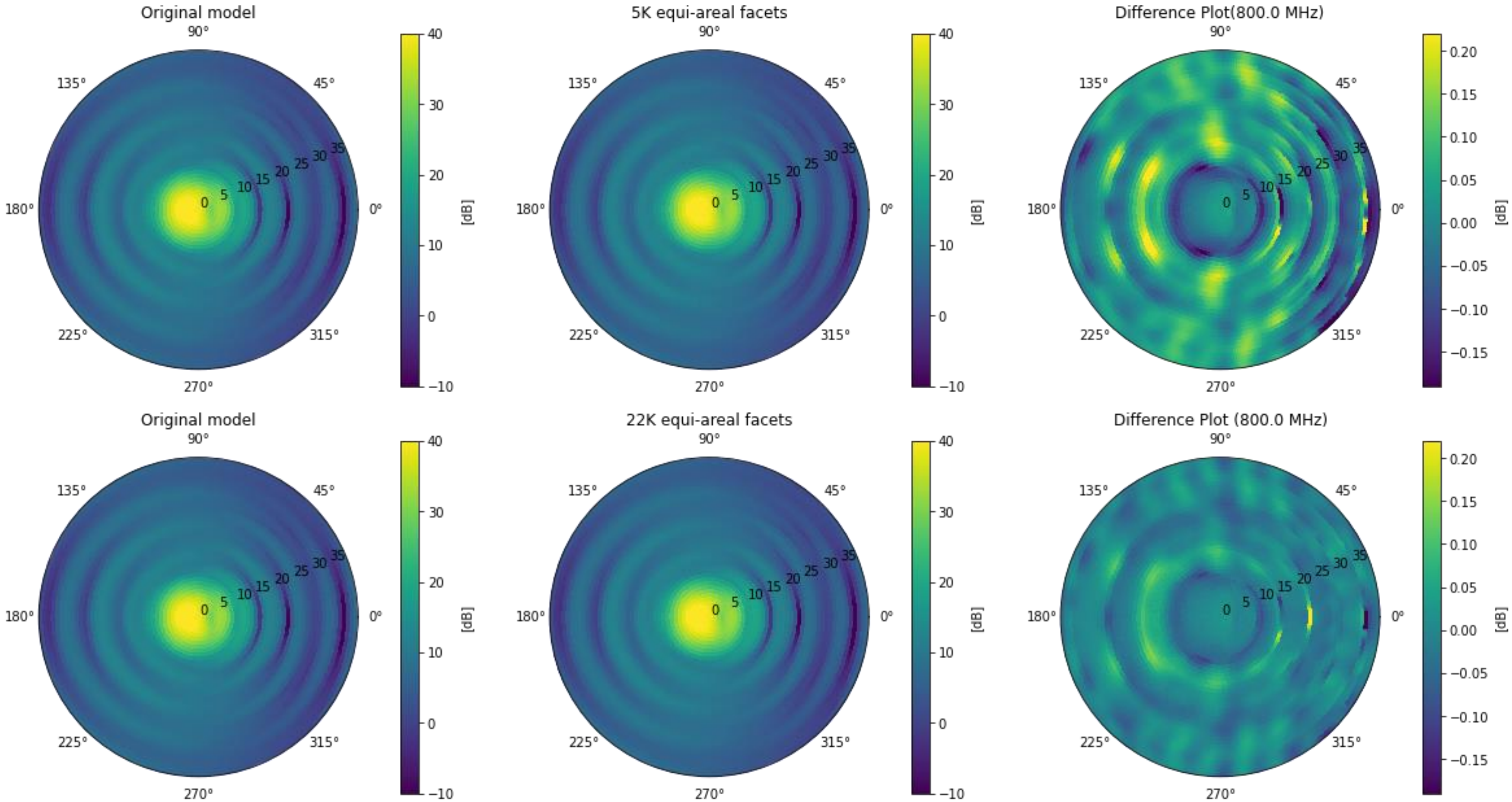
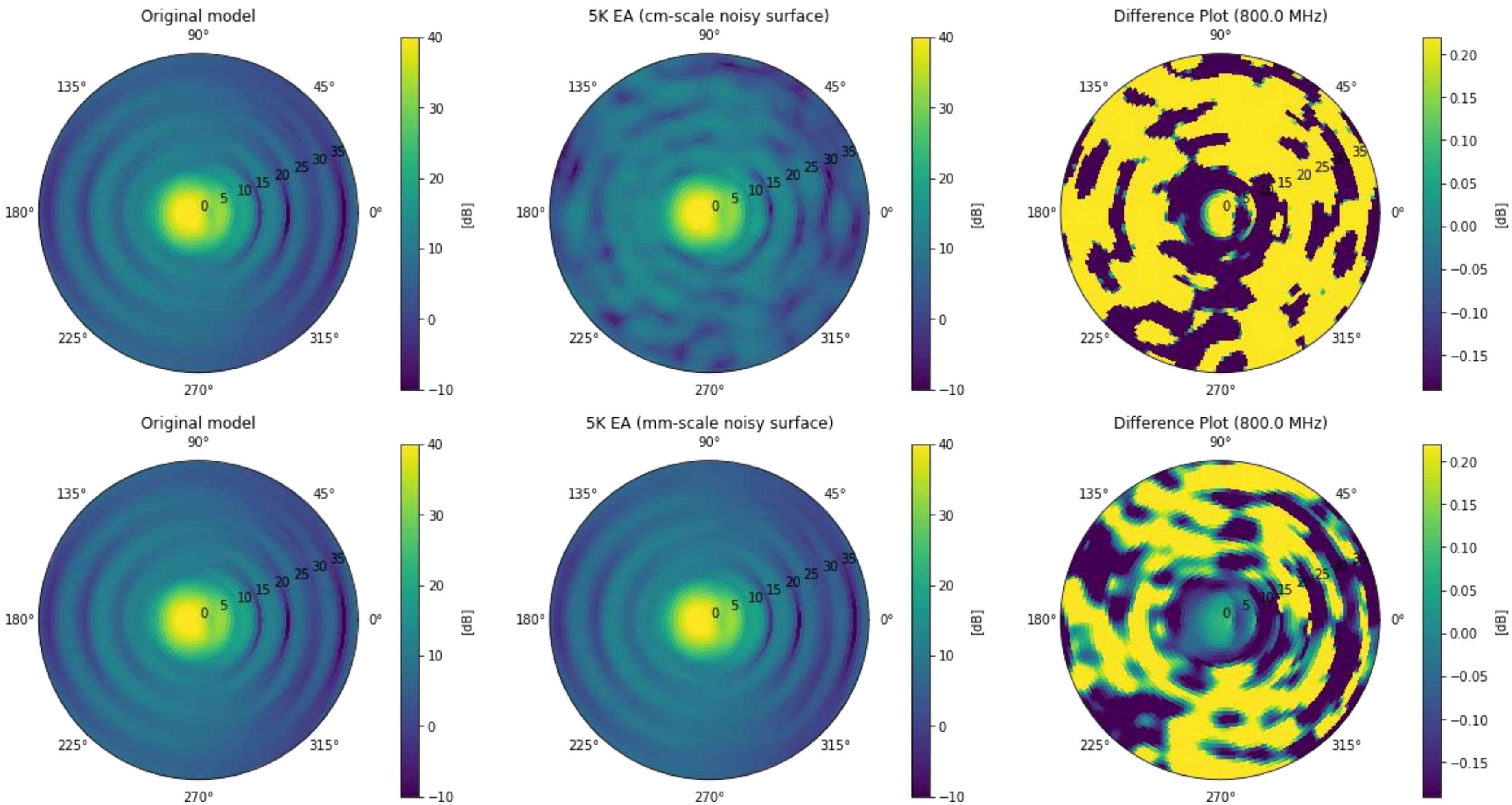
