IEEE Coastal Los Angeles Section

RF Modeling of Instrument Antennas for Flight Projects: from Initial Concept to on Orbit Validation

Paolo Focardi

Jet Propulsion Laboratory
California Institute of Technology

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Agenda

- Introduction
- RF Modeling trends
- NISAR
- COWVR
- SMAP
- Conclusions

Introduction

- In recent years RF Modeling tools like HFSS™ and GRASP™ have reached capabilities that were unimaginable just a few years ago
- At the same time, computer power and available memory have been increasing steadily
- Thanks to this fertile grounds now it's possible to run extremely complex RF simulations of very large structures in a relatively short time with very good results
- The following slides will guide you through a few examples of flight missions where very complex RF models have provided extremely accurate results

RF Modeling Trends

- Message Passing Interface (MPI)
- Domain Decomposition
- Multi Level Fast Multiple Method (MLFMM)
- Body of Revolution (BoR)
- These are just some of the latest algorithms and techniques implemented in commercial tools like Ticra's GRASP™ and Ansys HFSS™ that allow you to run extremely complex problems with limited resources OR… extremely large problems with extremely large resources…

NASA

NISAR

NASA - ISRO SAR Mission

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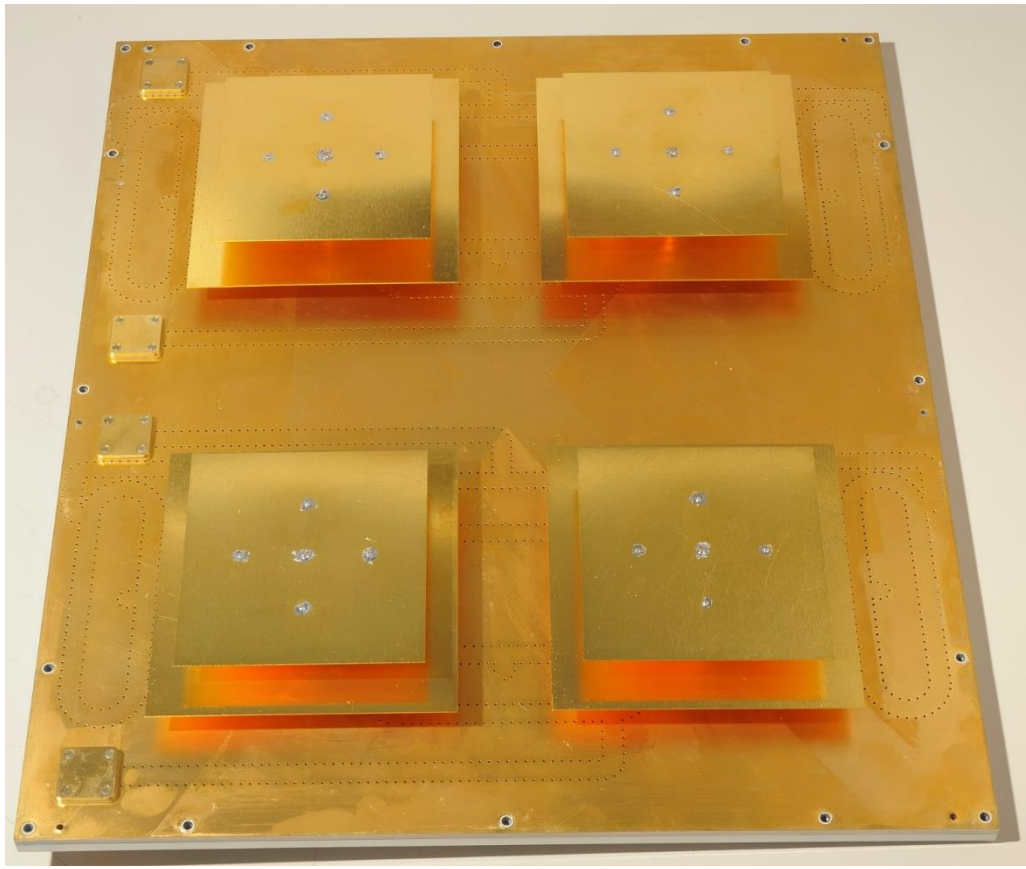
NISAR Agenda

- Mission Overview
- Observatory Configuration
- L-SAR Instrument
- Sweep-SAR Measurement Technique
- Radar Antenna Subsystem
- L-Band Feed Array
- L-FRAP/LFTA RF Models
- Preliminary Results

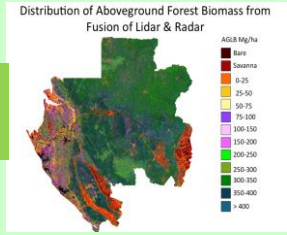


Prototype L-Band Feed Tile without Radome

Mission Overview

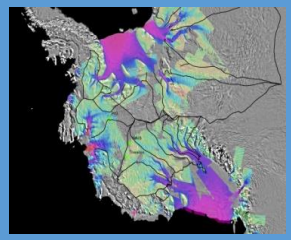
Mission Science

Ecosystem Structure



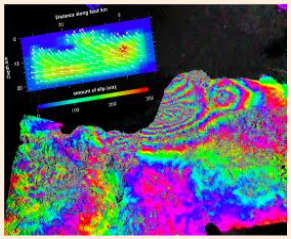
Biomass disturbance; effects of changing climate on habitats and CO_2

Cryosphere



Ice velocity, thickness; response of ice sheets to climate change and sea level rise

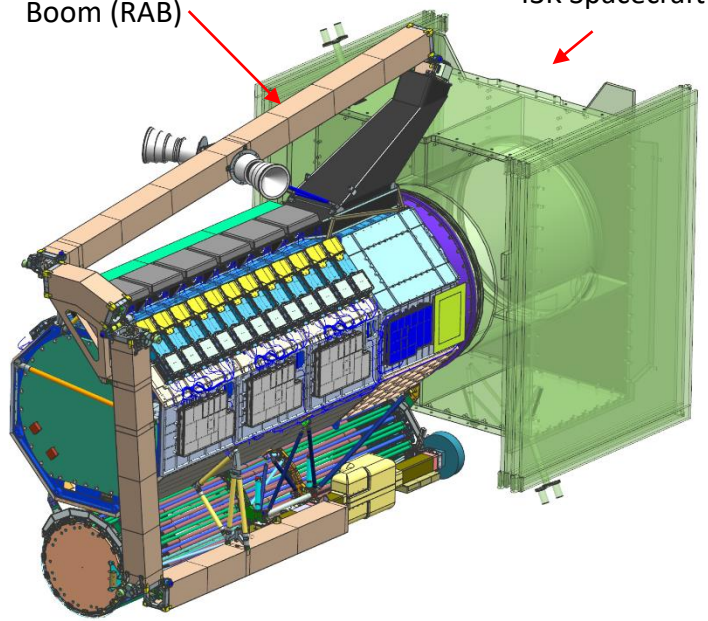
Solid Earth

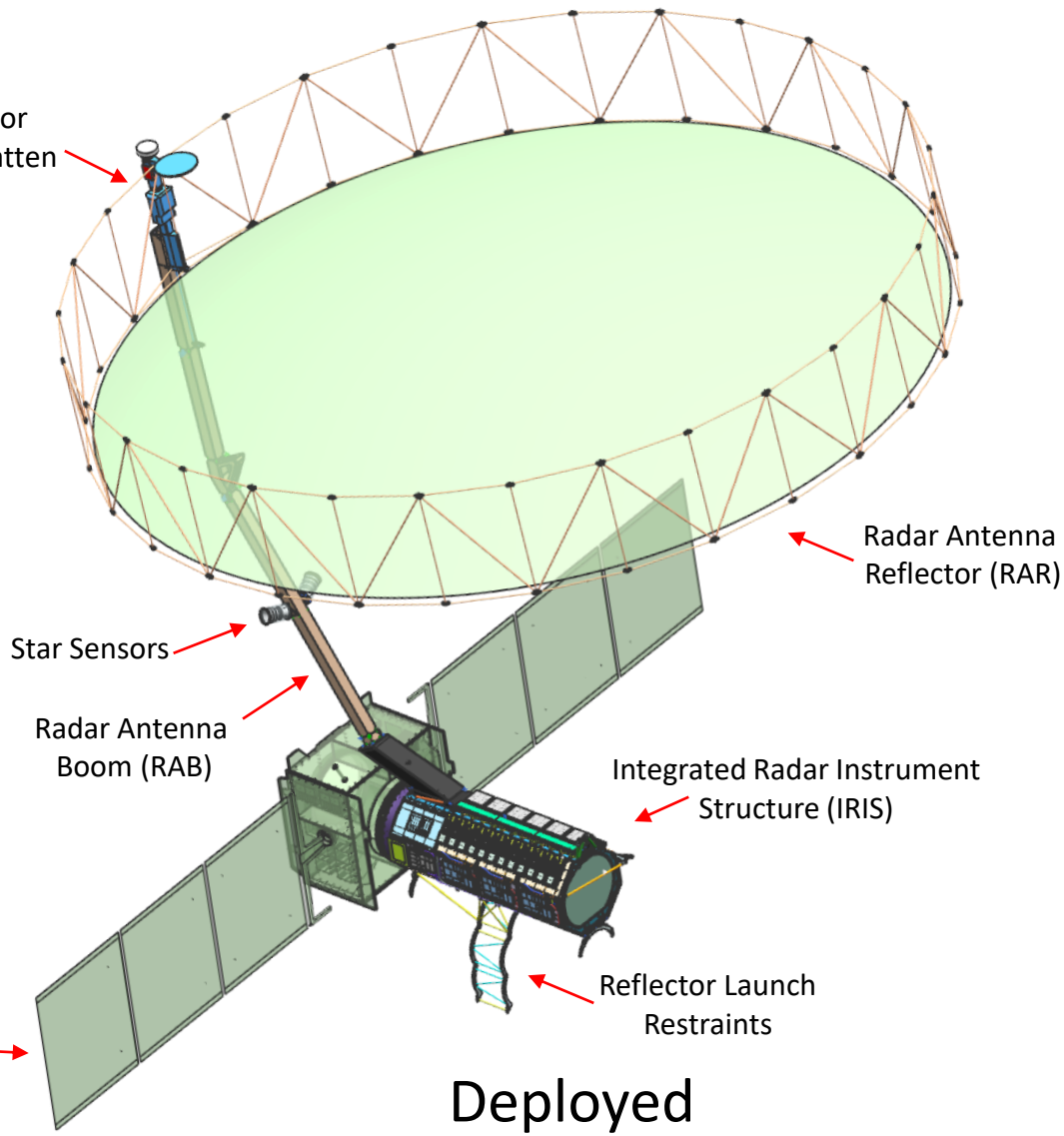


Surface deformation; geo-hazards; water resource management

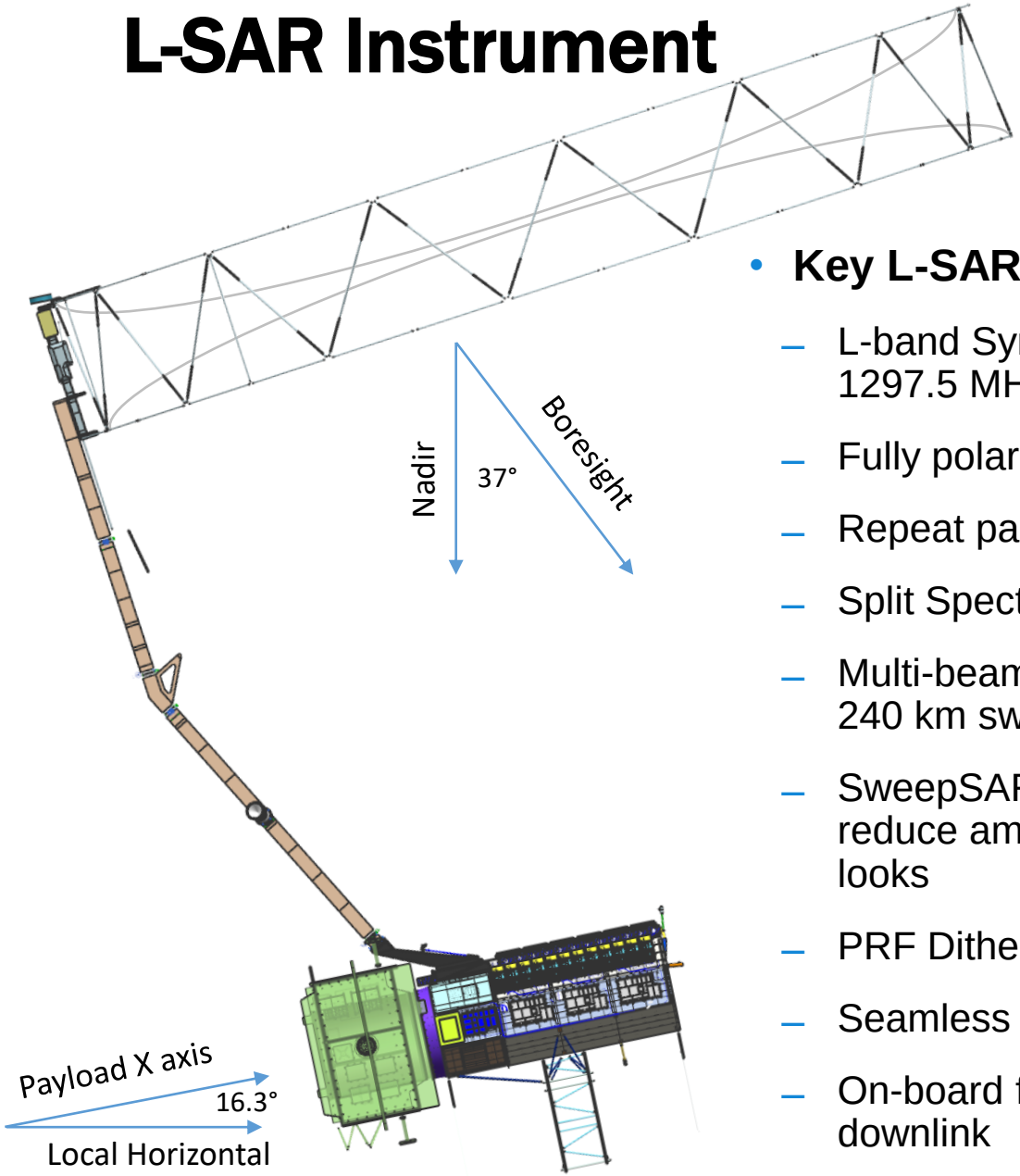
- Directed mission within the Earth Systematic Missions Program under NASA Earth Science Division
- Major international partner: Indian Space Research Organization (ISRO) who is supplying the launch vehicle, S/C, and S-band radar
- Baseline launch date: Not earlier than December 2020
- Dual frequency L- and S-band Synthetic Aperture Radar (SAR)
  - L-band SAR from NASA and S-band SAR from ISRO
- Sweep SAR technique (large swath) for global data collection
- Baseline orbit: 747 km altitude circular, 98 degrees inclination, sun-synchronous, dawn-dusk (6 PM–6 AM), 12-day repeat
- Repeat orbit within ± 250 m
- Spacecraft: ISRO I3K (flown at least 9 times)
- Launch vehicle: ISRO Geosynchronous Satellite Launch Vehicle (GSLV) Mark-II (4-m fairing)
- 3 years science operations (5 years consumables)
- All science data (L- and S-band) will be made available free and open, consistent with the long-standing NASA Earth Science open data policy

Observatory Configuration





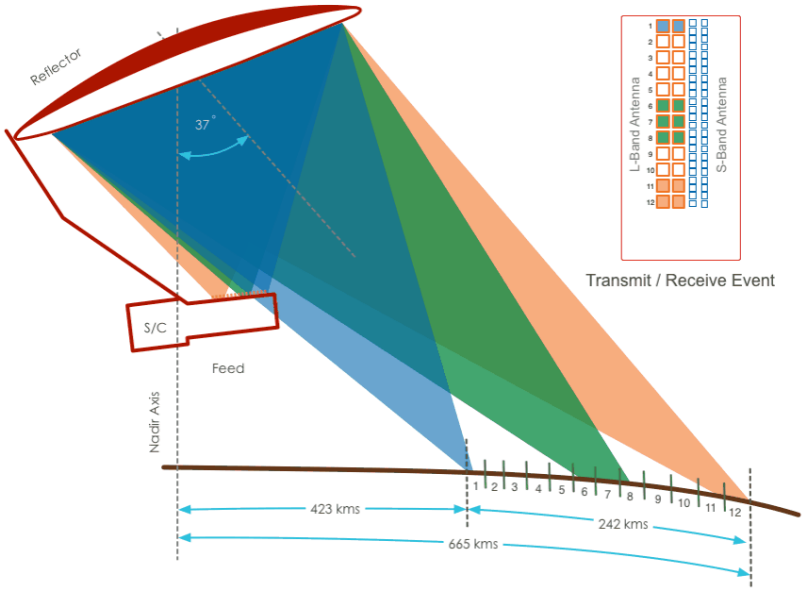
L-SAR Instrument

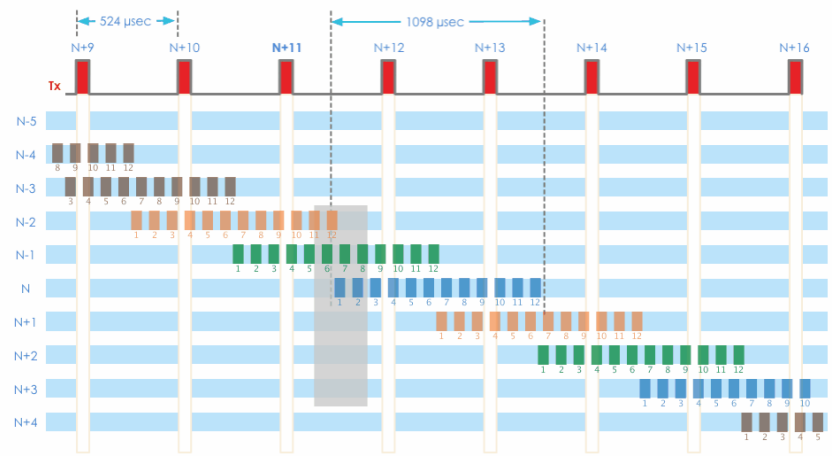


- **Key L-SAR Instrument Features:**
  - L-band Synthetic Aperture Radar (1215.5 – 1297.5 MHz)
  - Fully polarimetric for classification and Biomass
  - Repeat pass interferometry for deformation
  - Split Spectrum for Ionosphere mitigation
  - Multi-beam Array fed Reflector to achieve a 240 km swath
  - SweepSAR timing and Digital Beam Forming to reduce ambiguities and preserve resolution / looks
  - PRF Dithering to fill transmit interference gaps
  - Seamless mode transitions to minimize data loss
  - On-board filtering and compression to reduce downlink

Sweep-SAR Measurement Technique

- **SweepSAR Basics**
  - On Transmit, illuminate the entire swath of interest (red beam)
  - On Receive, steer the beam in fast time to follow the angle of the echo coming back to maximize the SNR of the signal and reject range ambiguities
  - Allows echo to span more than 1 Inter Pulse Period (IPP)
- **Consequences**
  - 4 echoes can be simultaneously returning to the radar from 4 different angles in 4 different groups of antenna beams
  - Each echo needs to be sampled, filtered, Beam-formed, further filtered, and compressed
  - On-Board processing is not reversible – Requires on-board calibration before data is combined to achieve optimum performance

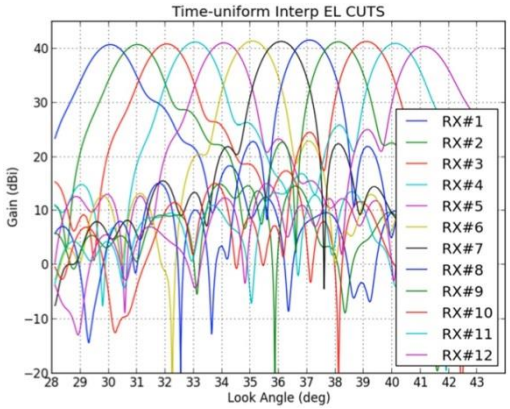


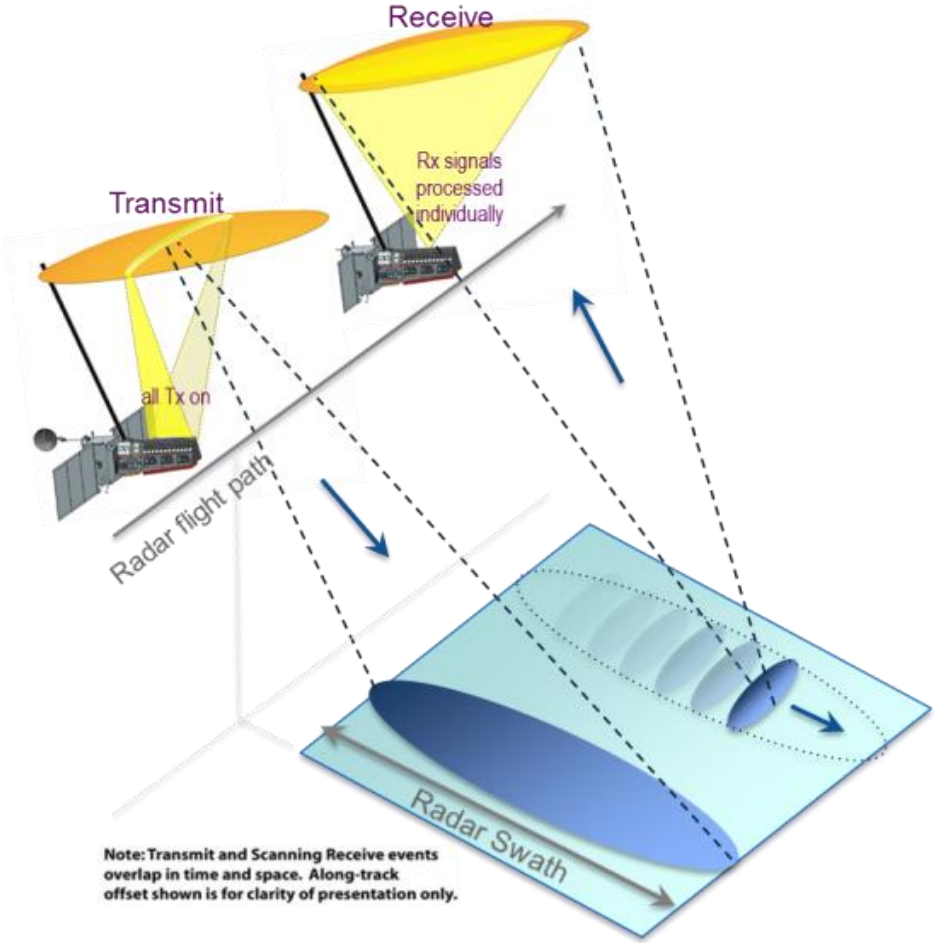


PRF = 1910 Hz, PRI = 524 µsec. Echo time difference between 423 km to 665 km swath = 1098 µsec

Radar Antenna Subsystem

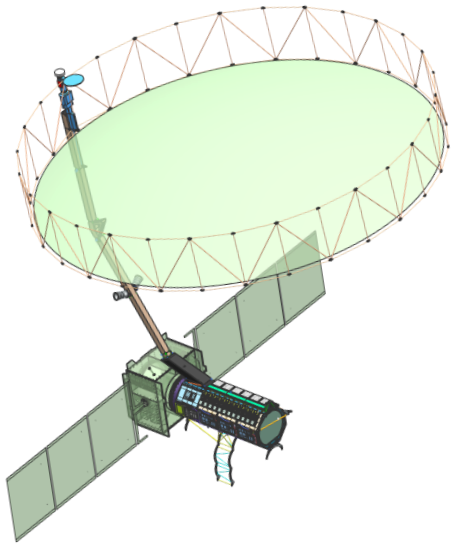
- Reflector: 12m deployable mesh reflector by Northop-Grumman Astro
- Boom: JPL In-house co-development with SWOT
- L-Band Feed (aka L-FRAP): 2x12 element dual linearly-polarized patch array; JPL in-house design
- S-Band Feed (aka S-FRAP): 2x24 element dual linearly-polarized patch array; ISRO in-house design
- High power: Nominal peak power is ~3kW for L-Band, and ~8kW for S-Band
- Transmit mode: All feed elements are used to generate a large swath
- Receive mode: Individual patch pairs are used to create small beams, with digital beamforming performed in post-processing

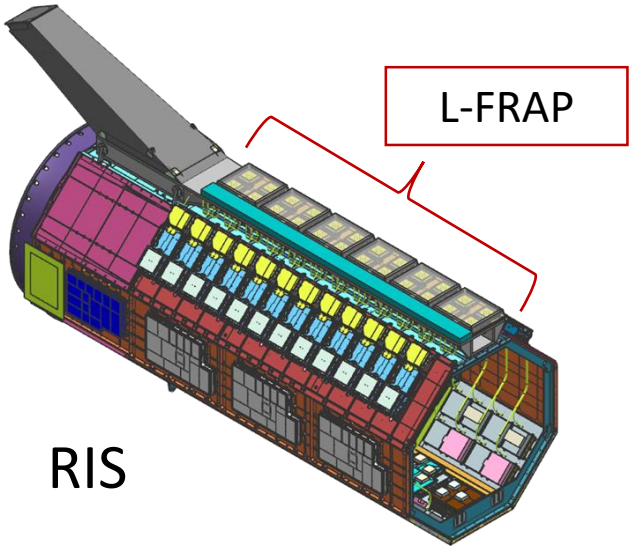




L-Band Feed Array

- The L-Band 2x12 element array is made by six 2x2 patch tiles
- Each pair of patches in the short dimension of the array function as a single element with dual linear polarization
- This results in 12 H-pol and 12 V-pol beams
- During transmit operations, each patch pair is fed with a linear phase ramp to scan the beam 5°. This affects the return loss
- The Radar Instrument Structure (RIS), lies in the projected aperture of the 12m reflector. This also affects the return loss seen at the tile

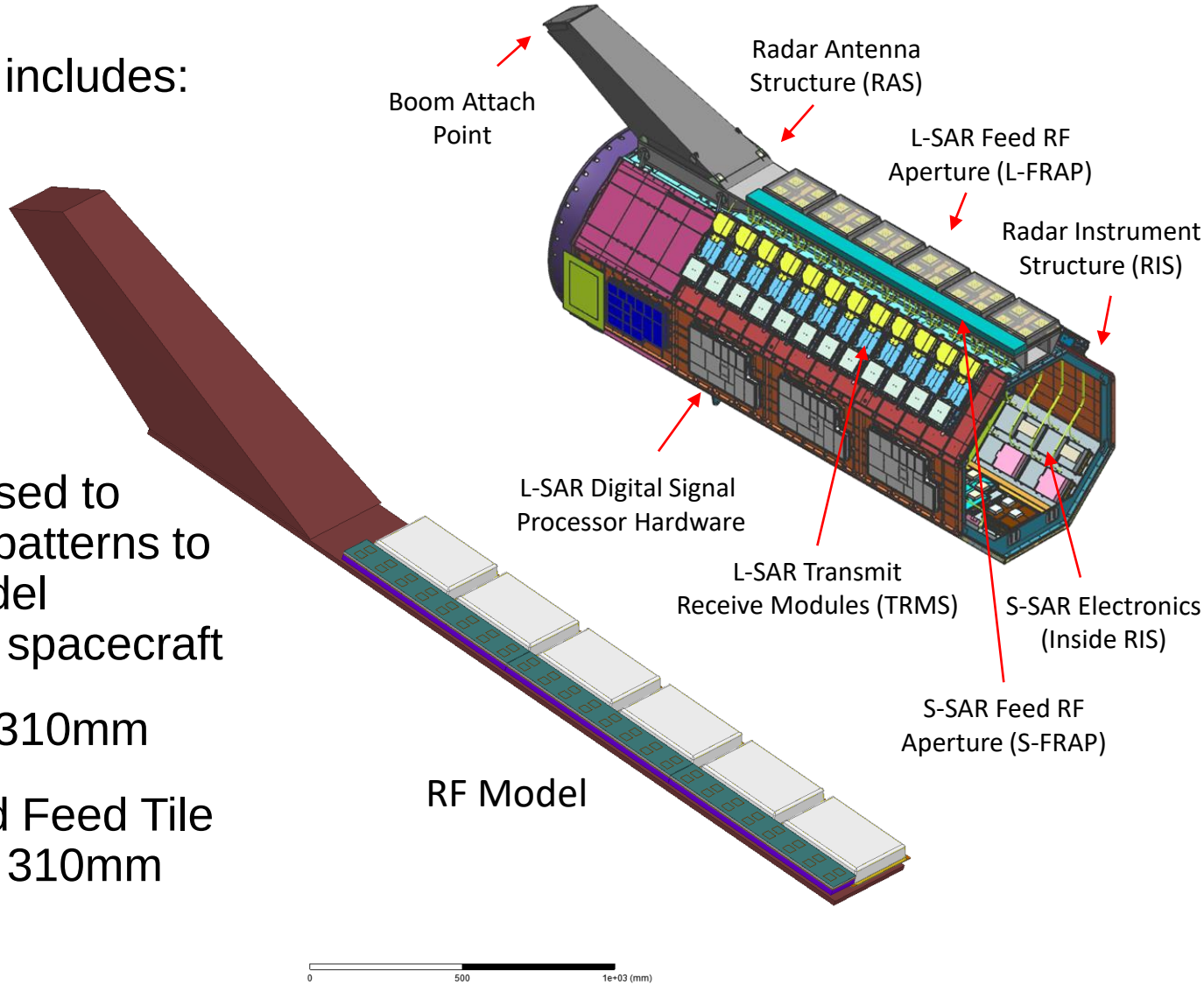




L-FRAP RF Model

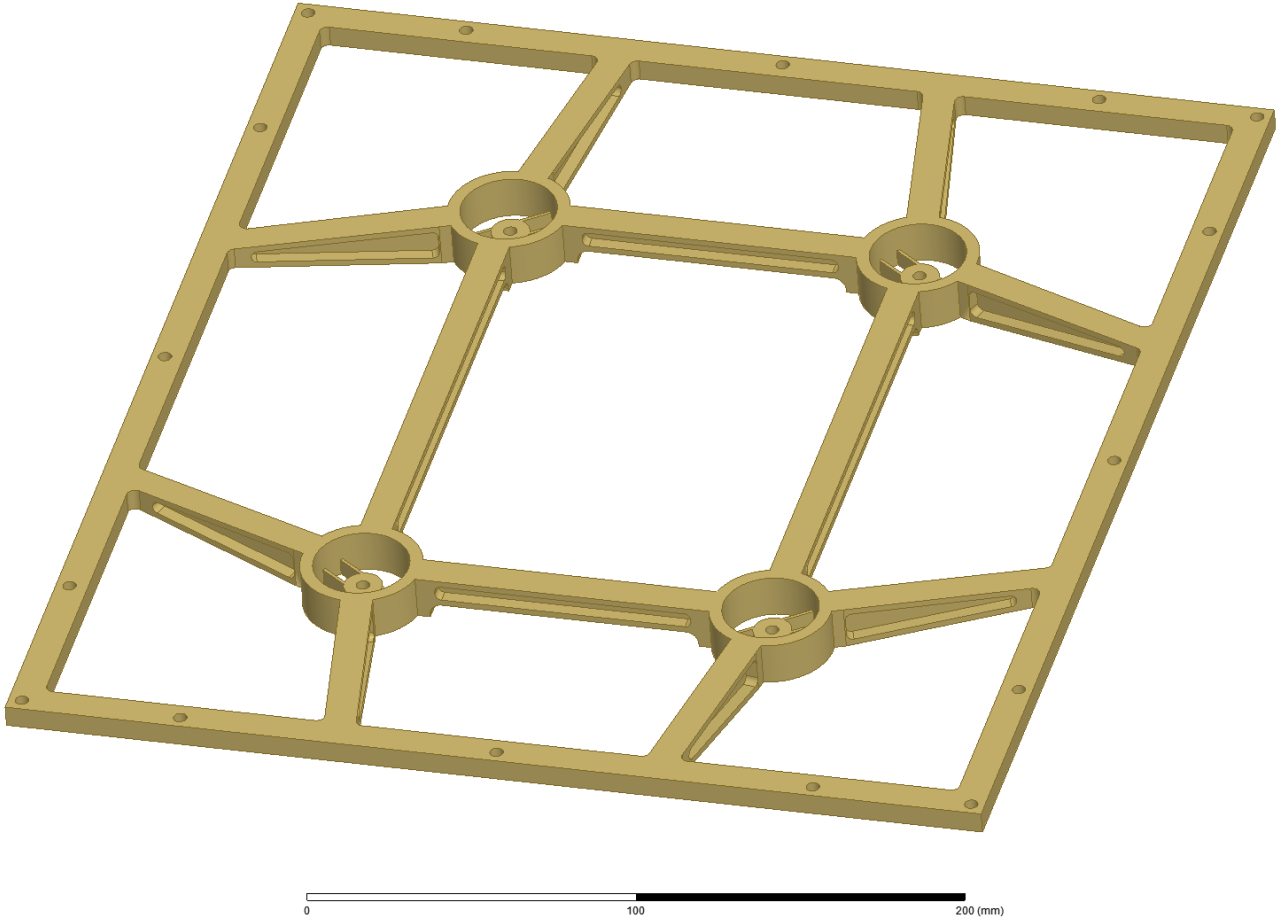
- RF model in HFSS includes:
  - L-FRAP
  - S-FRAP
  - Top RAS plate
  - Boom base

- L-FRAP model is used to generate radiation patterns to feed a GRASP Model including the entire spacecraft
- L-FRAP is 2,158 x 310mm
- Each LFTA (L-Band Feed Tile Assembly) is 358 x 310mm



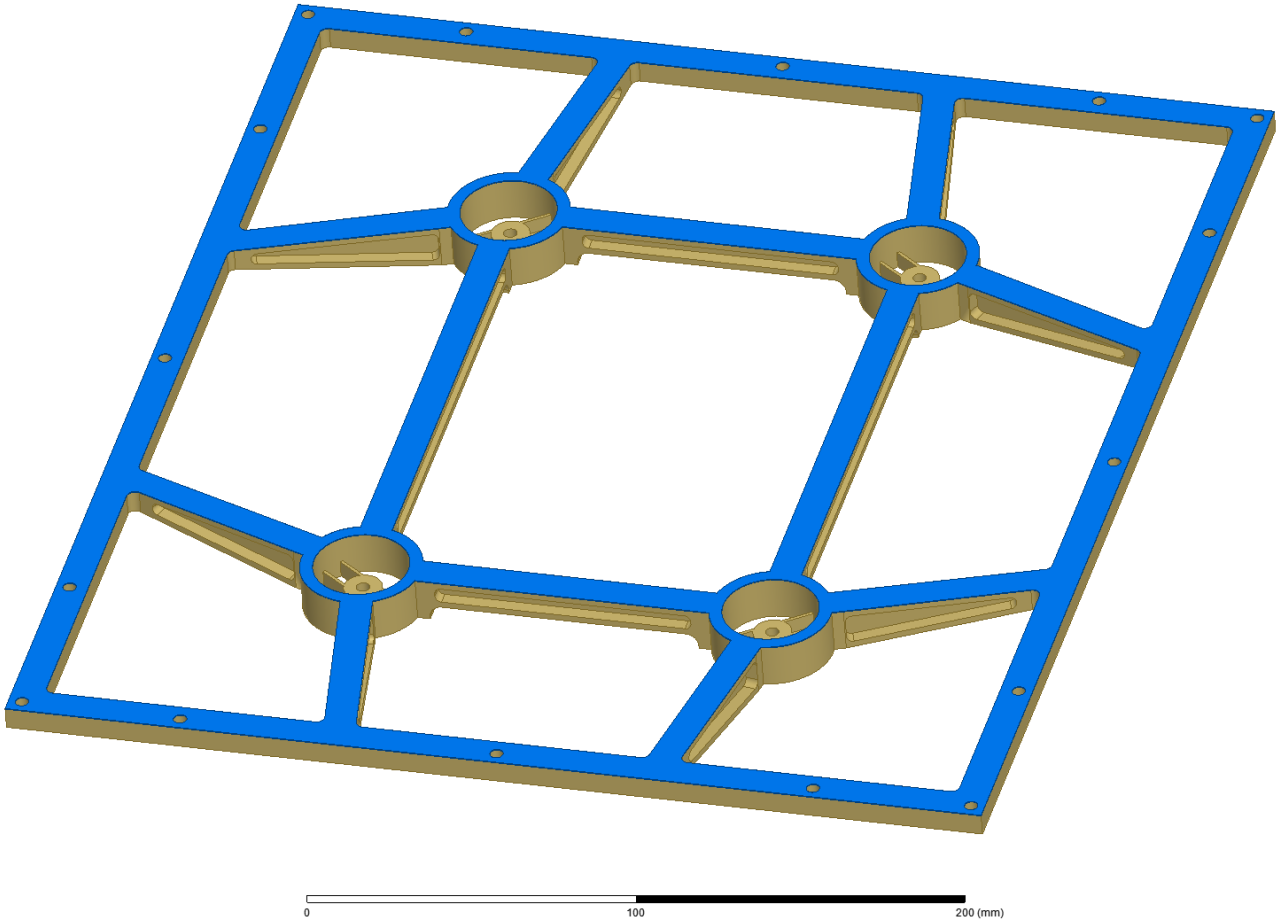
LFTA RF Model

Aluminum frame



LFTA RF Model

Adhesive



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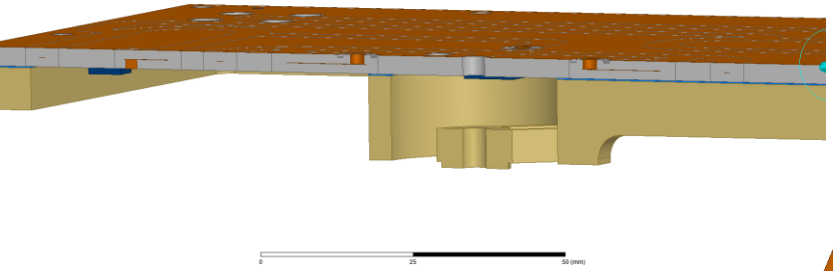
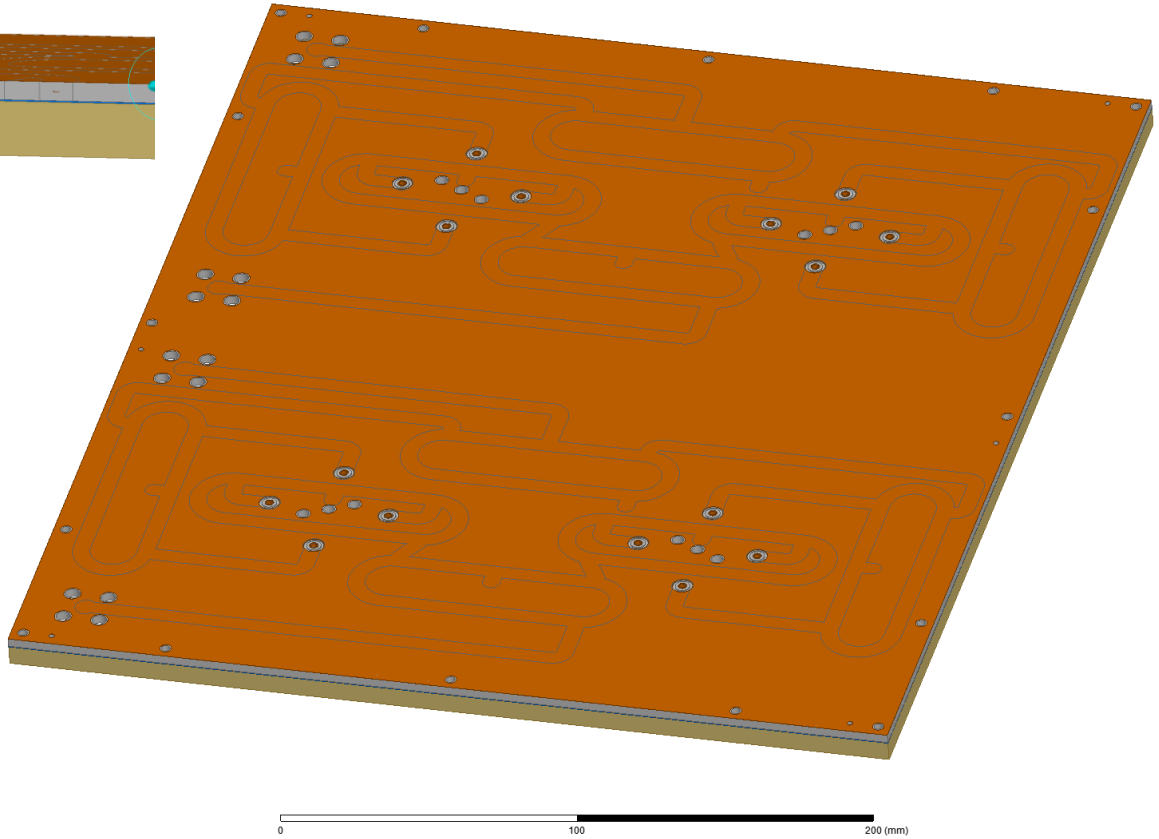
LFTA RF Model

