Antenna Systems for Space Applications at NASA Jet Propulsion Laboratory

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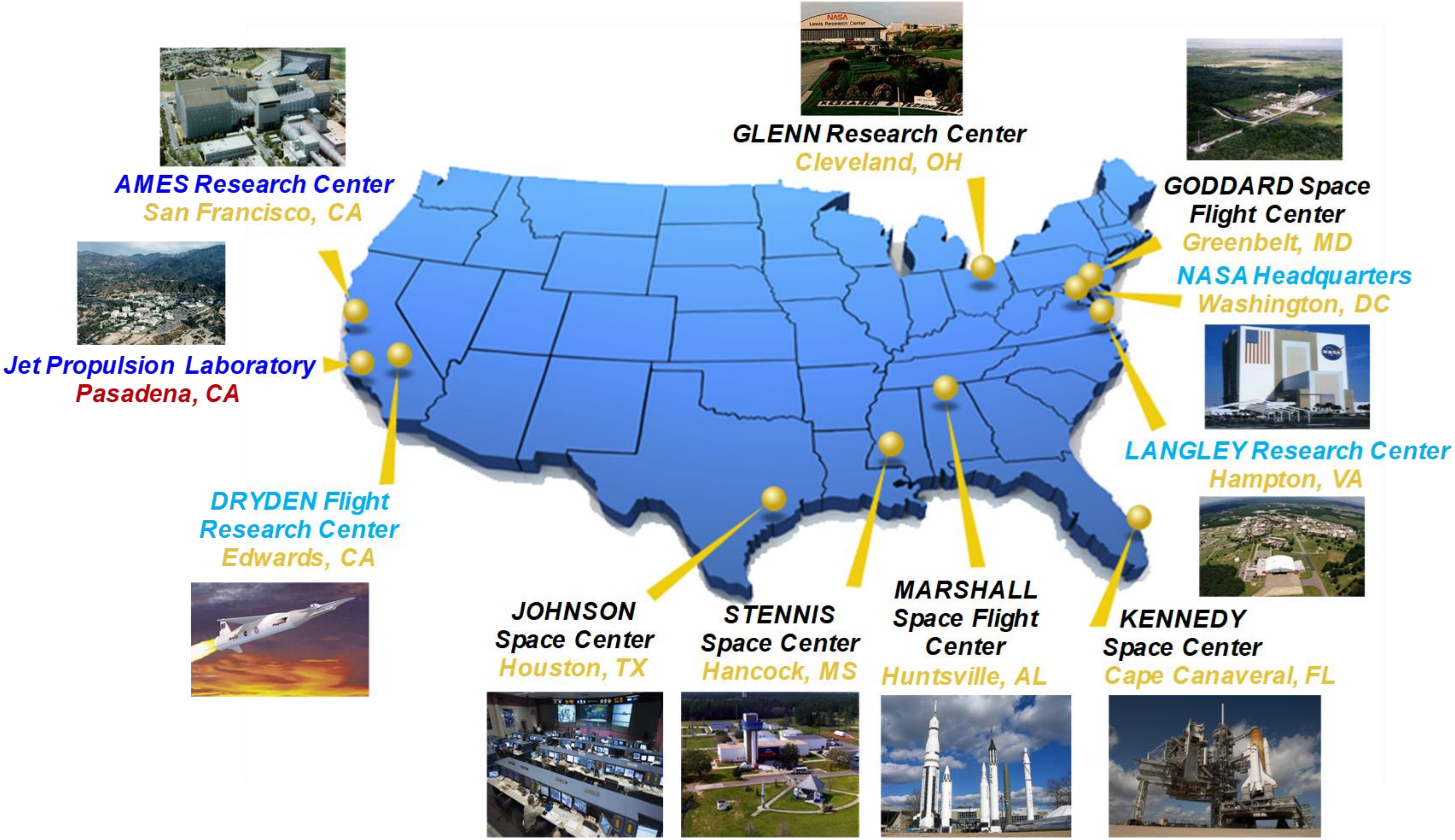
Group Lead for Technology Development

(Source: Courtesy of JPL NASA)*

*Unless otherwise noted, all figures in these slides are from the following source: Jet Propulsion Laboratory, National Aeronautics Space Administration (JPL NASA)

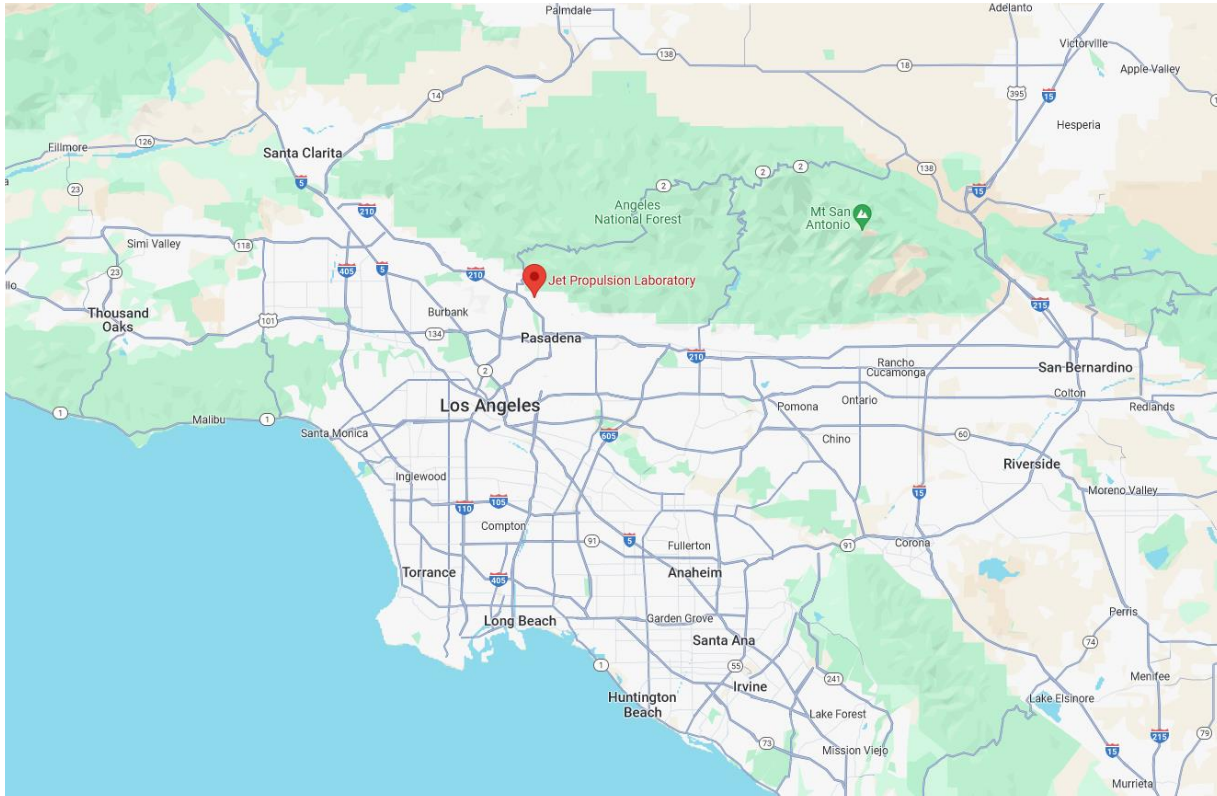
NASA Centers



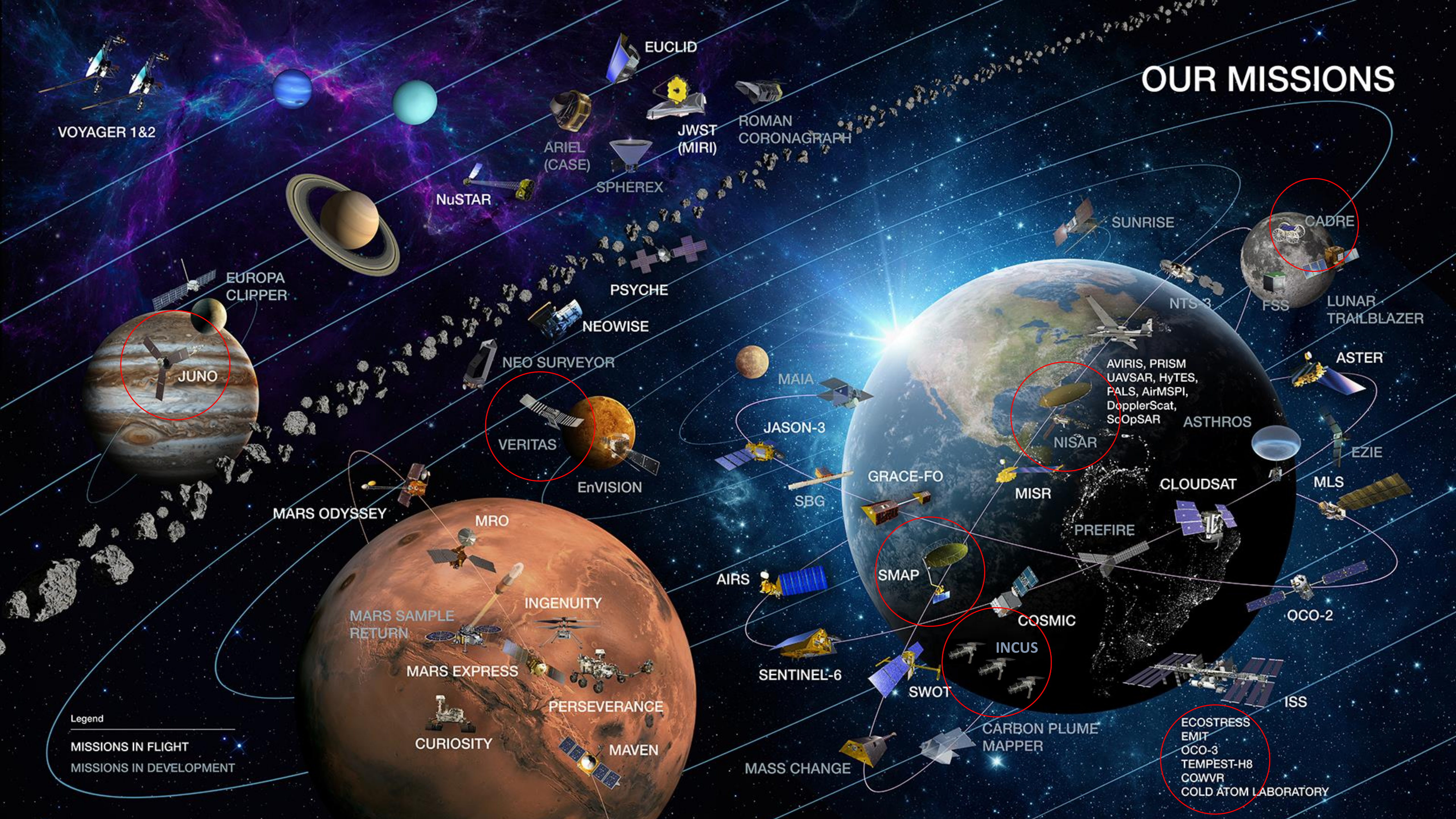
Jet Propulsion Laboratory (JPL)

- JPL is about 10 miles north of downtown Los Angeles.

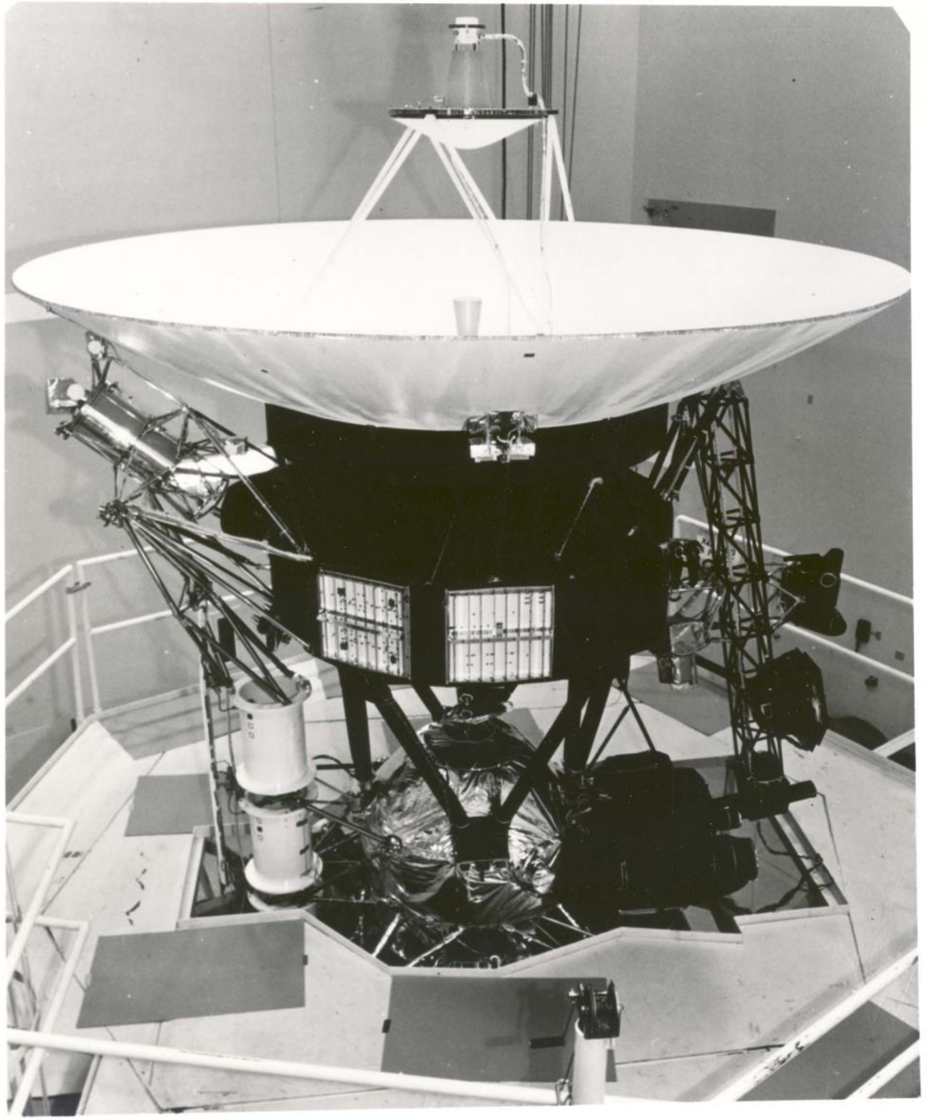
- Part of Southern California’s historic aerospace industry.