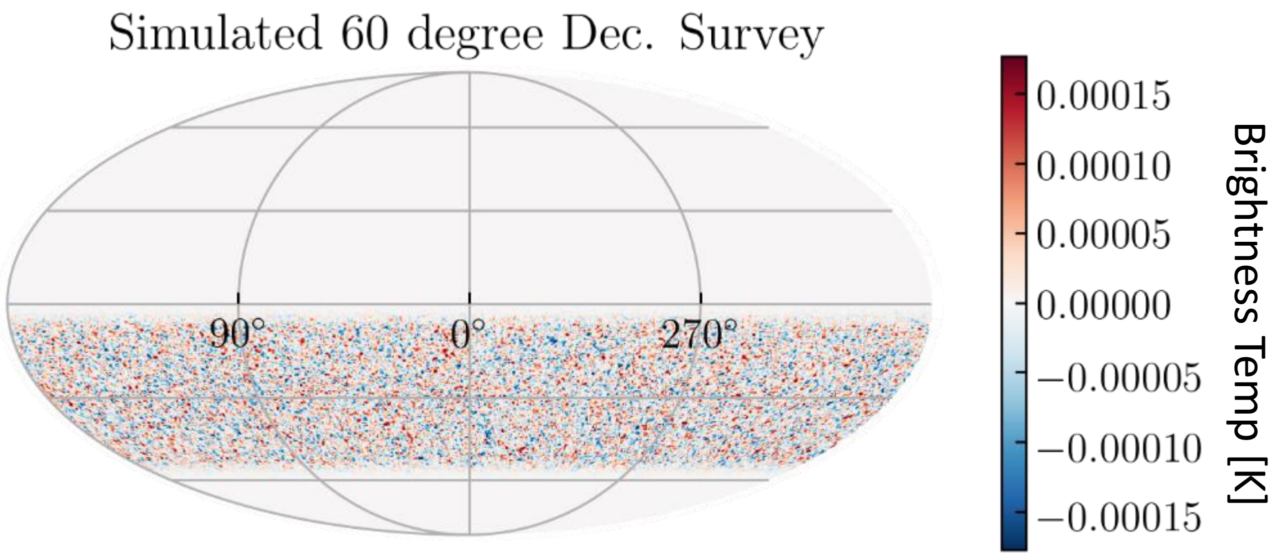