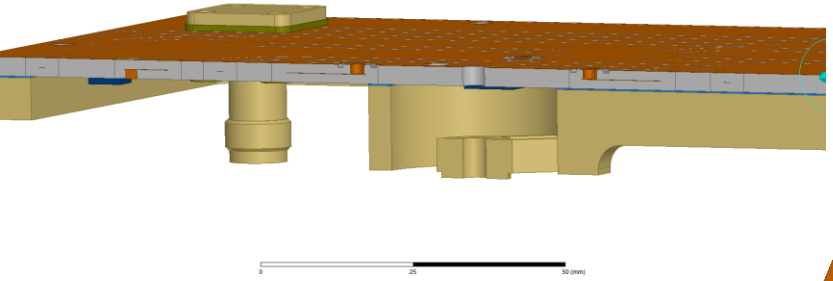
Feeding Network board made of Rogers 6002

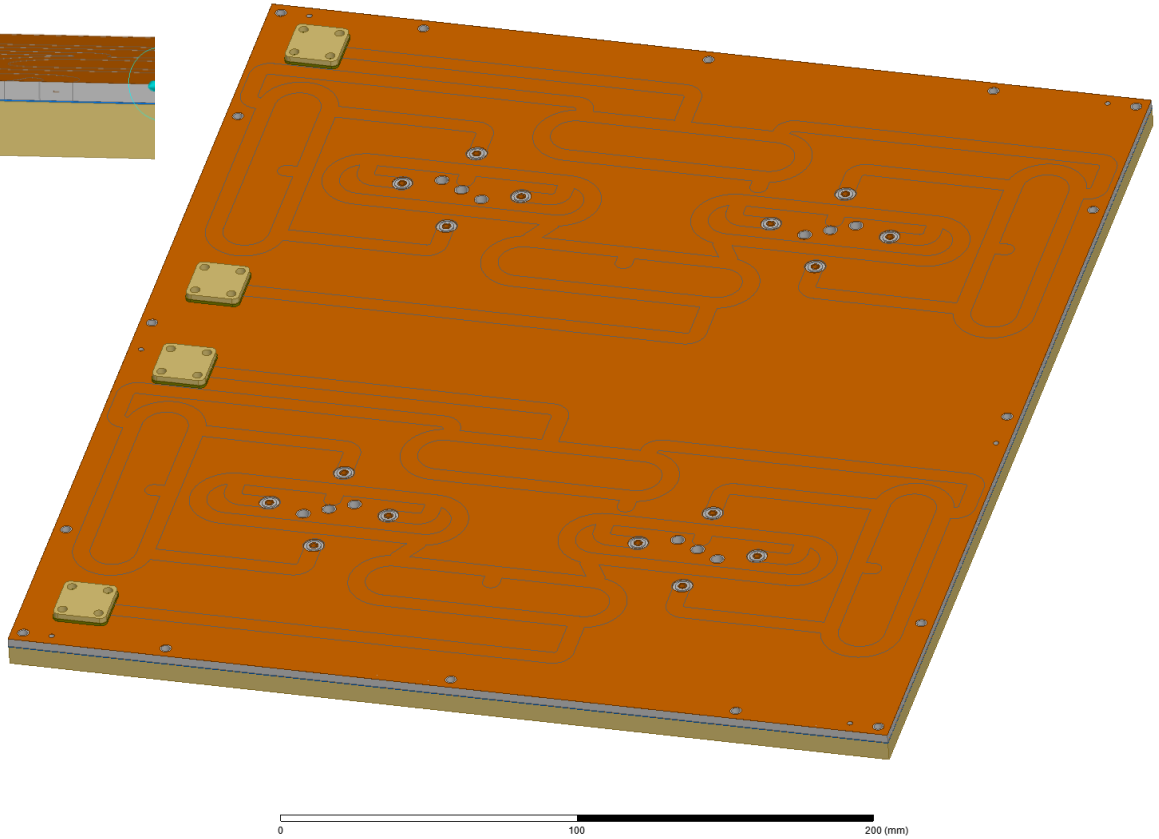




LFTA RF Model

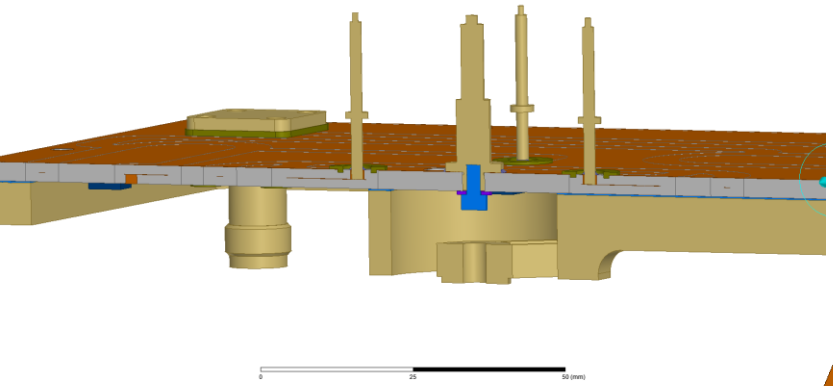
TNC Connectors

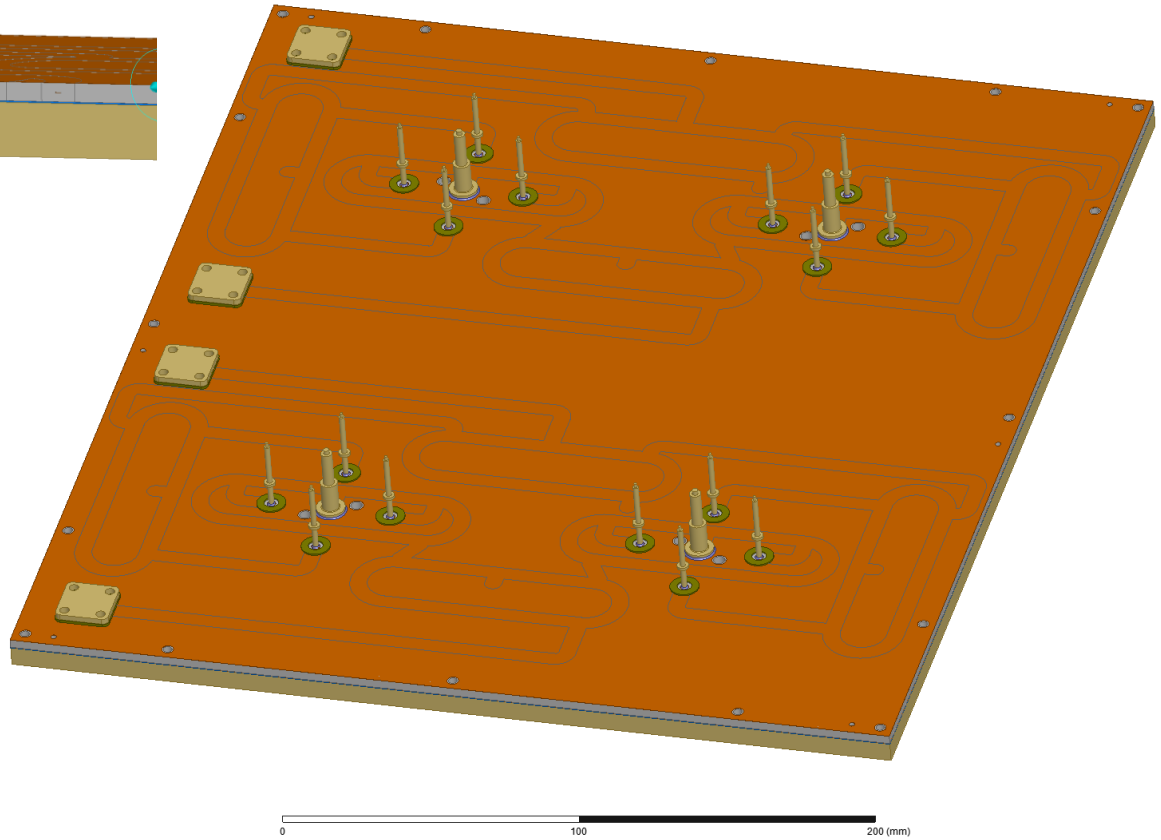




LFTA RF Model

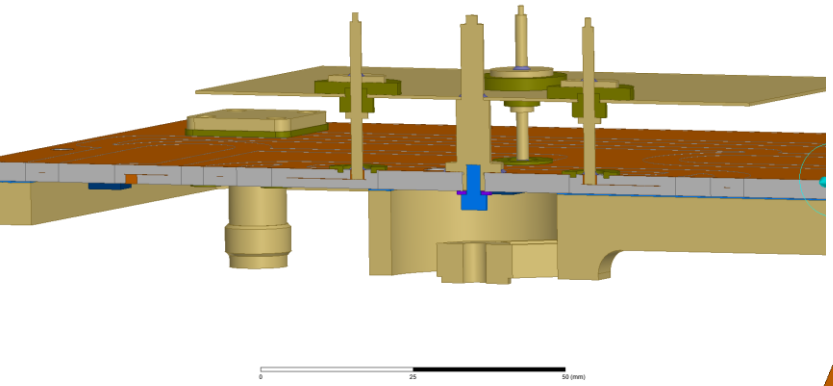
Patch probes, center posts and dielectric washers

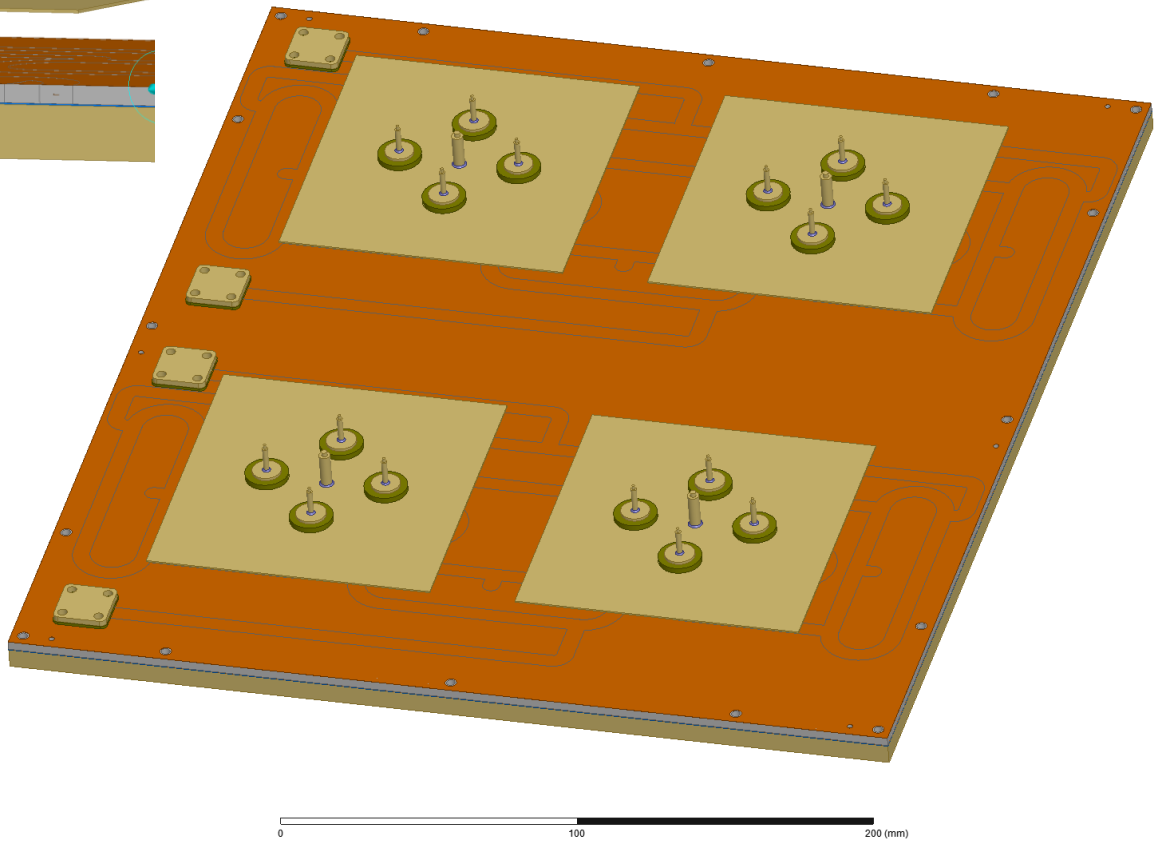




LFTA RF Model

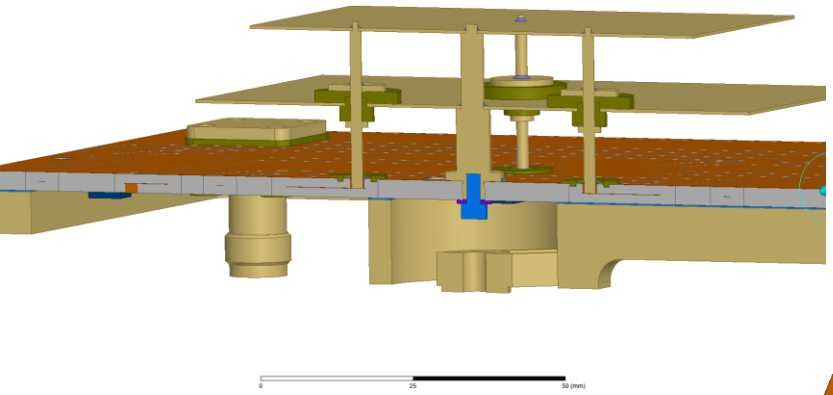
Lower patches

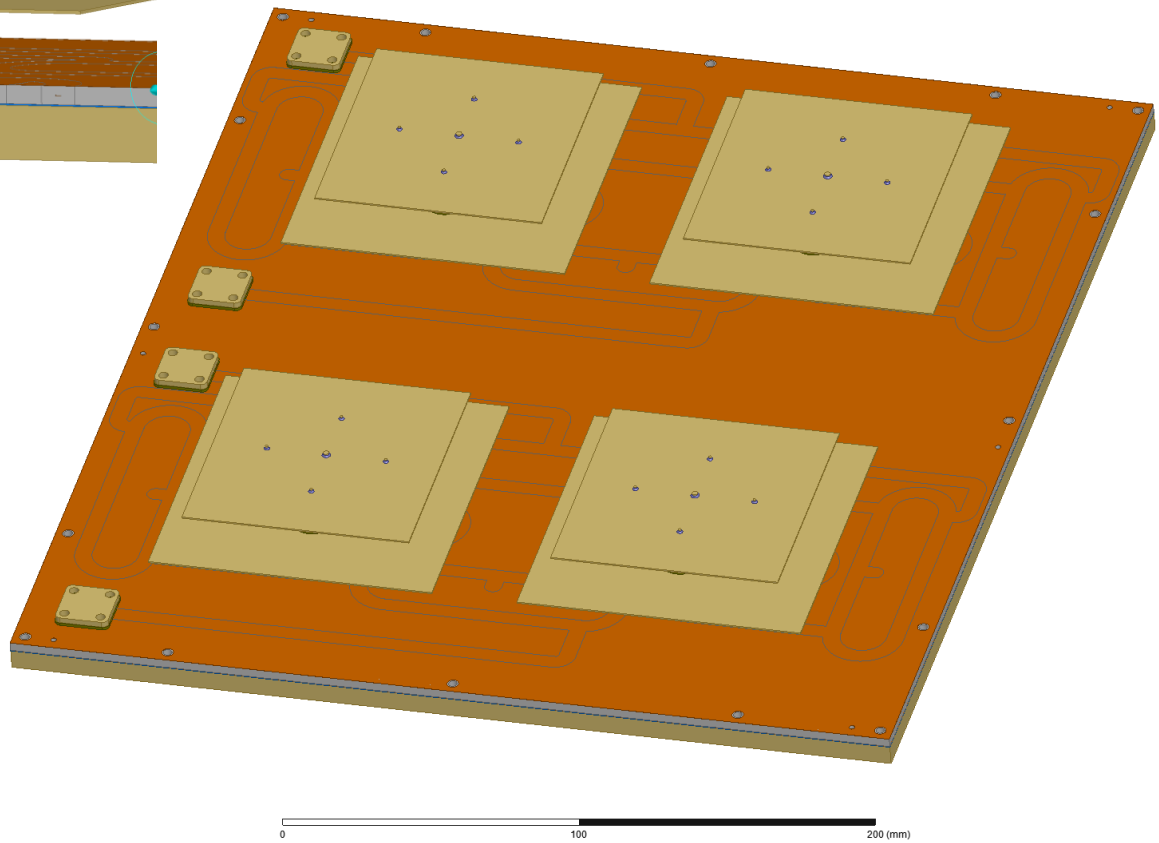




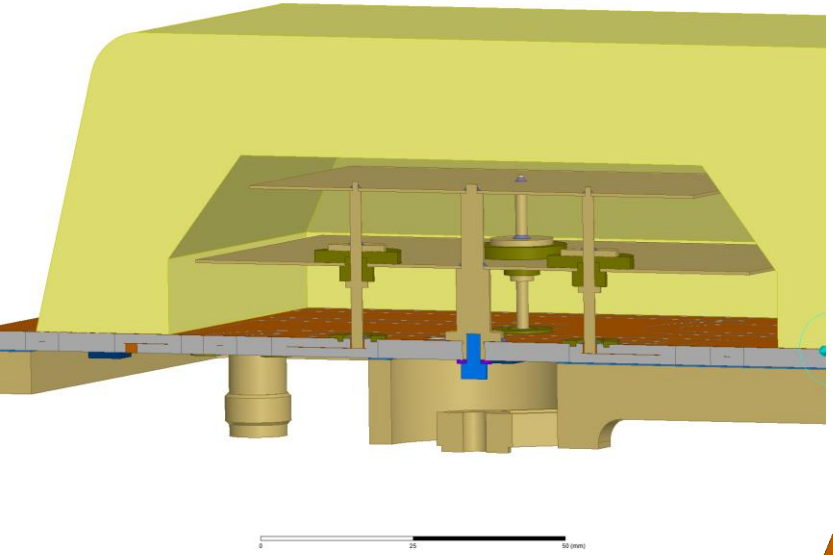
LFTA RF Model

Upper patches

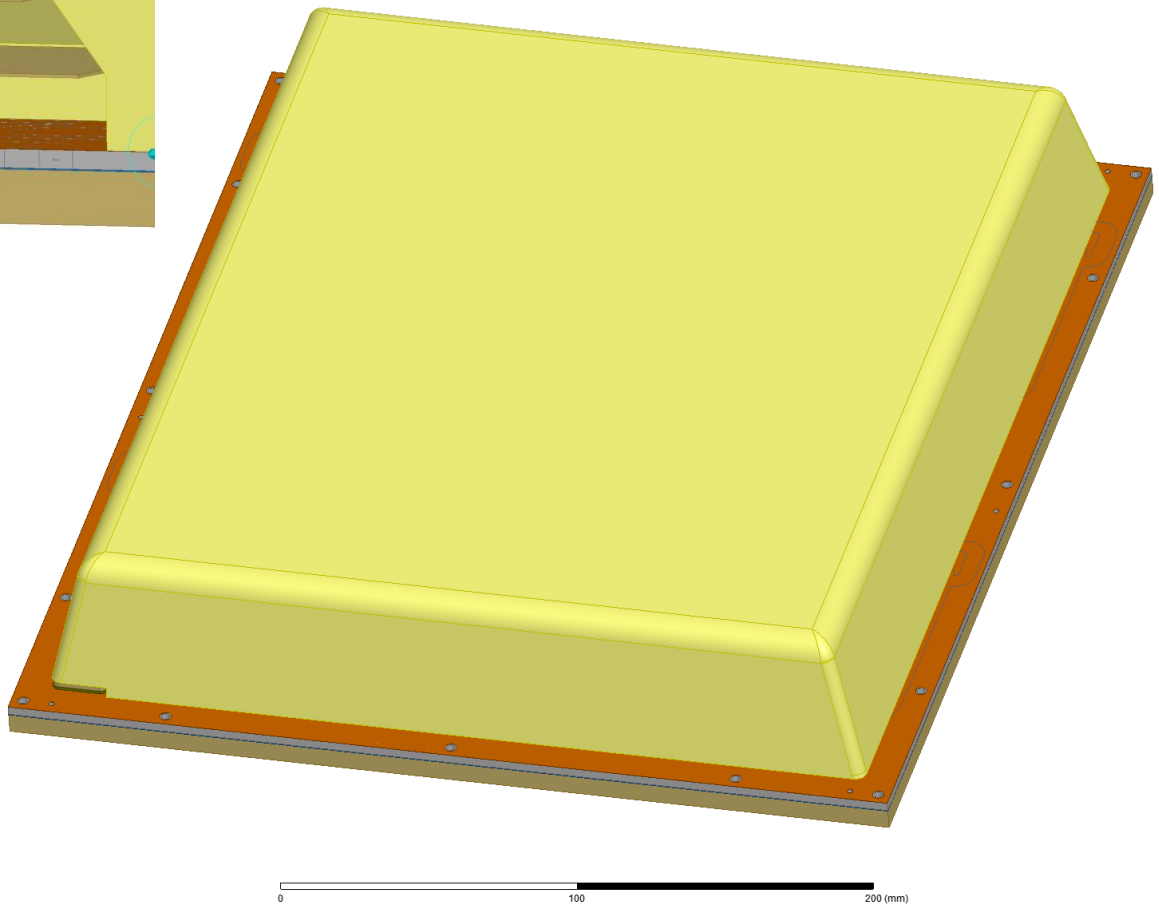




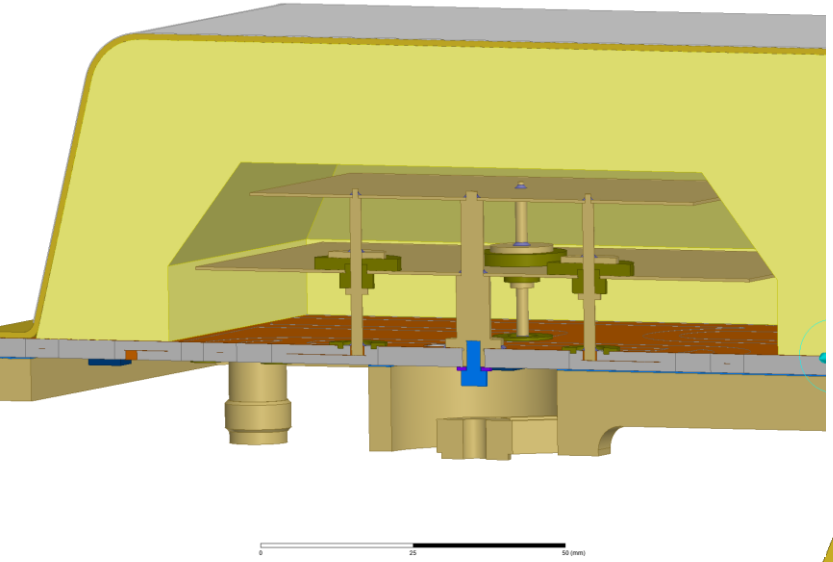
LFTA RF Model



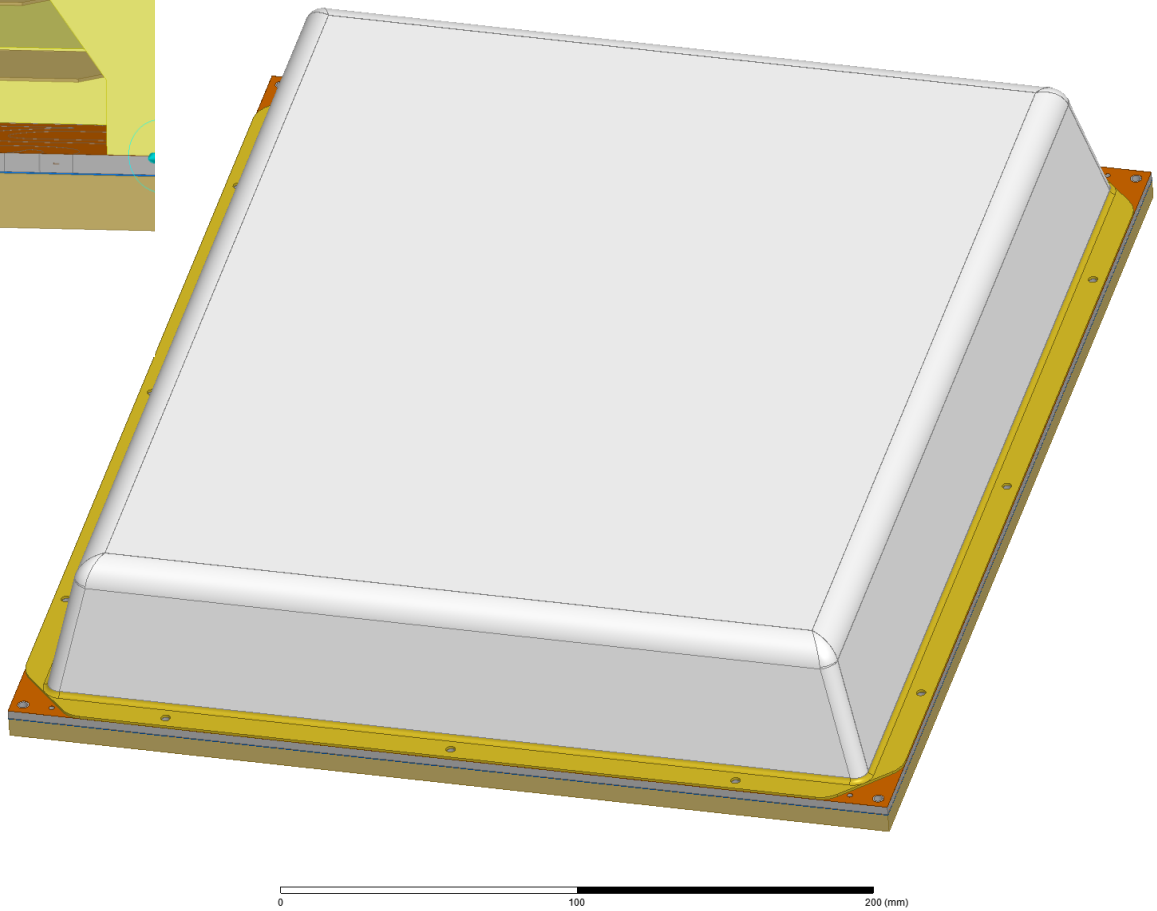
Radome foam



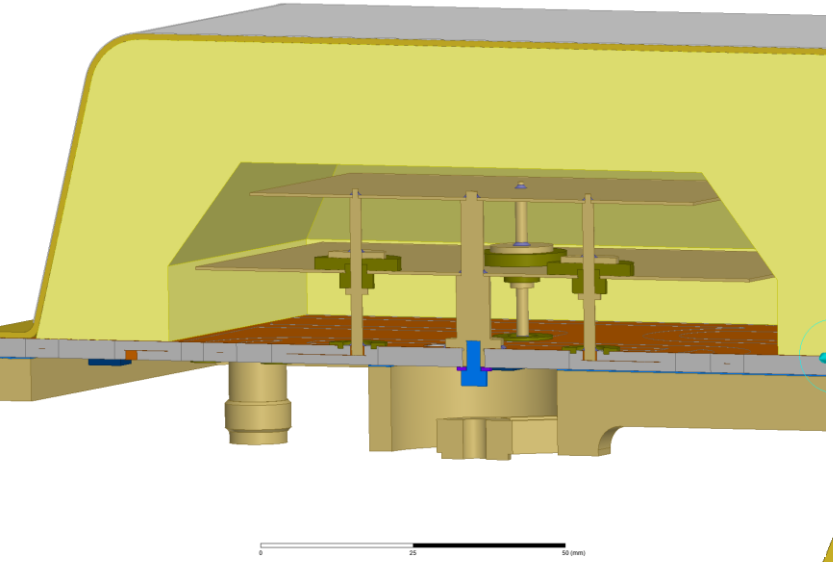
LFTA RF Model



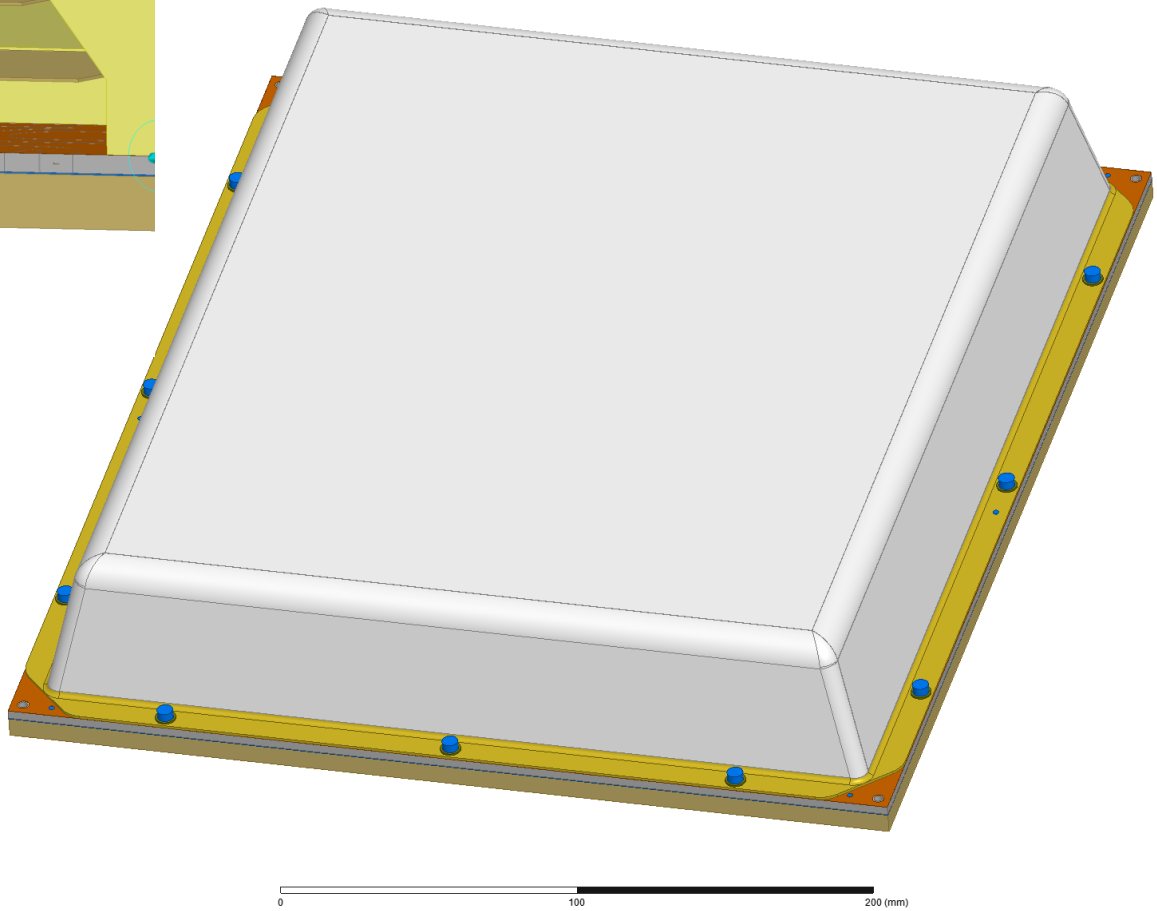
Painted radome shell



LFTA RF Model

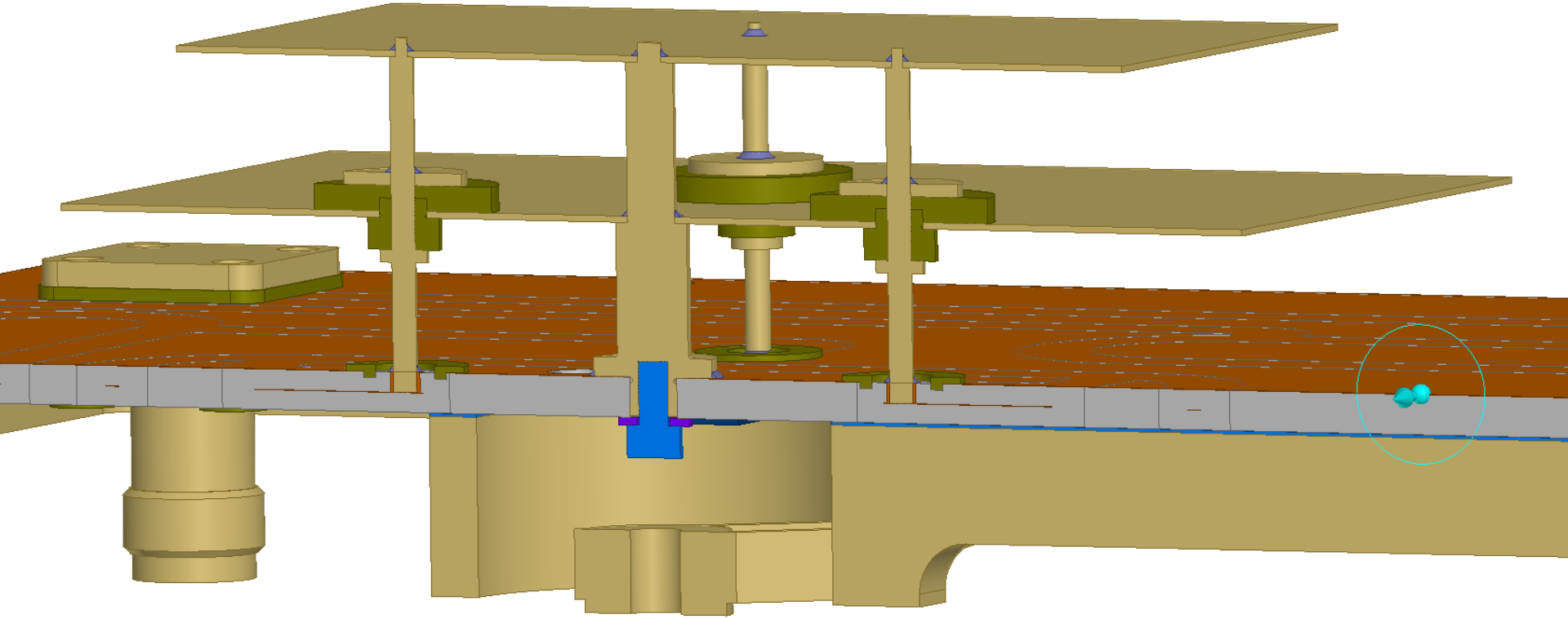


Fasteners



LFTA RF Model

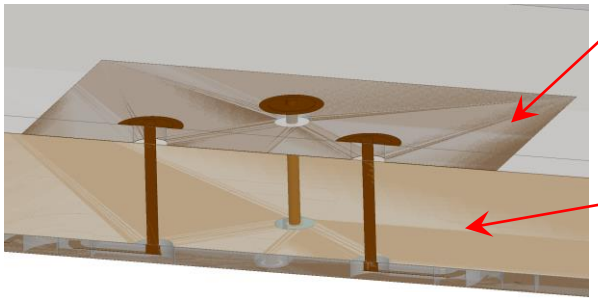
- Each patch pair is fed by its own feeding network capable of radiating H-Pol and V-Pol independently
- Each patch assembly is made of a stacked patch configuration with a center post and 4 probes
- Each probe is tuned with a dielectric bushing and a metal washer soldered above the lower patch