- **JPL** is a **federally funded research and development center** funded by NASA and managed by Caltech.
- > **5,500** employees
- > **$2B/year** budget, at the mercy of Congressional funding decisions


OUR MISSIONS
VOYAGER 1&2
EUCLID
ARIEL (CASE)
JWST (MIRI)
ROMAN CORONAGRAPH
SPHEREX
NuSTAR
SUNRISE
CADRE
EUROPA CLIPPER
PSYCHE
NTS-3
FSS
LUNAR TRAILBLAZER
NEOWISE
NEO SURVEYOR
JUNO
MAIA
AVIRIS, PRISM
UAVSAR, HyTES,
PALS, AirMSPI,
DopplerScat,
ScOpSAR
ASTHROS
ASTER
JASON-3
VERITAS
NISAR
EZIE
GRACE-FO
MISR
CLOUDSAT
MLS
MARS ODYSSEY
EnVISION
SBG
MRO
PREFIRE
SMAP
AIRS
INGENUITY
MARS SAMPLE RETURN
COSMIC
OCO-2
INCUS
SENTINEL-6
MARS EXPRESS
SWOT
ISS
PERSEVERANCE
CARBON PLUME MAPPER
ECOSTRESS
EMIT
OCO-3
TEMPEST-H8
COWVR
COLD ATOM LABORATORY
CURIOSITY
MAVEN
MASS CHANGE
Legend
MISSIONS IN FLIGHT
MISSIONS IN DEVELOPMENT

Voyager, Interstellar Space, 1977



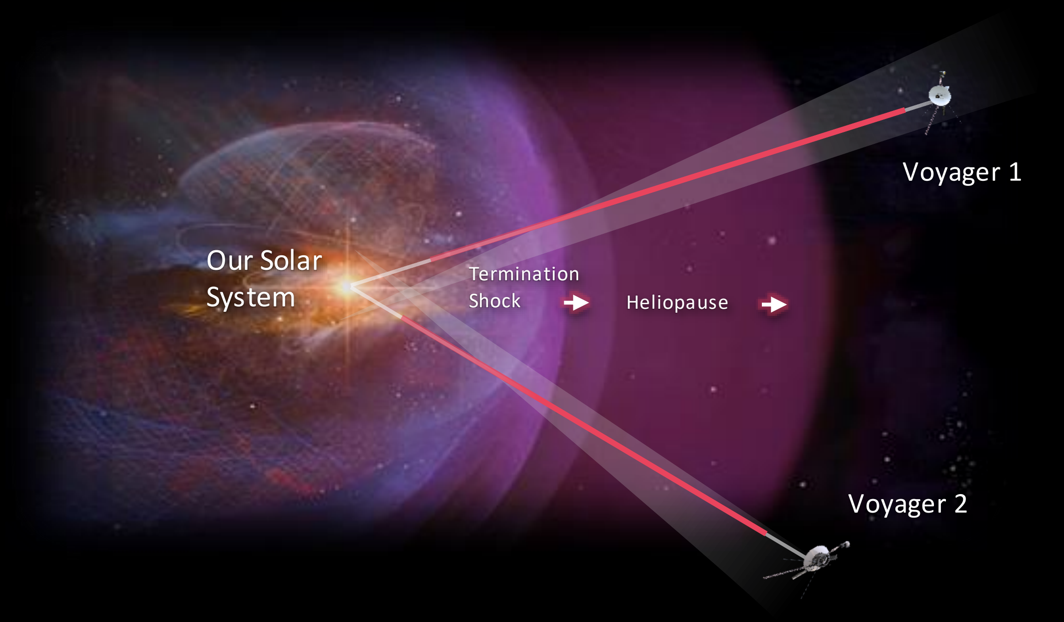
Voyager High-Gain Antenna

- 3.66-m diameter parabolic reflector
- F/D = 0.338
- S-band, TX & RX
- X-band, TX only

Voyager is powered by 3 radioisotope thermoelectric generators and uses **13-W radio frequency (RF) transmitters.**

Very Far & Very Fast

Distance	Miles Away	AU
Voyager 1	15.2 billion	163
Voyager 2	12.7 billion	137



Light Times	One Way (HH:MM)	Two Way (HH:MM)
Voyager 1	22:30	45:00
Voyager 2	19:00	38:00

Speed	Miles/Hour	KM/Second	AU/Year
Voyager 1	38,025	17.0	3.6
Voyager 2	34,390	15.4	3.2
Solar System	492,126	220	46.3

Magellan, Venus, 1989

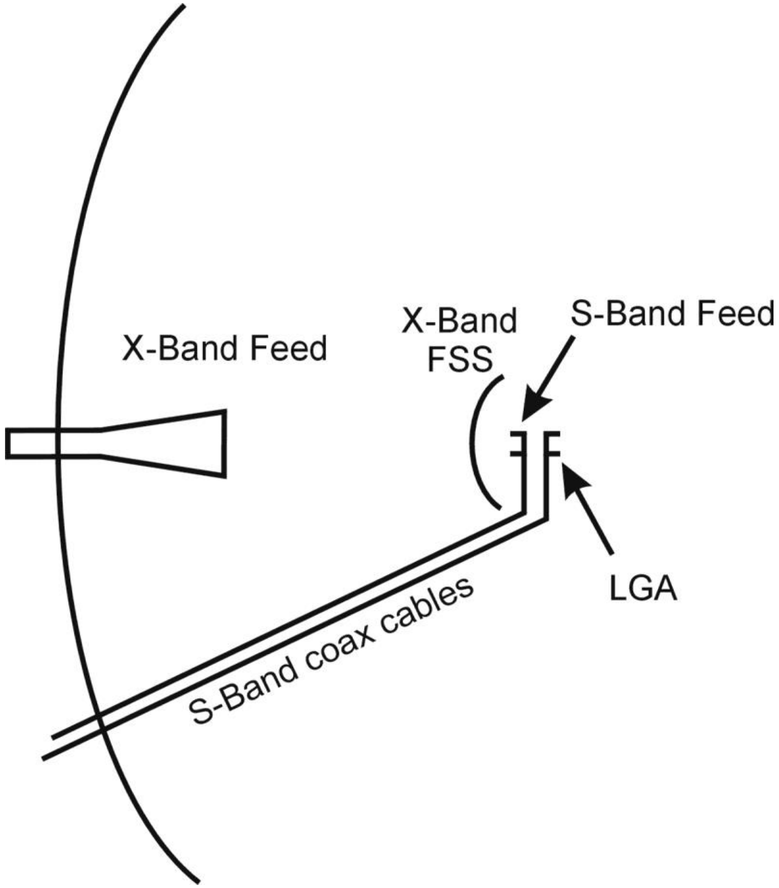
The Magellan spacecraft being deployed by the Space Shuttle Atlantis during STS-30, along with its inertial upper stage. To the left of the reflector antenna, the altimeter antenna instrument is also visible.

The Voyager high-gain antenna was integrated with an S-band instrument that operated in three modes:

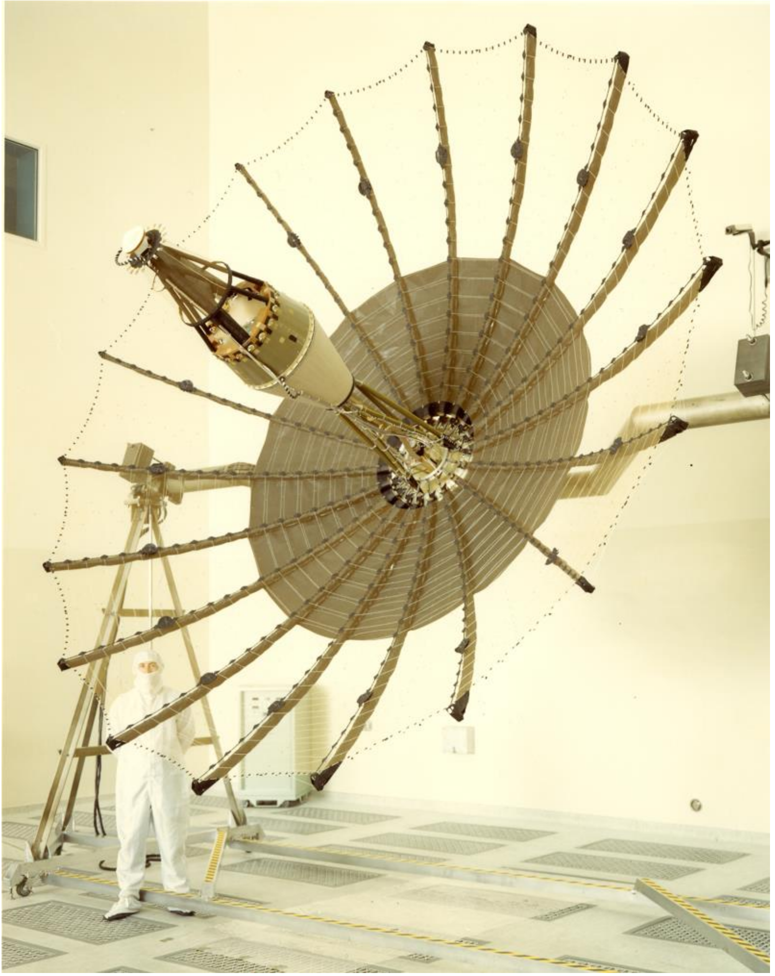
1. synthetic aperture radar (SAR)
2. altimeter
3. radiometer

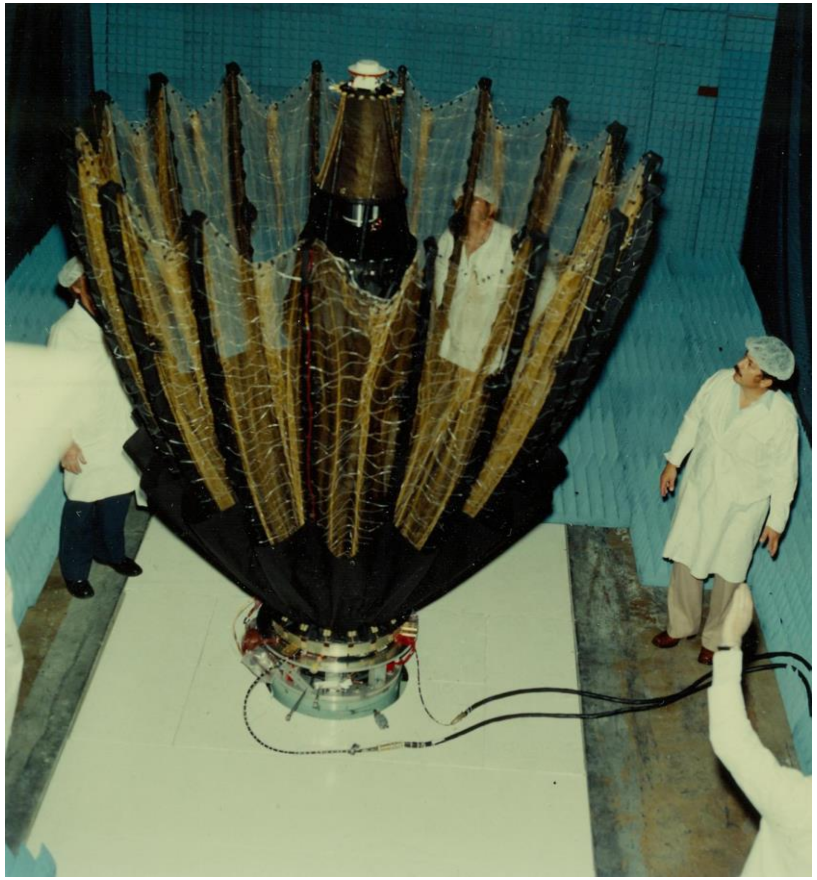
For the first time, the side-looking SAR provided a remarkably detailed map of Venus's surface, which is not visible due to the planet's dense atmosphere. The technology proven by Magellan was later used on the Shuttle Radar Topography Mission.

Antenna Schematic Diagram



Galileo, Jupiter, 1989

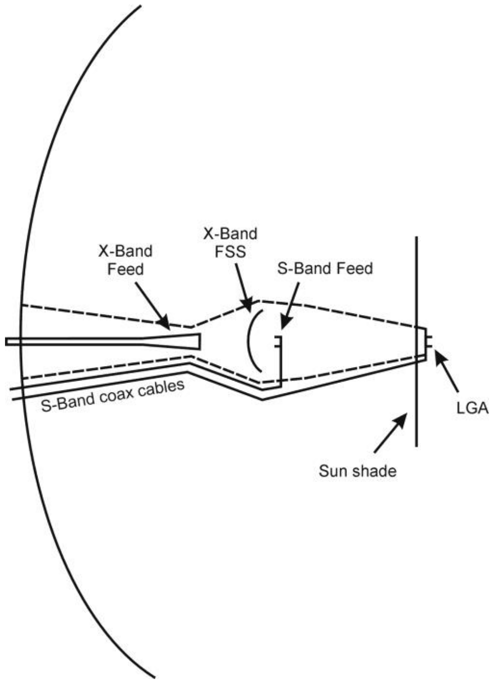




The Galileo antenna fully deployed (left) and partially deployed (above) while being tested on the plane polar nearfield antenna range at JPL's MESA Antenna Test Facility.

Galileo S/C with stowed antenna.

Antenna Schematic Diagram



Galileo High-Gain Antenna

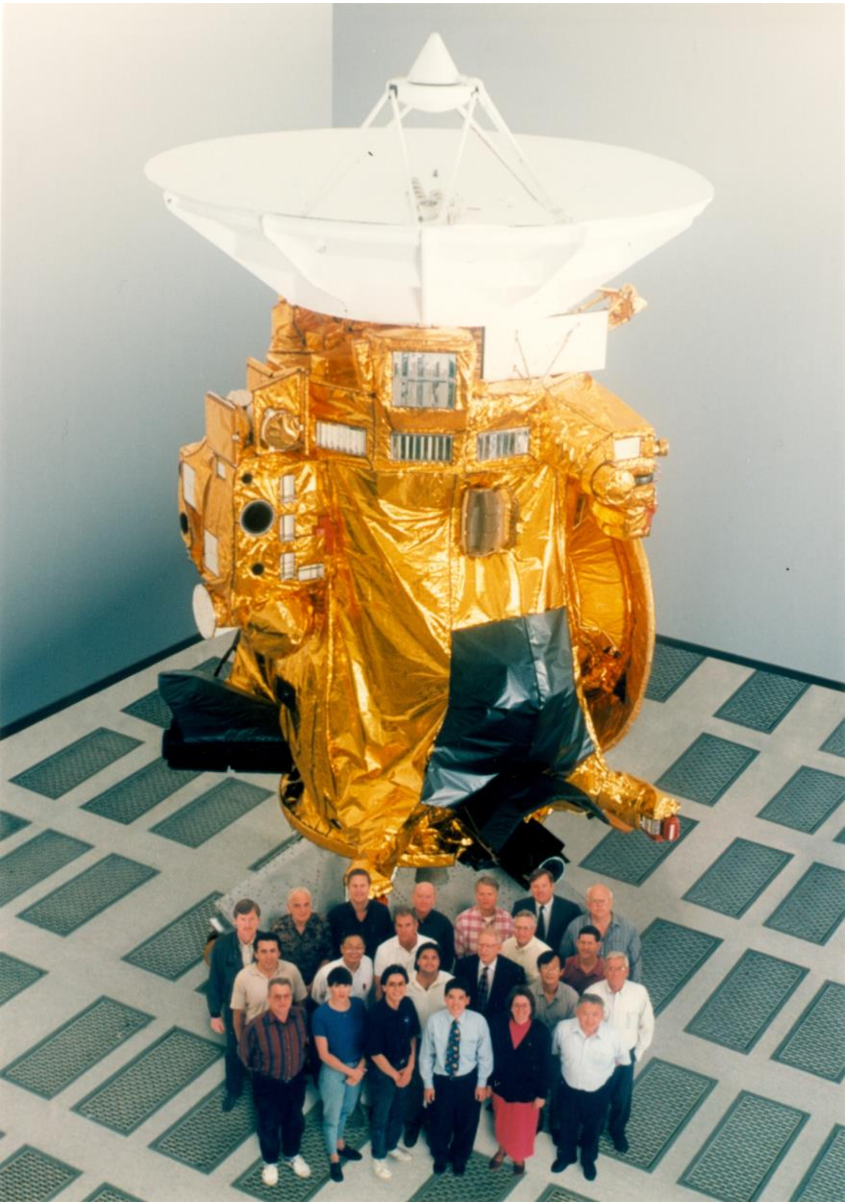
- 4.755-m diameter parabolic reflector
- Radial rib mesh deployable reflector, 10 opi mesh
- S-band & X-band, TX & RX

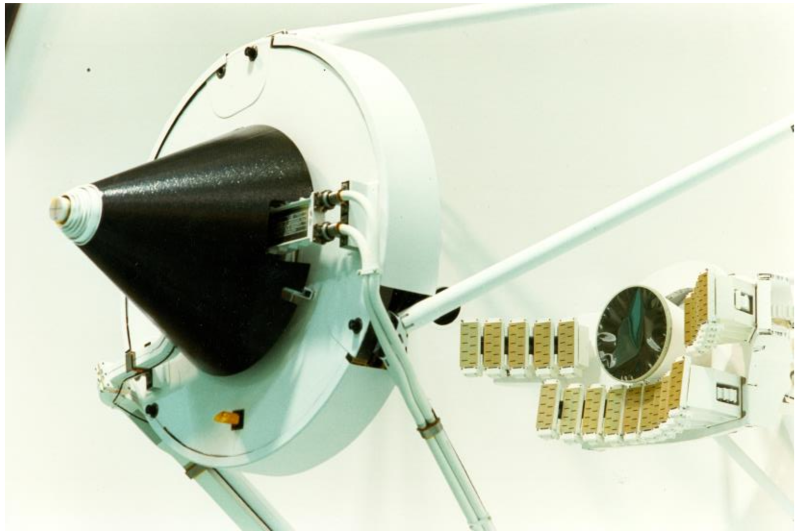
Space Shuttle Atlantis launching Galileo into orbit on October 18, 1989.