Deformed Dish vs Perfect Paraboloid



Cosmology Simulations

- Devin Crichton (UKZN) developing cosmo sim pipeline for HIRAX
- Produces synthetic visibilities by mock observing simulated skies, uses m-mode analysis of Shaw et al. (https://arxiv.org/abs/1401.2095)
- Exploring the influence of survey design and systematics on our power spectrum sensitivity, and working towards an understanding how this will affect our ability to remove foregrounds.
- Using importing CST beams from simulated dishes for end-to-end, instrument to cosmology modeling



Derived Specifications

- Using cosmology simulations observed with varying CST beams, we set specifications for the necessary accuracy of instrument parameters to achieve desired foreground removal and cosmo param accuracy.
- We find symmetry of telescope mechanical assembly very important, and repeatability across array.
- Specifications highly significant for setting necessary manufacturing accuracy, and assessing cost of construction and assembly
- E.g., will need to use small number of dish molds, to reduce variations in dishes.

Element	Specification	Notes
Axial symmetry of receiver support	± 1 mm	
Receiver support RF attenuation	< 0.5 dB	
Deviation of power cabling from boresight	± 2 mm	
Rigidity of receiver support	± 0.5 mm	In x,y, and z dimensions
Positioning of receiver relative to focal point	± 0.5 mm	In x,y, and z dimensions
Orientation of receiver relative to boresight	± 2.5 arcmin ± 1.5 arcmin	polar angle azimuthal angle
Dish diameter	± 3 mm ± 1 mm	Accuracy Precision
Dish shape accuracy	± 3 mm	Deviation from ideal paraboloid
Dish electrical connectivity	< 5 mm	Maximum dimension of gaps
Dish surface conductivity	$> 1 \times 10^6$ S/m	

Summary

- Feed columns may be slightly better for beams, feed legs necessary for large feeds.
- Symmetry is very important!
- Very deep dishes seem to do well at suppressing array crosstalk, at reasonable cost in aperture efficiency.
- We can now simulate realistic deformed dish surfaces, and propagate all beam effects forward to cosmology!