Feed Tile Design Evolution

Old Design

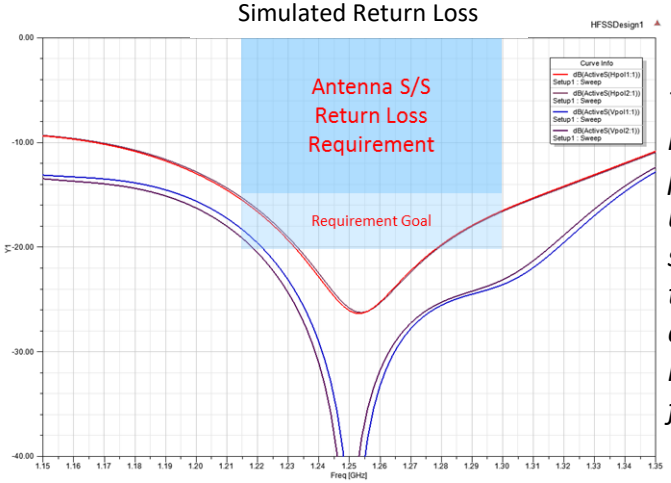
No radome, which resulted in large temperature gradient predictions through the honeycomb layer



Single patch layer

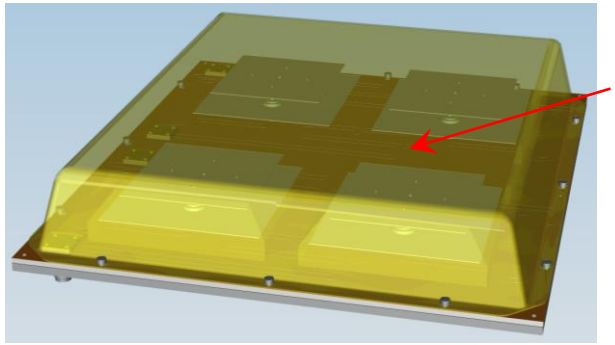
Honeycomb layer between patch and ground plane (not shown)

Simulated Return Loss



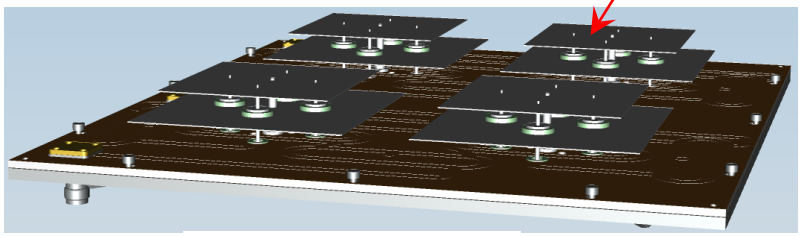
The measured return loss on the single prototype tile varied up to 3 dB from the simulated results, so the design was not expected to meet the requirement over the full band

New Design

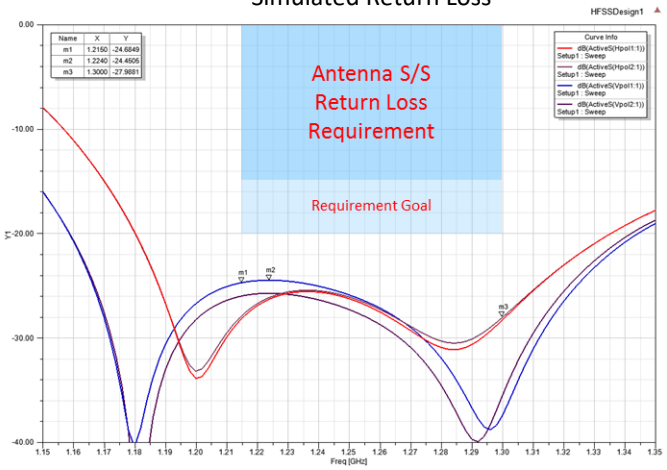


Radome with rigid outer shell and foam interior

Stacked patches, air dielectric



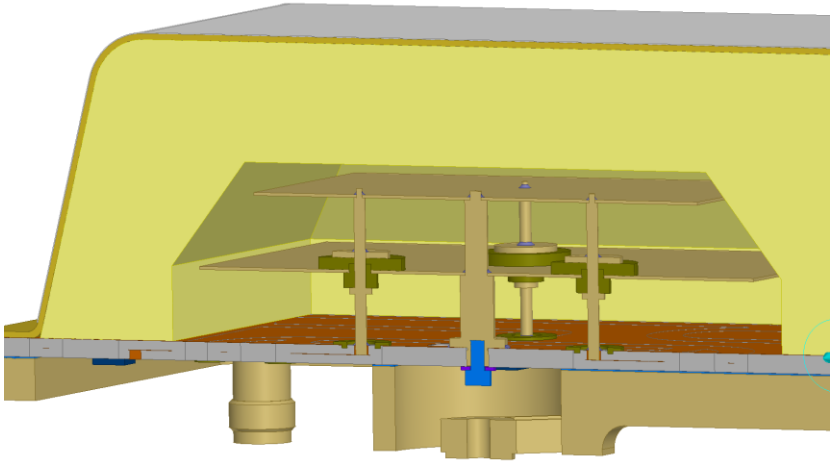
Simulated Return Loss



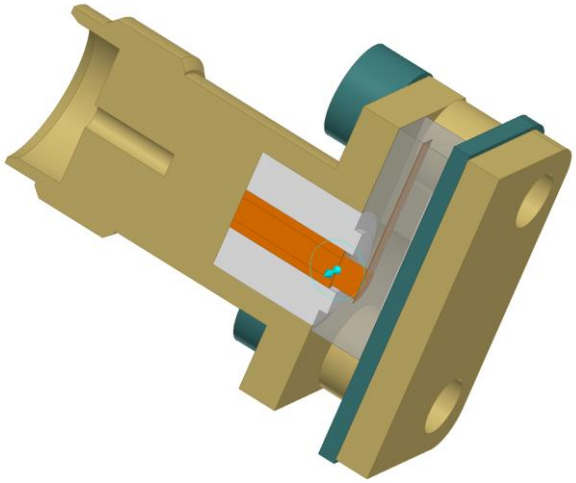
The new design shows enough margin that the requirement is expected to be met with margin

RF Design Highlights

- The mission thermal environment drove us toward a metal patch design without dielectric support
- The RF Bandwidth requirement made us add a second patch in stacked configuration
- A center post was added for mechanical support and has the added advantage of minimizing the second harmonic
- Radome and heaters were added to minimize thermal gradients
- A number of features were added to increase the power handling capabilities of the feed assembly

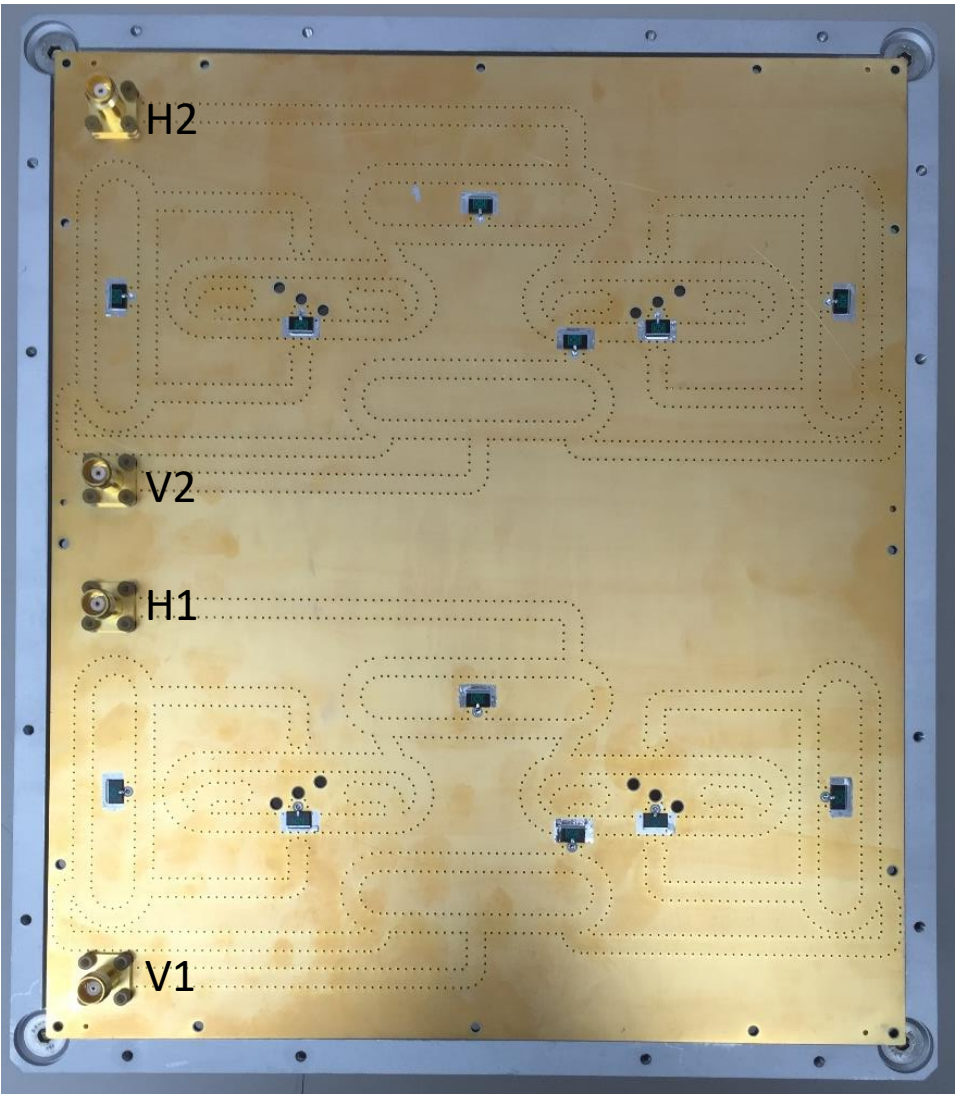


Feed Tile Assembly Section

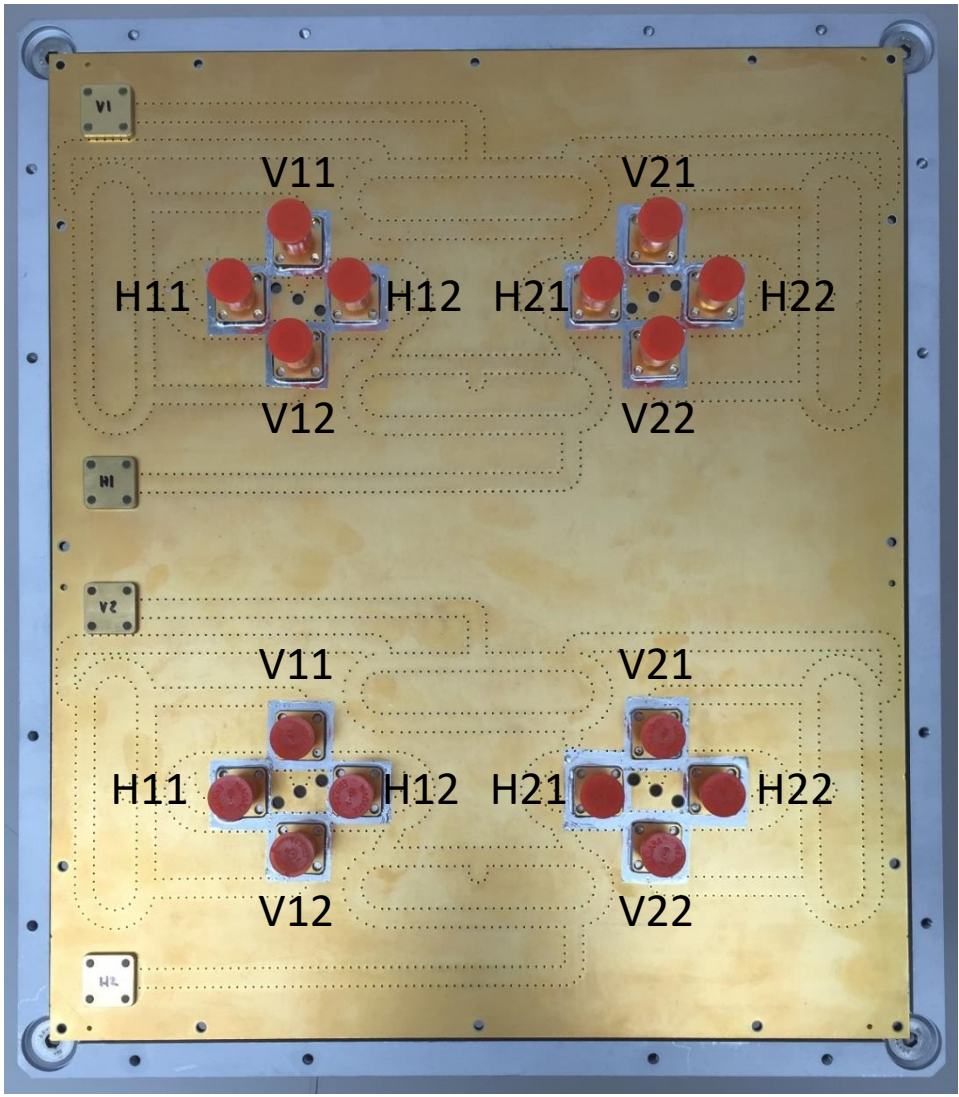


Modified TNC Connector

Feeding Network Test Board

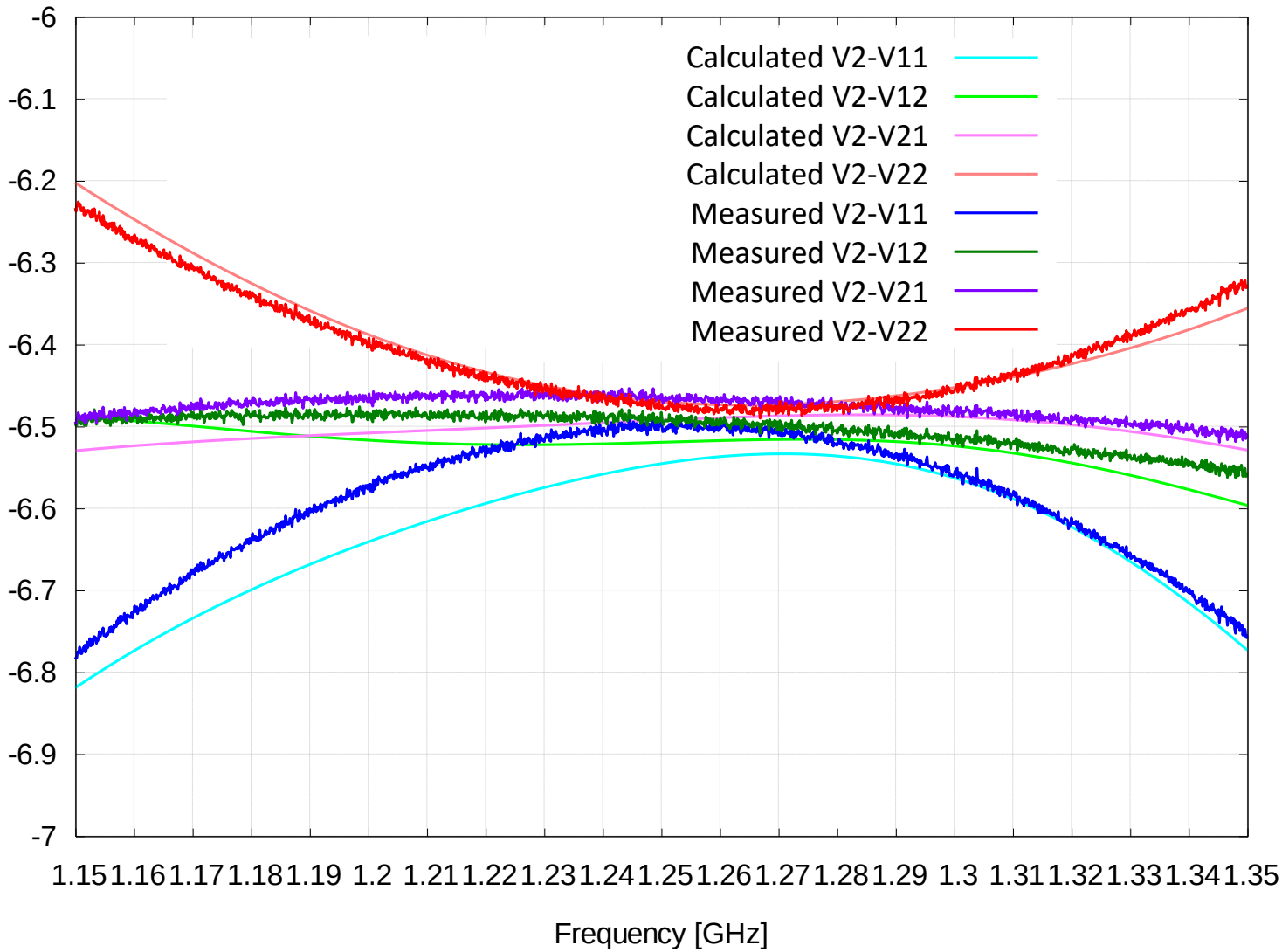


Bottom View

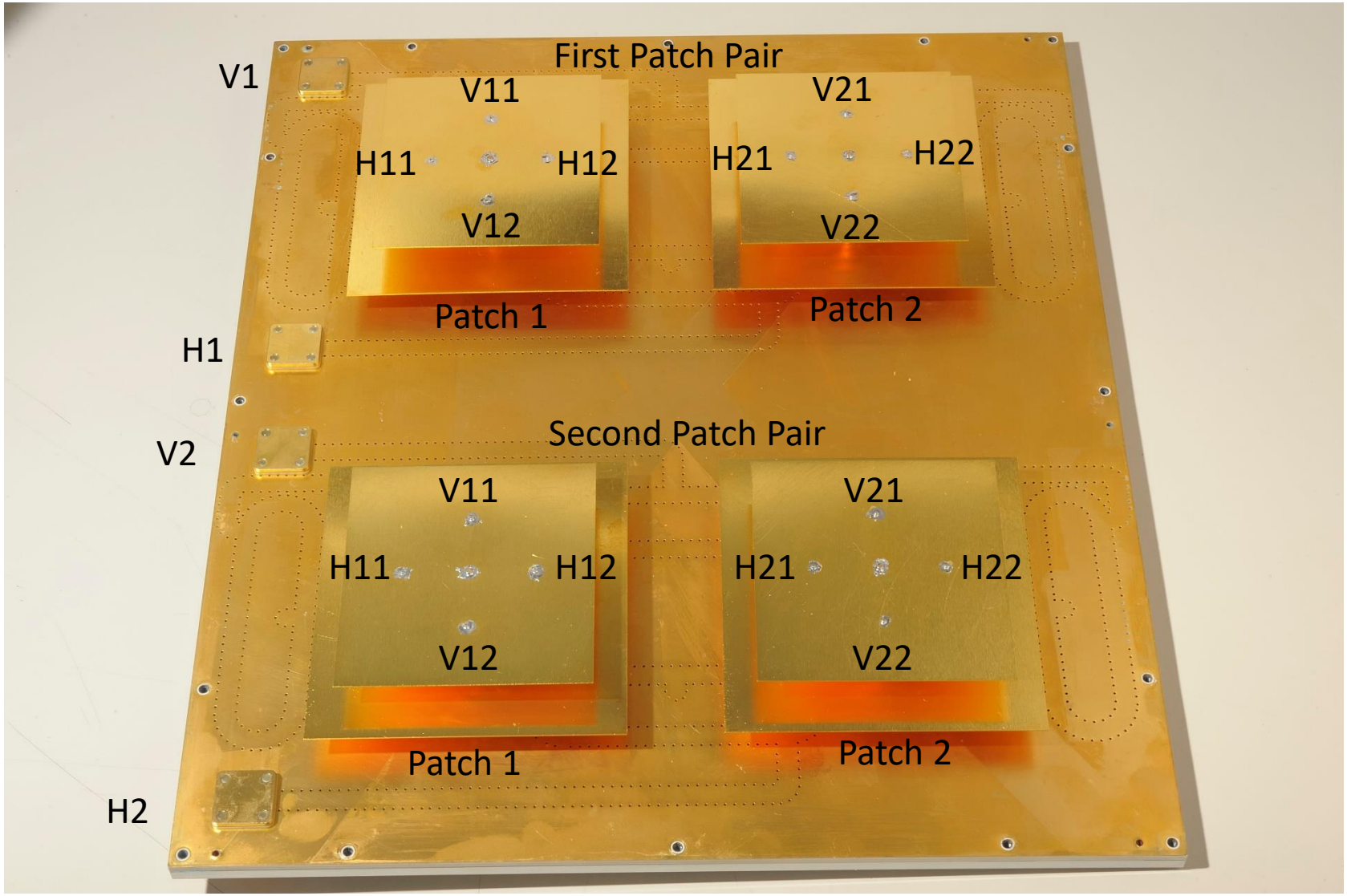


Top View

Power Distribution – V-Pol

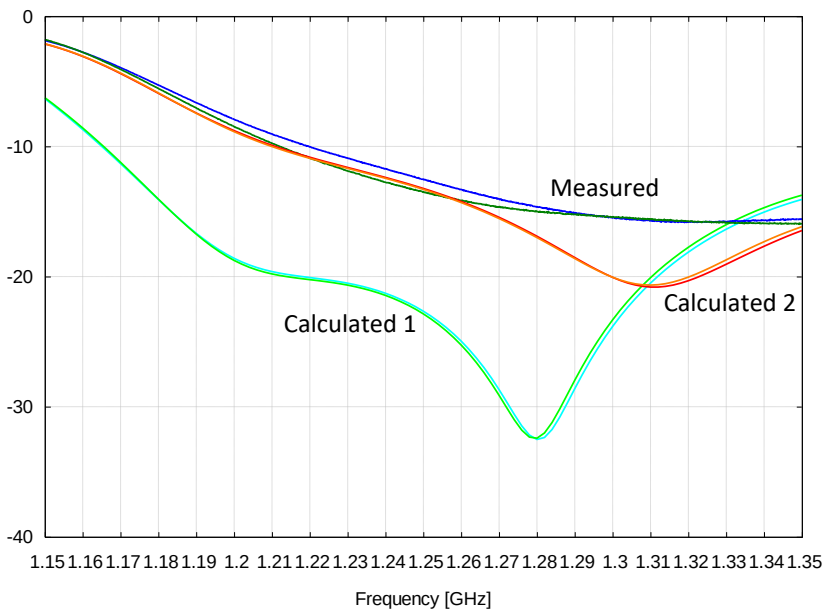


Prototype Tile – Under the "Hood" View

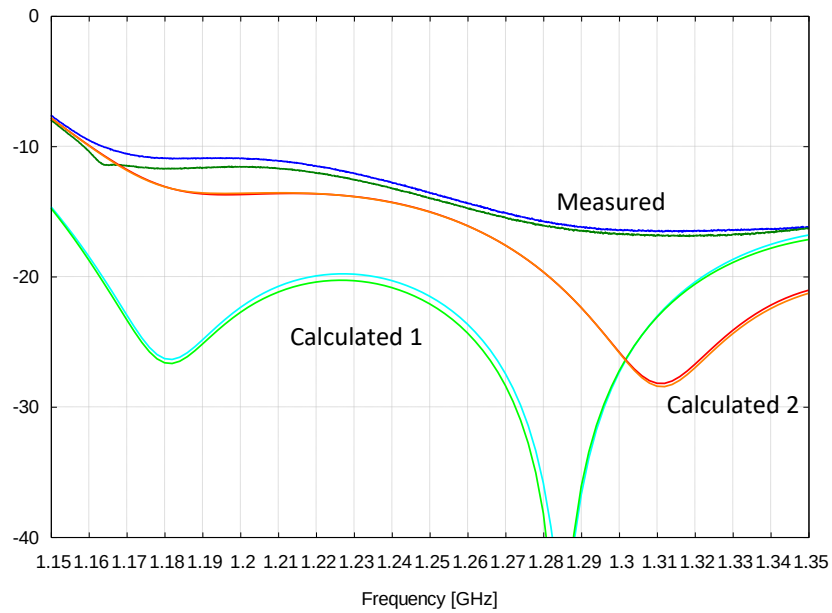


Return Loss, Measured Vs. Calculated

H-Pol



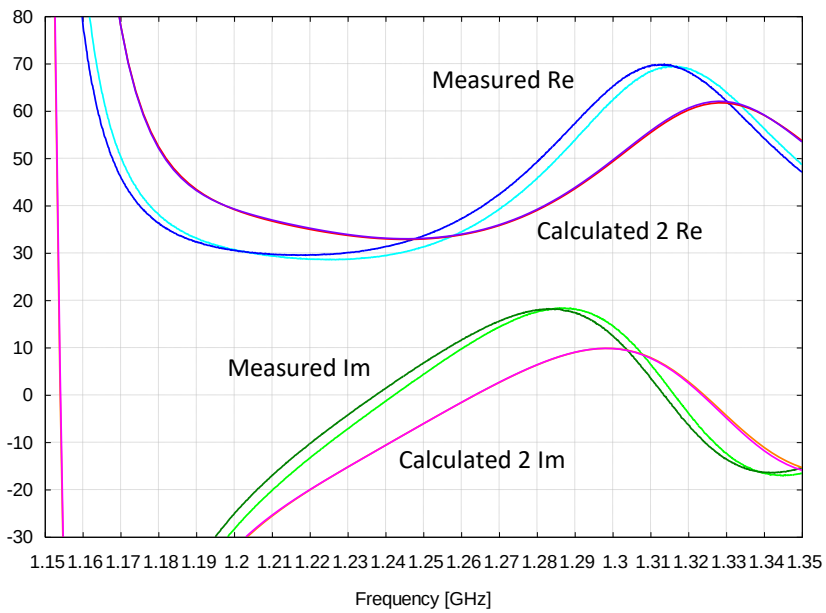
V-Pol



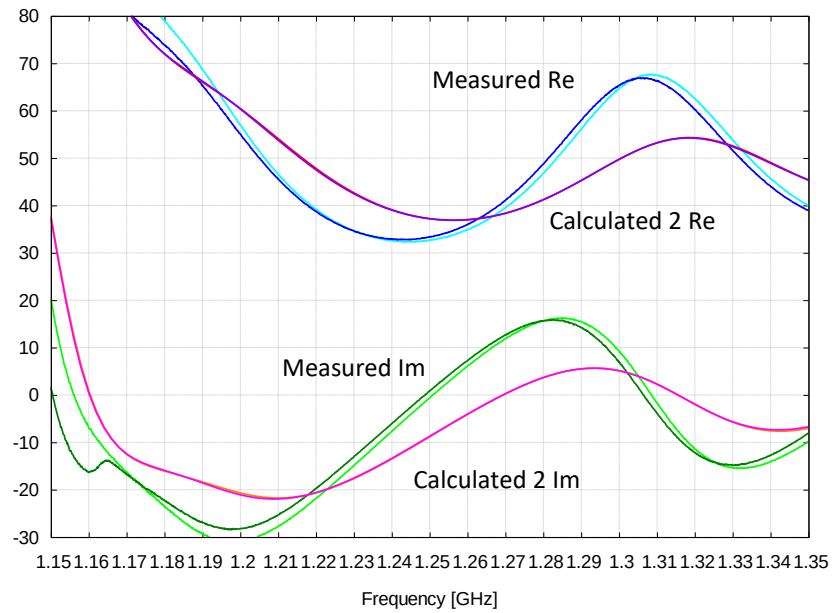
Measured results are from SN2 after thermal cycling

Input Impedance, Measured Vs. Calculated

H-Pol

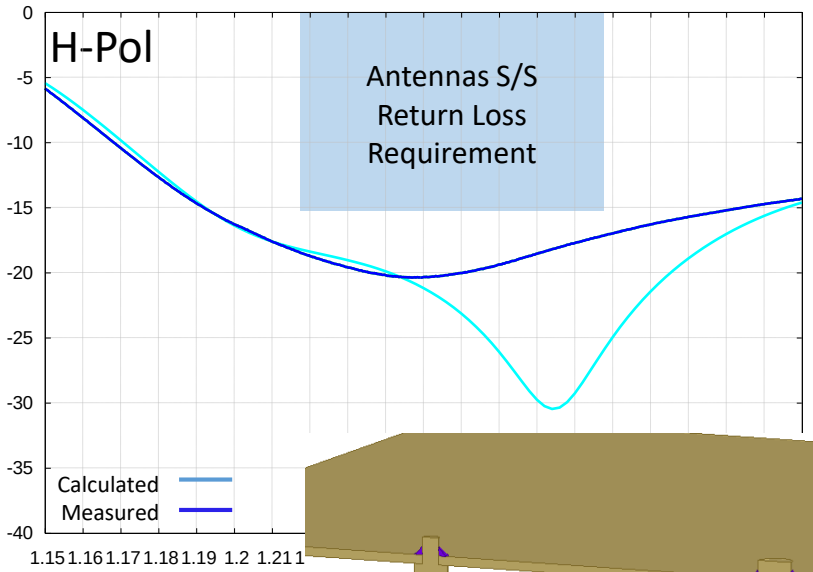


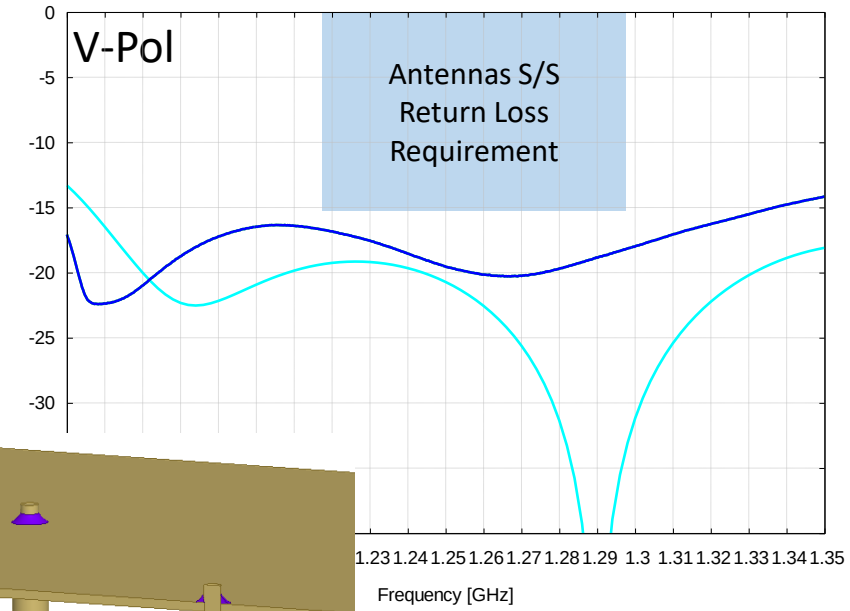
V-Pol

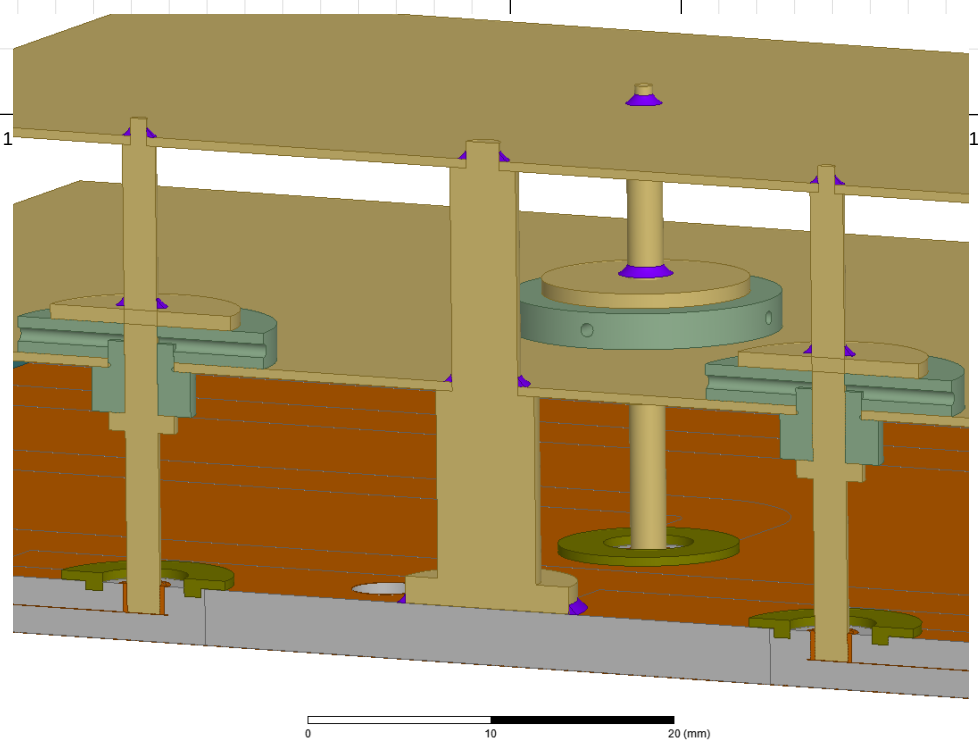


Measured results are from SN2 after thermal cycling

Re-Tuned Tiles

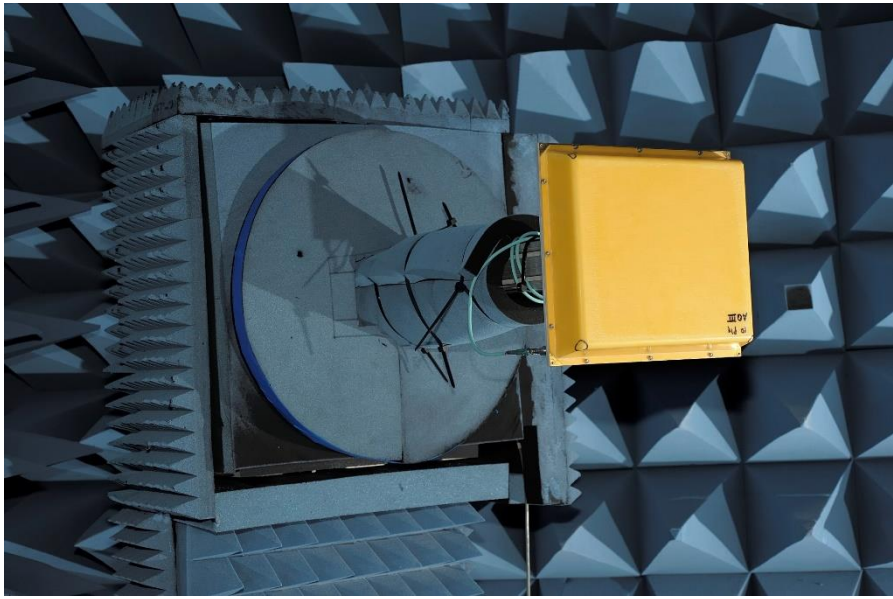




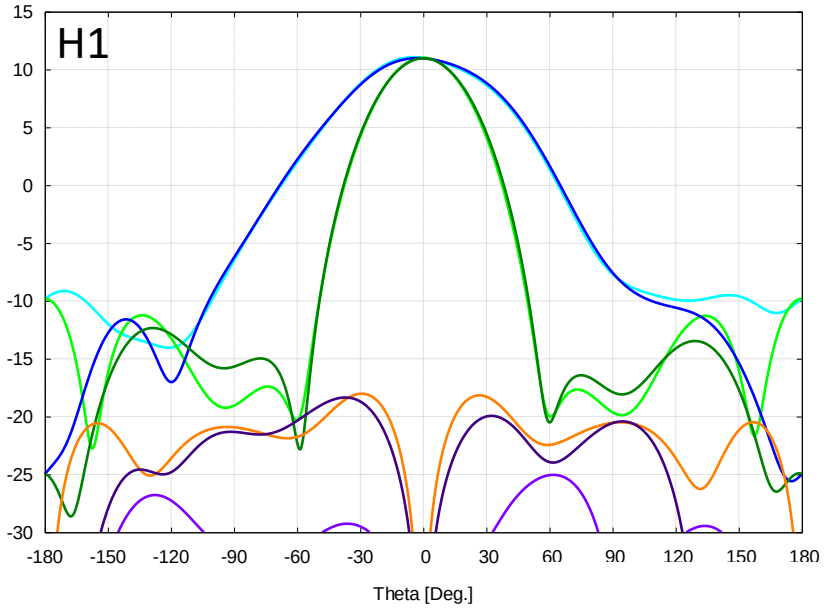


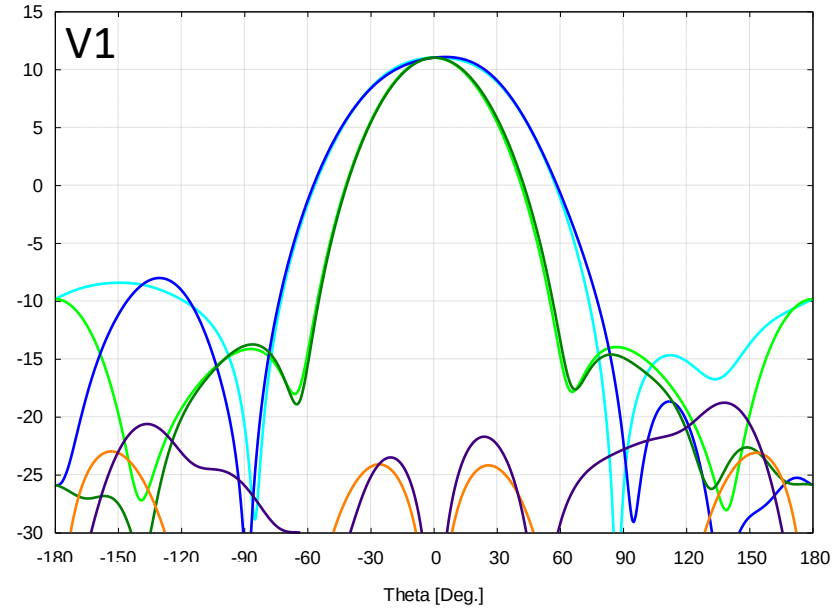
Prototype Tile Radiation Patterns

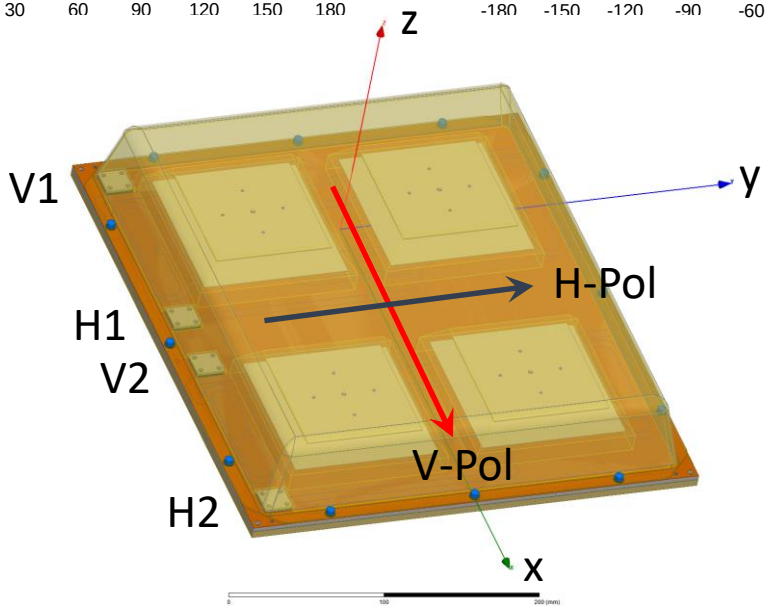
- Both prototype tiles were measured at NSI in a spherical near field range
- Standard Gain Horn was also measured in the same chamber
- Alignment was performed using a laser tracker