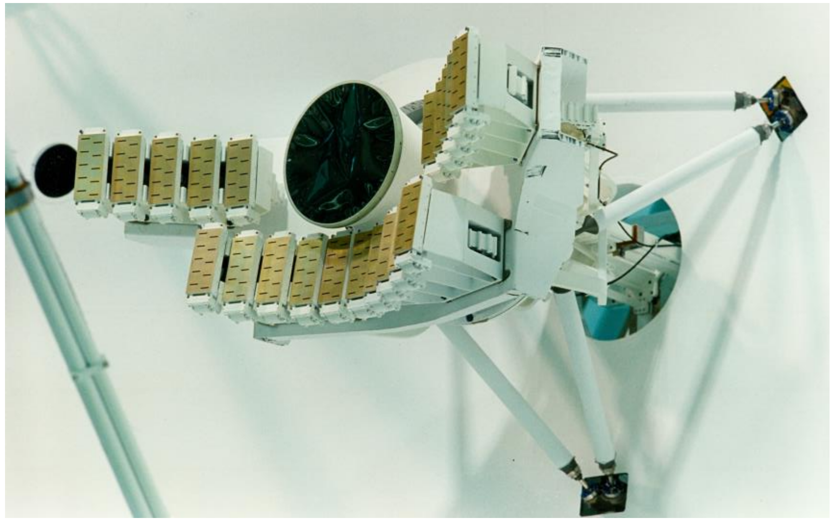
Cassini, Saturn, 1997

Cassini High-Gain Antenna

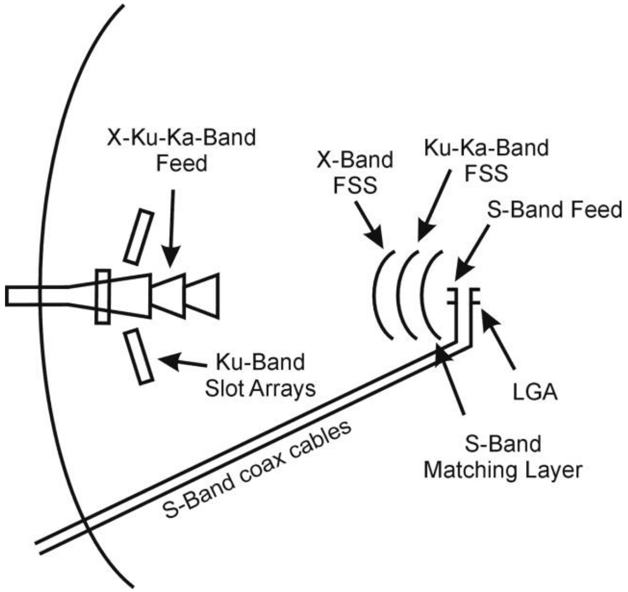
- 4-m diameter parabolic reflector
- F/D = 0.33
- S-X-Ku-Ka-band operations



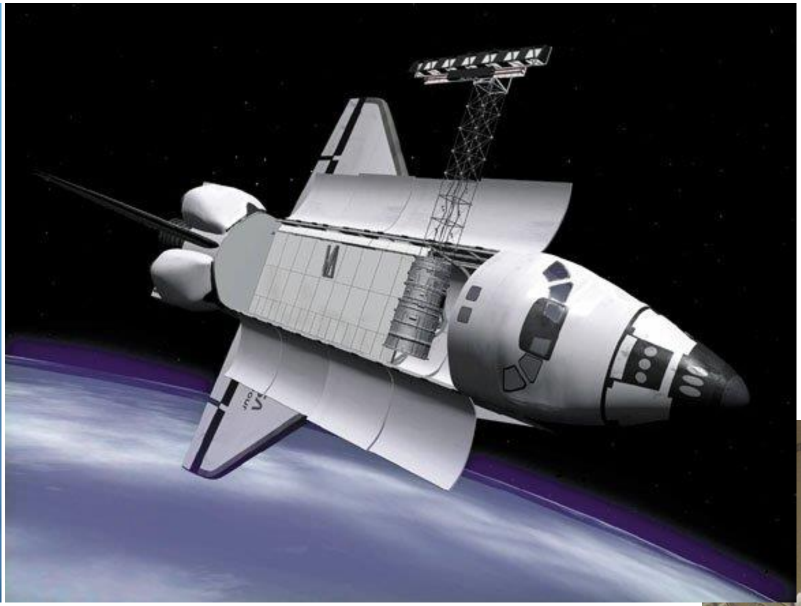


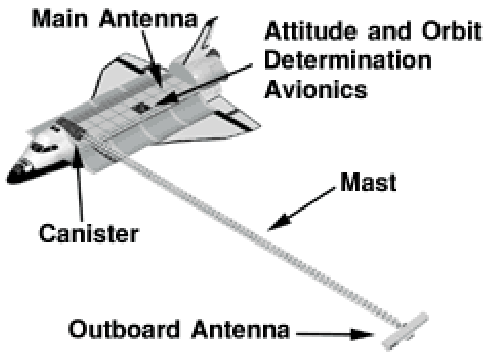


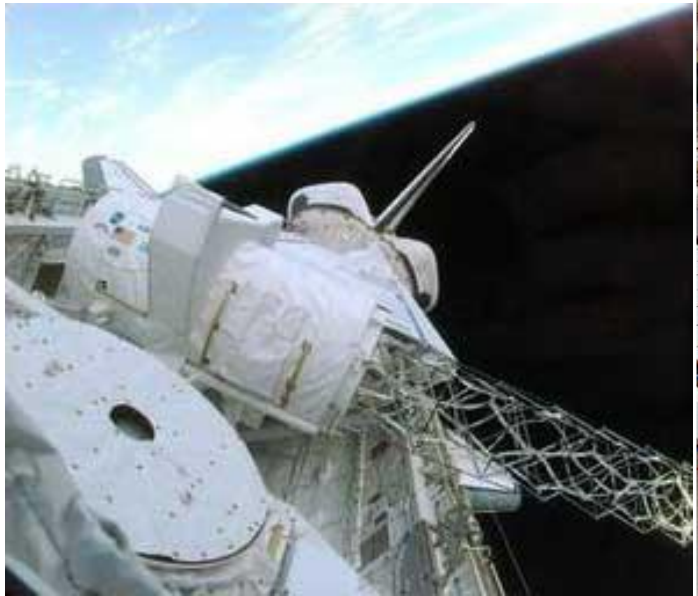
Antenna Schematic Diagram



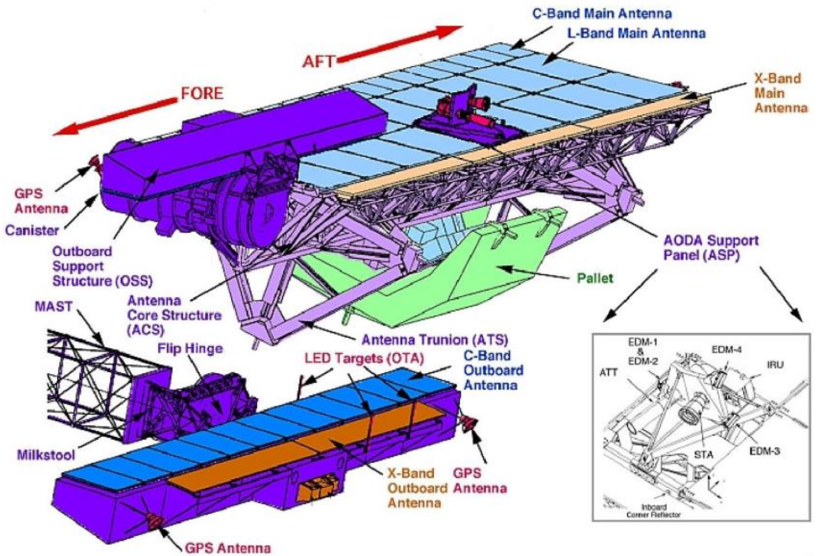
Shuttle Radar Topography Mission, 2000

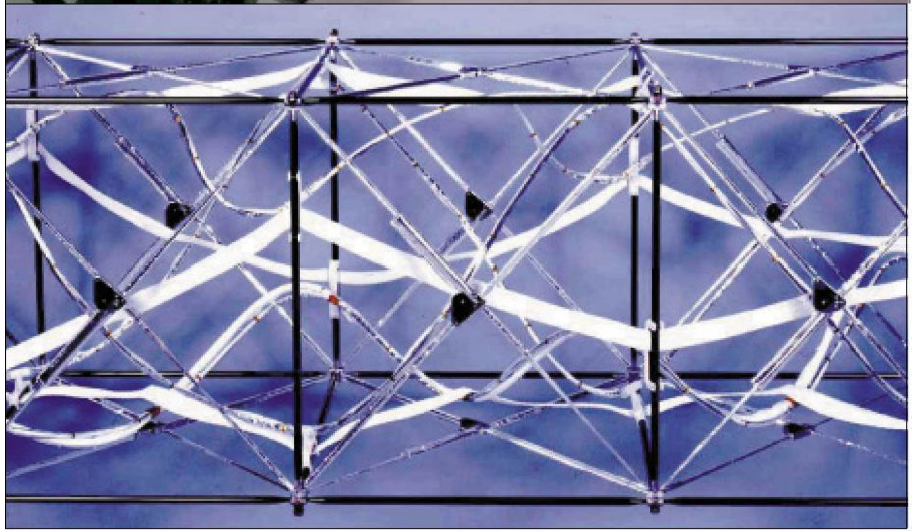






RX-Only Antennas and 60-m Boom





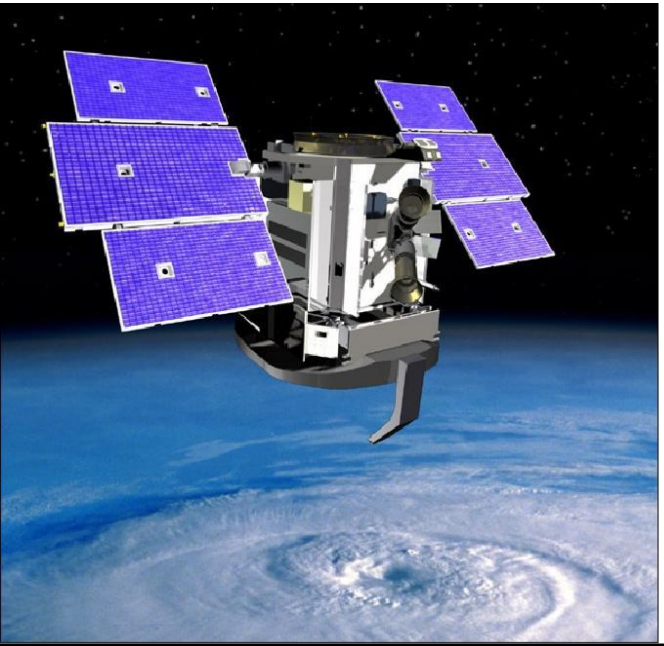
- TX/RX Antennas
  - C-band, 12 m x 0.75 m patch array
  - X-band, 12 m x 0.40 m slotted waveguide
- RX-Only Antennas
  - C-band, 8 m x 0.75 m patch array
  - X-band, 6 m x 0.40 m slotted waveguide

Space Shuttle Endeavour at the California Science Center

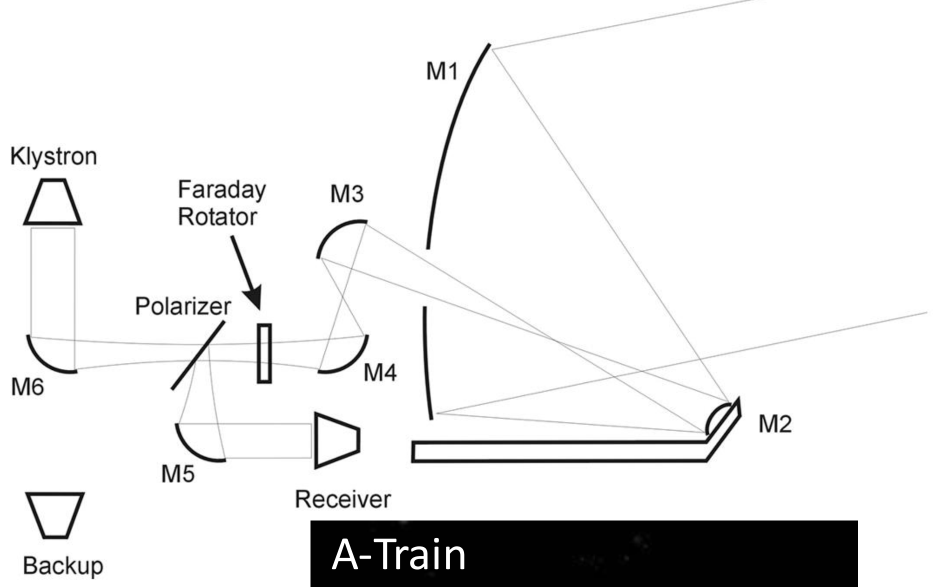
Space Shuttle Endeavour successfully completed its last mission to space in 2011 and then arrived in LA in 2012 with a flyby over JPL.

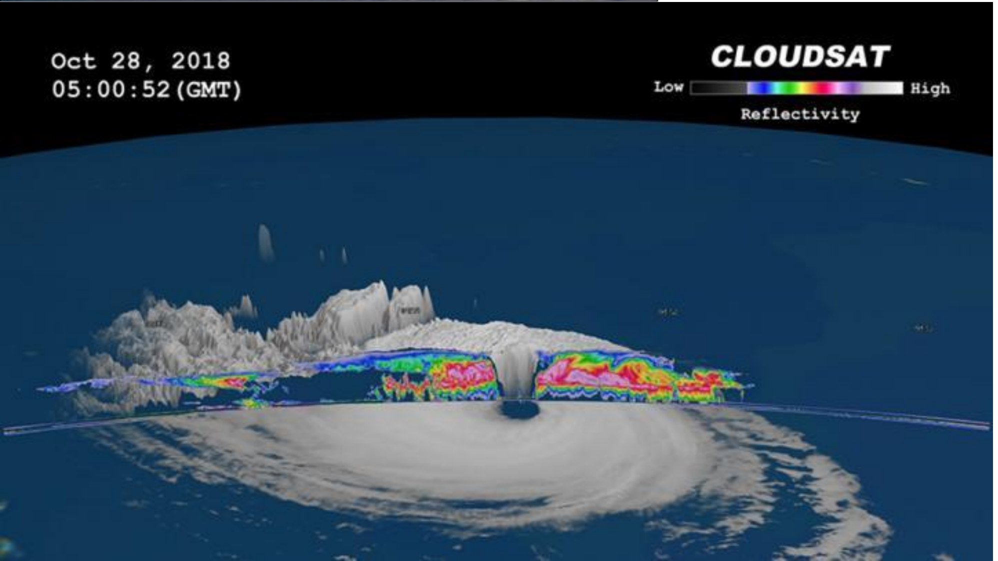
CloudSat, Cloud Profiling Radar, 2006

CloudSat Antenna
- 1.85-m offset Cassegrain reflector with QOTL
- W-band operations

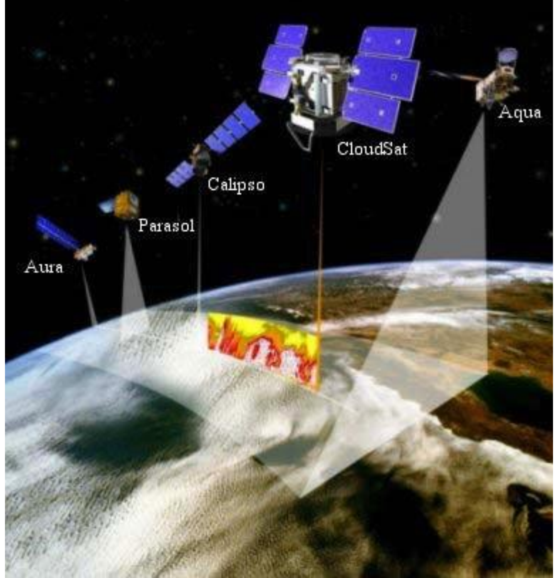


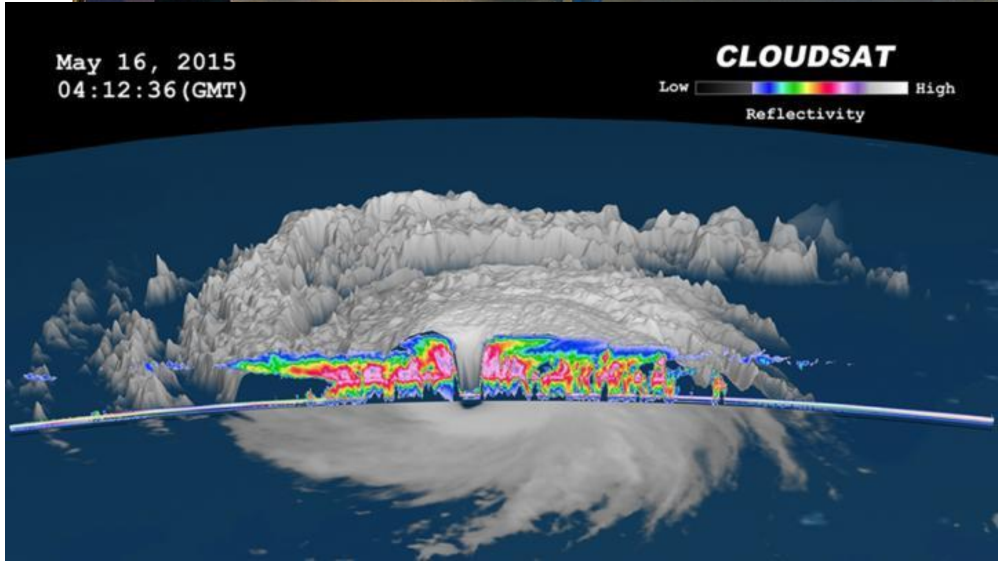
Antenna Schematic Diagram



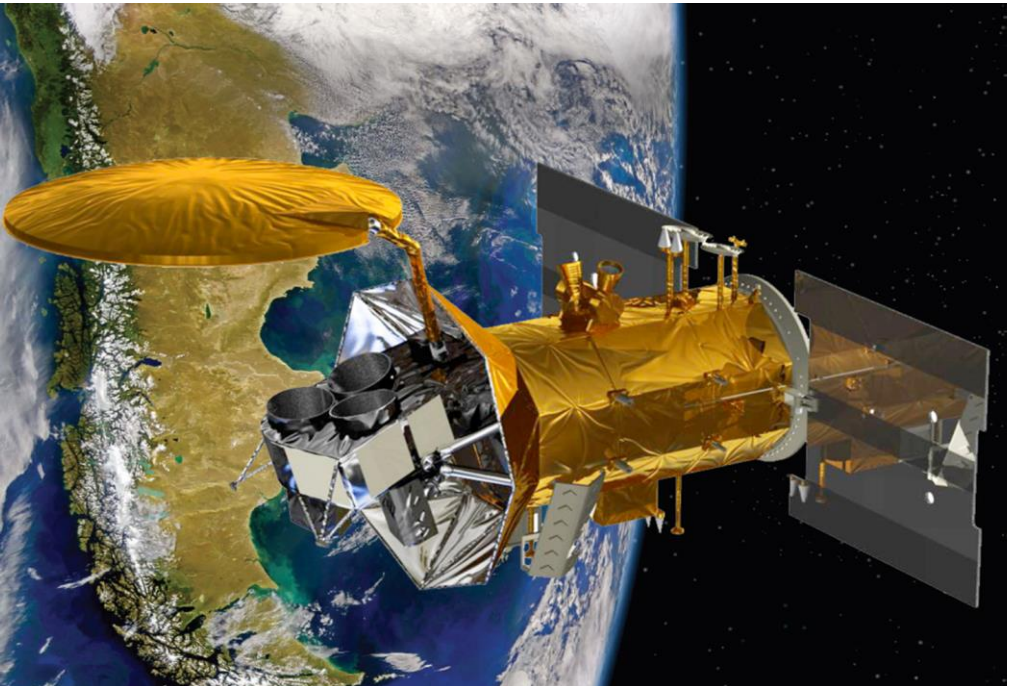


A-Train





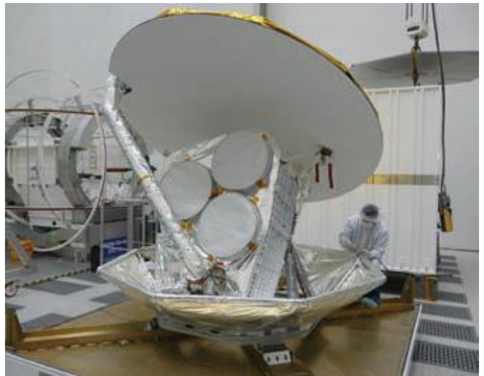
Aquarius, Ocean Water Salinity, 2011



SAC-D/Aquarius
Satélite de Aplicaciones Científicas-D

Aquarius Horn

Aquarius Instrument



- SAC-D/Aquarius was a collaboration between:

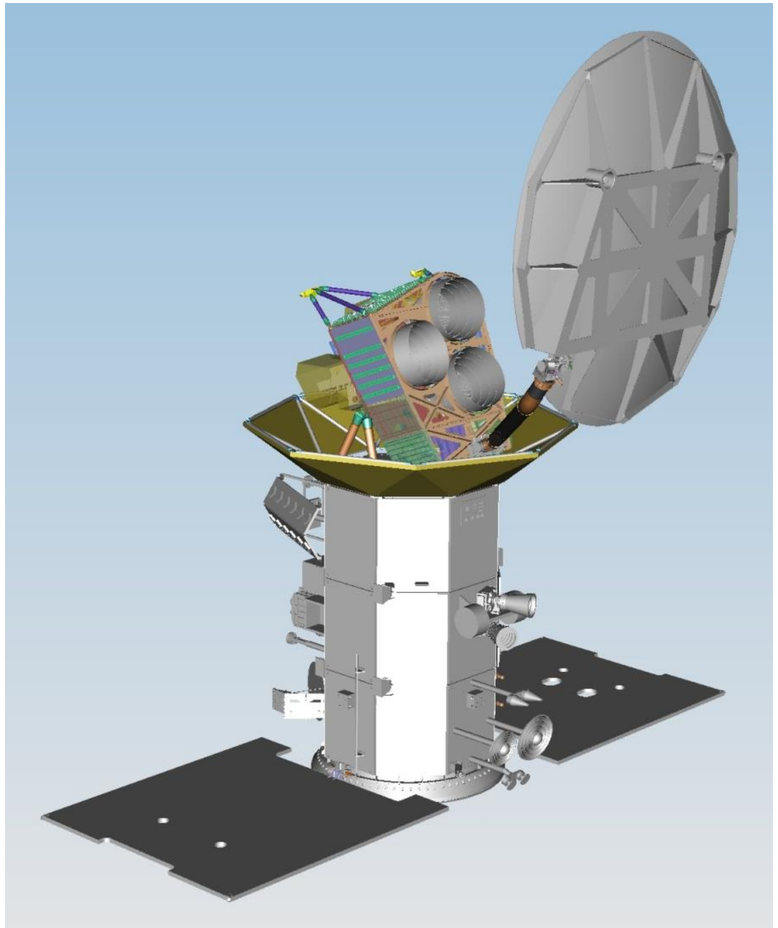
Goddard Space Flight Center
Jet Propulsion Laboratory
California Institute of Technology

CONAE
Comisión Nacional de Actividades Espaciales

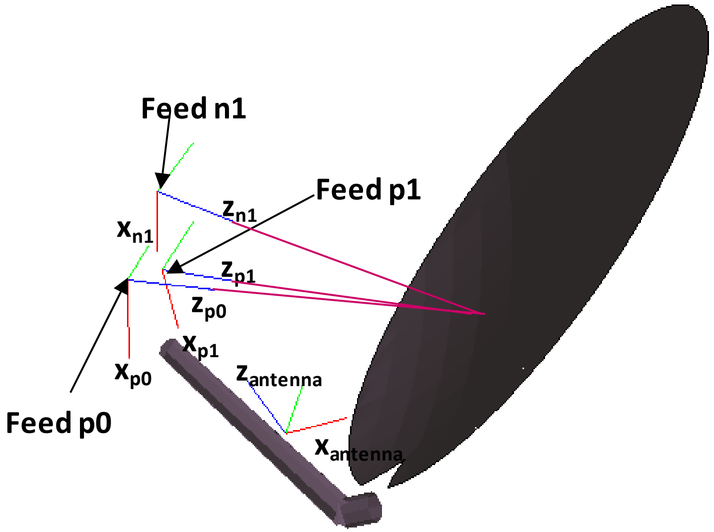
- Its mission was to measure ocean water salinity from space.
- The Aquarius instrument was delivered by Goddard and JPL to CONAE and was integrated with the SAC-D spacecraft.
- It was launched on June 10, 2011, from Vandenberg Air Force Base (AFB), CA.
- It consisted of:
  - 2.5 m solid (graphite composite) deployable offset reflector
  - Three dual-pol, corrugated L-band feed horns
  - Three L-band radiometers (one for each feed)
  - An L-band radar for sea-surface roughness error correction of radiometric measurements
- Mission was terminated on June 8, 2015, because of the failure of a component of onboard power regulation and attitude control.

Aquarius RF Modeling

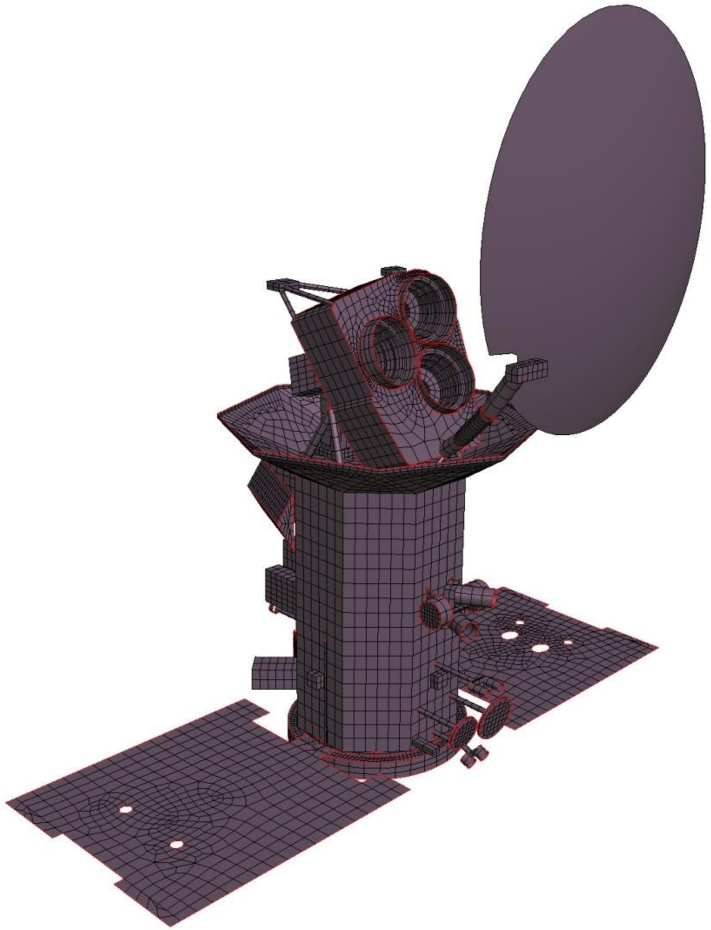
Mechanical Model



2002 RF Model



2011 RF Model



Aquarius Model RF Currents

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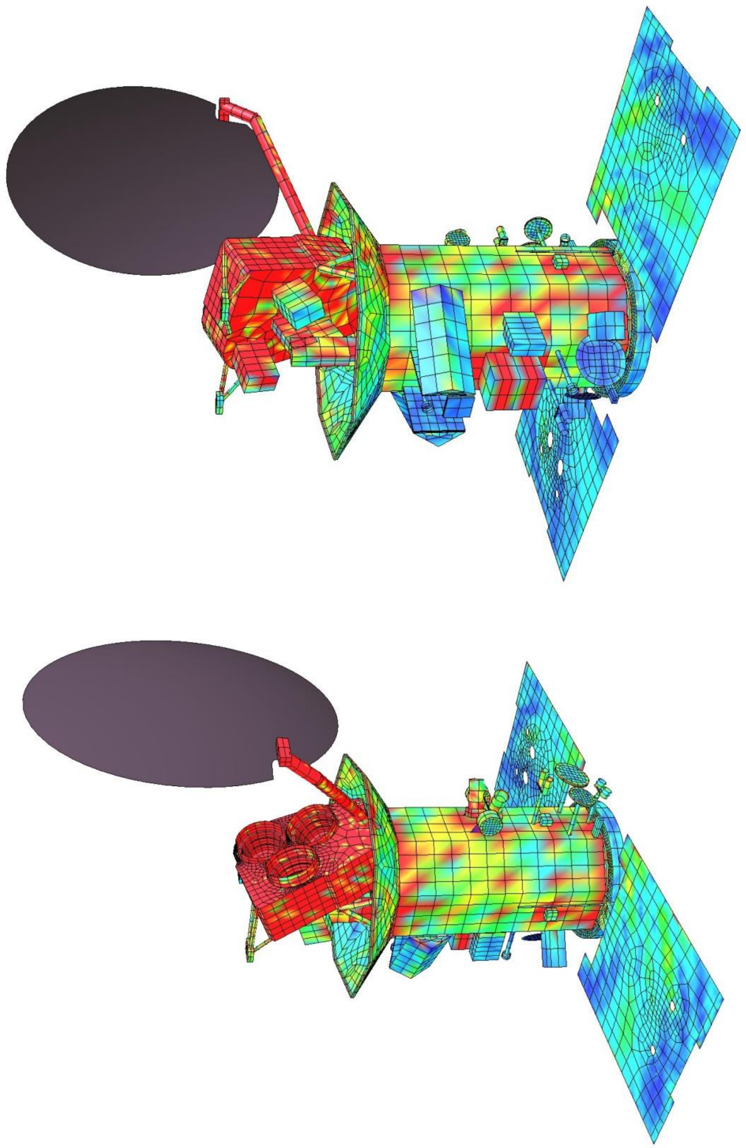
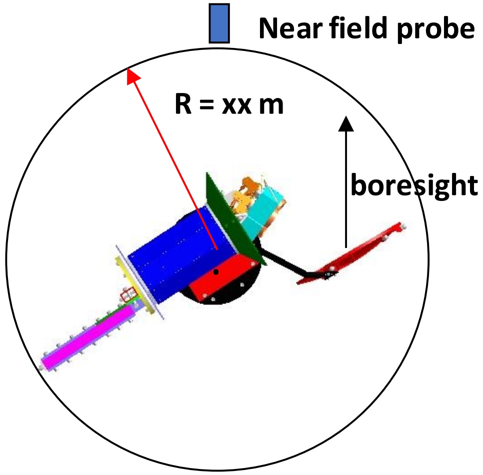
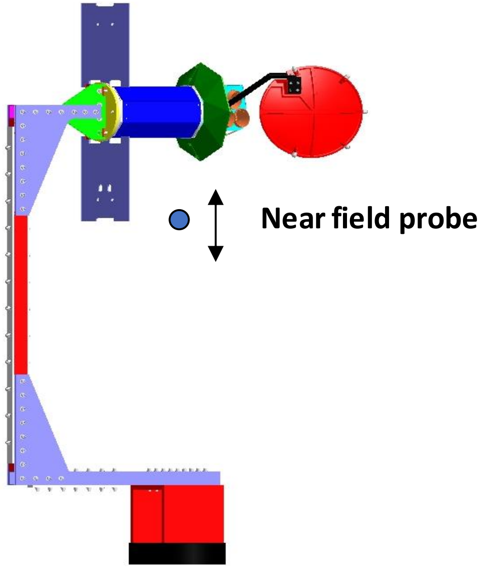
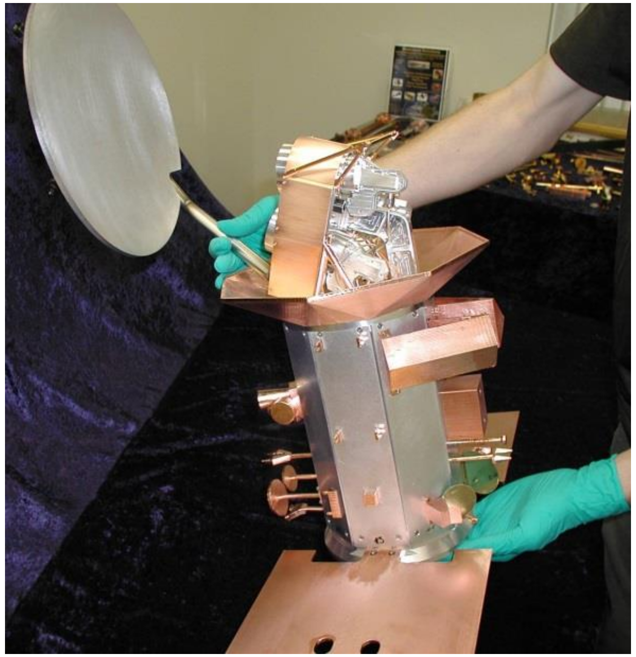
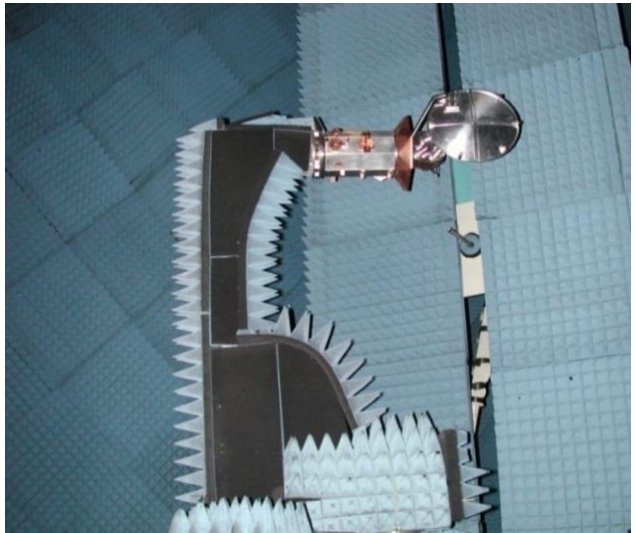