Calculated Vs. Measured Patterns

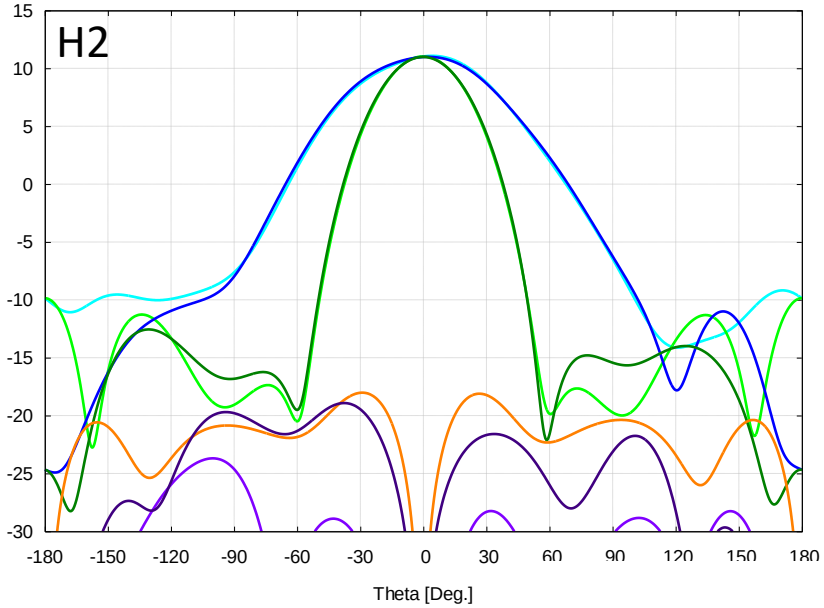


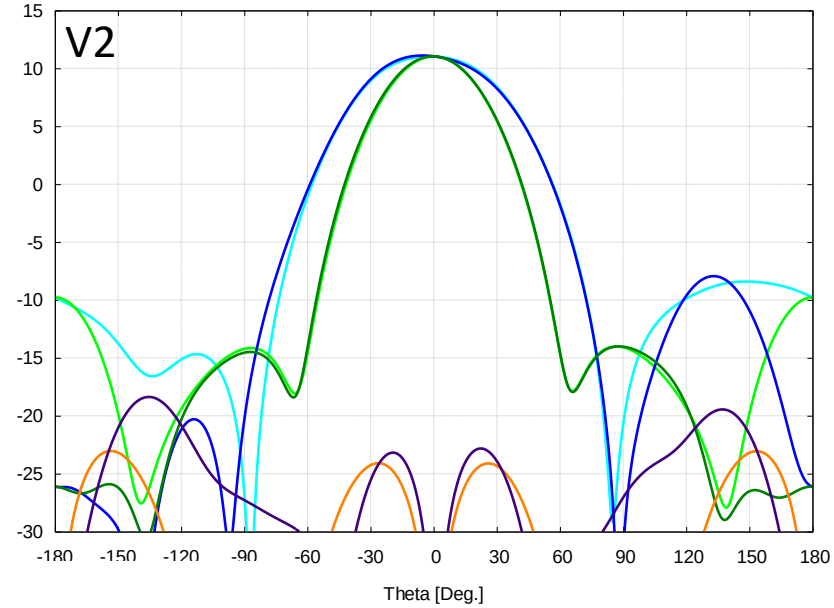


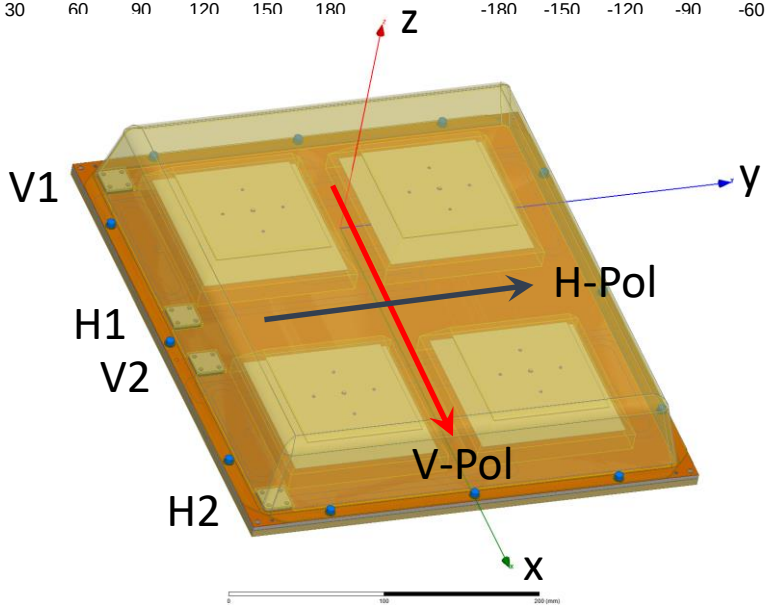


Calculated Co-pol 00°
Calculated Co-pol 90°
Measured Co-pol 00°
Measured Co-pol 90°
Calculated Cx-pol 00°
Calculated Cx-pol 90°
Measured Cx-pol 00°
Measured Cx-pol 90°

Calculated Vs. Measured Patterns

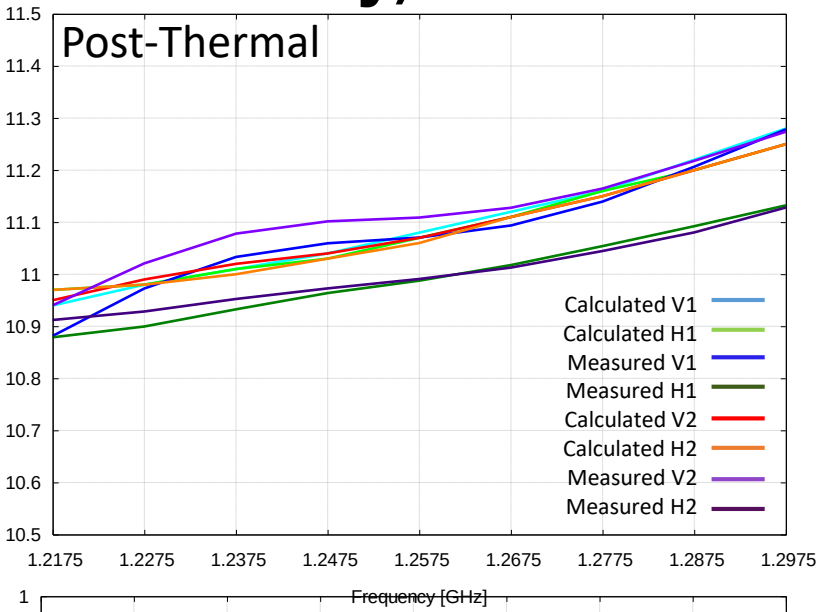


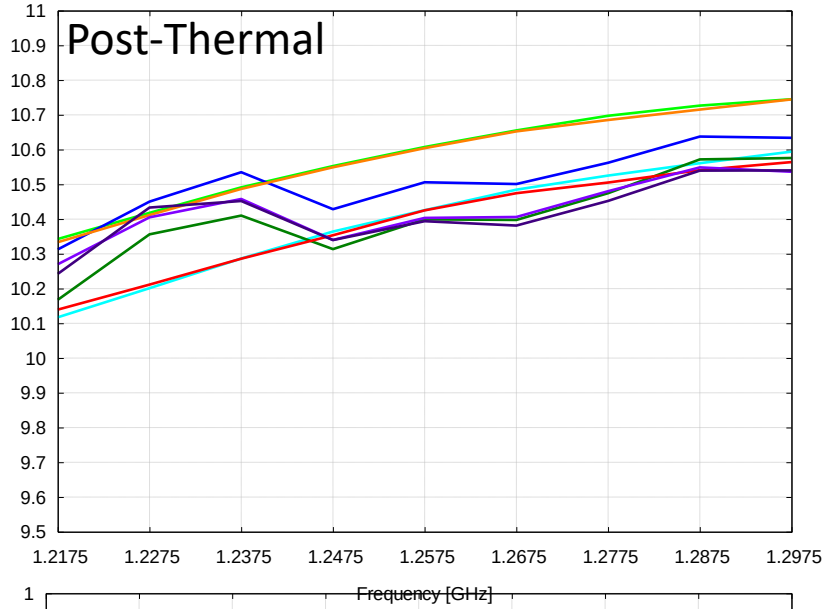


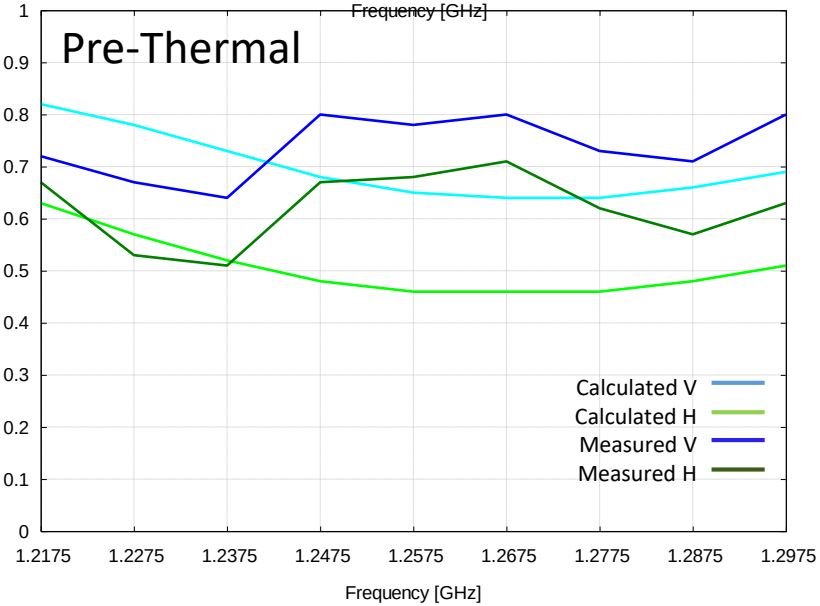


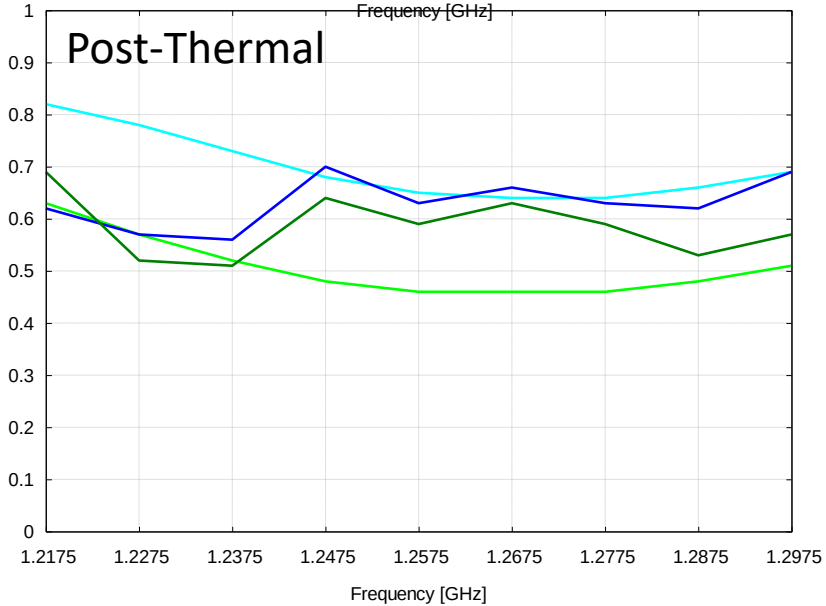
Calculated Co-pol 00°
Calculated Co-pol 90°
Measured Co-pol 00°
Measured Co-pol 90°
Calculated Cx-pol 00°
Calculated Cx-pol 90°
Measured Cx-pol 00°
Measured Cx-pol 90°

Directivity, Gain & Insertion Loss









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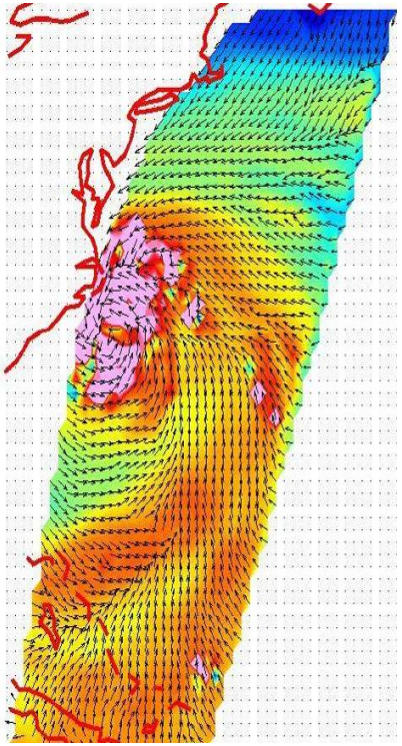
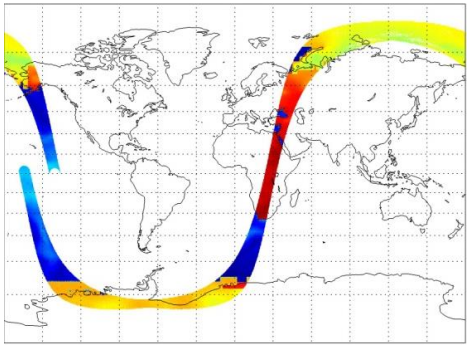
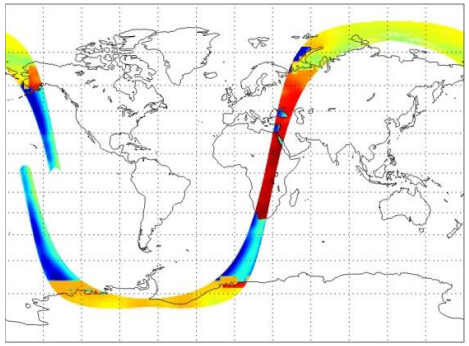
Space and Missile Systems Center

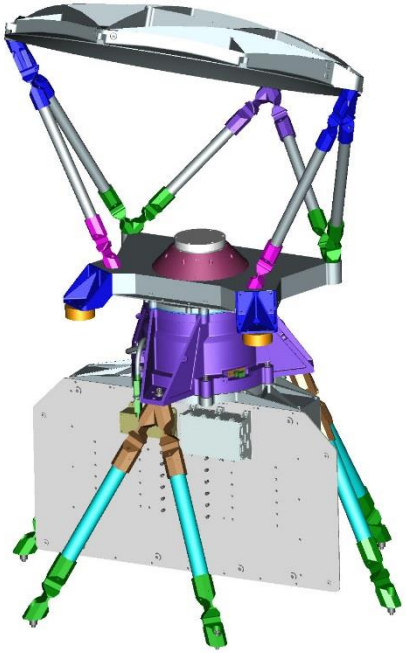
COWVR

Compact Ocean Wind Vector Radiometer



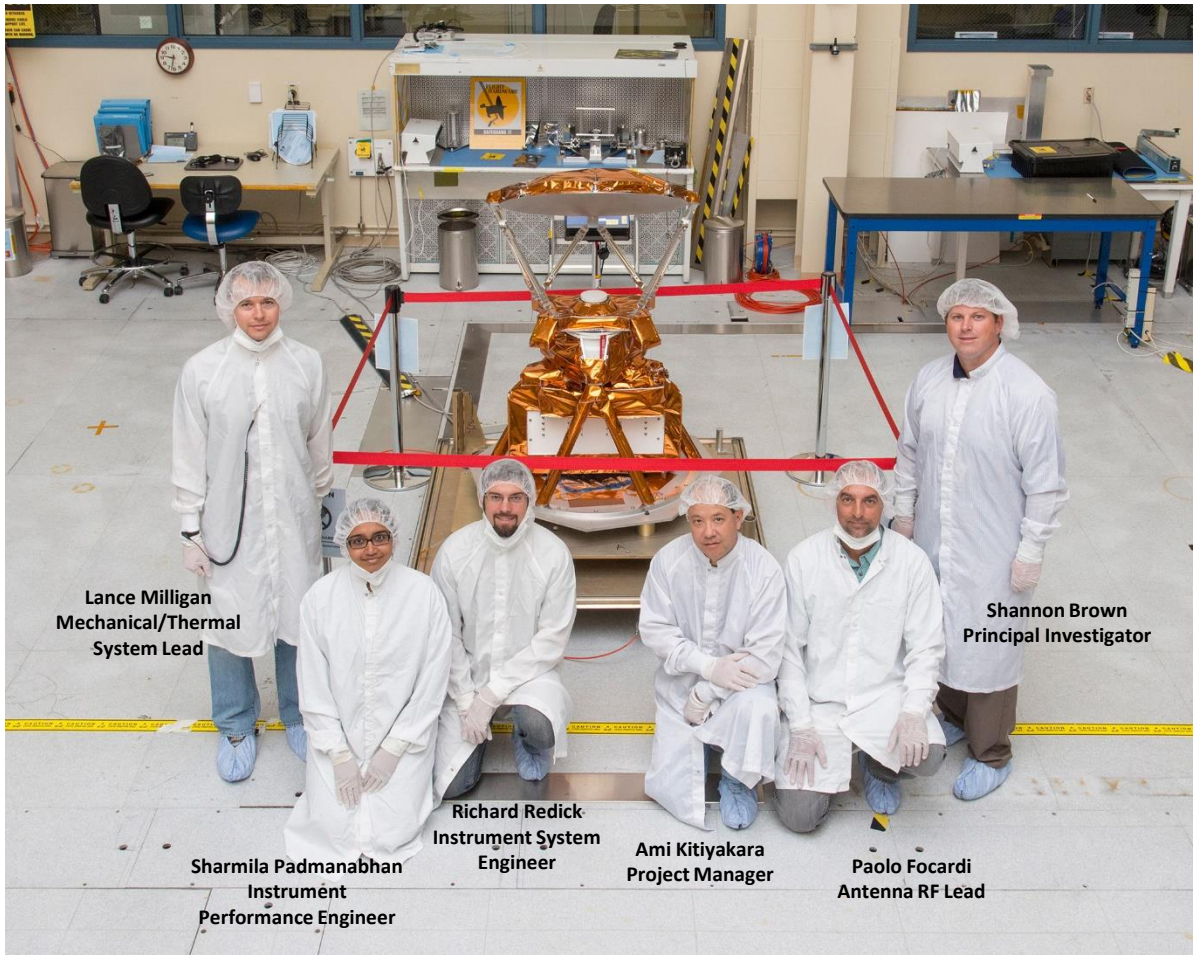






COWVR Agenda

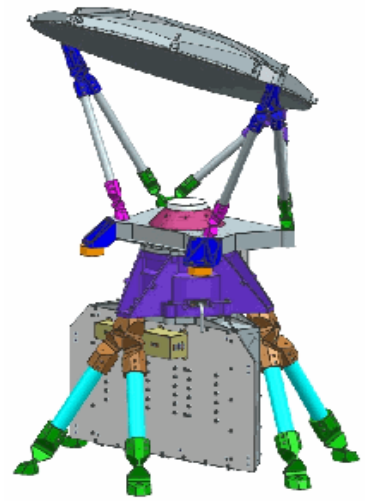
- Overview of Antenna System
- Initial RF Model
- Performance Verification
- Improved RF Model
- Latest Results

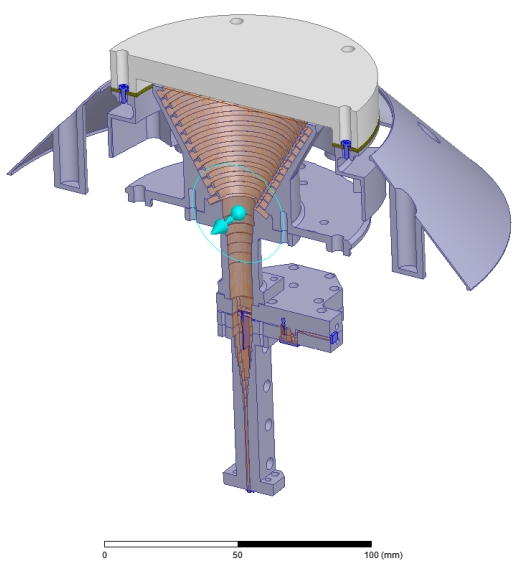


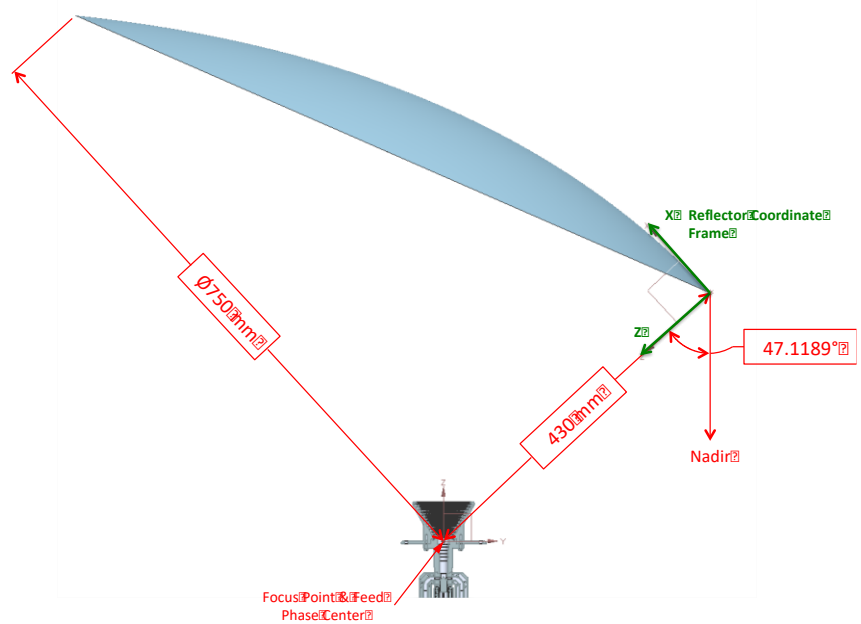
COWVR System Engineering Team

Antenna RF System

- Antenna RF System consists of a single fixed (non-rotating) feed horn illuminating a 75 cm rotating reflector
- Feed design was inherited from Jason 3 covering 18.7 GHz, 23.8 GHz and 33.9 GHz bands
- Entire feed assembly is modeled with HFSS
- Calculated radiation pattern includes surrounding baffle and the EPS Radome
- The baffle was added in order to reduce interaction between reflector and top deck

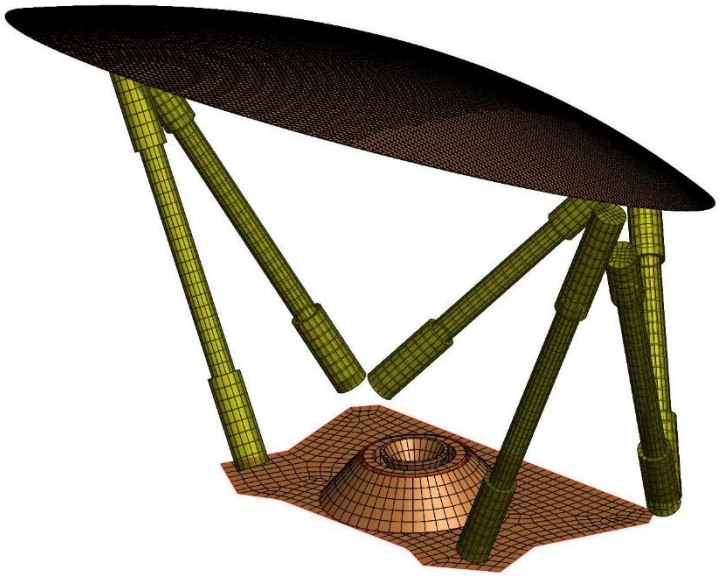


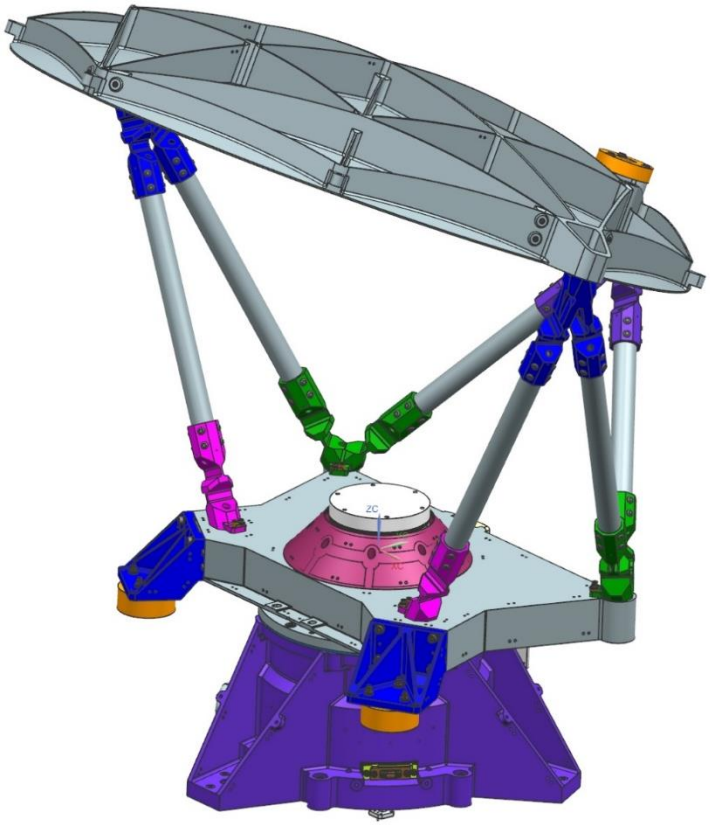




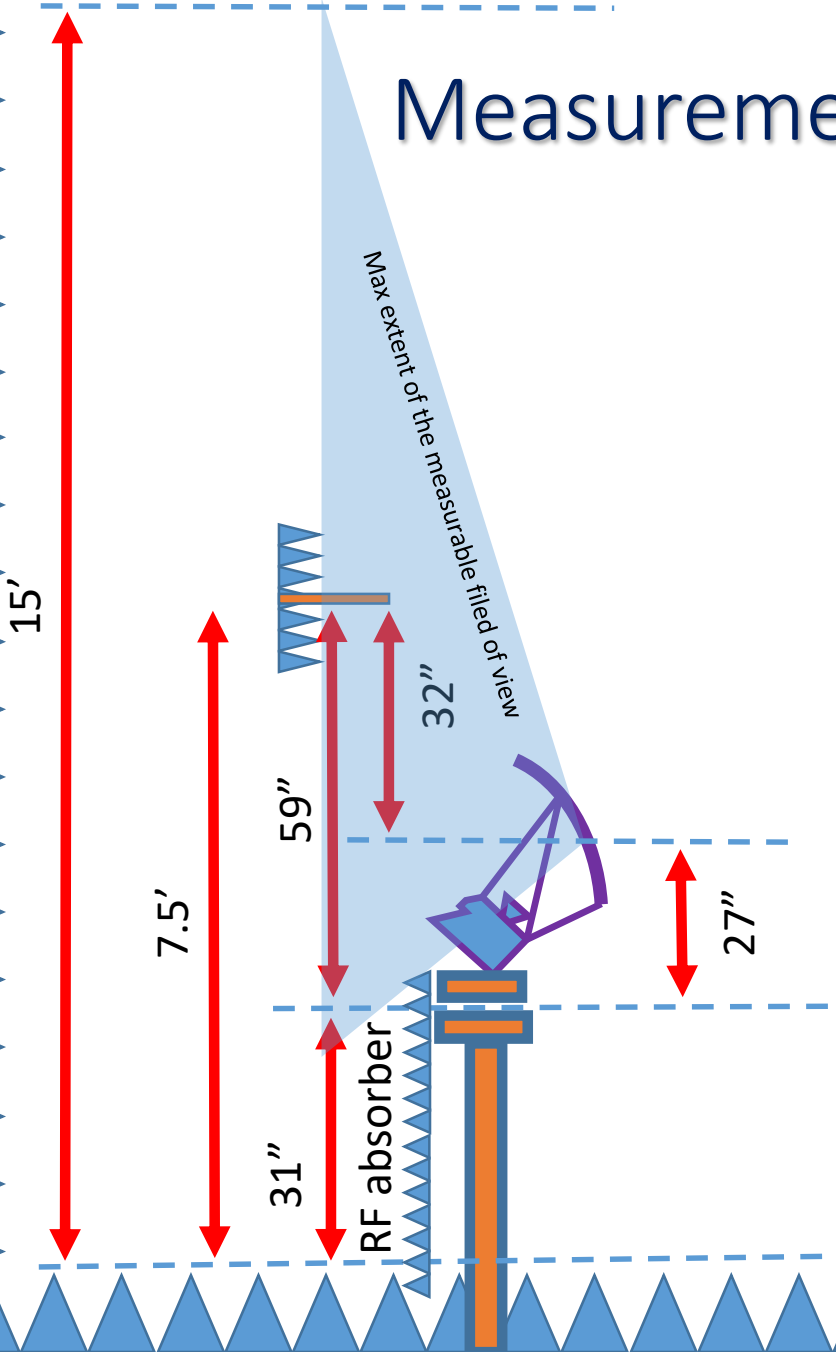
Initial RF Model

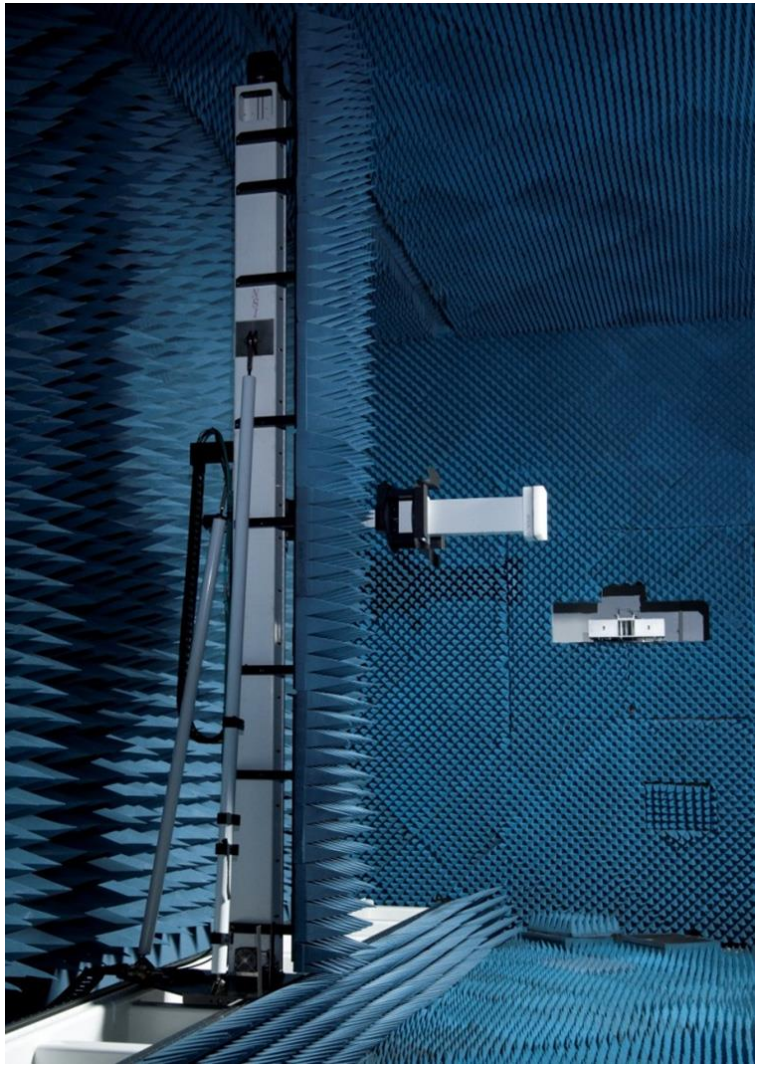
- As-built reflector surface from photogrammetry data
- As-built position and orientation of the feed
- Calculated feed pattern from HFSS model
- Top deck and struts with simplified geometry



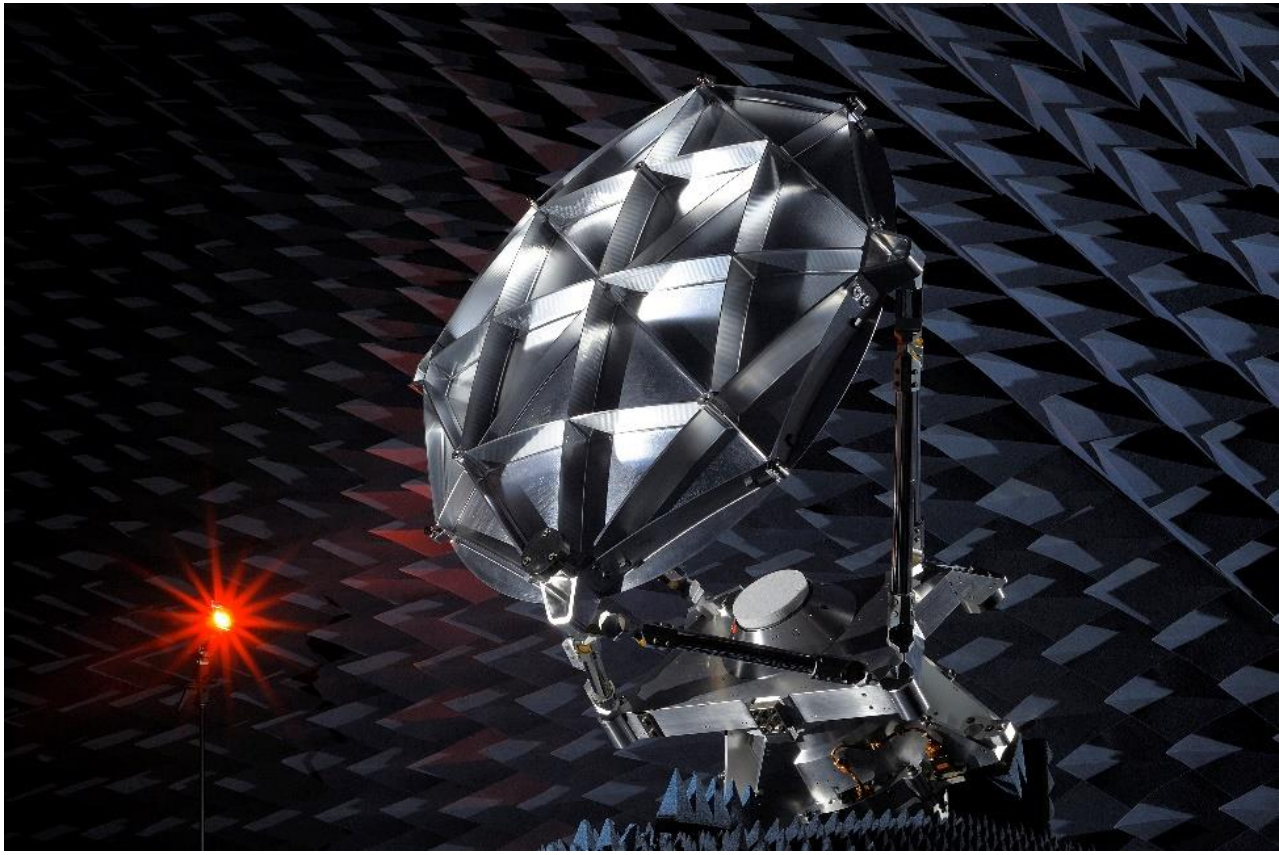


Measurement Range Layout

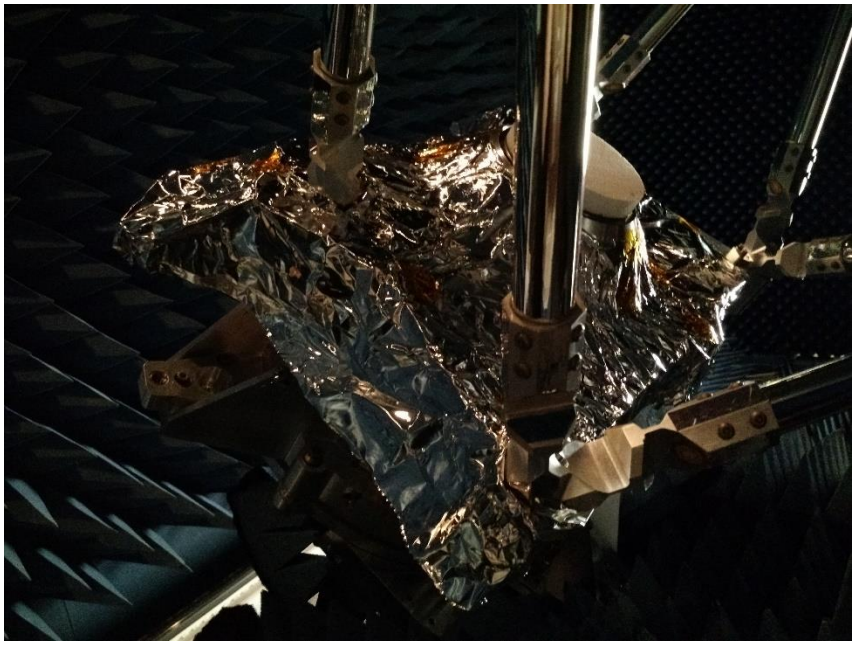


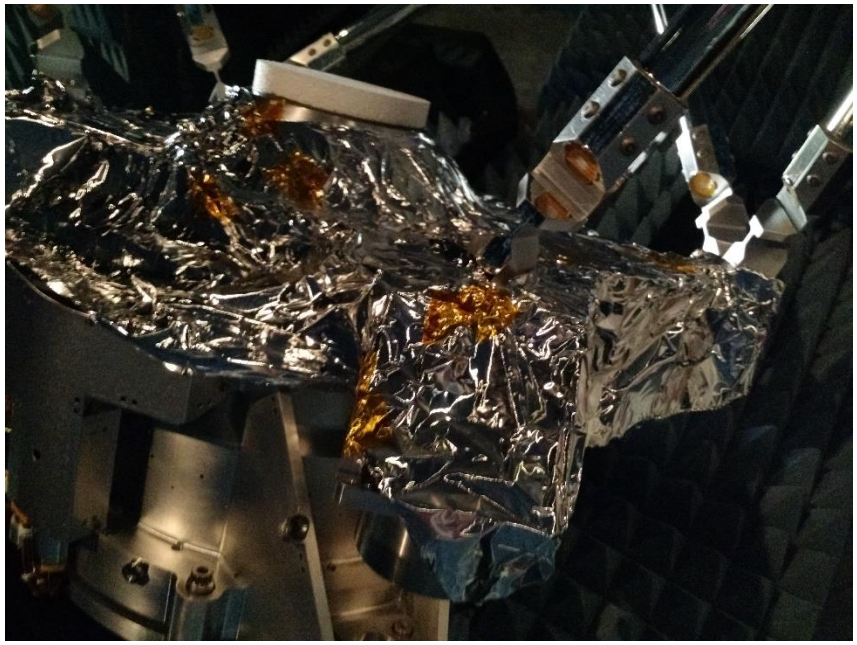


COWVR Instrument During RF Tests



Test Case with Al Foil

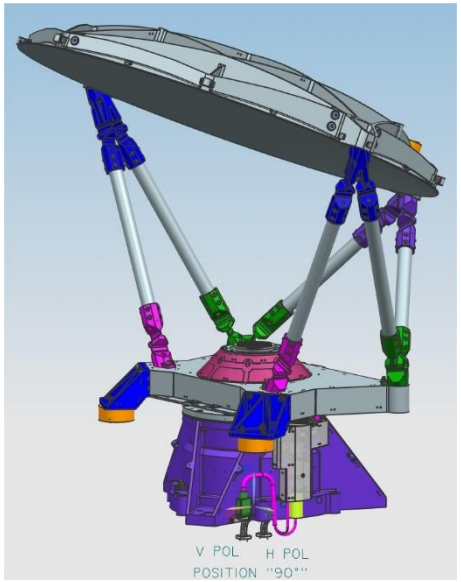


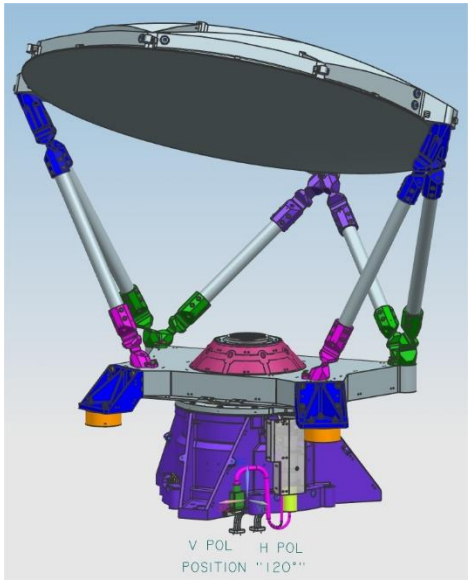


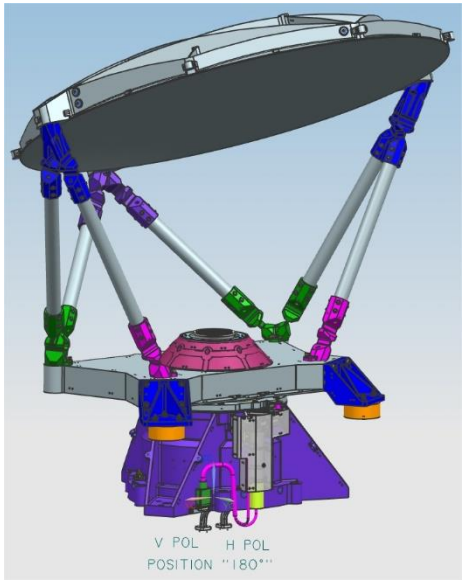
- One data set was repeated after installation of Al foil on the top deck in order to simulate the effect of thermal blankets
- Results confirmed that thermal blankets won’t affect instrument performance