Aquarius Scale Model



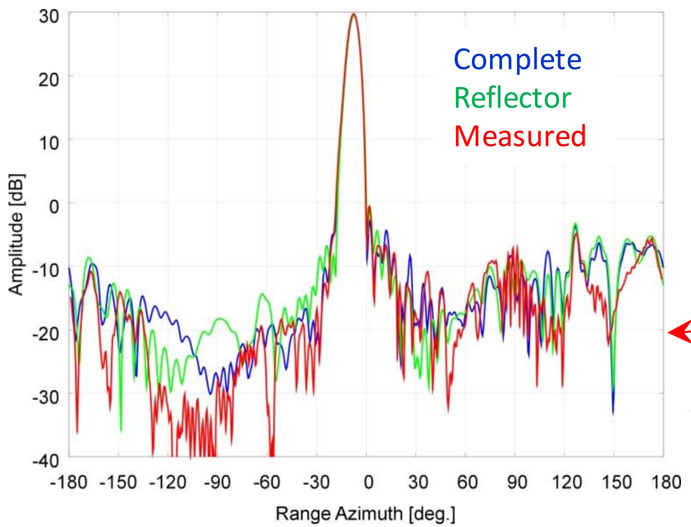




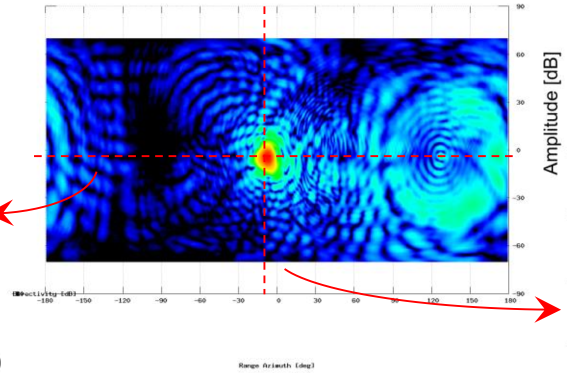


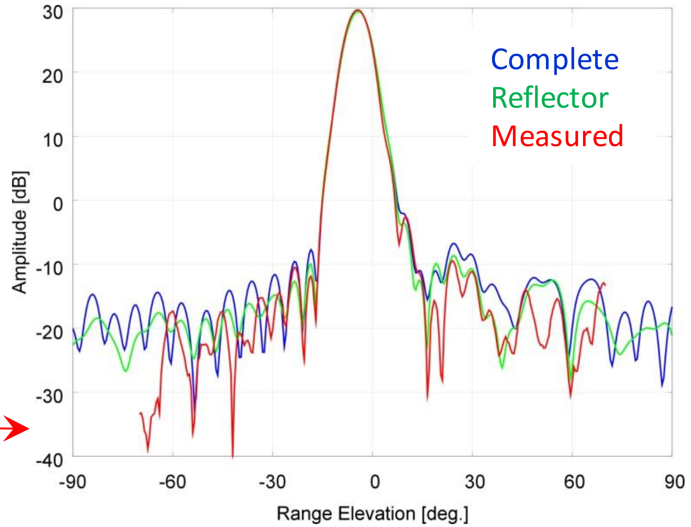
- 1/10th scale model (operating frequency scaled to Ku-band)
- Measured in cylindrical near-field antenna range at JPL

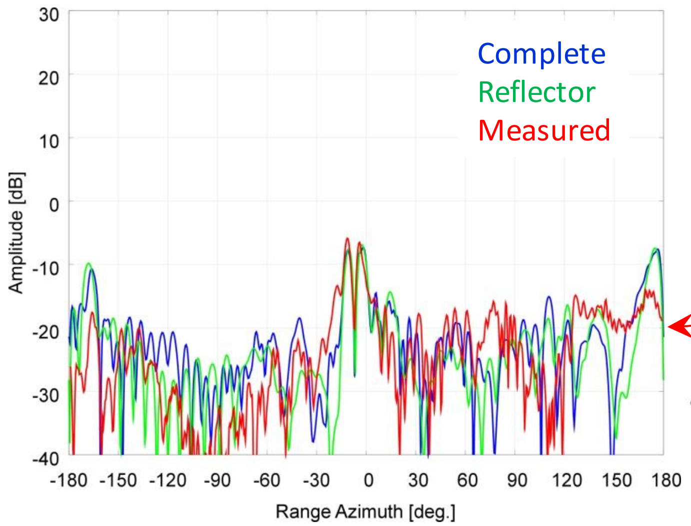
Calculated & Measured Radiation Patterns



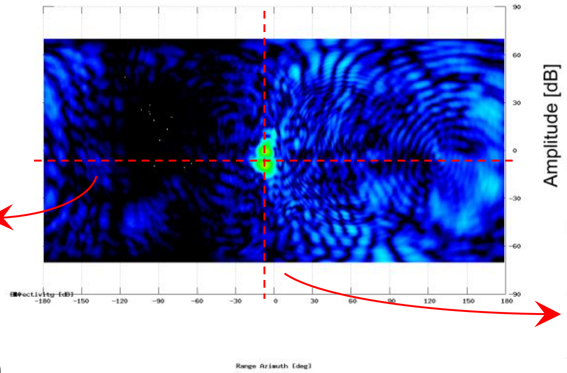
Measured
Co-pol patterns

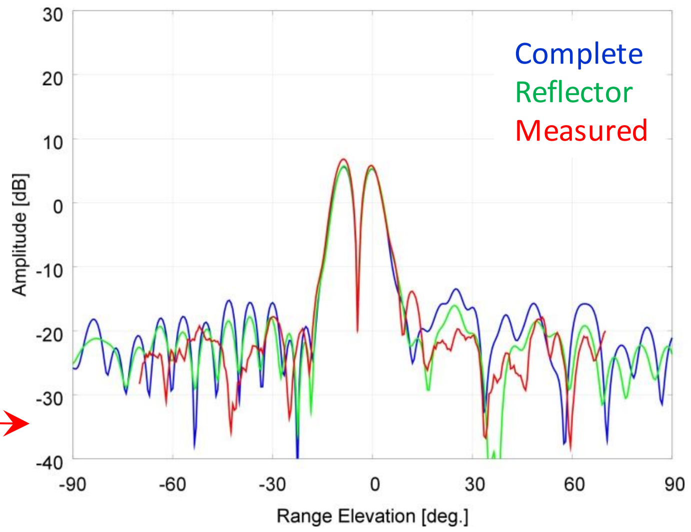




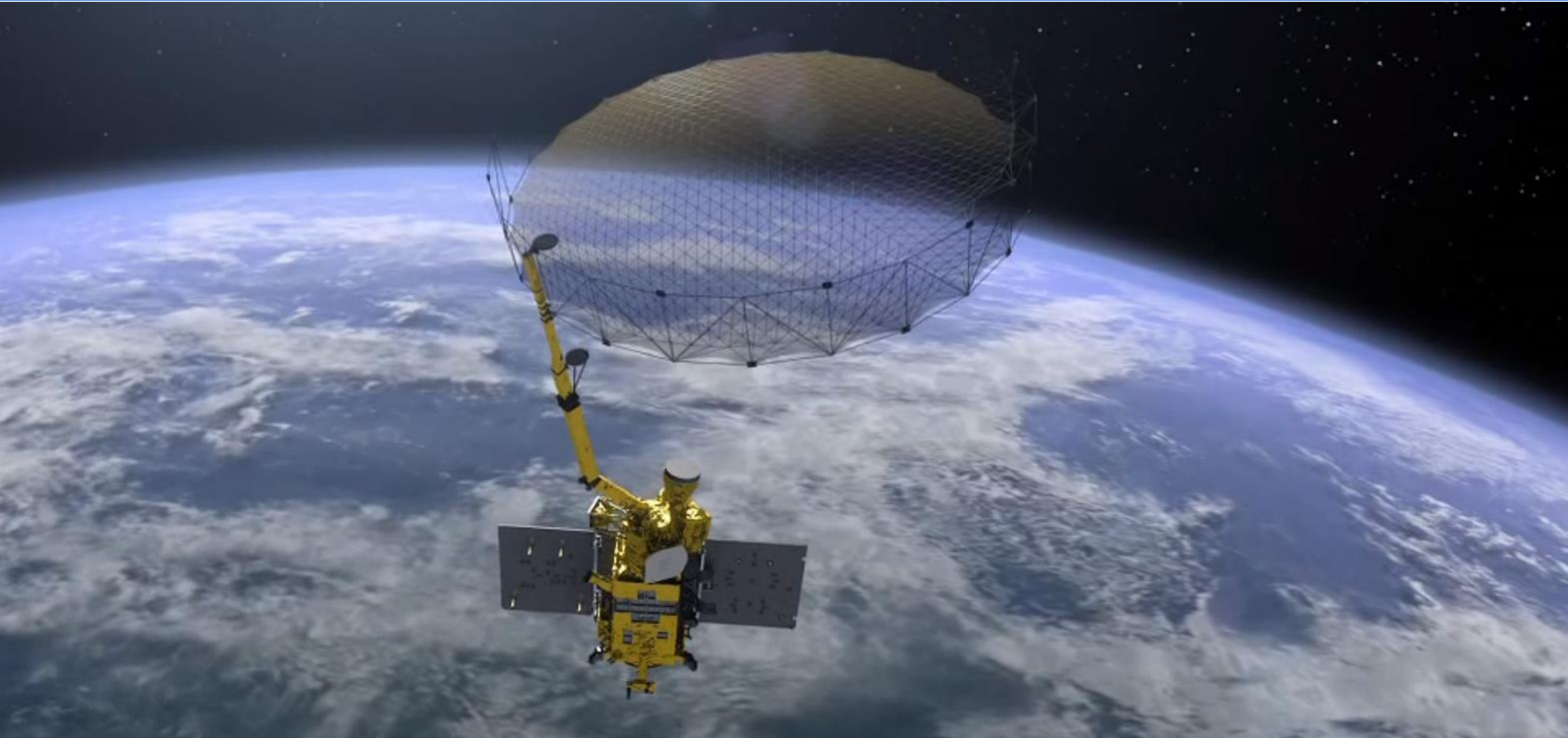


Measured
Cx-pol patterns





SMAP, Soil Moisture Active Passive, 2015



SMAP, Soil Moisture

- SMAP's mission is to measure soil moisture and its freeze/thaw state.
- It was launched on January 31, 2015, from Vandenberg AFB, CA.
- The instrument consists of:
  - 6 m deployable mesh offset reflector
  - A single dual-band, dual-pol, corrugated feed horn
  - L-band SAR
  - L-band radiometer
- The antenna boresight beam is pointed 35.5° off of Nadir.
- The antenna instrument spins at ~14.6 RPM around Nadir.
- The radiometer data is more accurate than the SAR data but has a spatial resolution of about 40 km.
- The SAR spatial resolution is 1-3 km.
- In July 2015, the radar ceased its operations due to a sudden failure of the low-voltage power supply.
- The radiometer is still operational and has provided a large amount of calibrated soil moisture data on a global scale.

Delivery to Vandenberg AFB

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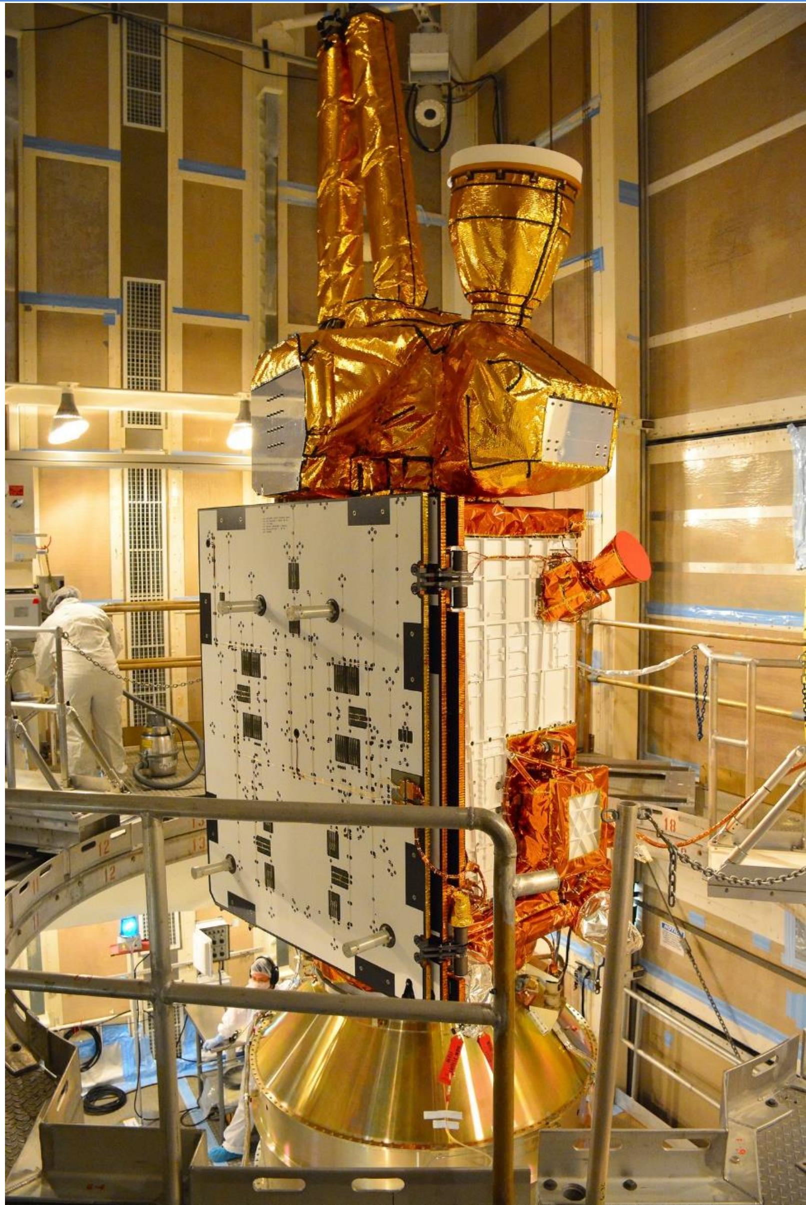

Delta II Launch Vehicle

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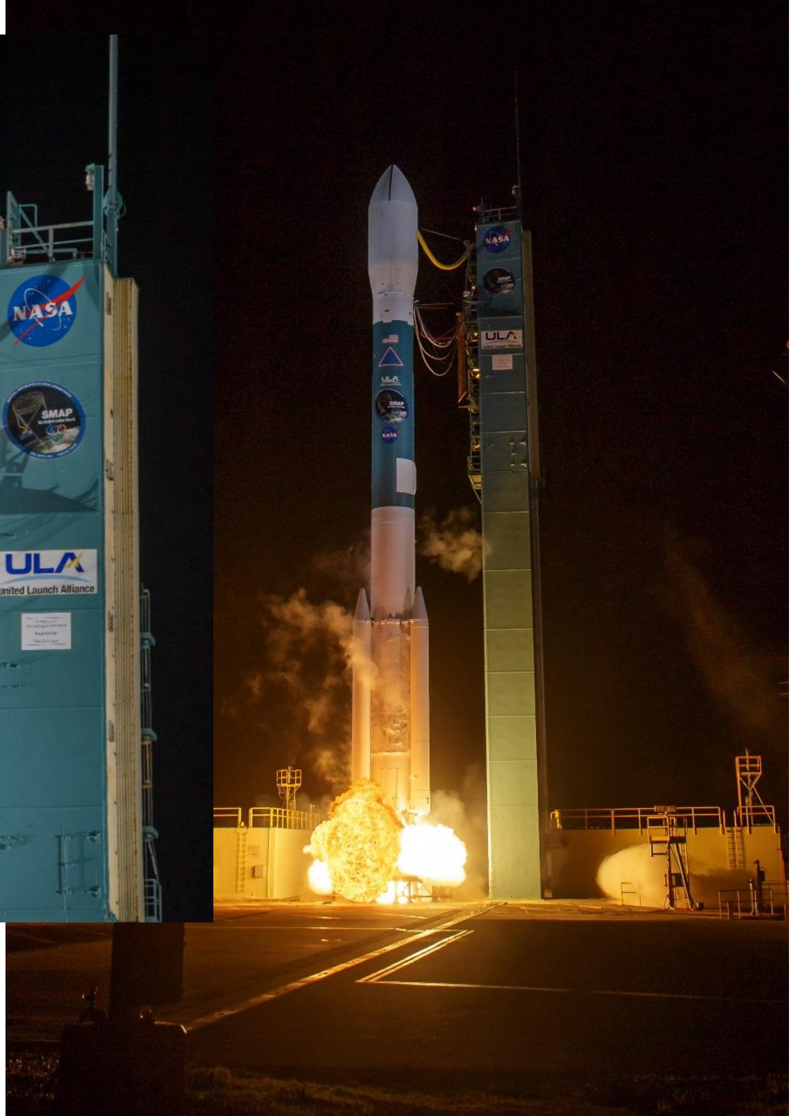
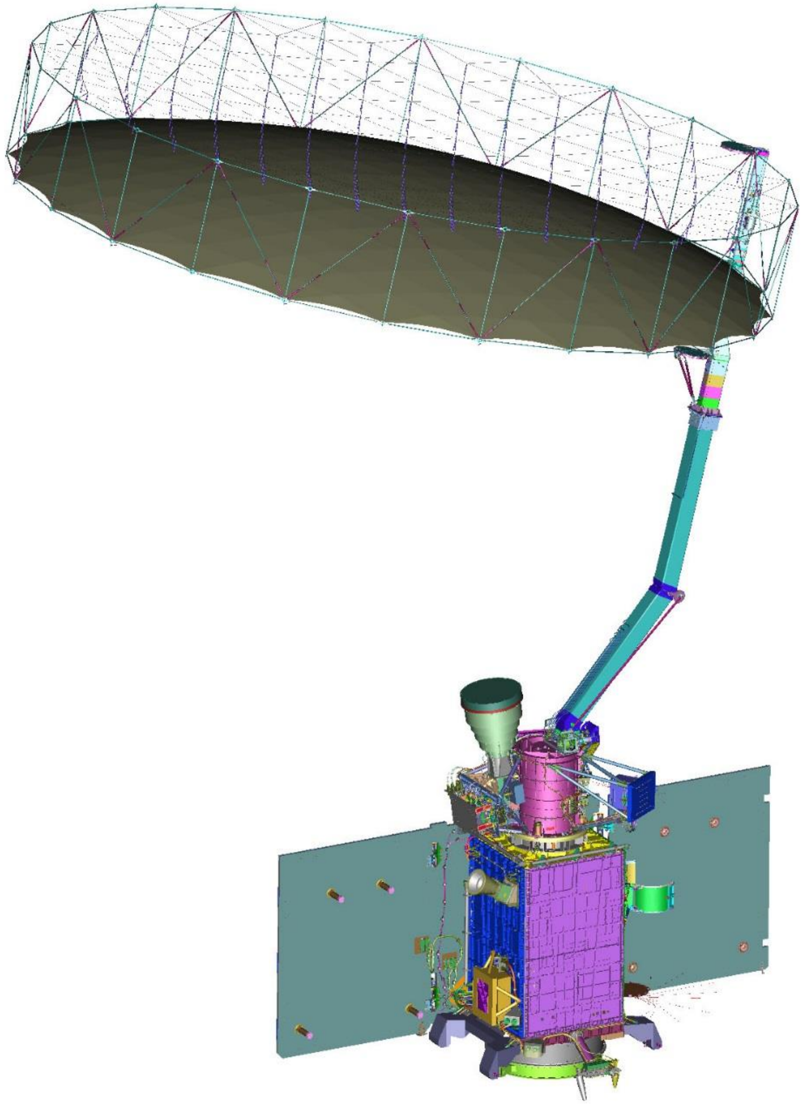
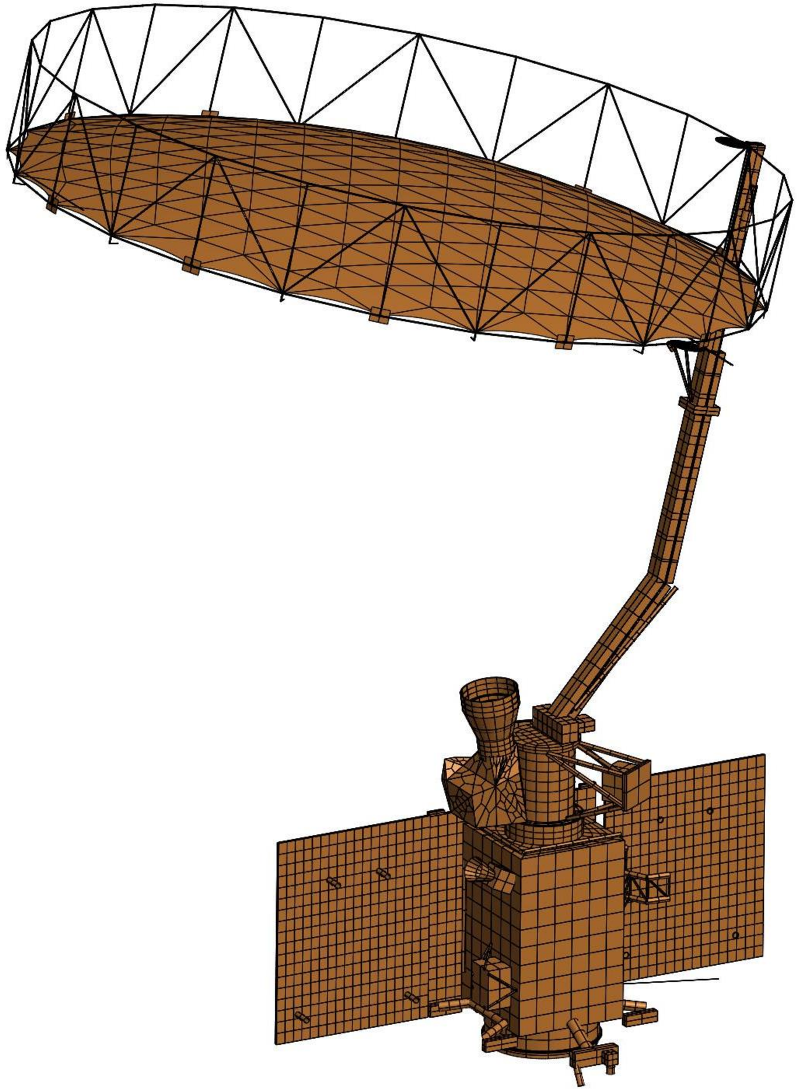
January 31, 2015 @ 6:23AM PST