Test Overview

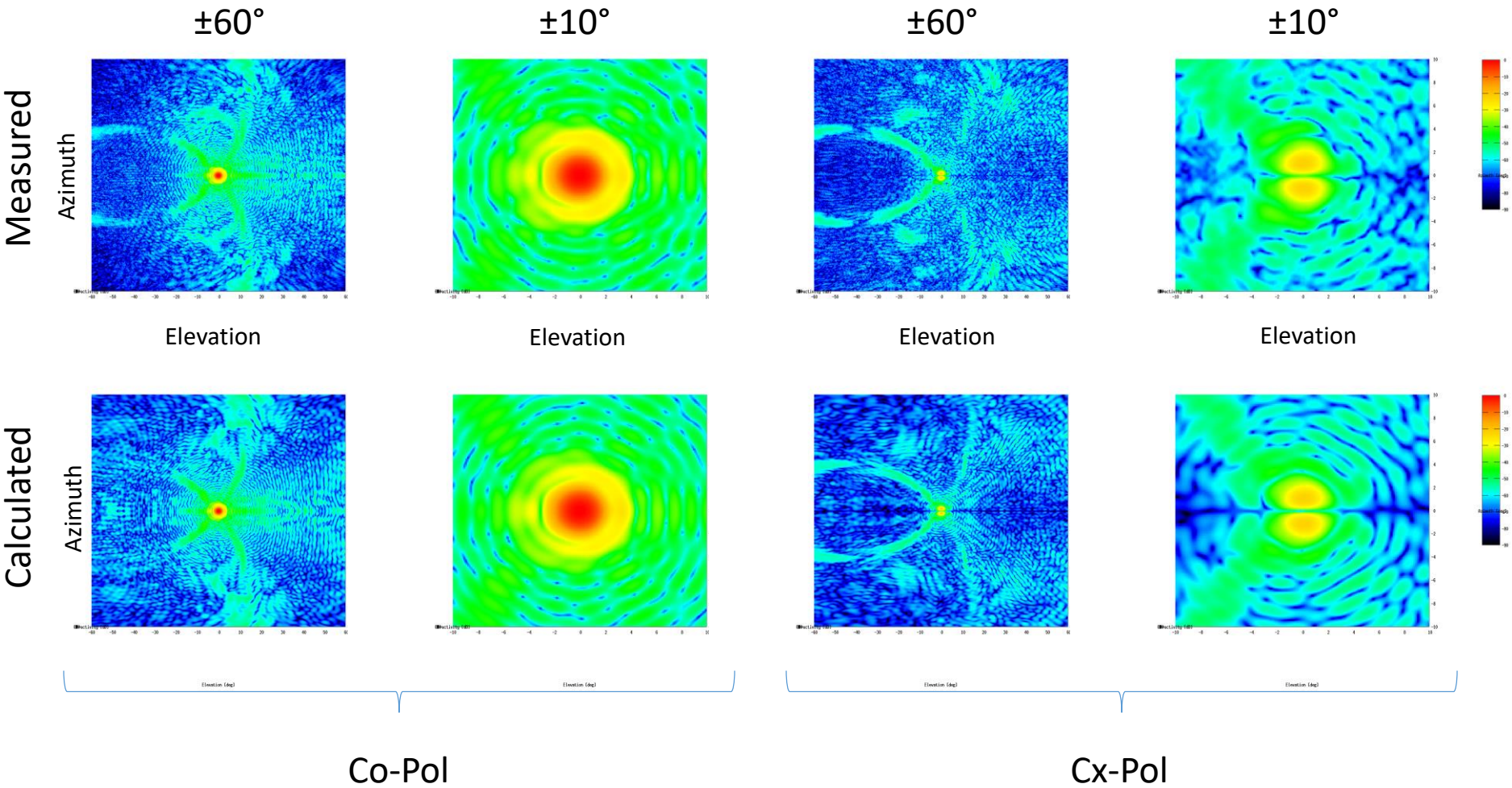
- The performance of the COWVR Instrument, including the SMA and the top deck assembly, was measured with the Planar Near Field Range facility in the 60’ chamber of the JPL Mesa on April 2015
- 3 positions of the top deck (90°, 120° and 180°) were measured, plus one test case for the 180° case with aluminum foil on the top deck to simulate the presence of thermal blankets
- Each position was correlated with metrology data to assess the actual pointing of the instrument in the range reference system





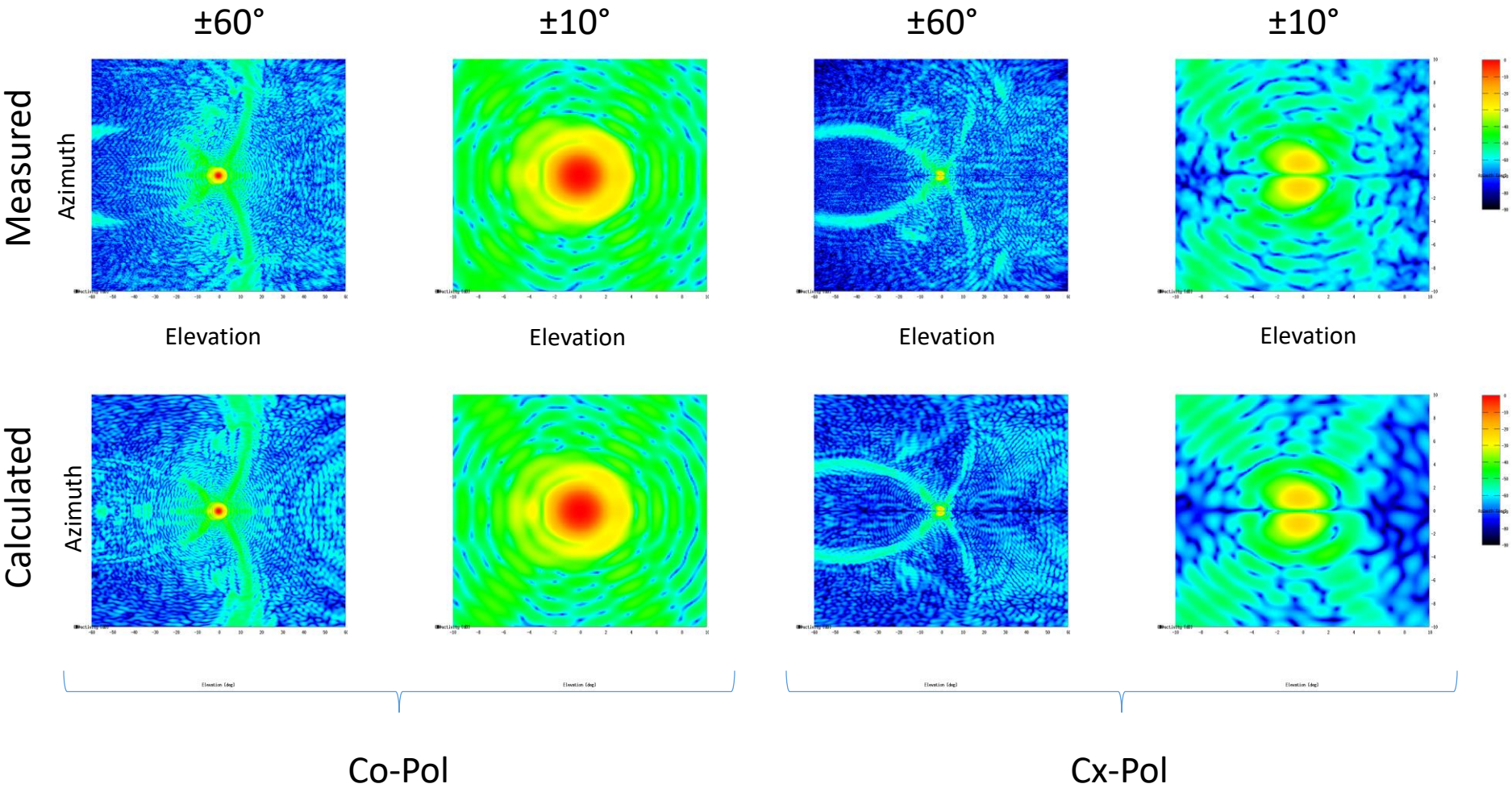


H-Pol Results. 180°. 18.7 GHz



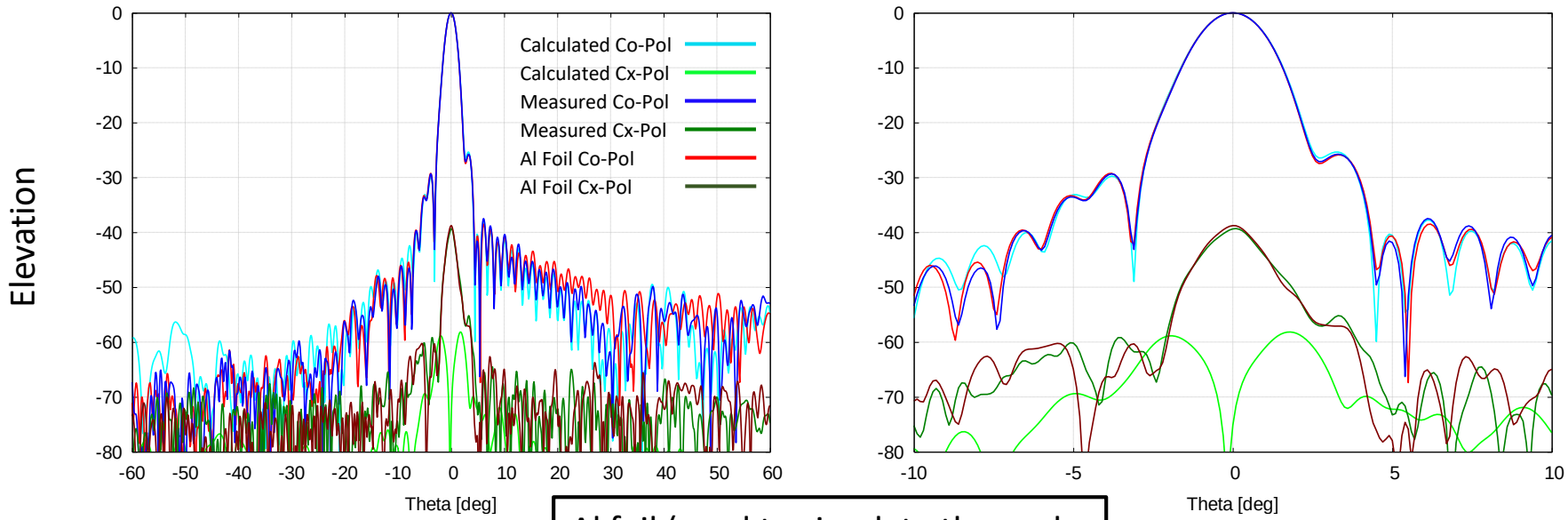
For reference: green = -45dB, light blue = -60dB

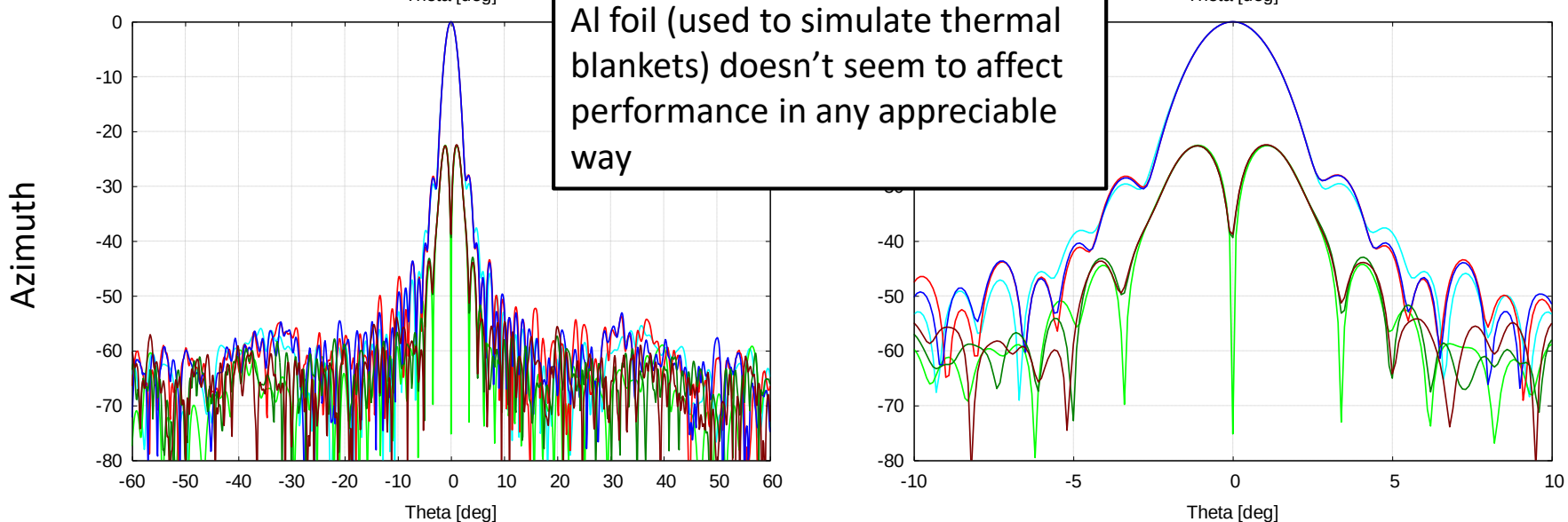
V-Pol Results. 180°. 18.7 GHz



For reference: green = -45dB, light blue = -60dB

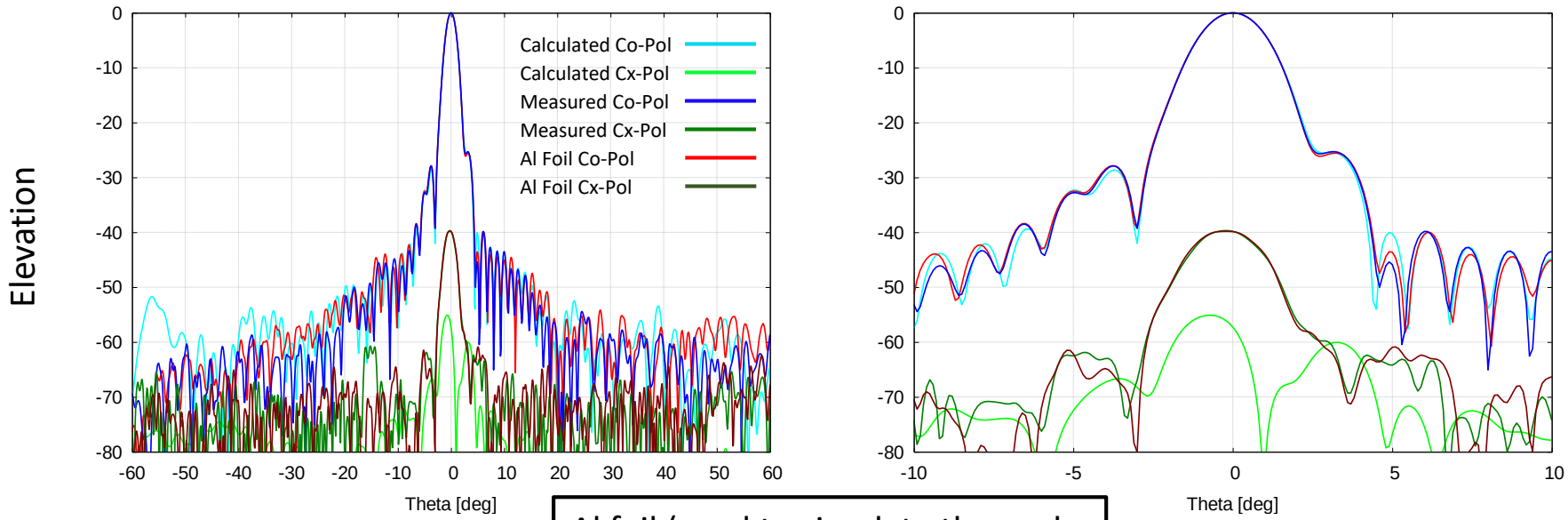
H-Pol Cuts, 180°, 18.7 GHz

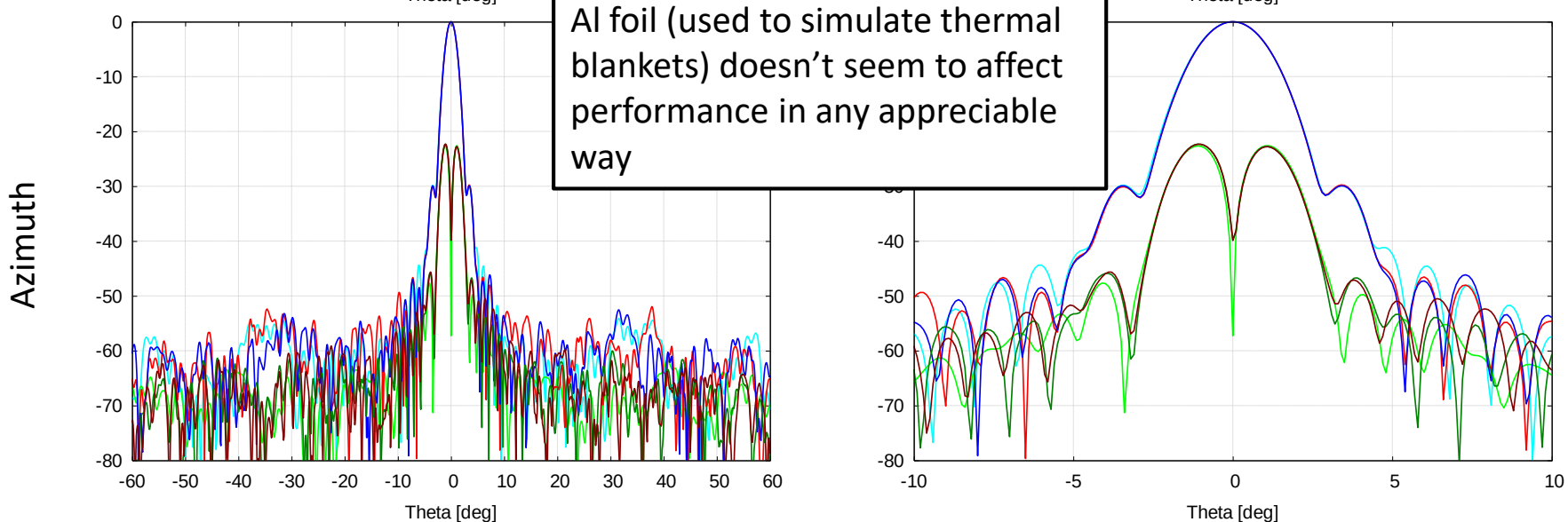




Al foil (used to simulate thermal blankets) doesn't seem to affect performance in any appreciable way

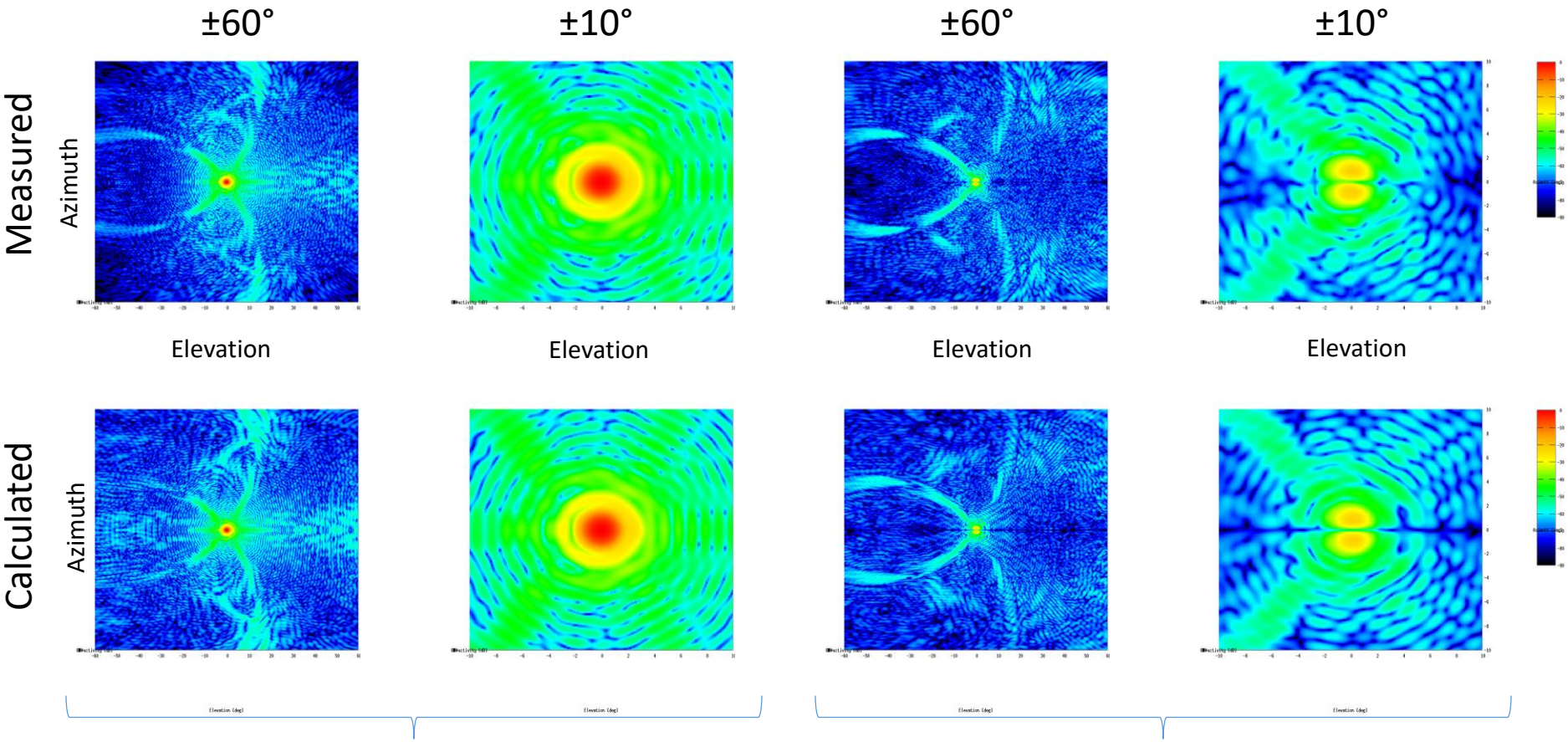
V-Pol Cuts, 180°, 18.7 GHz





Al foil (used to simulate thermal blankets) doesn't seem to affect performance in any appreciable way

H-Pol Results. 180°. 23.8 GHz



For reference: green = -45dB, light blue = -60dB

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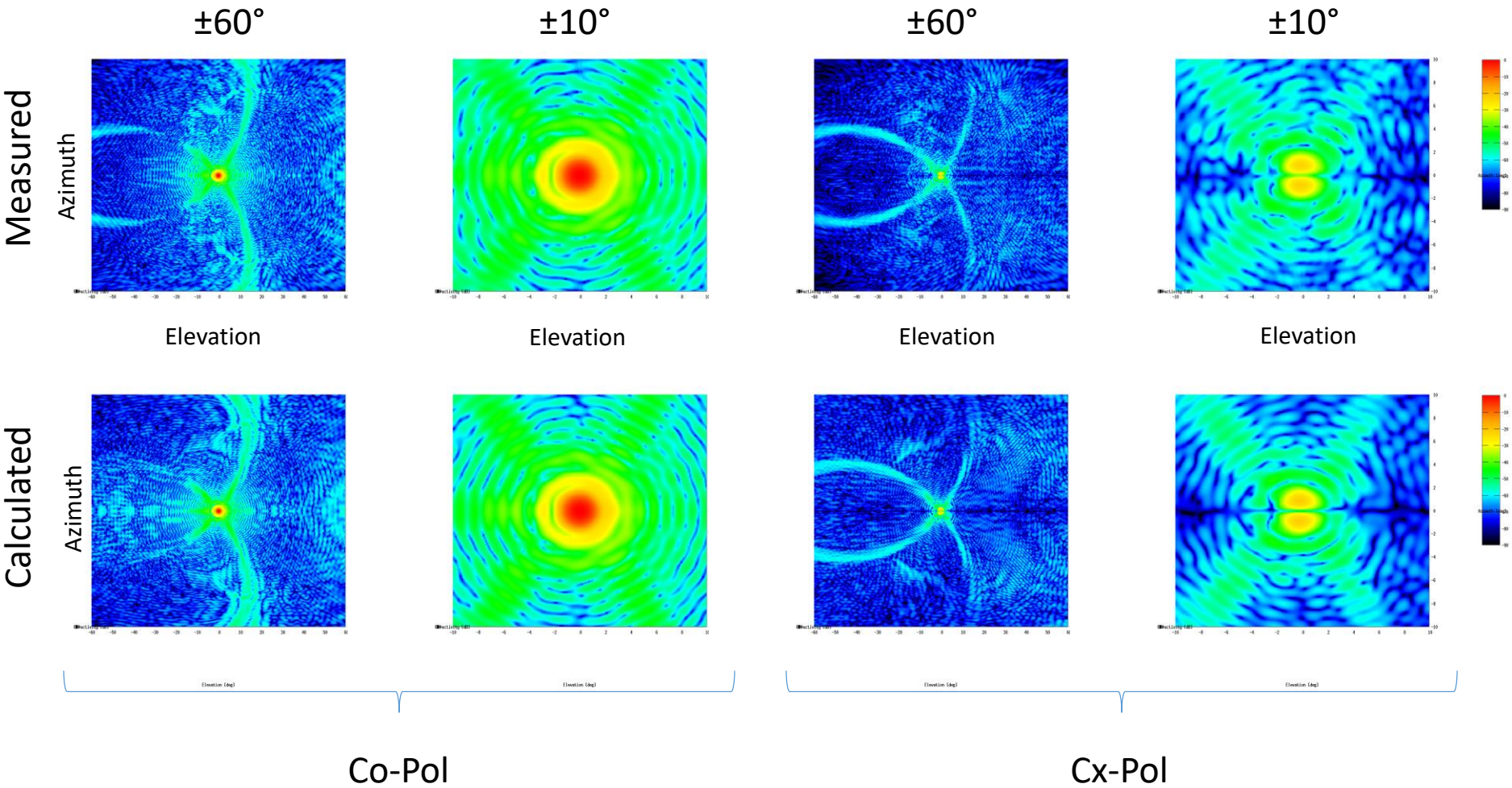
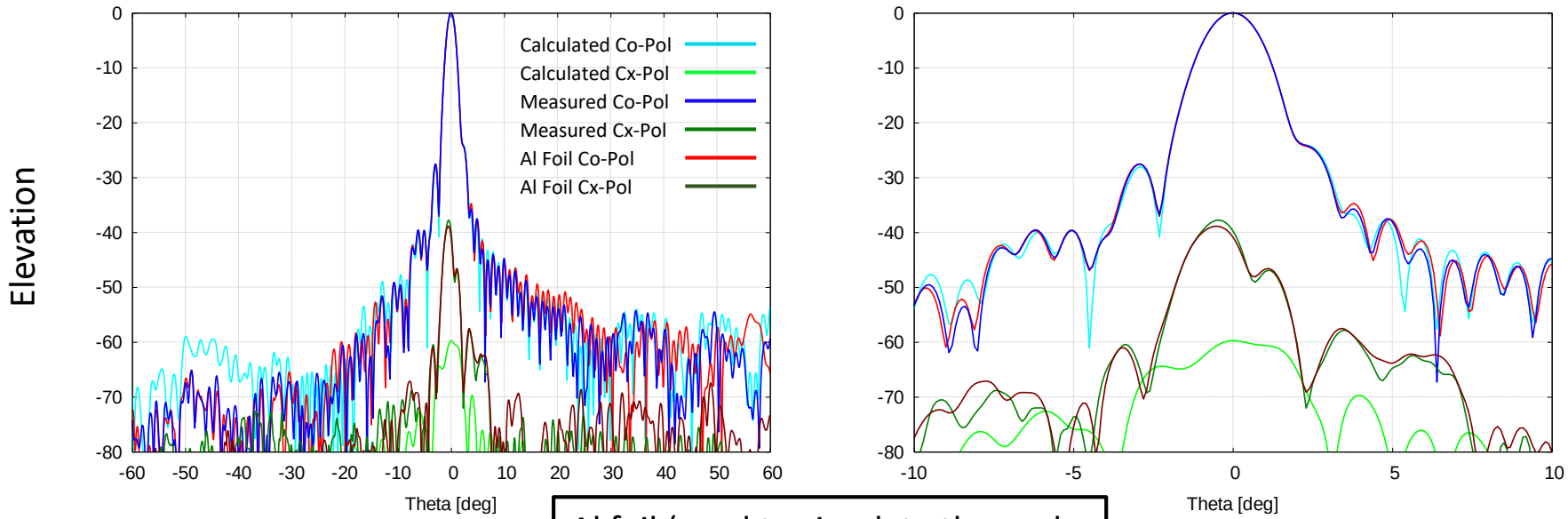
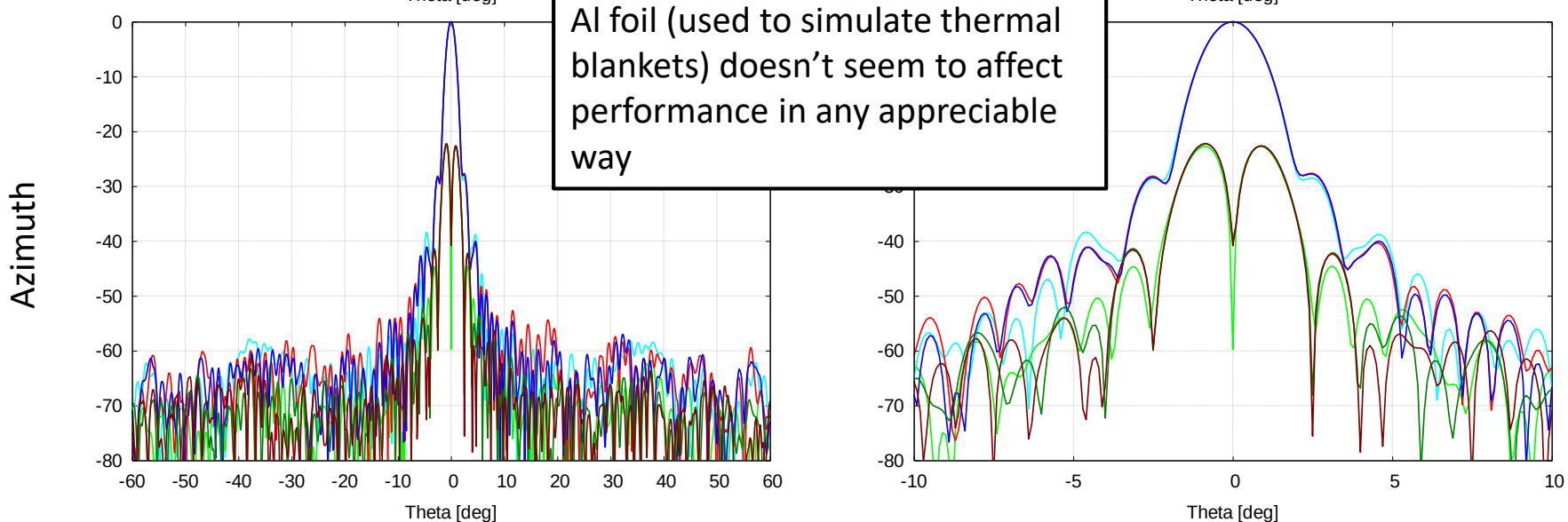
V-Pol Results. 180°. 23.8 GHz