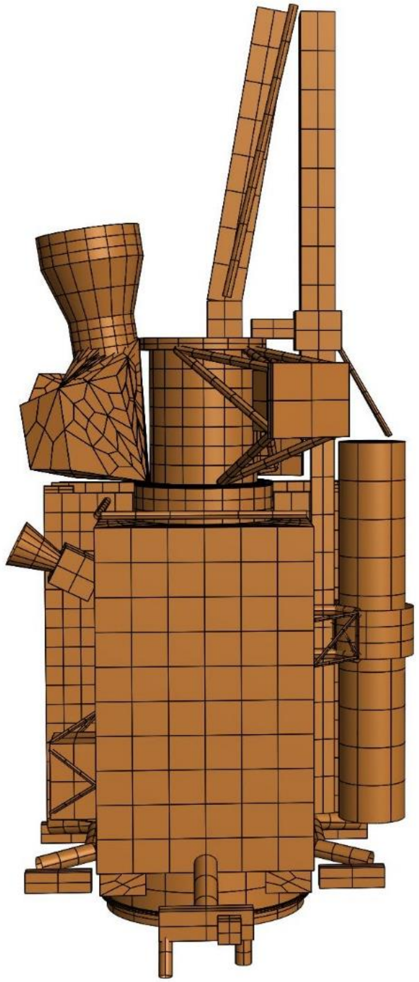


SMAP CAD & RF Models

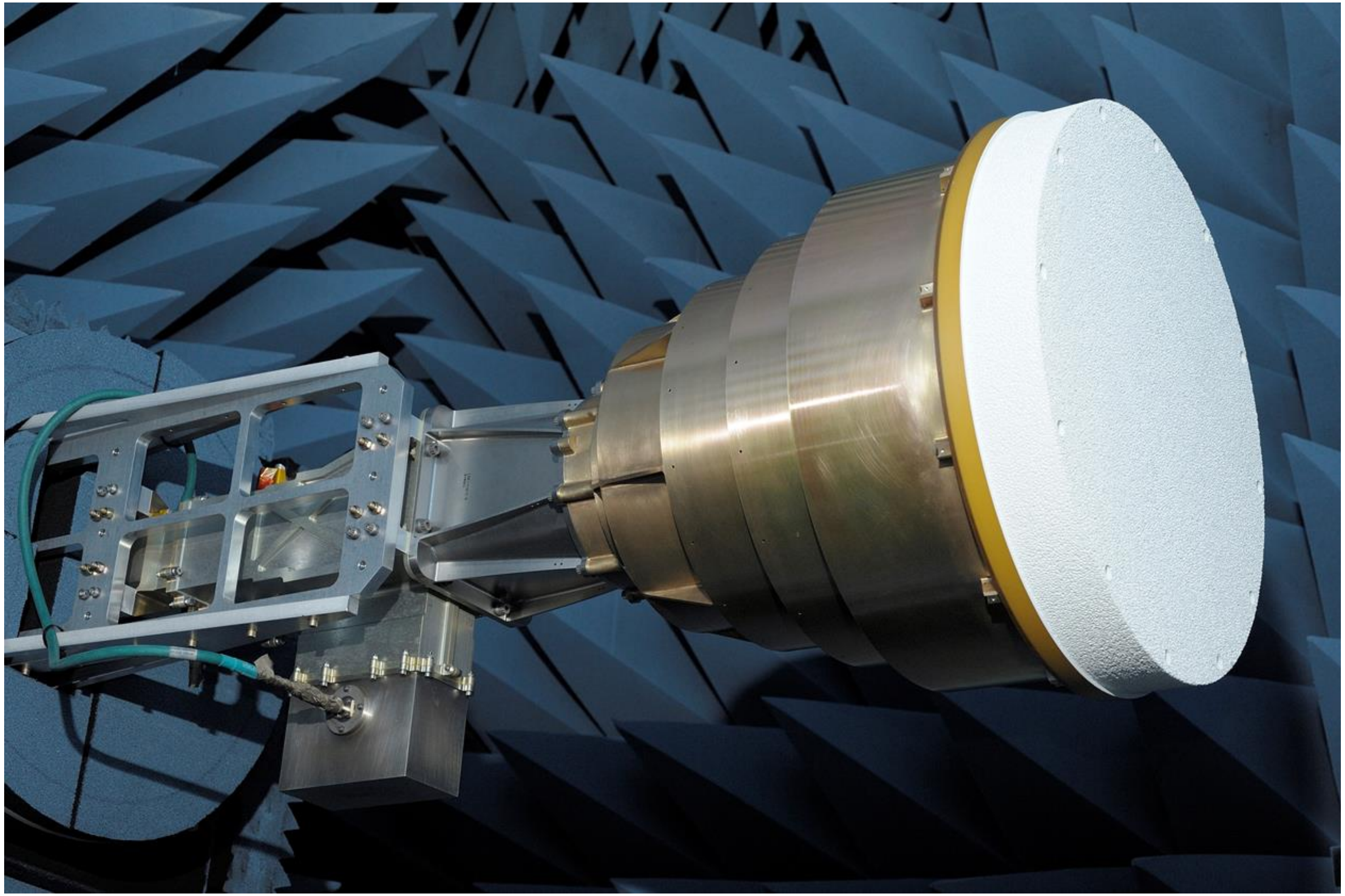




Spacecraft With Stowed AstroMesh™ Reflector



Feed Horn



Isometric View

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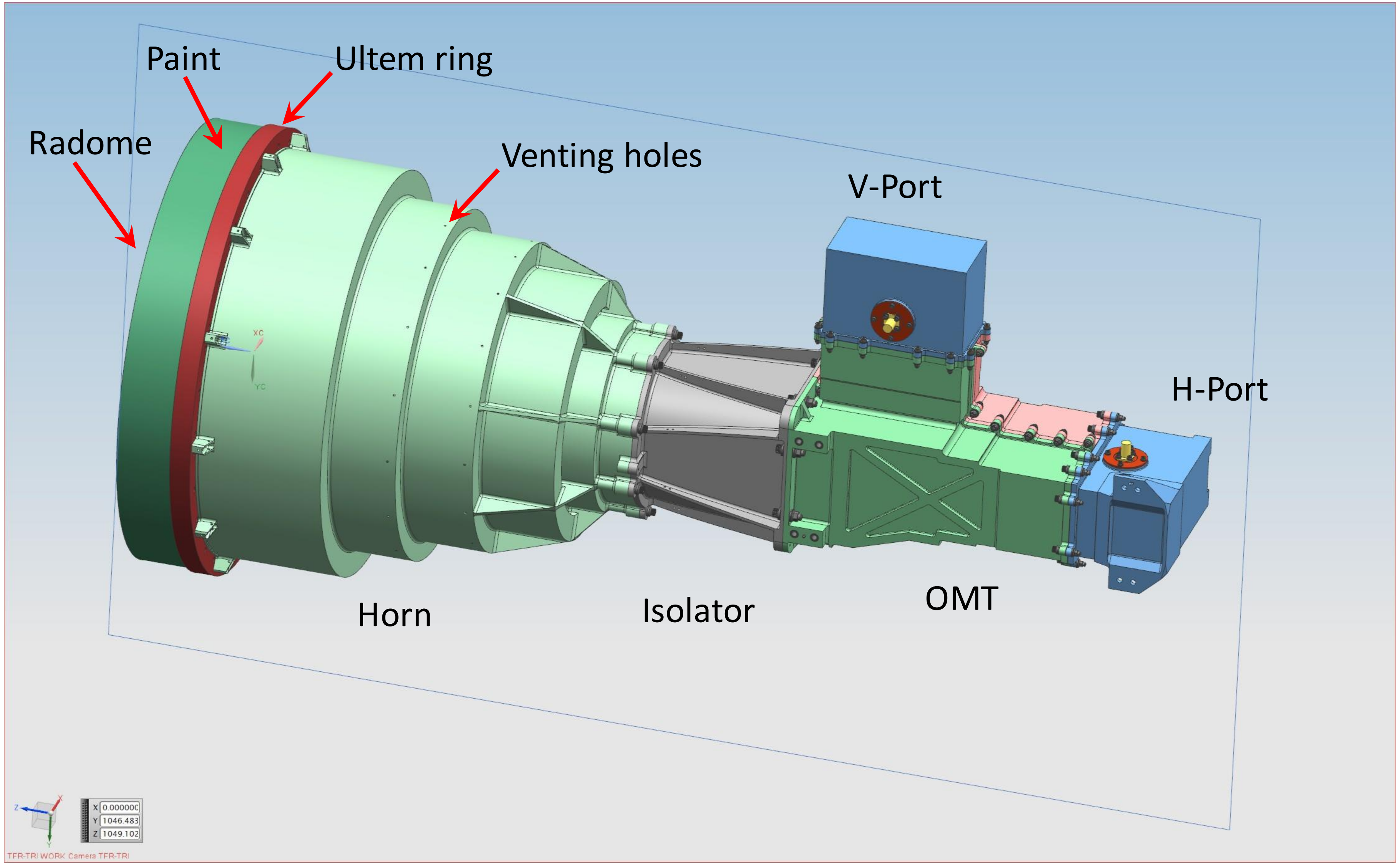
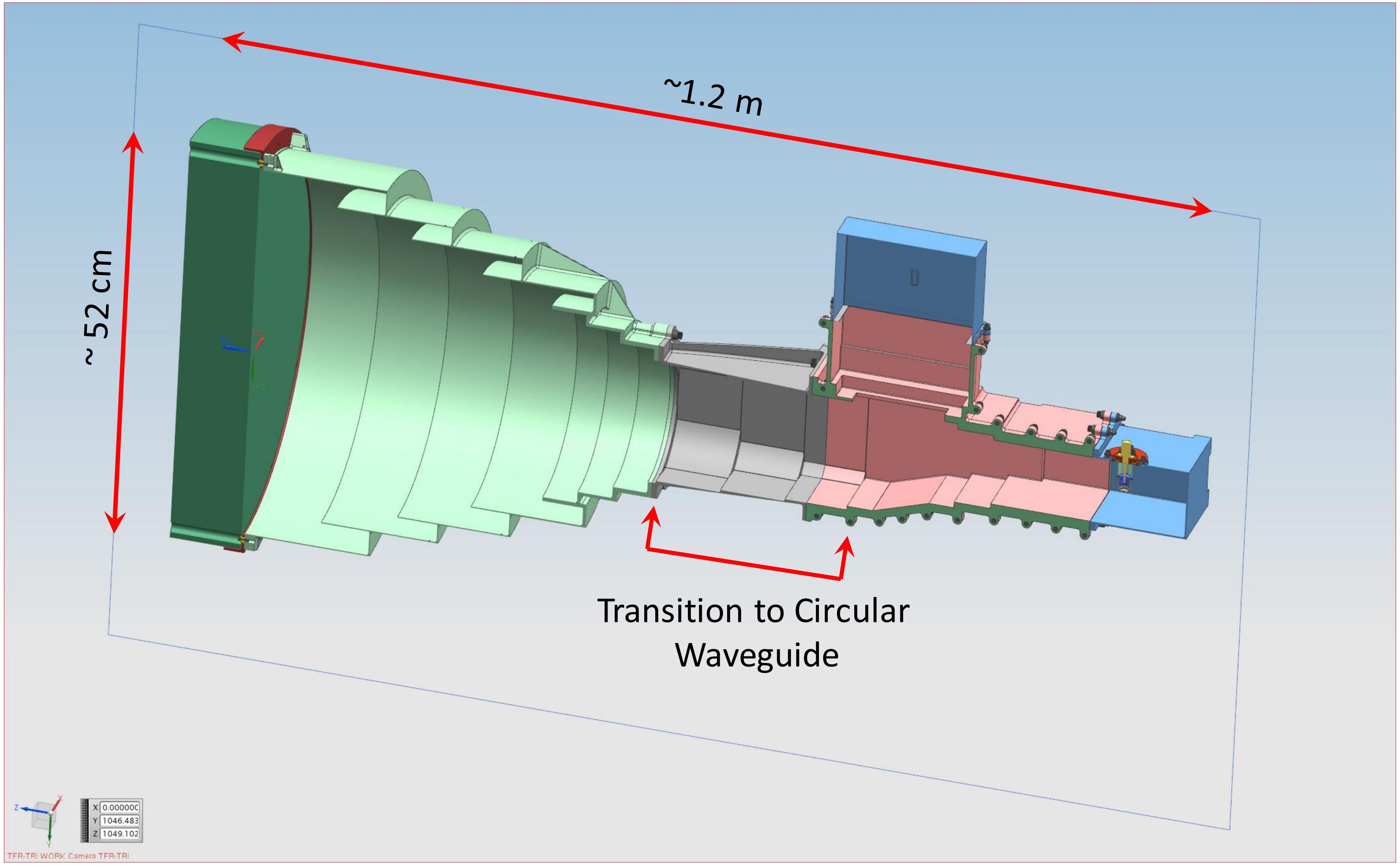
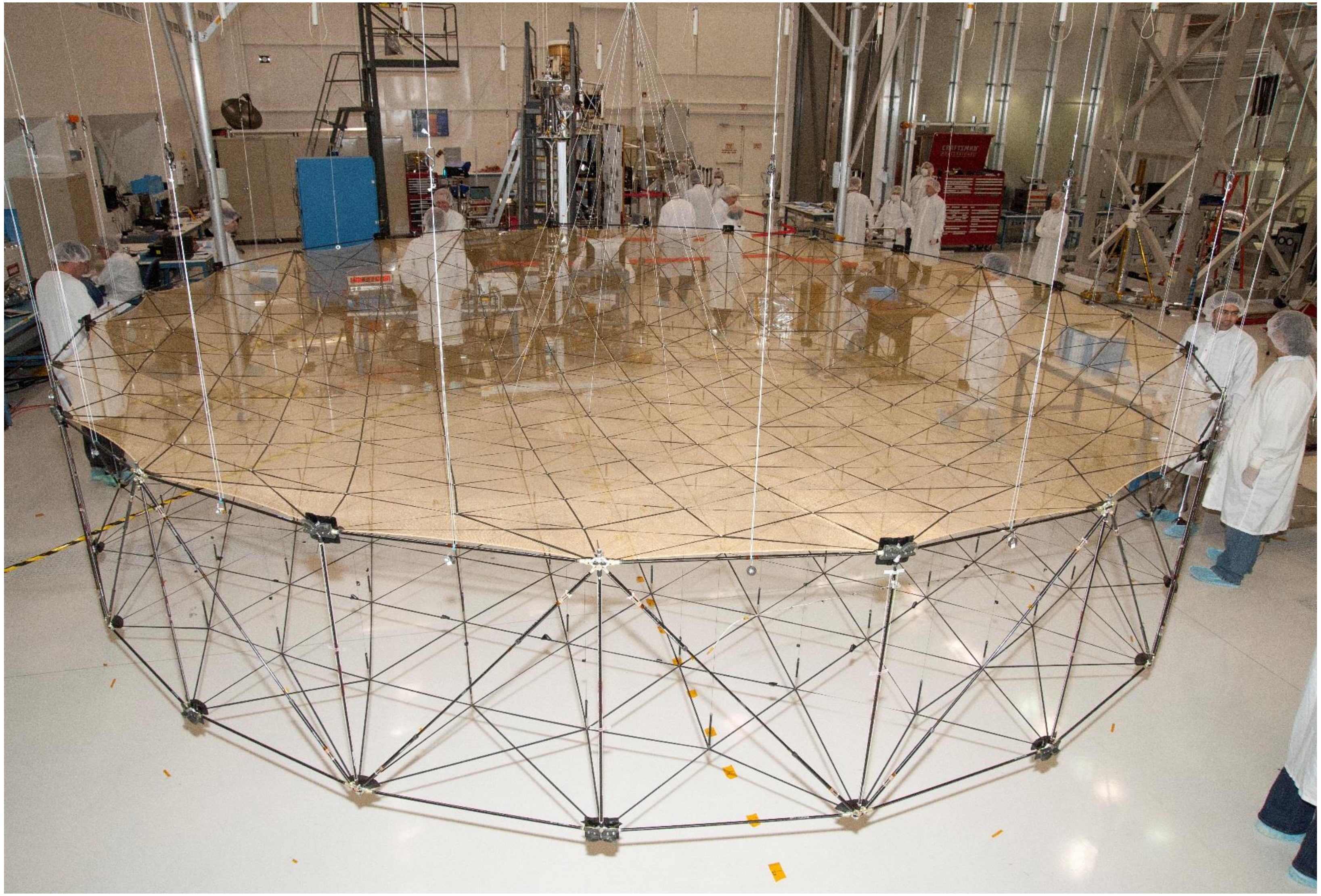


Cutaway Isometric View



Fully Deployed AstroMesh™ Reflector

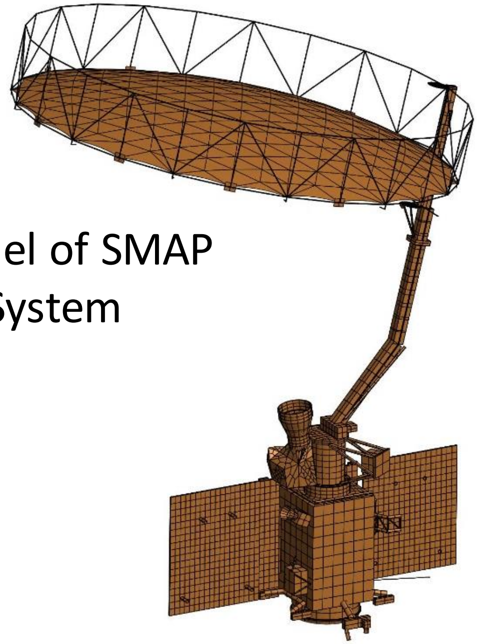


Reflector surface RF model included a variety of small surface imperfections

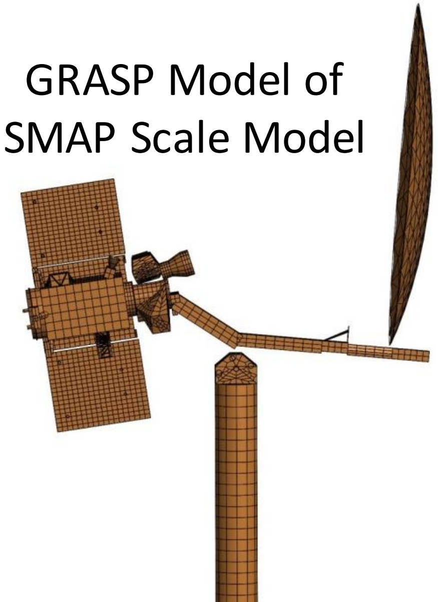
SMAP RF Modeling

- 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.
- An 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.