For reference: green = -45dB, light blue = -60dB

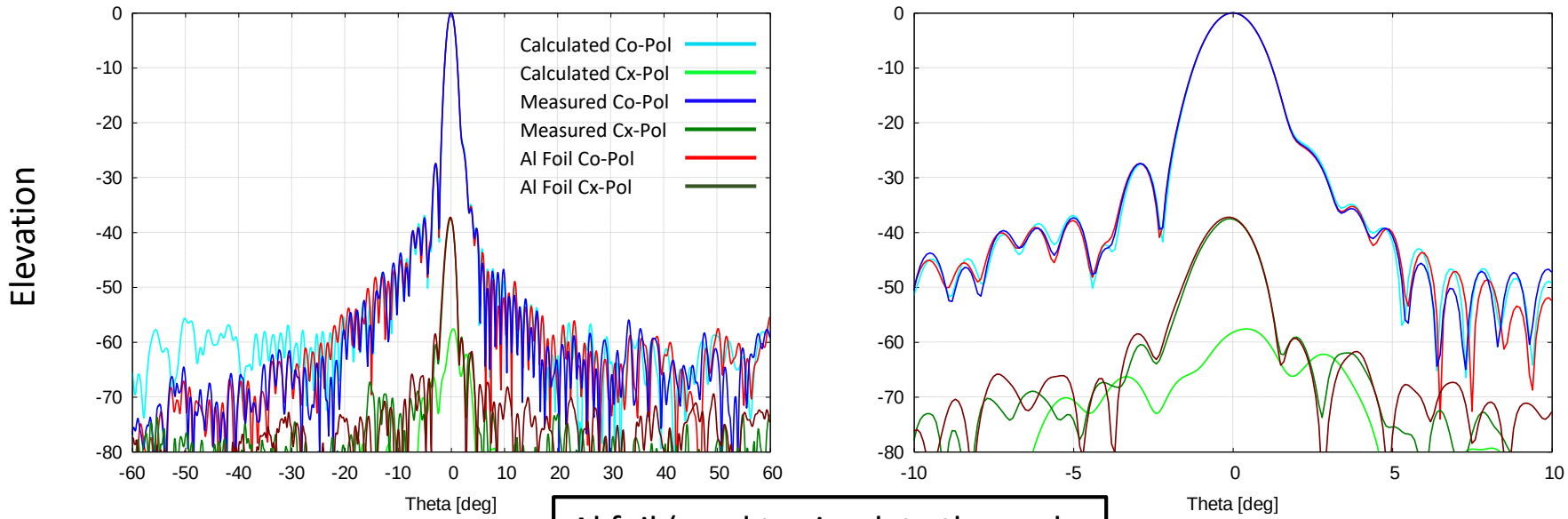
H-Pol Cuts, 180°, 23.8 GHz

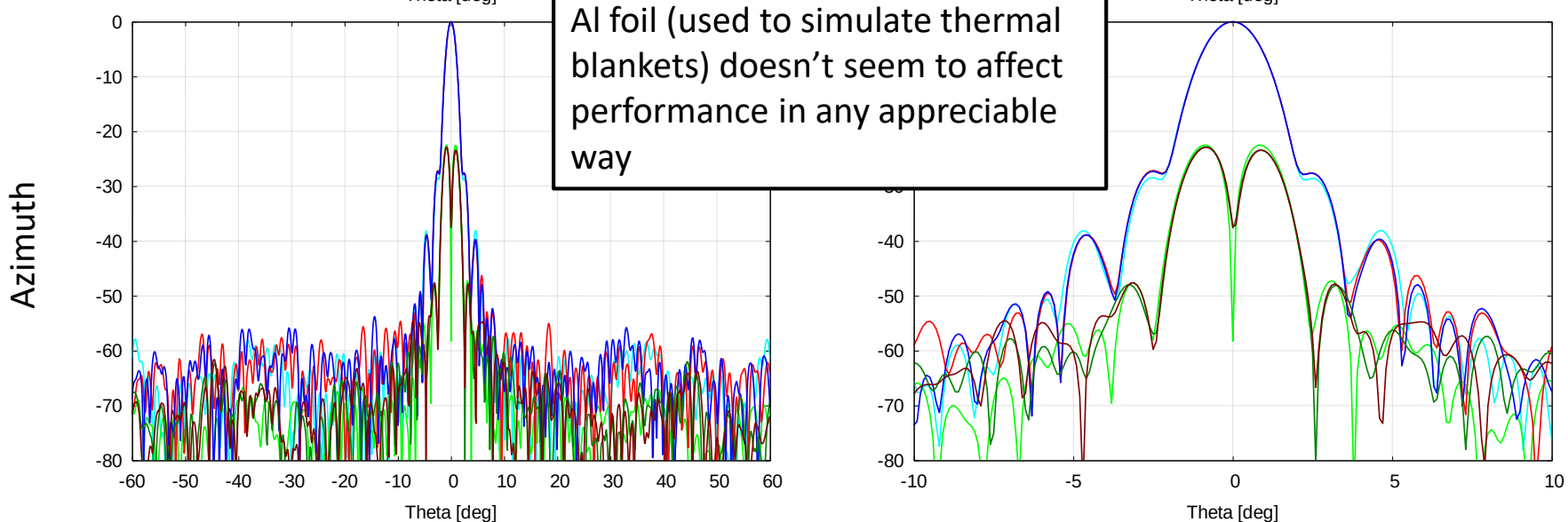




Al foil (used to simulate thermal blankets) doesn't seem to affect performance in any appreciable way

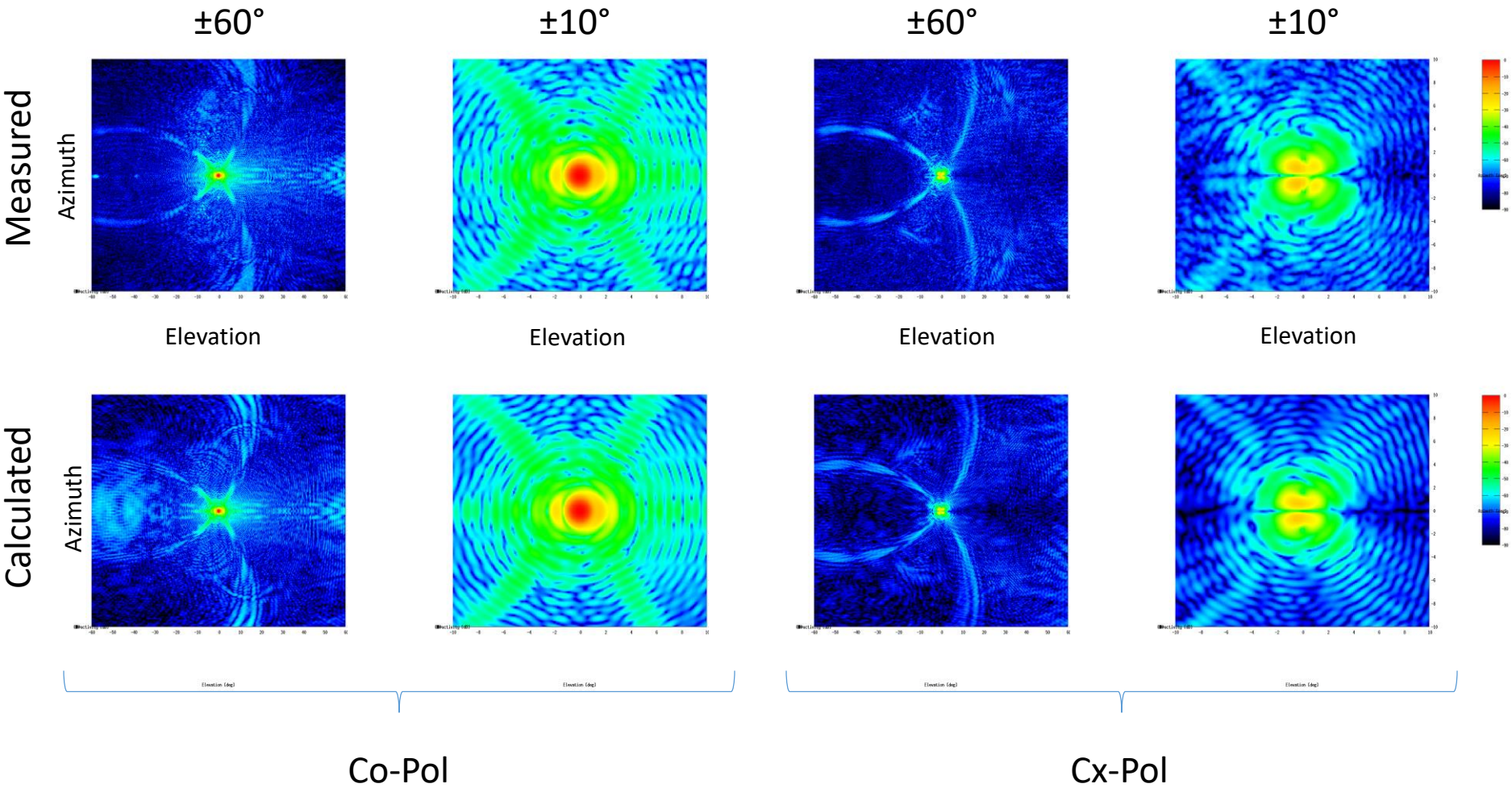
V-Pol Cuts, 180°, 23.8 GHz





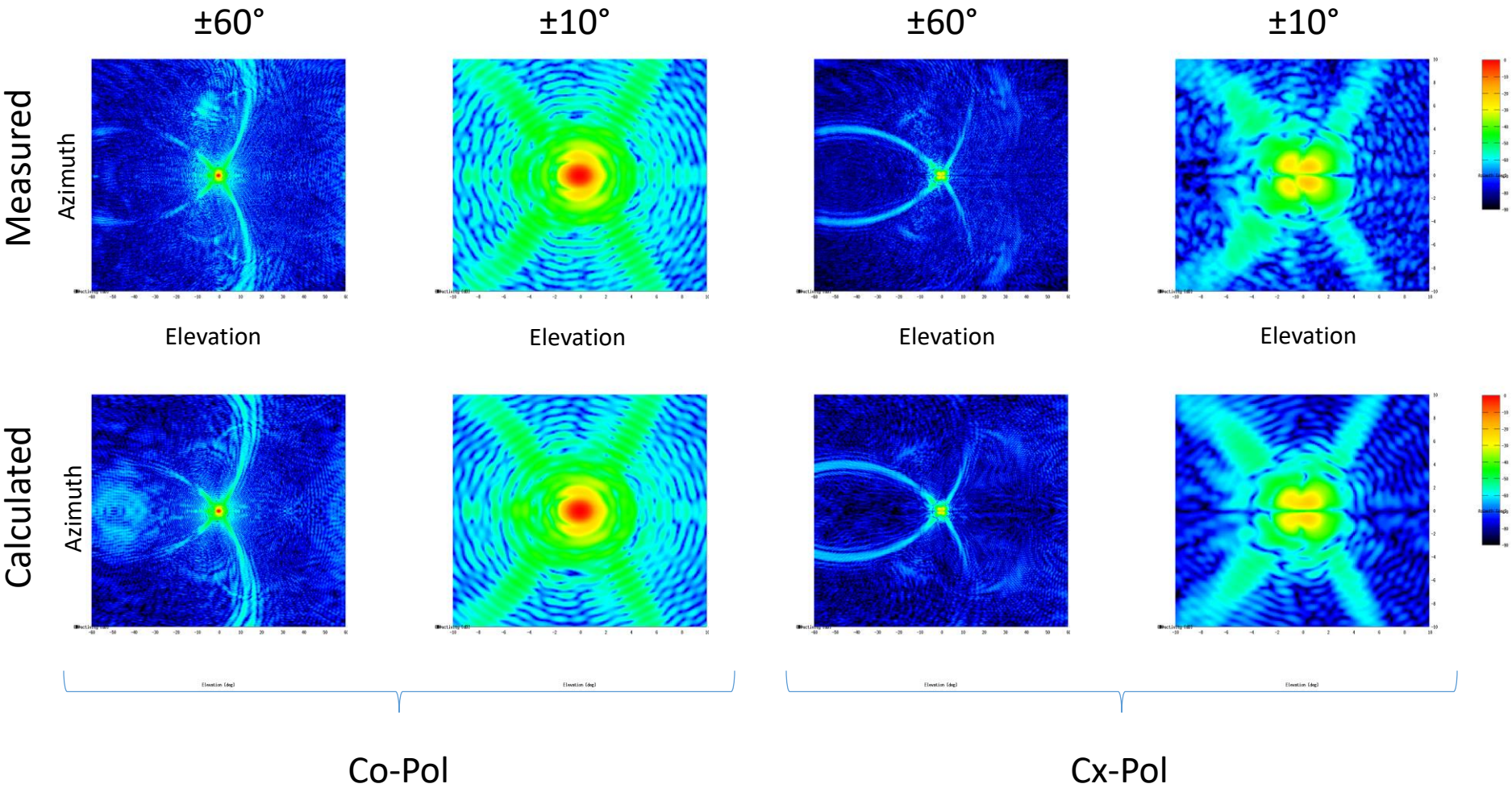
Al foil (used to simulate thermal blankets) doesn't seem to affect performance in any appreciable way

H-Pol Results. 180°. 33.9 GHz



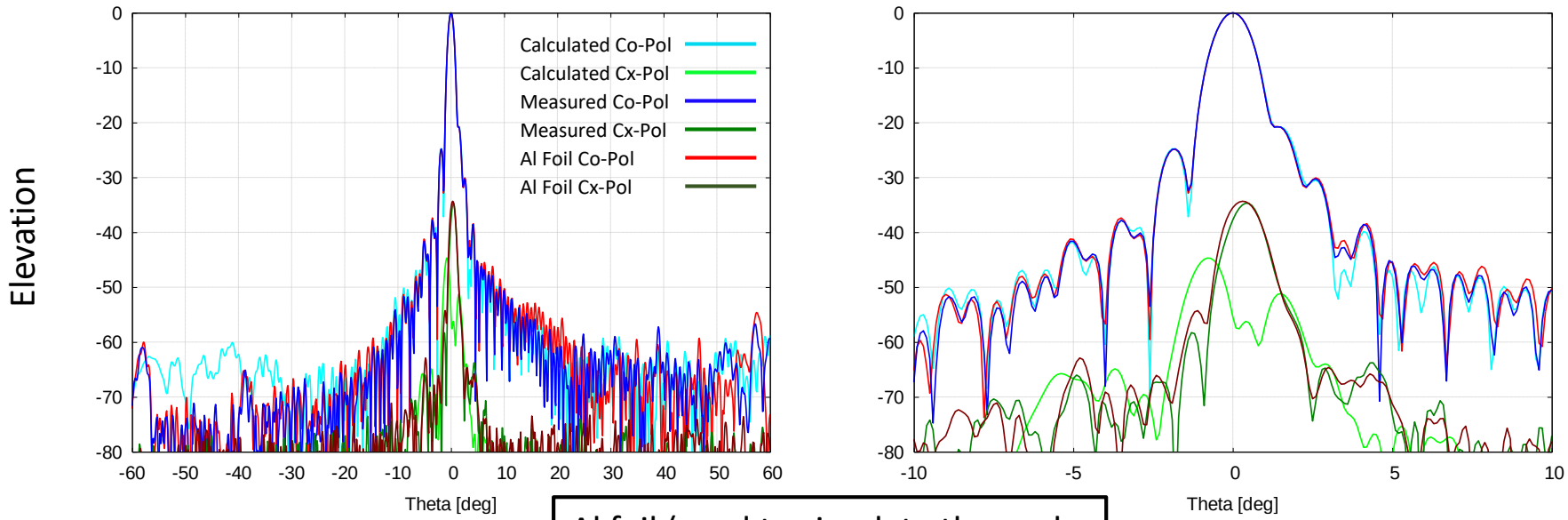
For reference: green = -45dB, light blue = -60dB

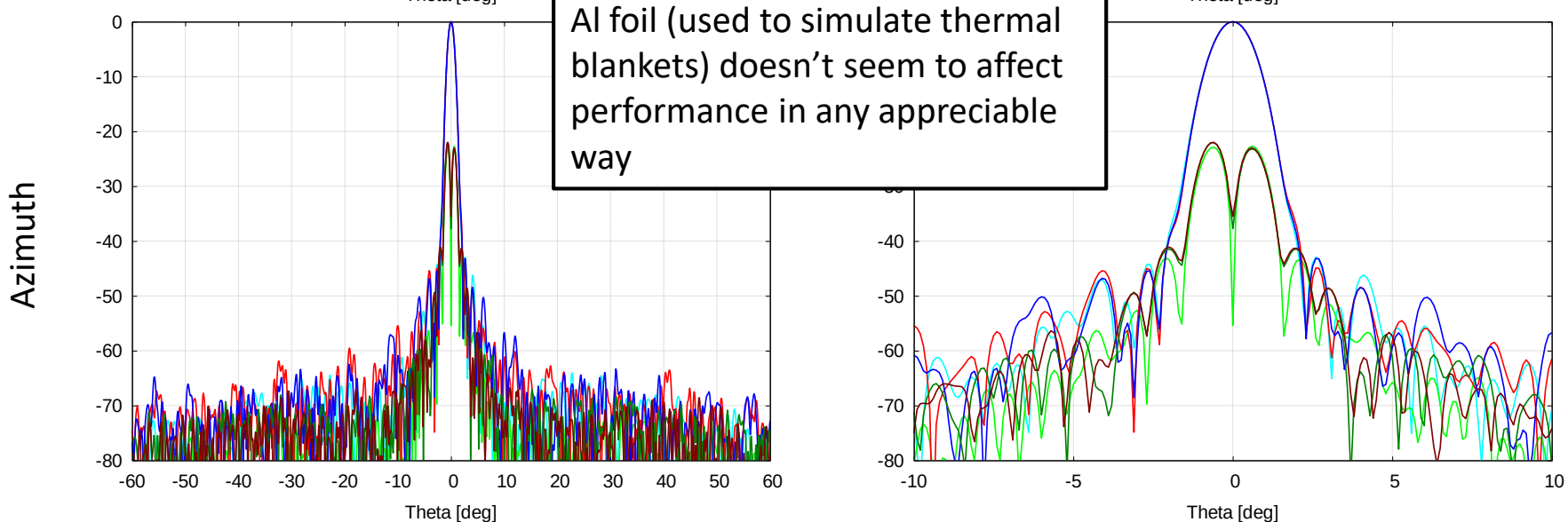
V-Pol Results. 180°. 33.9 GHz



For reference: green = -45dB, light blue = -60dB

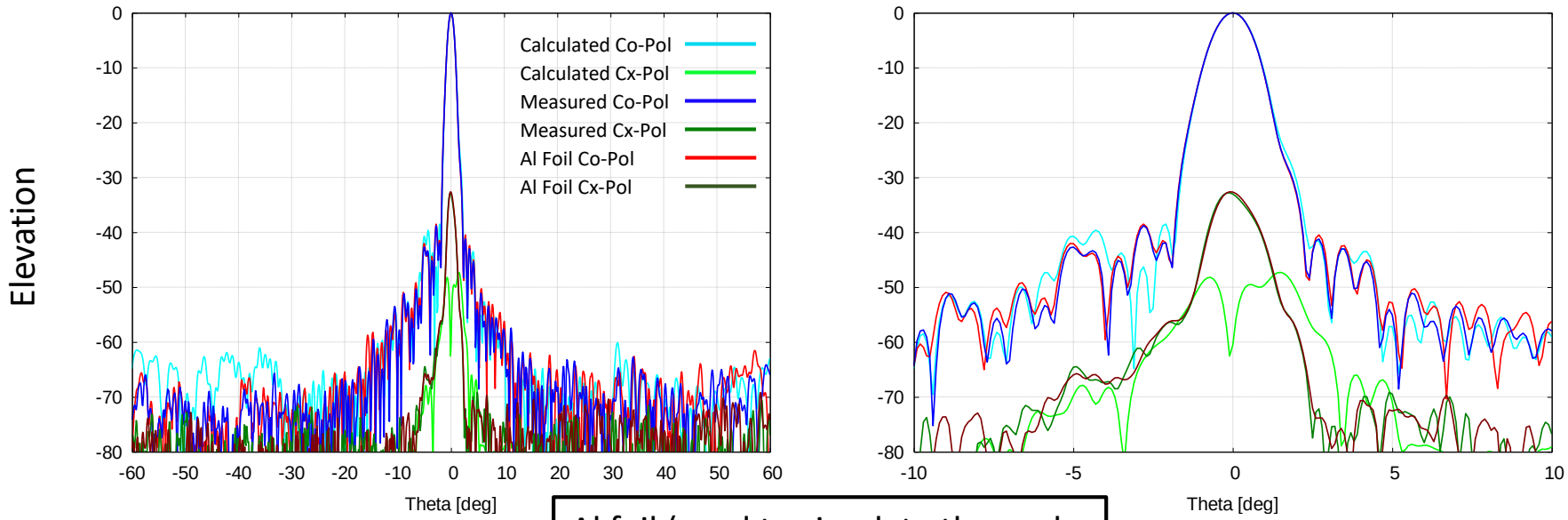
H-Pol Cuts, 180°, 33.9 GHz

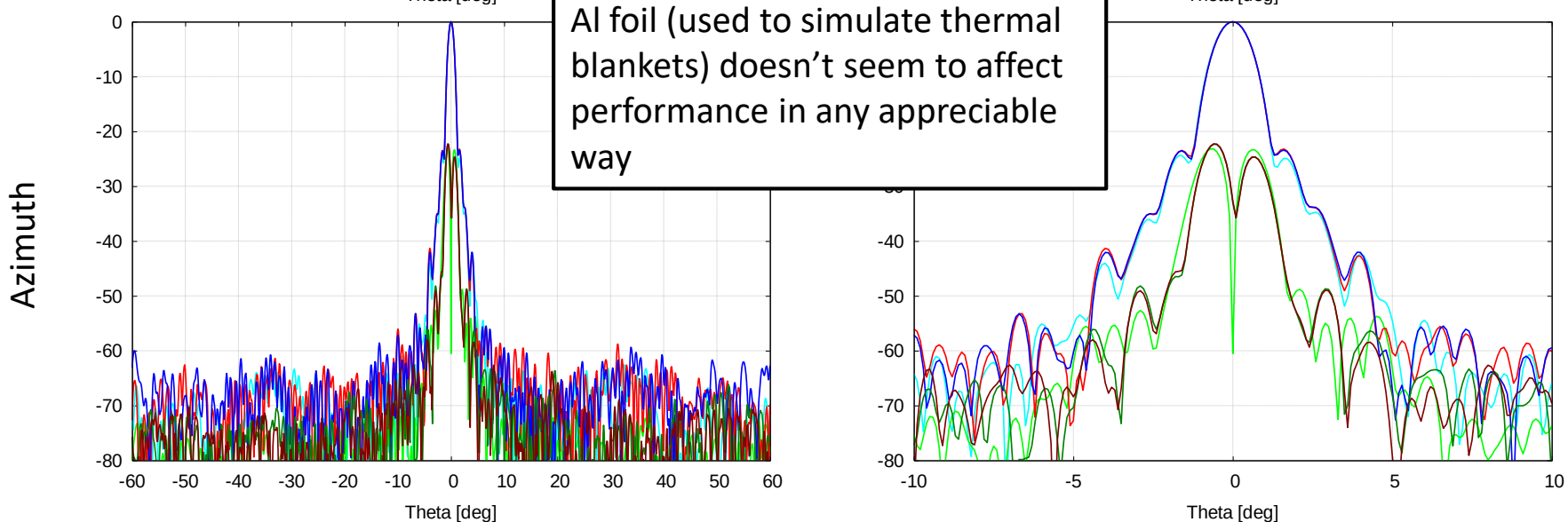




Al foil (used to simulate thermal blankets) doesn't seem to affect performance in any appreciable way

V-Pol Cuts, 180°, 33.9 GHz

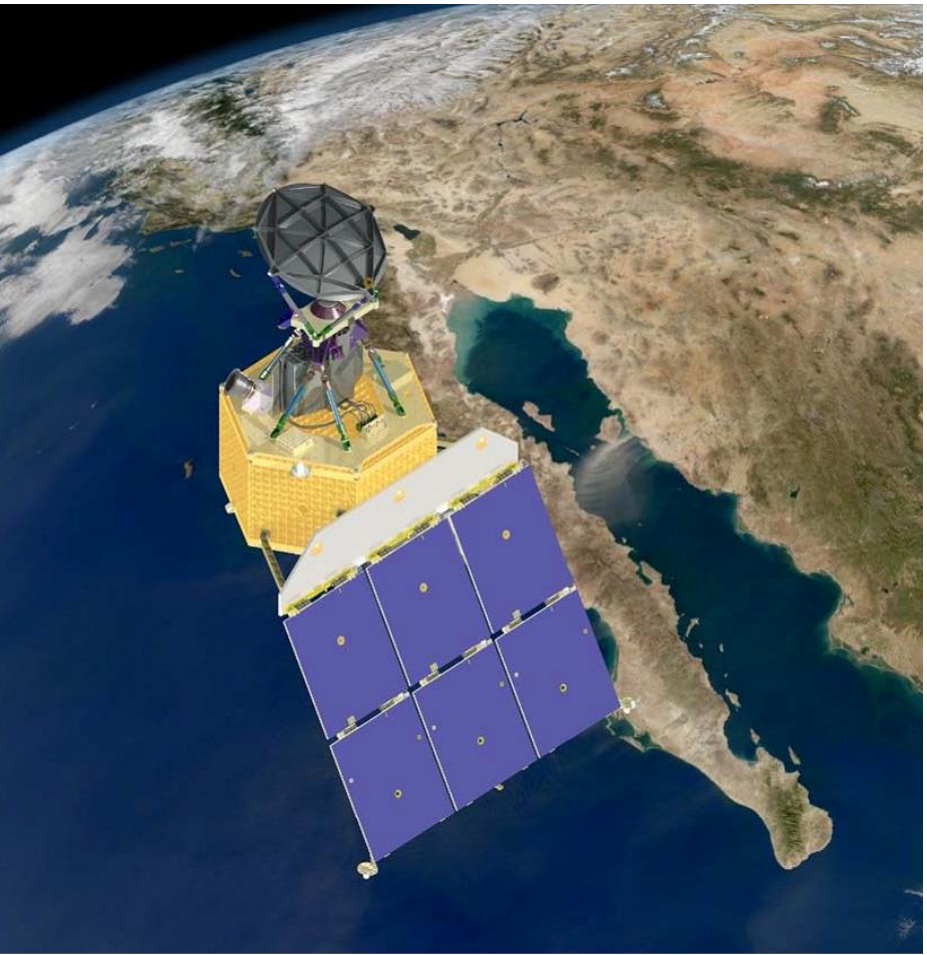


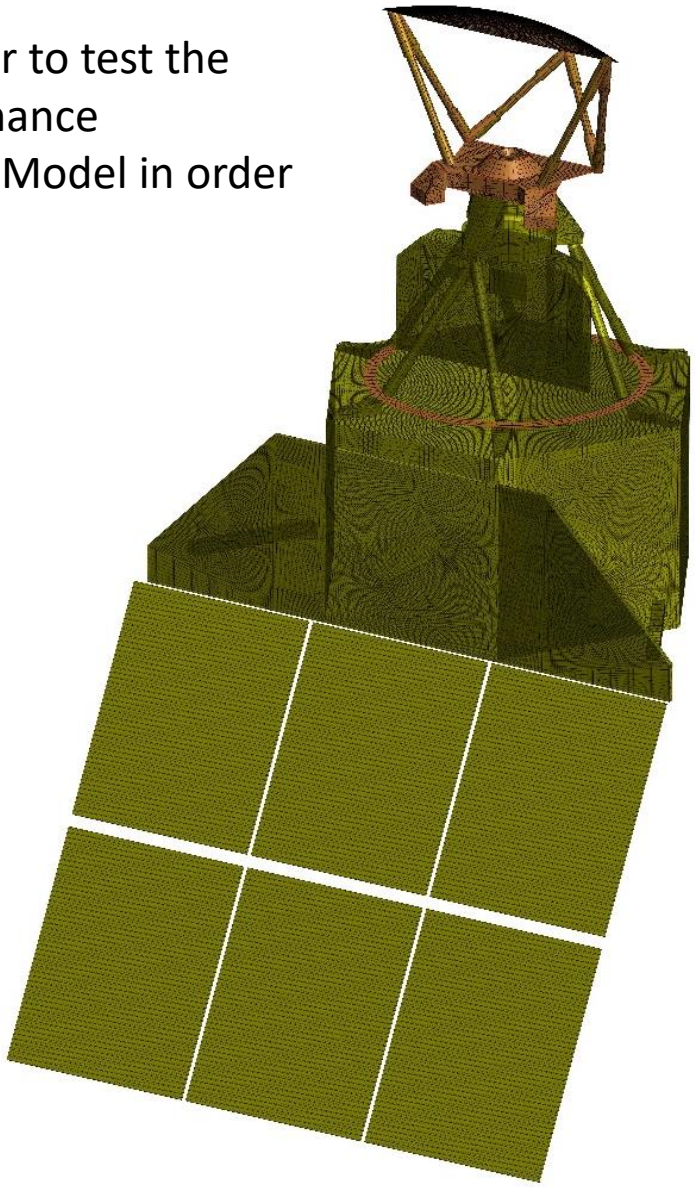


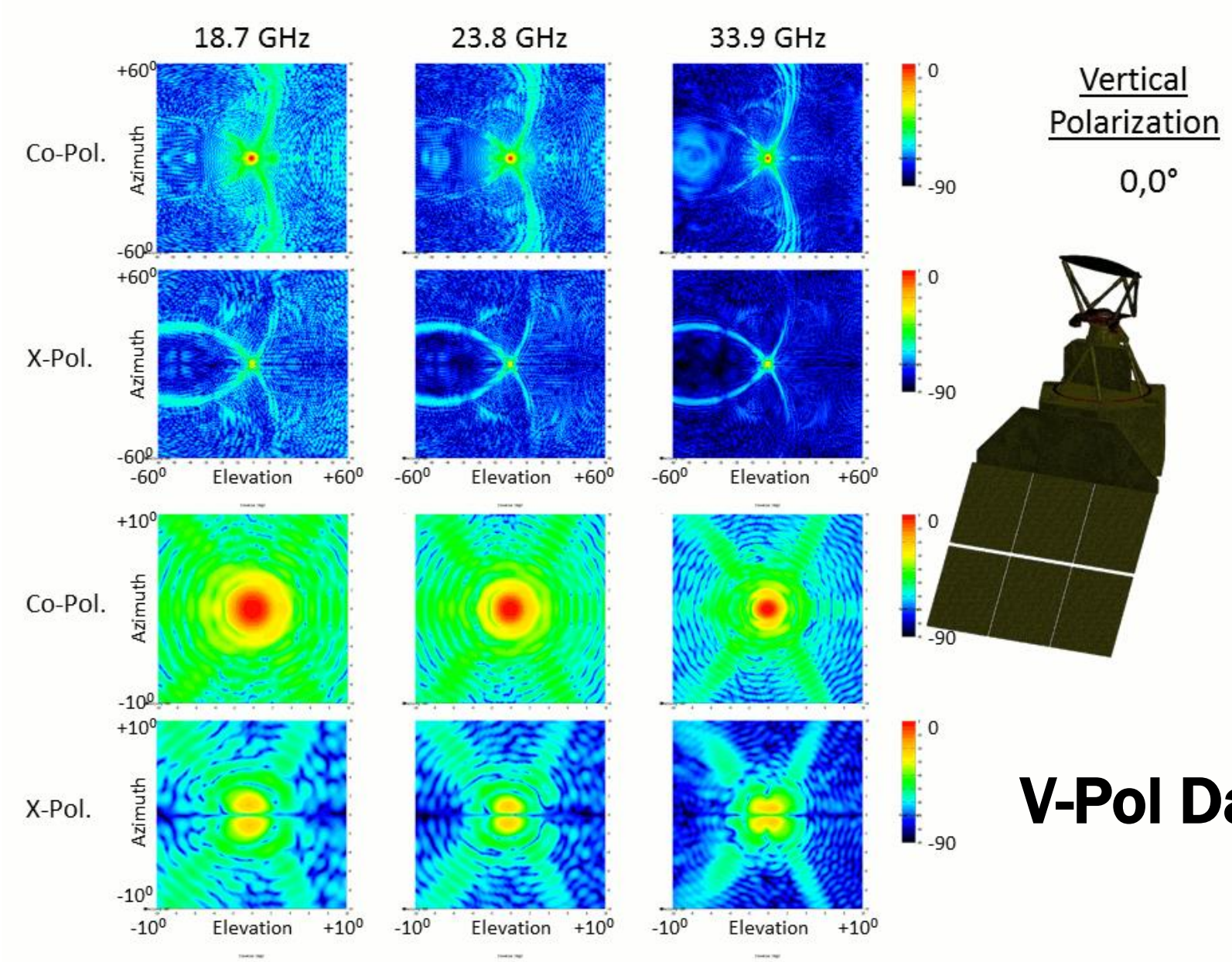
Al foil (used to simulate thermal blankets) doesn't seem to affect performance in any appreciable way

Improved RF Model

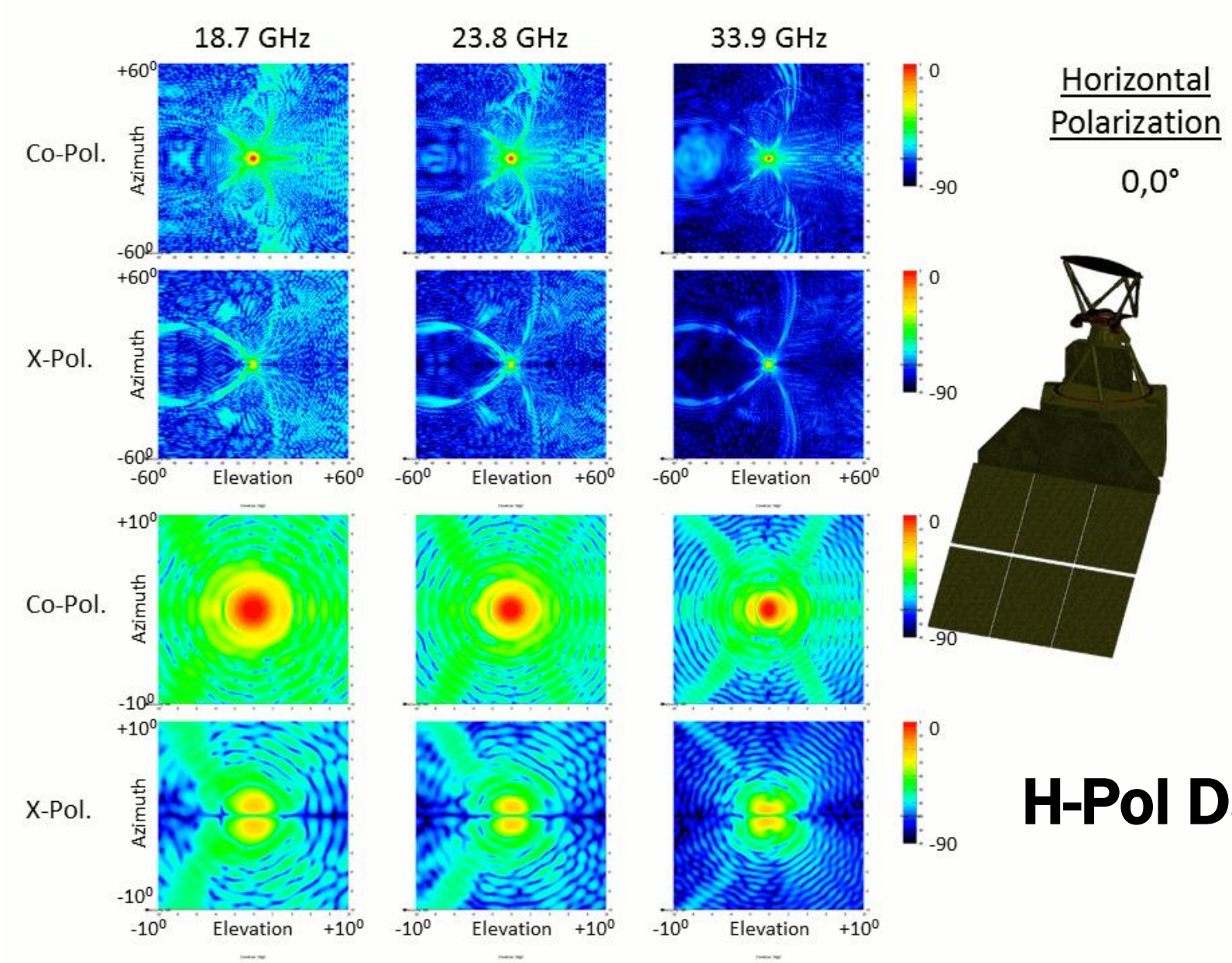
- A Larger RF Model was also made in GRASP in order to test the effect of the Solar Array on the instrument performance
- TICRA's help was instrumental in optimizing the RF Model in order to be able to run it on a single machine



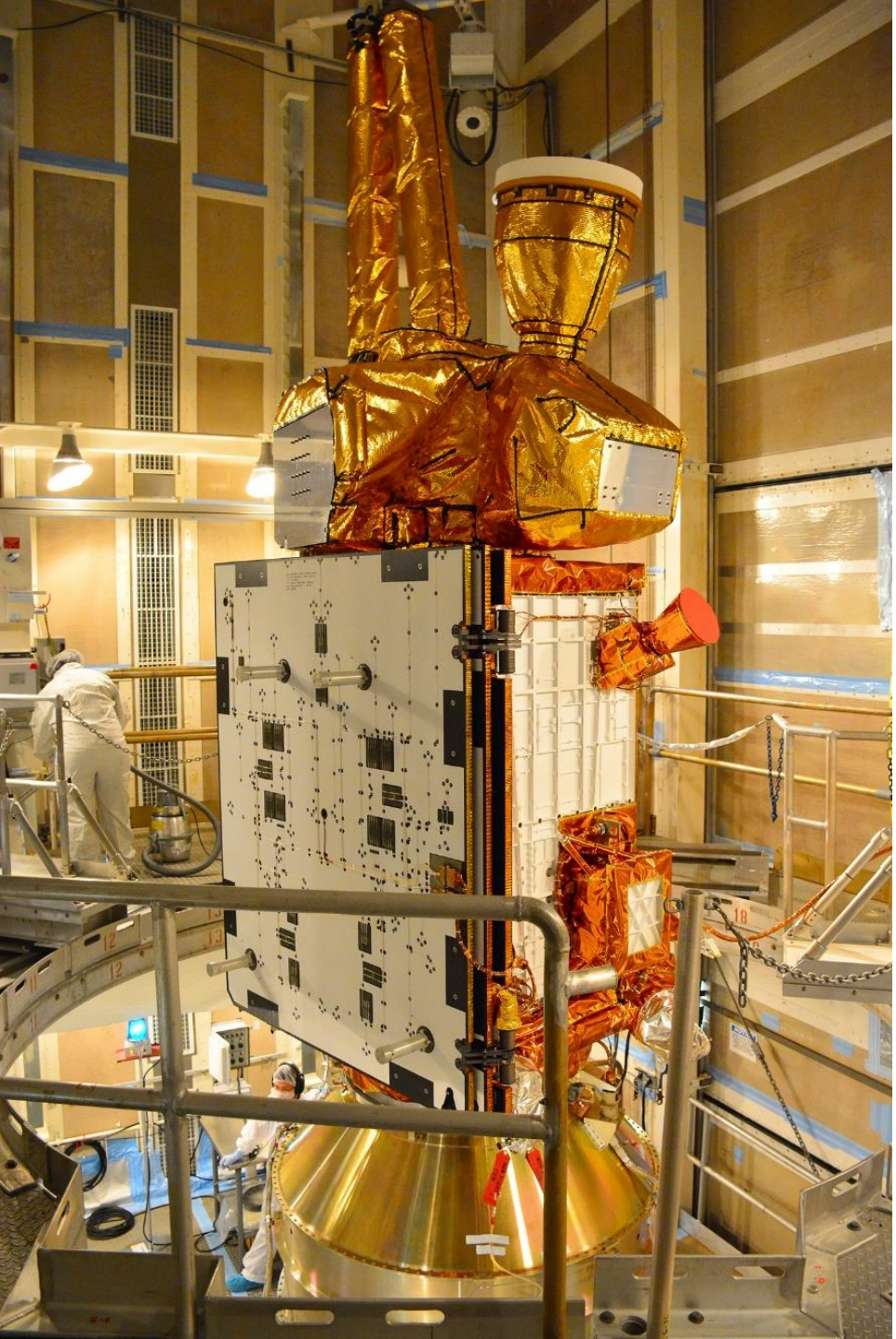



18.7 GHz
23.8 GHz
33.9 GHz
Co-Pol.
X-Pol.
Co-Pol.
X-Pol.
Azimuth
Elevation
+60⁰
-60⁰
+10⁰
-10⁰
0
-90
Vertical Polarization
0,0°

V-Pol Data


18.7 GHz
23.8 GHz
33.9 GHz
Co-Pol.
X-Pol.
Co-Pol.
X-Pol.
Azimuth
Elevation
+60⁰
-60⁰
+10⁰
-10⁰
0
-90
Horizontal Polarization
0,0°

H-Pol Data



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SMAP

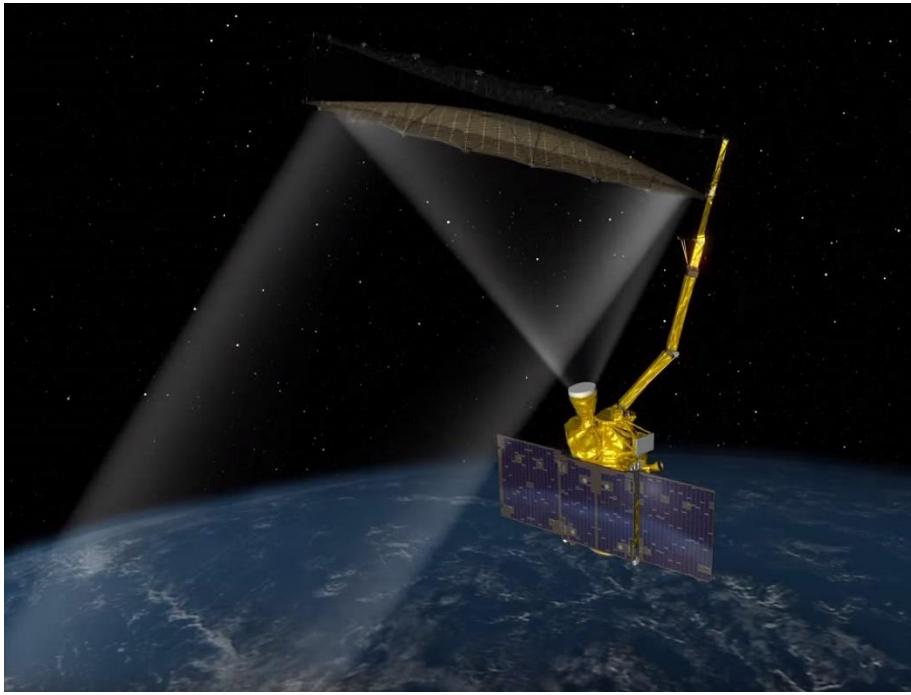
Soil Moisture Active Passive

SMAP Agenda

- Mission & Instrument Overview
- Latest Events
- Mission Timeline
- Instrument Implementation Strategy
- RF Model of SMAP Flight System
- 1/10th Scale Model
- Scale Model Measurements
- Flight System Data

Mission Overview

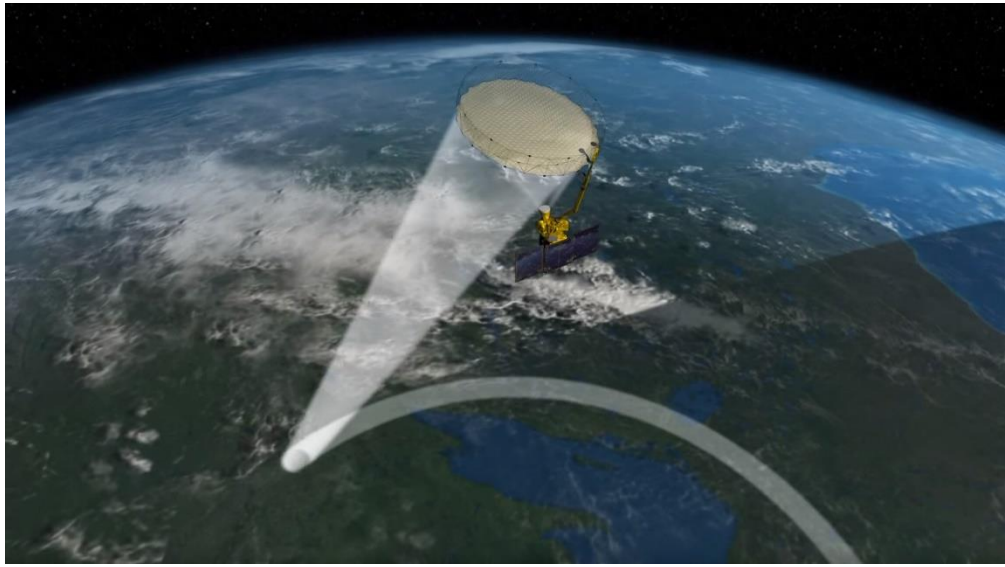
- NASA's Soil Moisture Active and Passive (SMAP) mission is measuring Earth's soil moisture and its freeze/thaw state over a 3 year period



- Applications:
  - More accurate and longer-term weather and climate predictions
  - Earlier drought warnings
  - Improved flood and landslide predictions
  - Improved agricultural production predictions
  - Better understanding of the global carbon cycle
- Near-polar, sun-synchronous orbit of 680 km
- Launched on January 31st, 2015 from Vandenberg AFB

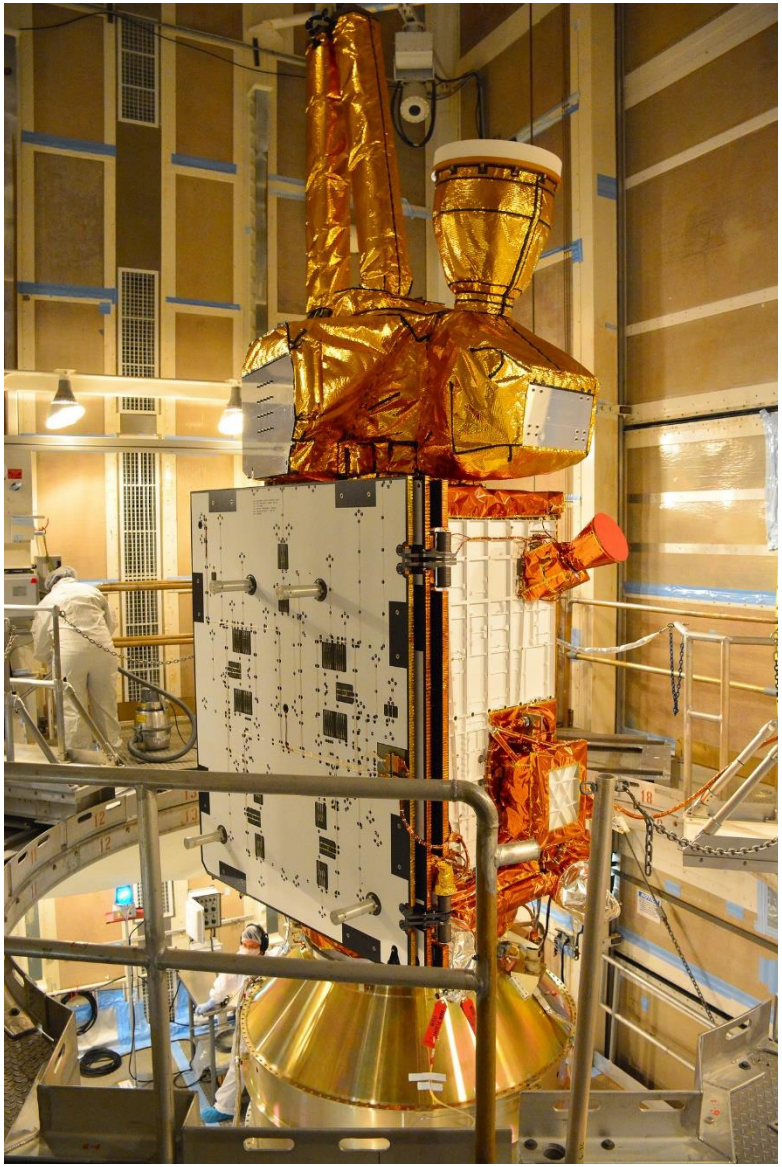
Instrument Overview

- An L-band Synthetic Aperture Radar (SAR) and L-band radiometer (RAD) share an offset 6-m deployable mesh reflector and the feed
- The antenna boresight beam is pointed 35.5° off of Nadir



- The instrument spins at approximately 14.6 RPM around Nadir
- The result is a 1000-km swath on the ground
- The RAD data is more accurate than the SAR data, but has a spatial resolution of about 40-km while the SAR spatial resolution is instead 1-3 km

Delivery to Vandenberg AFB and Integration



Delta II Launch Vehicle

Ignition and Lift off

January 31st, 2015 @ 6:23AM PST

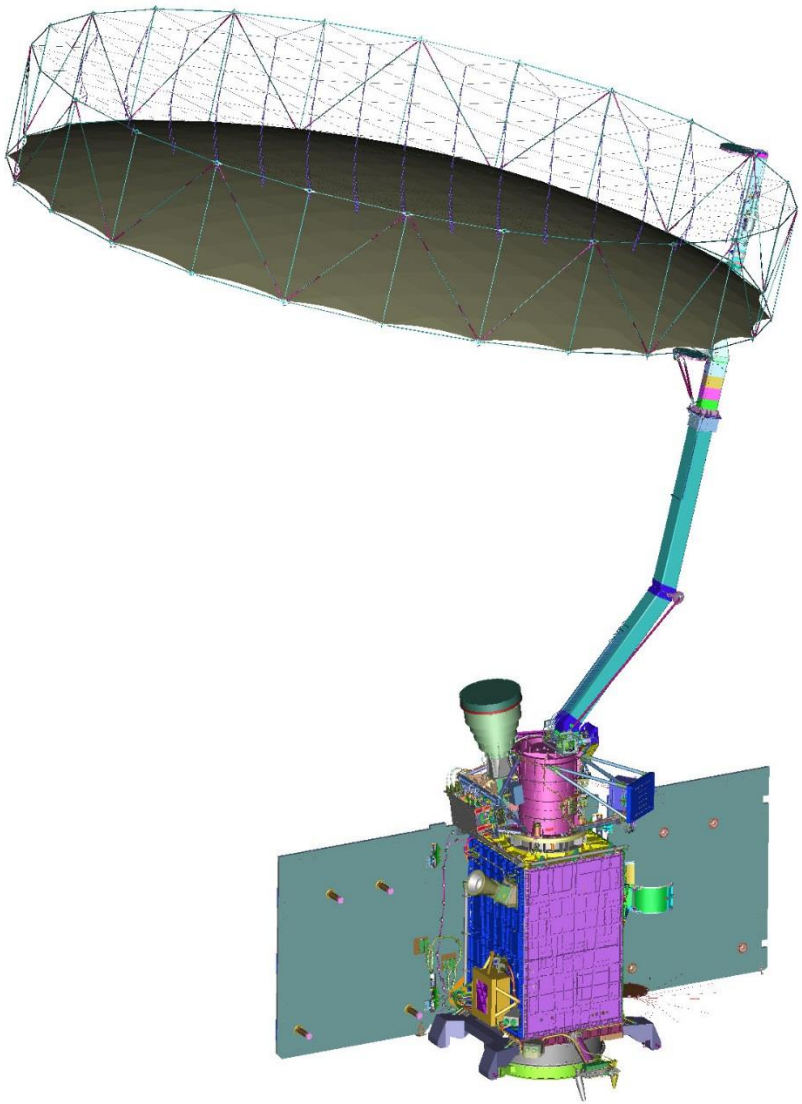
Mission Timeline

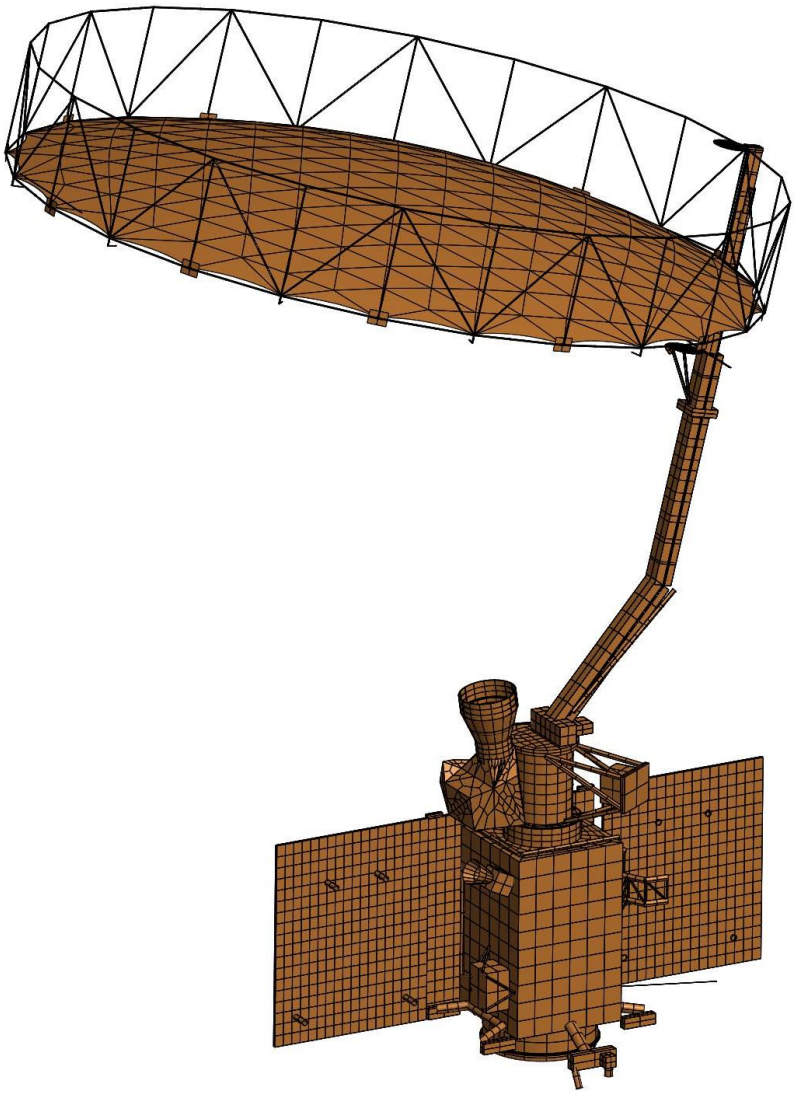
- Launched in January 2015
- Successfully began active mission in May 2015
- In July 2015 the radar ceased its operations due to a sudden failure of the low voltage power supply
- Radiometer is still operational and so far has provided over 1 year worth of calibrated soil moisture data on a global scale

Instrument Implementation Strategy

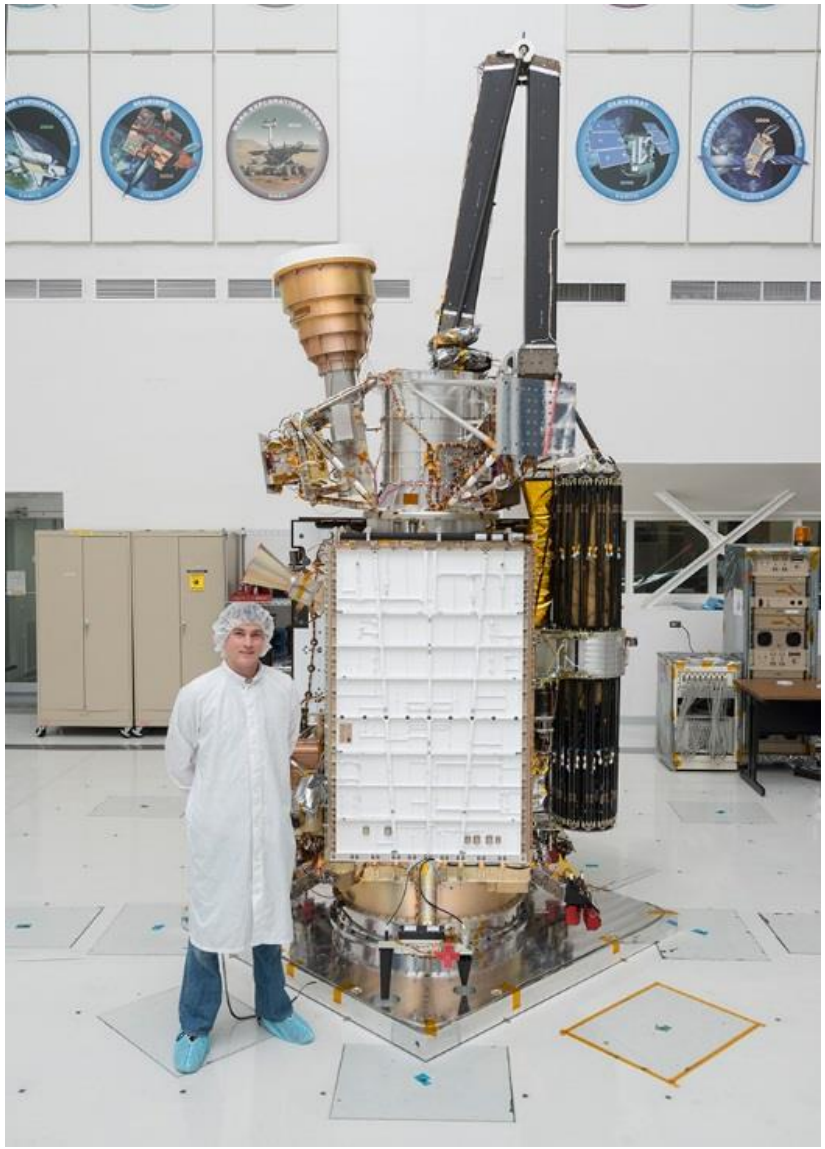
- The 6-m offset Reflector is an AstroMesh™ antenna from Northrop Grumman, Astro Aerospace
- The Feed Assembly is a JPL in-house design
- An Accurate antenna pattern knowledge was required for the RAD performance calibration
- The reflector antenna radiation pattern was not measured before launch
- Extensive and very accurate modeling was done with several software packages to predict RF performance of the complete instrument antenna
- A 1/10th scale model of the antenna and spacecraft was also built to verify the RF performance
- The requirements verification was done with a combination of
  - Flight Feed Assembly measurements
  - Scale Model predictions and measurements
  - Flight Model predictions

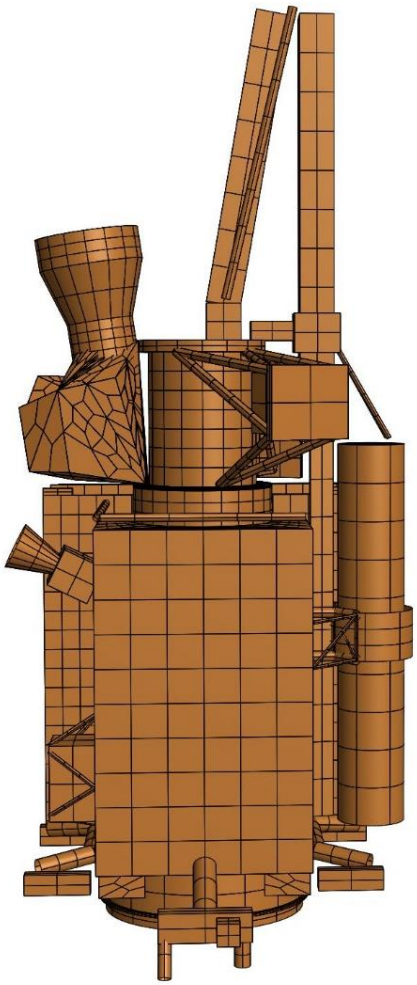
SMAP CAD & RF Models



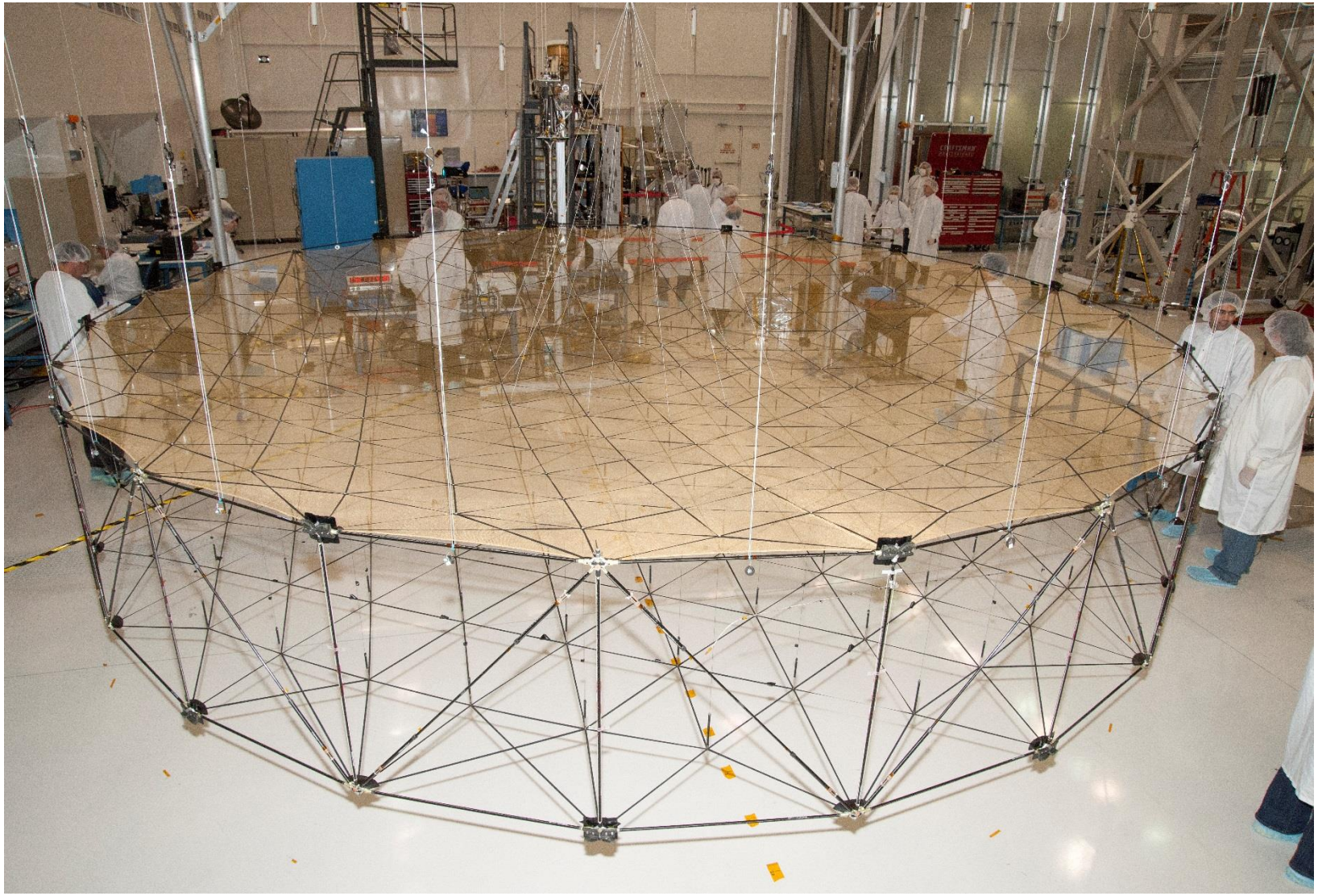


Fully Assembled S/C with Stowed AstroMesh™



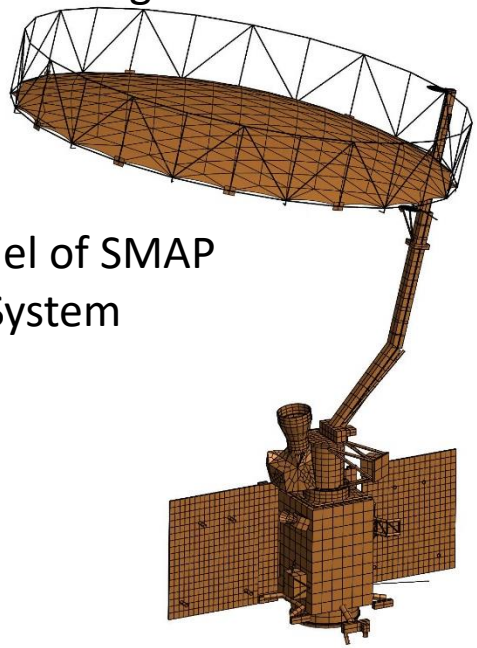


Fully Deployed AstroMesh™ Reflector

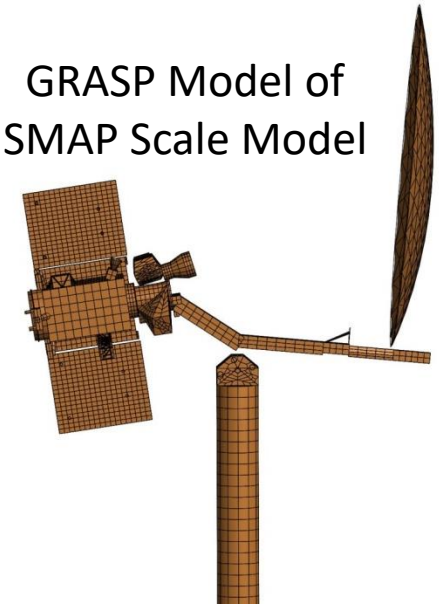


SMAP RF Modeling

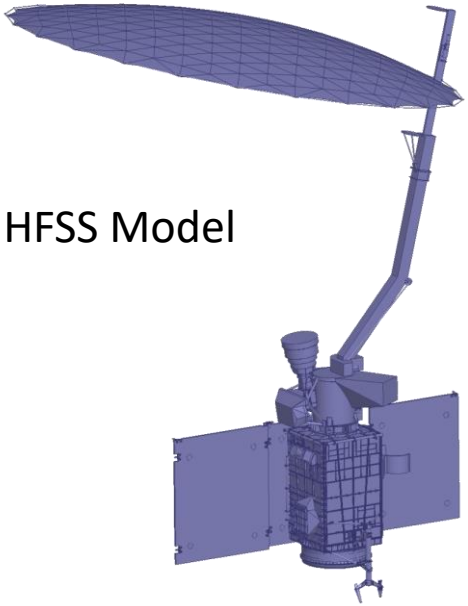
- SMAP modeling was mostly performed using the GRASP PO/MoM modeling approach (PO+PTD for the reflector, MoM for everything else)
- A GRASP model of the as-built scale model was also made for comparison with scale model radiation pattern measurements
- A HFSS model was also done as an additional method of validating the GRASP model (FEM for the Feed Assembly, IE for everything else)
- The Feed Assembly radiation pattern was provided either in the form of an HFSS model calculation or Flight Feed Assembly measurements when eventually available



GRASP Model of SMAP Flight System

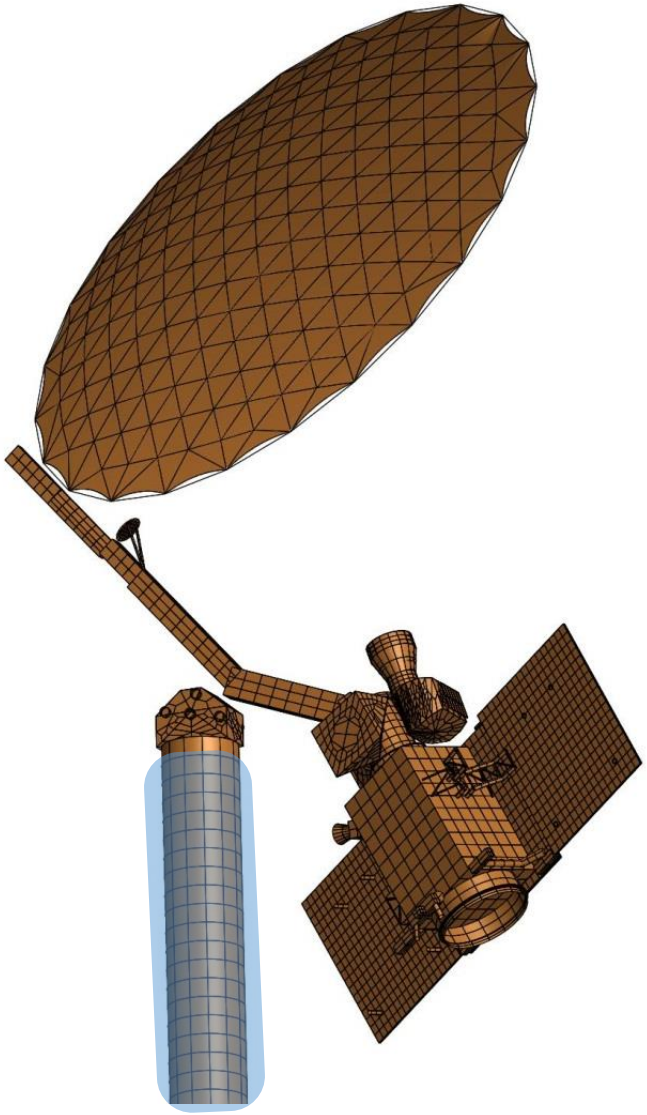


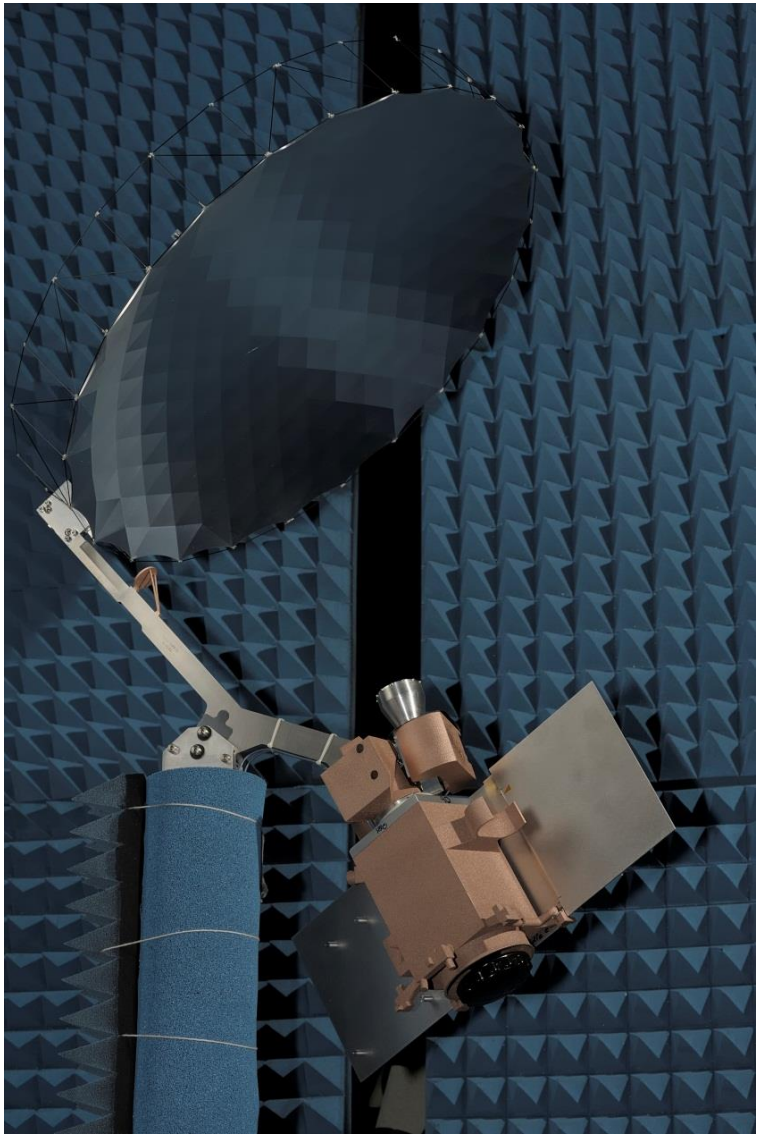
GRASP Model of SMAP Scale Model



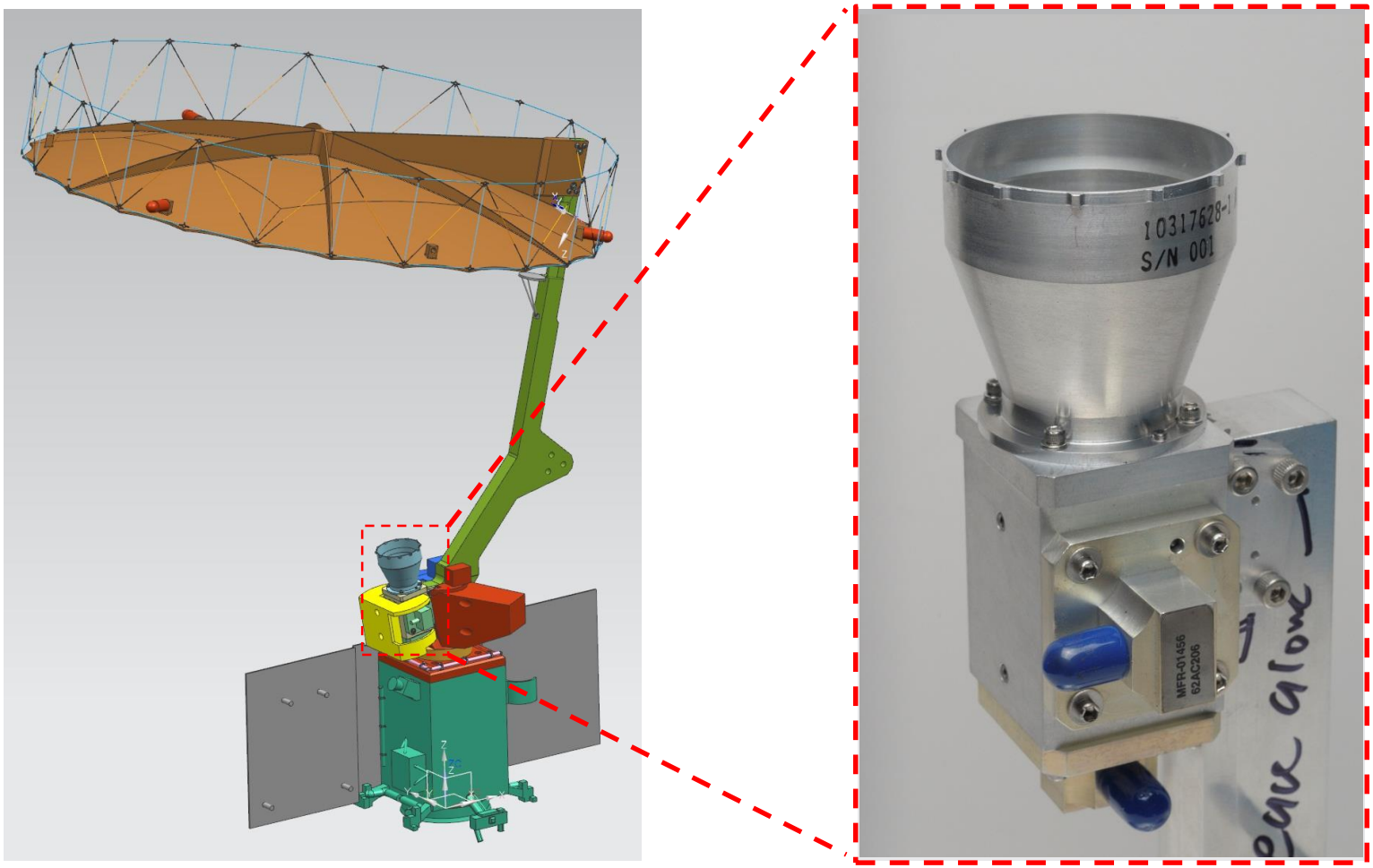
HFSS Model

SMAP 1/10th Scale Model

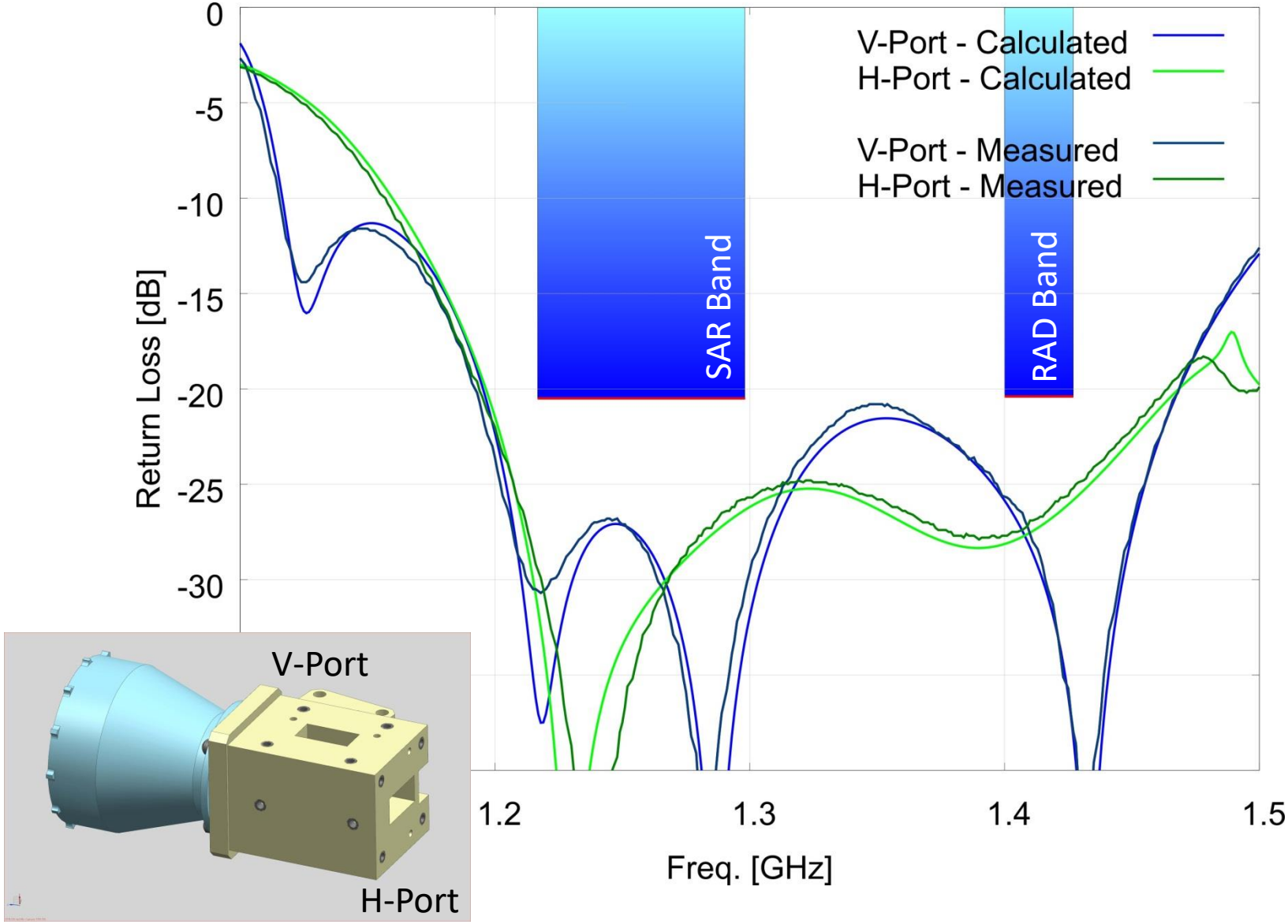




SMAP Scale Model

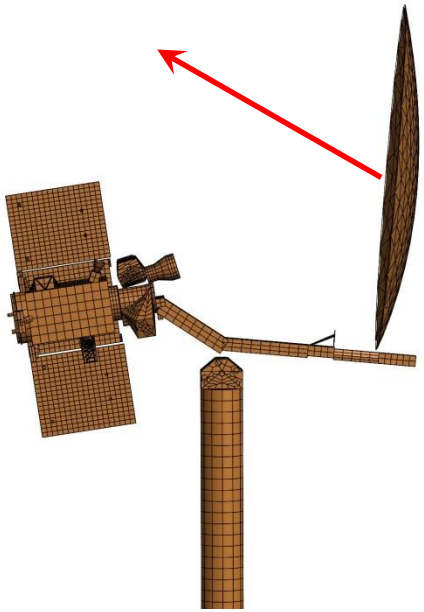


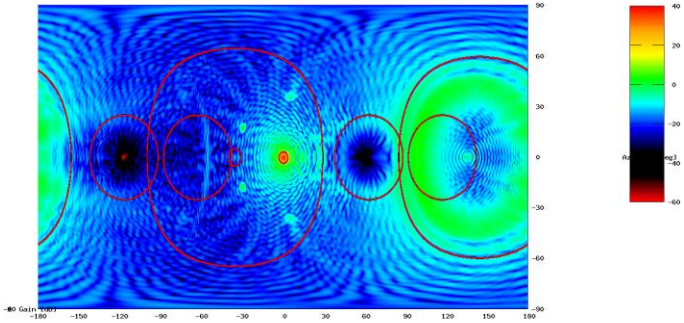
Feed Horn RL into SM OMT



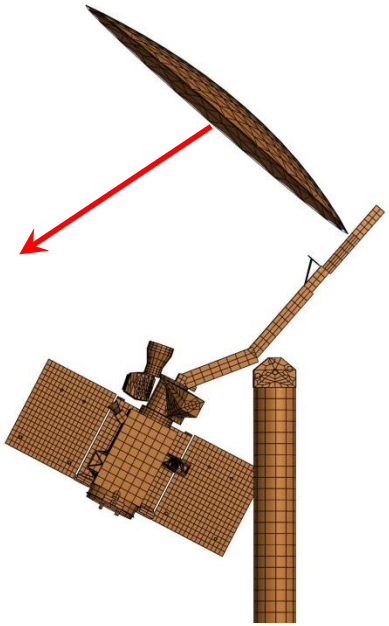
Examples of Scale Model Measured Patterns

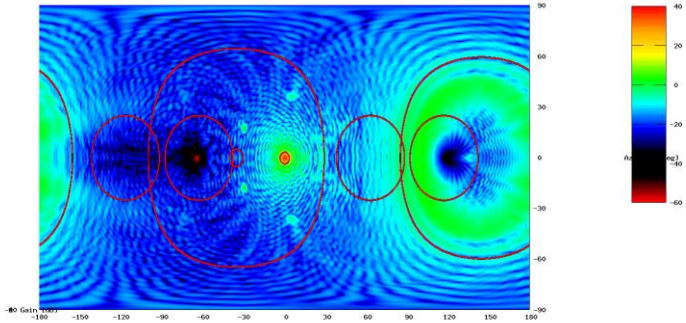
+27° Position





-27° Position





SAR V-Pol, 090

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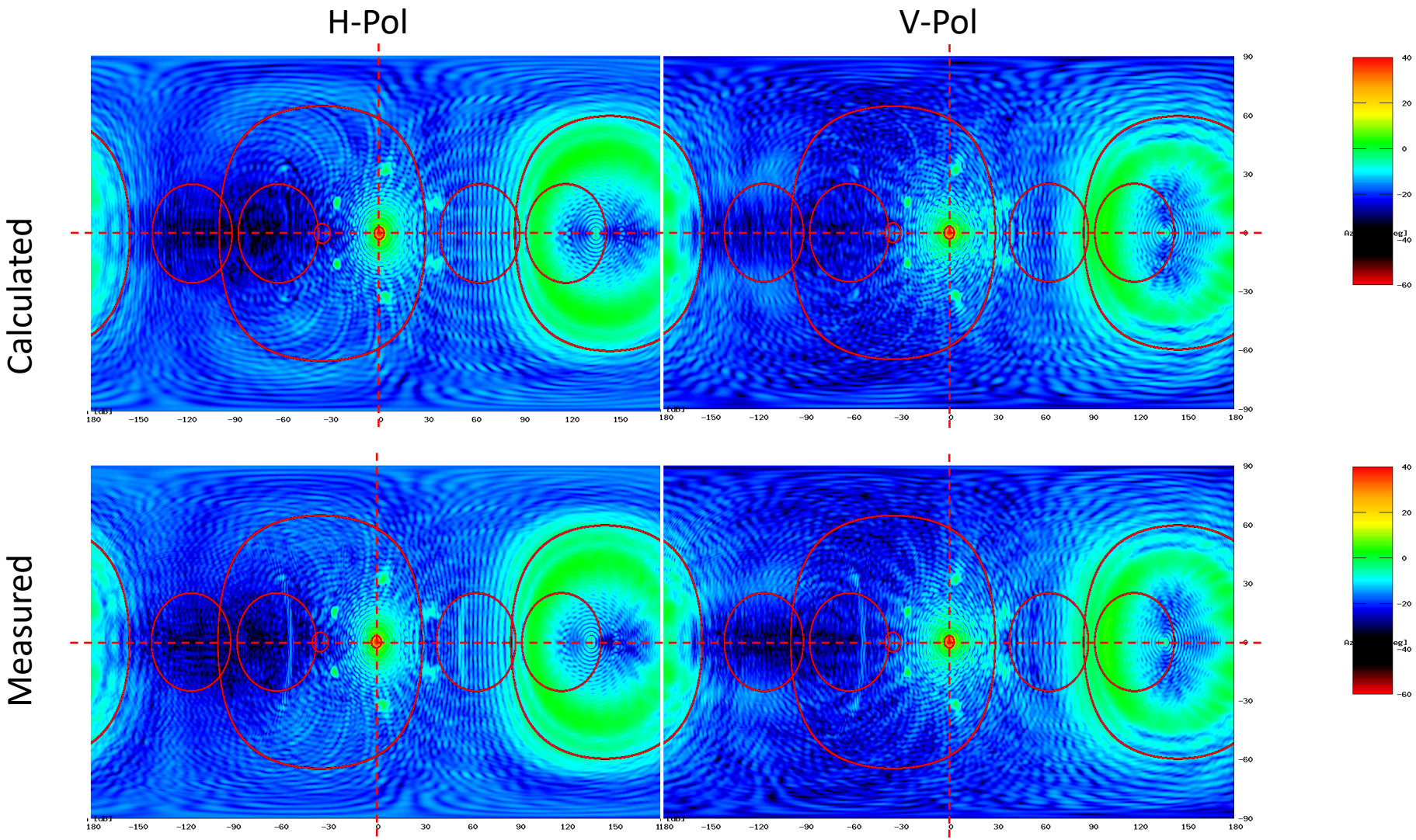
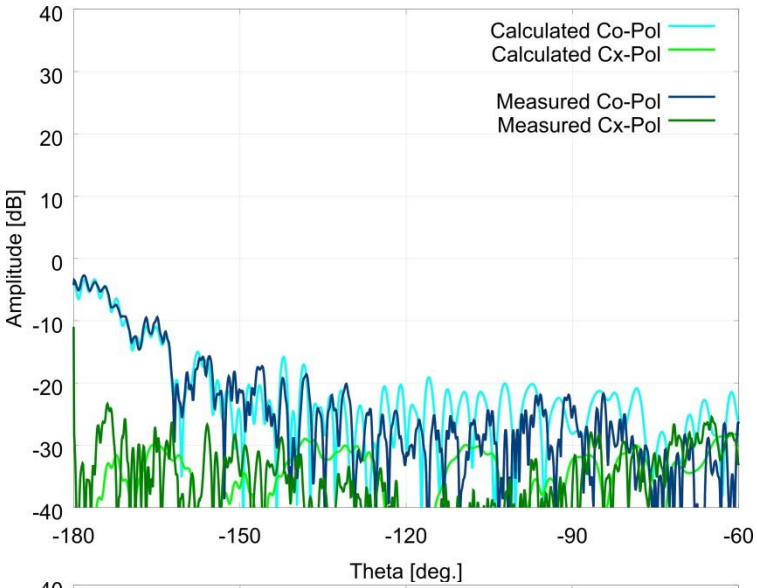
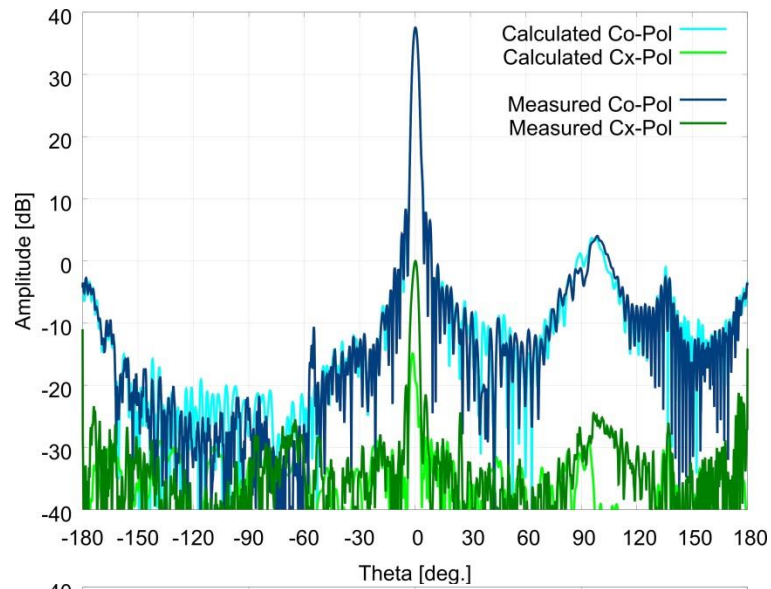
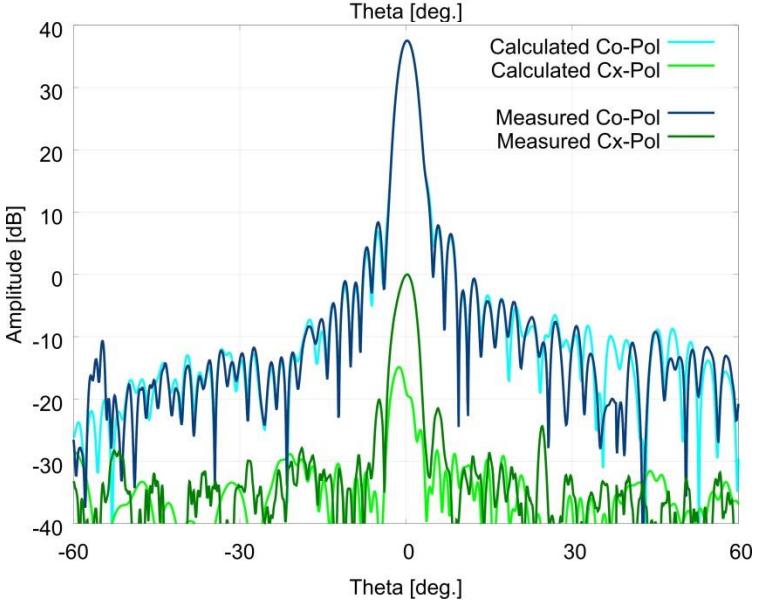
Radiation Pattern Comparison: RAD, 000

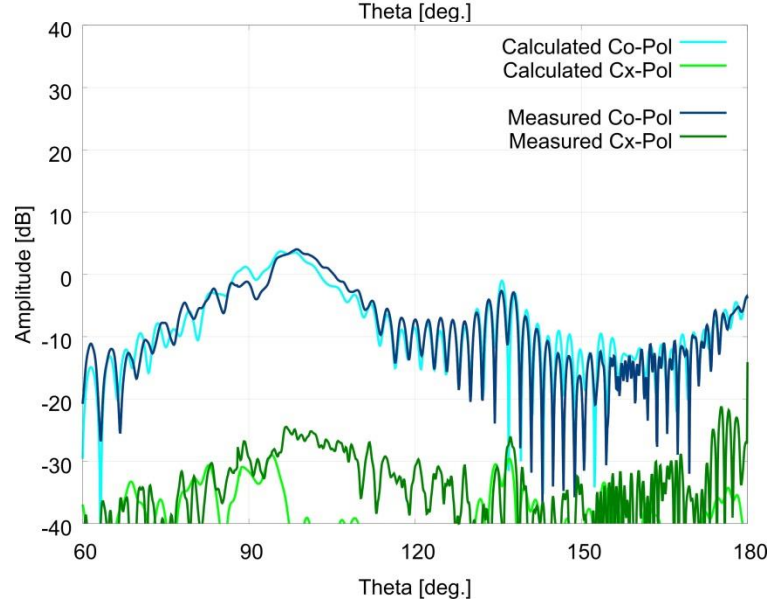


RAD V-Pol, Elevation Cut, 000

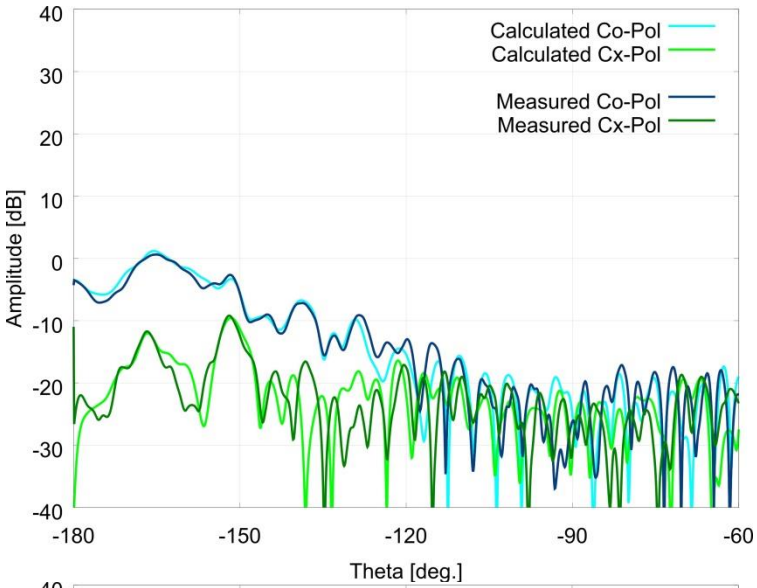


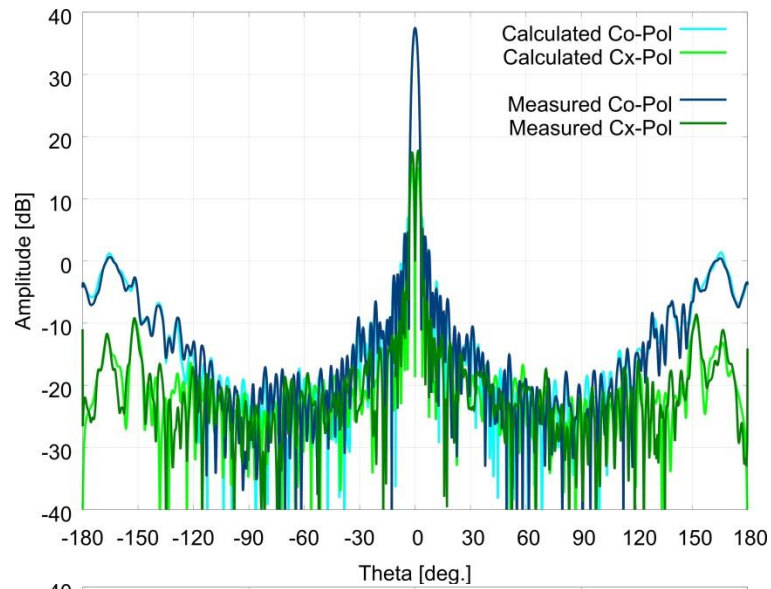


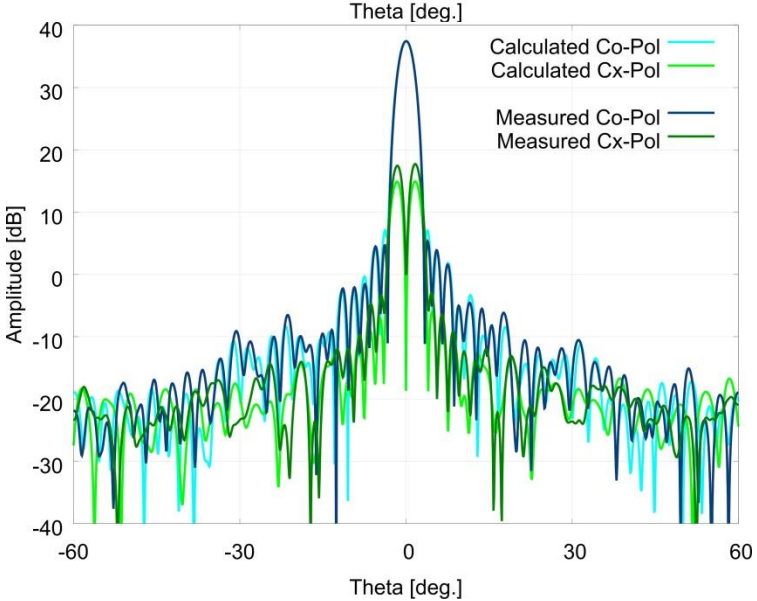


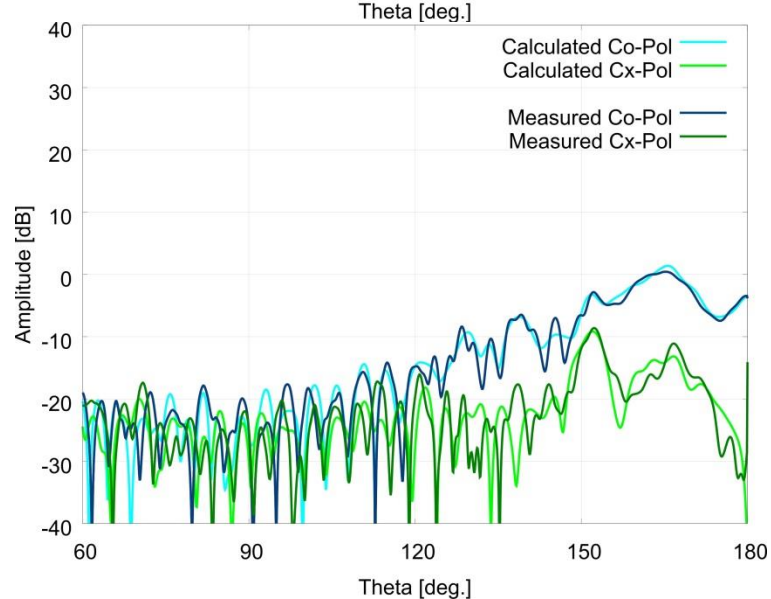


RAD V-Pol, Azimuth Cut, 000



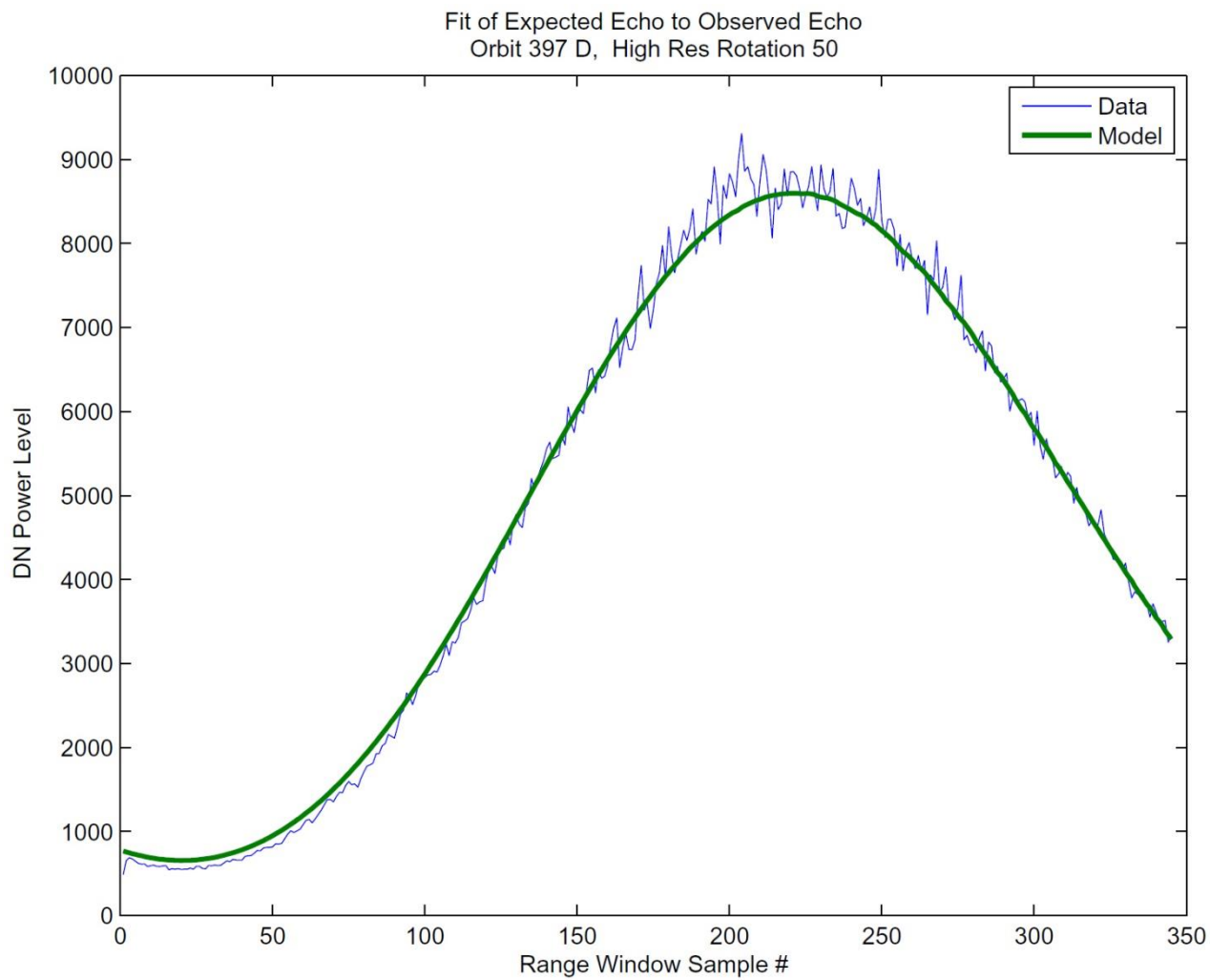






Measurement of Radar Echo from Space

- Calculated radiation pattern was able to predict on-orbit performance extremely well
- SAR Pointing was predicted to be 0.270° from nominal according to the RF Model
- With the help of corner reflectors on the ground, it was measured to be 0.291°, only 0.021° off from our calculations



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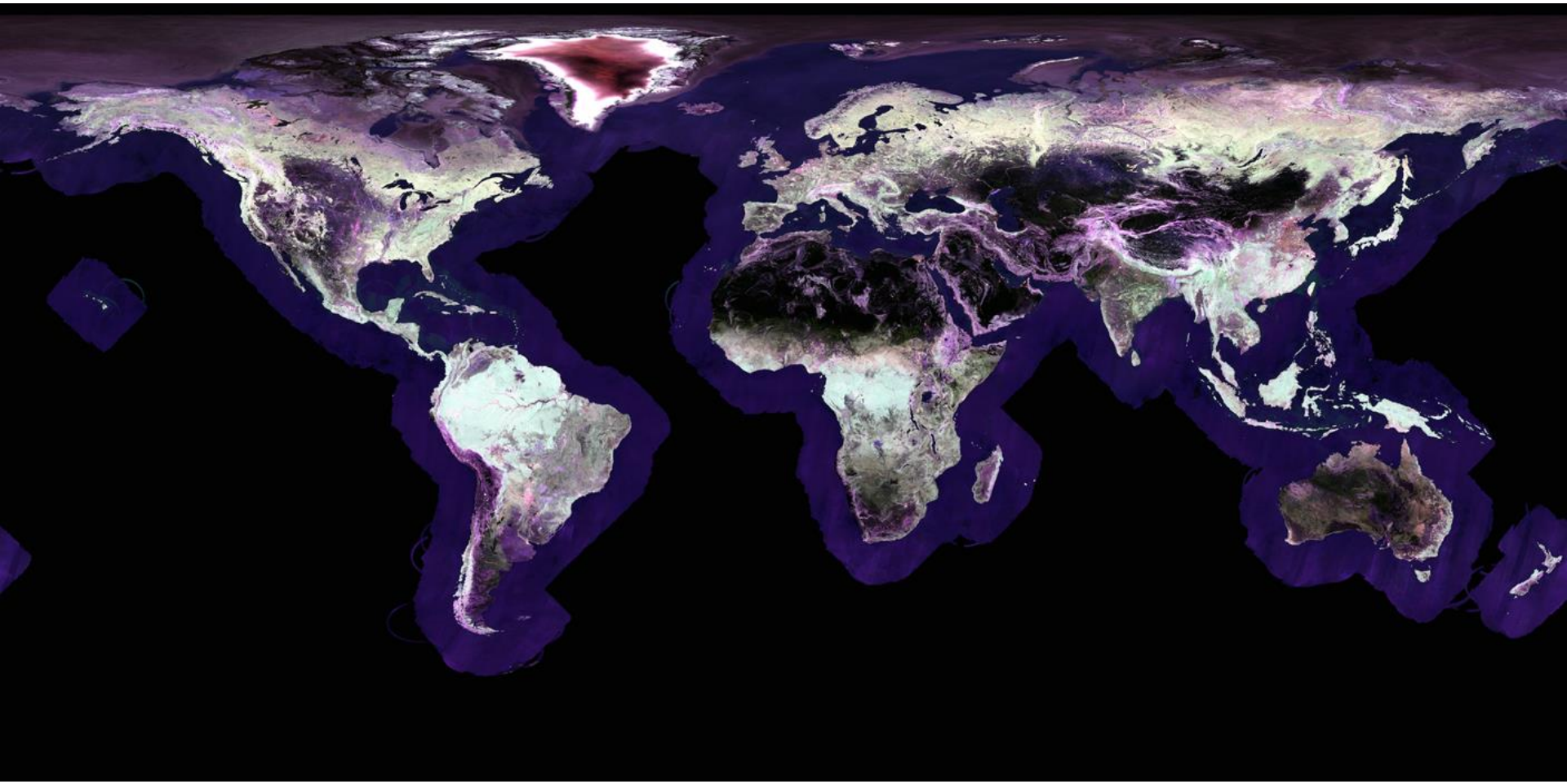
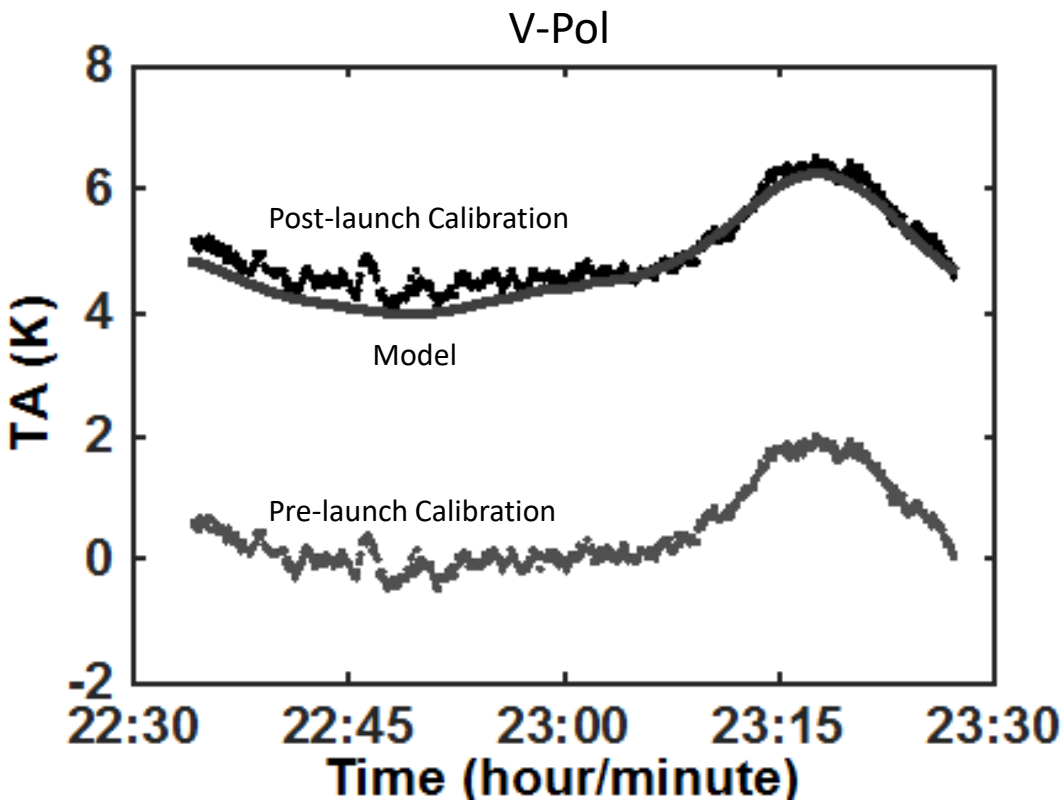
Radar Backscatter Cross Section from SAR Data



Radiometer Calibration

- First Radiometer Calibration was performed before reflector deployment with the Feed-horn pointed at cold sky
- Initial result for V-Pol has a 5°K bias, consistent with pre-launch calibration uncertainty
- H-Pol showed a smaller 1°K bias
- After reflector deployment the antenna pattern correction error was calculated to be of the order of 0.1%, about 10 times smaller than what was calculated for AQUARIUS



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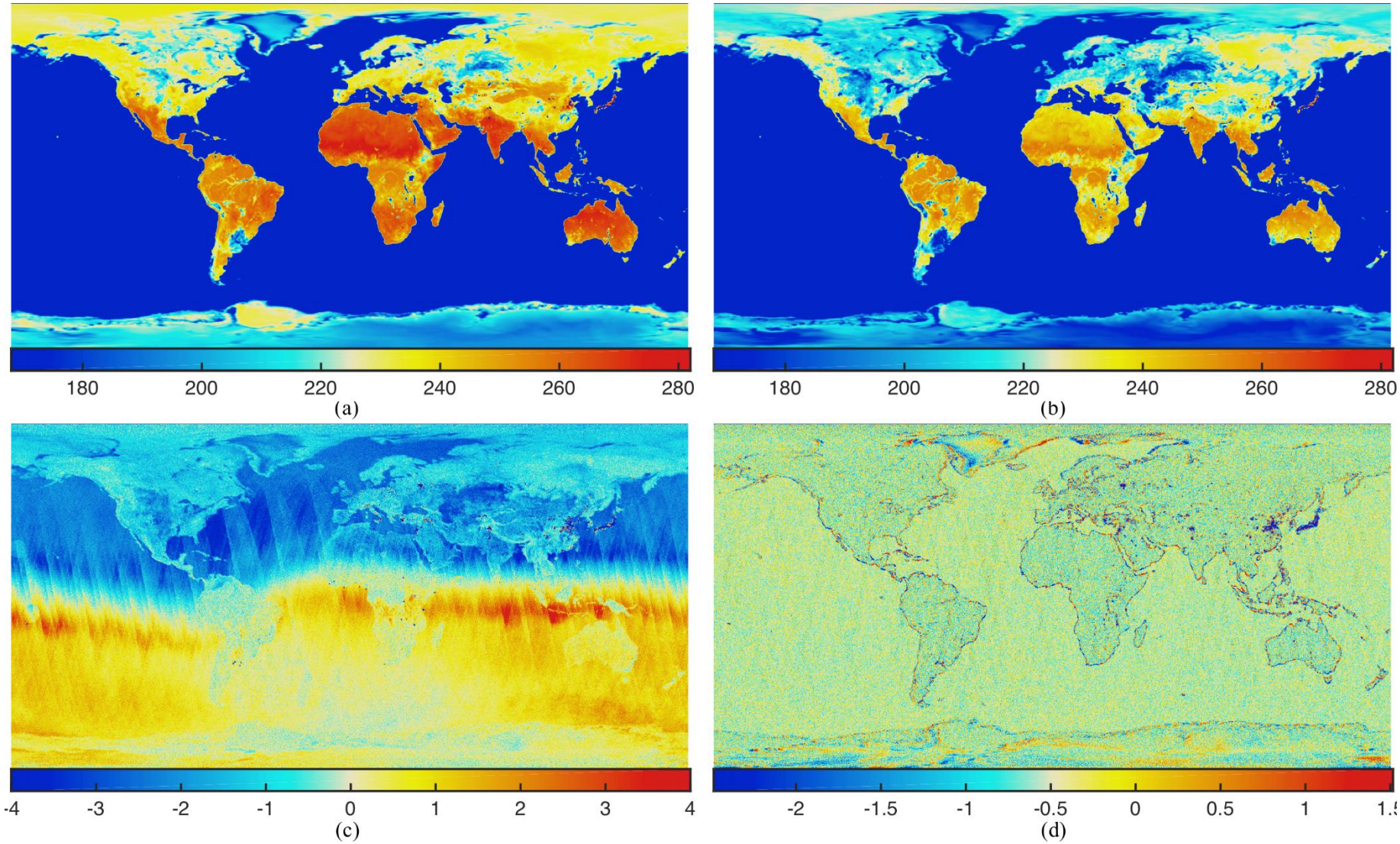
Radiometer Stokes Antenna Temperatures



(a) Vertically polarized, (b) Horizontally polarized, (c) Third and (d) Fourth Stokes parameters, respectively

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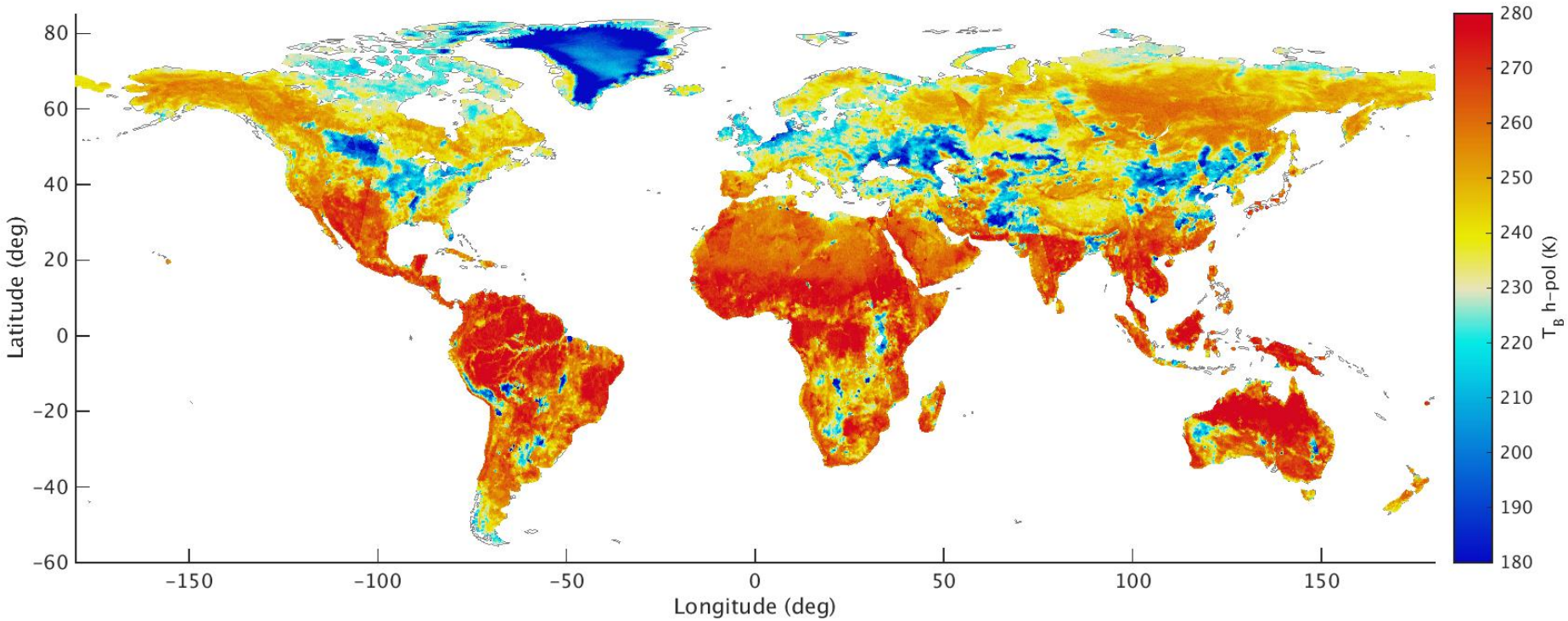
RAD Brightness Temperature (H-Pol) for First 4 Days



Conclusions

- High fidelity RF Models allowed us to predict the performance of various instrument antennas with very good accuracy as demonstrated by
  - Scale Model measurements (SMAP)
  - Prototype Model measurements (NISAR)
  - Flight Model measurements (COWVR)
  - Flight System Data from space (SMAP)
- Radiation patterns were predicted with unprecedented accuracy resulting in a residual antenna pattern correction error of just 0.1% for the SMAP radiometer
- A number of modeling tools can be integrated together to get the best predictions both in terms of S-parameters and/or radiation patterns
- Validation & Verification plans can now be based on RF model predictions rather than flight hardware measurements when necessary and/or cost effective, especially in the case of large deployable reflectors like SMAP and NISAR

Thank you!