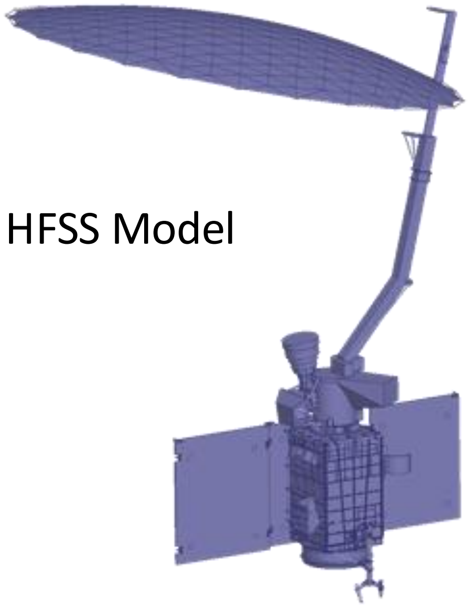
GRASP Model of SMAP Flight System



GRASP Model of SMAP Scale Model



HFSS Model



SMAP 1/10th Scale Model

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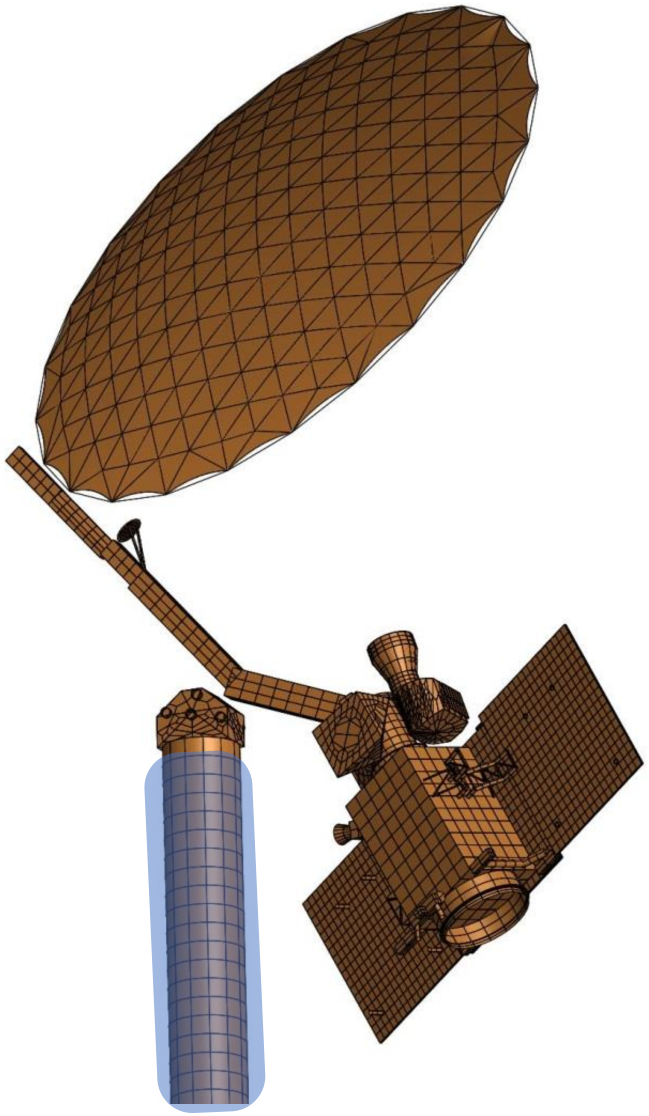
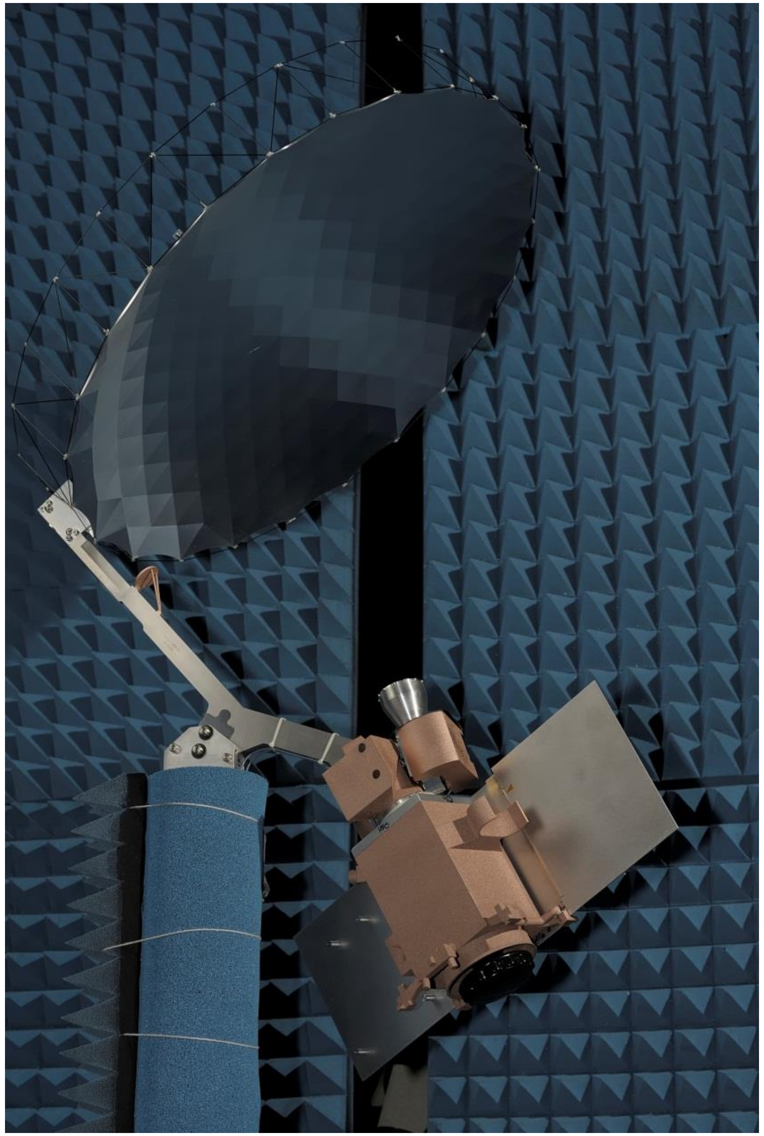
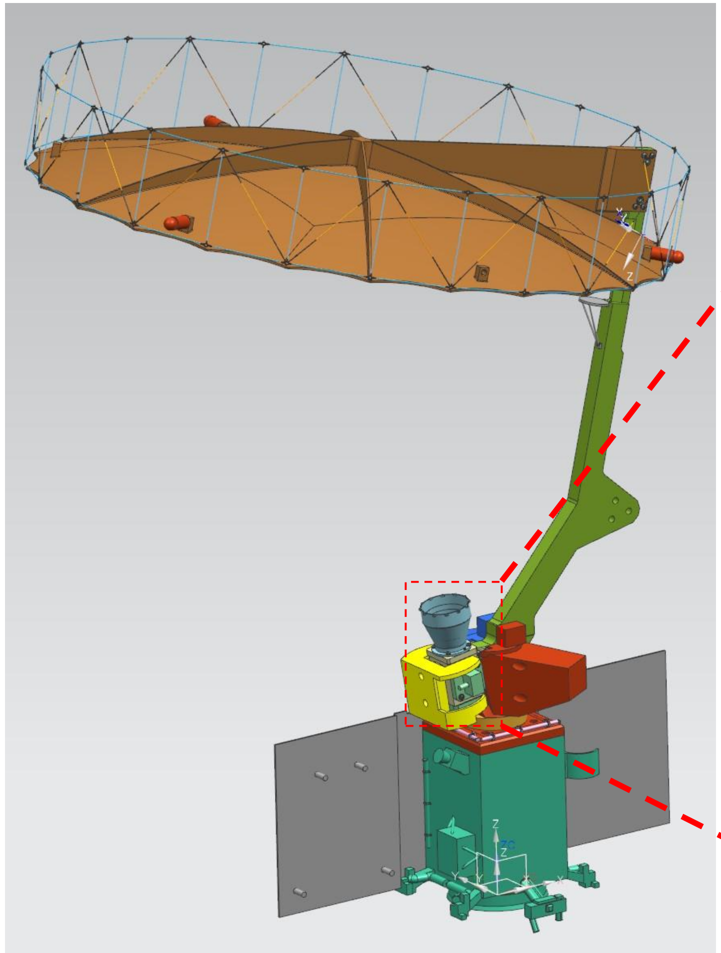
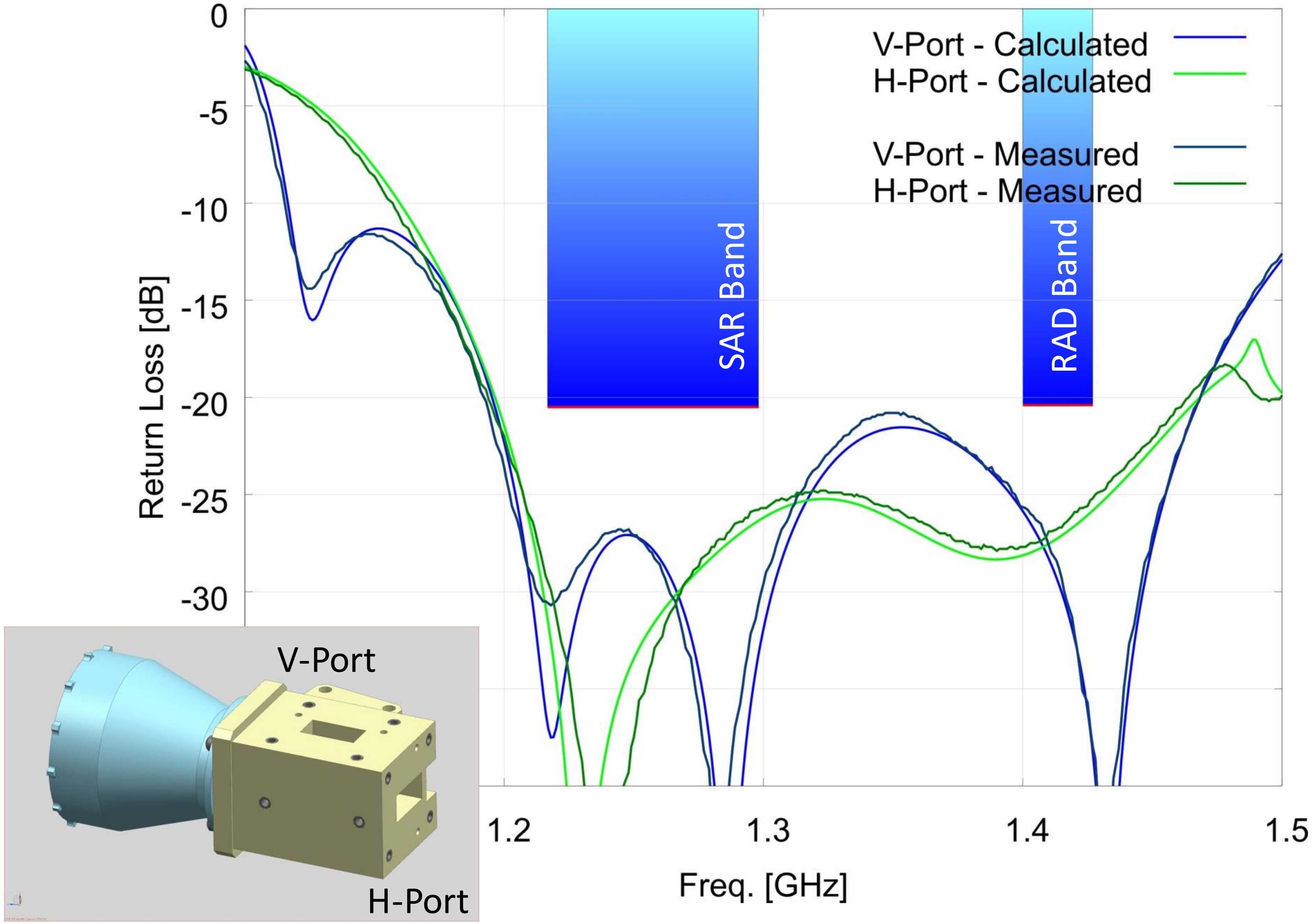




SMAP Scale Model



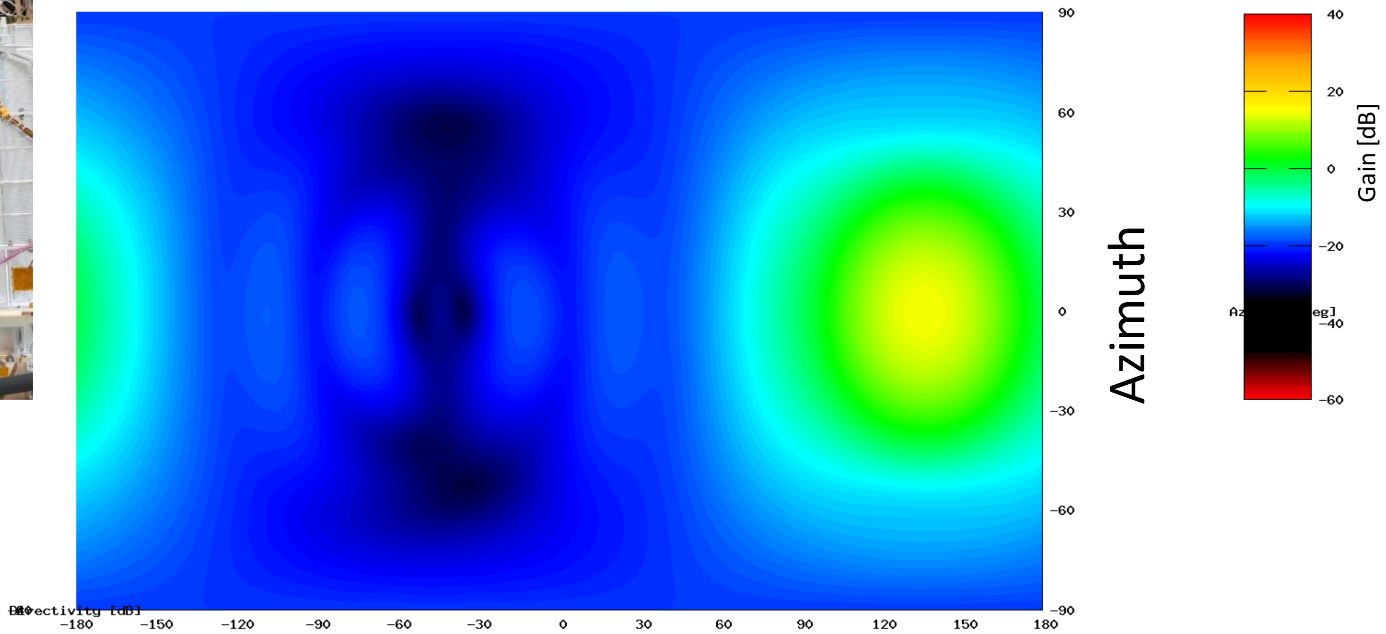
Feed Horn RL Into SM OMT



Radiation Pattern Components

SAR V-Pol

Measured Feedhorn Pattern



Azimuth

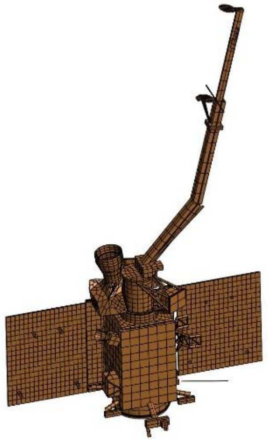
Elevation

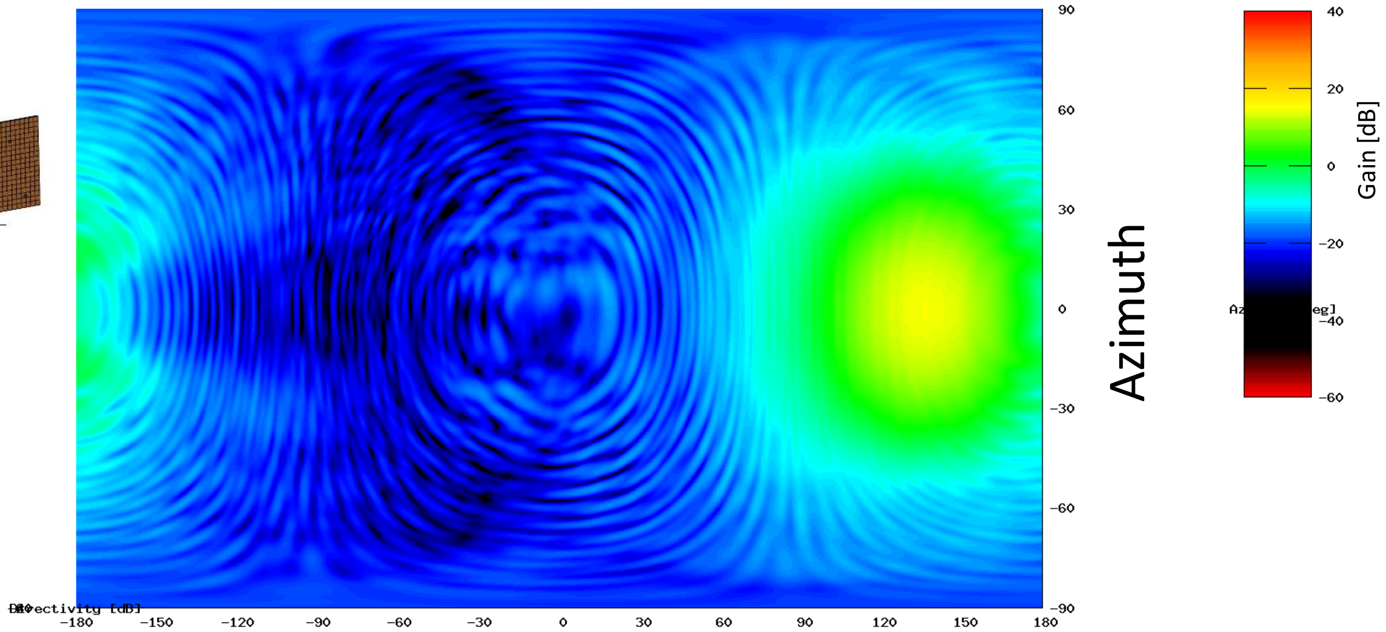
Radiation Pattern Components

This document has been reviewed and determined not to contain export controlled CUI.

SAR V-Pol

Measured Feedhorn Pattern +
Scattering From S/C & Boom



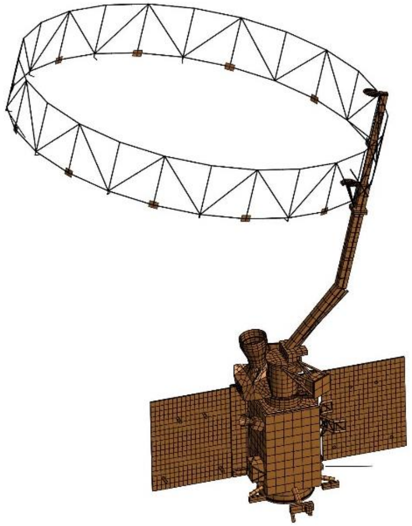


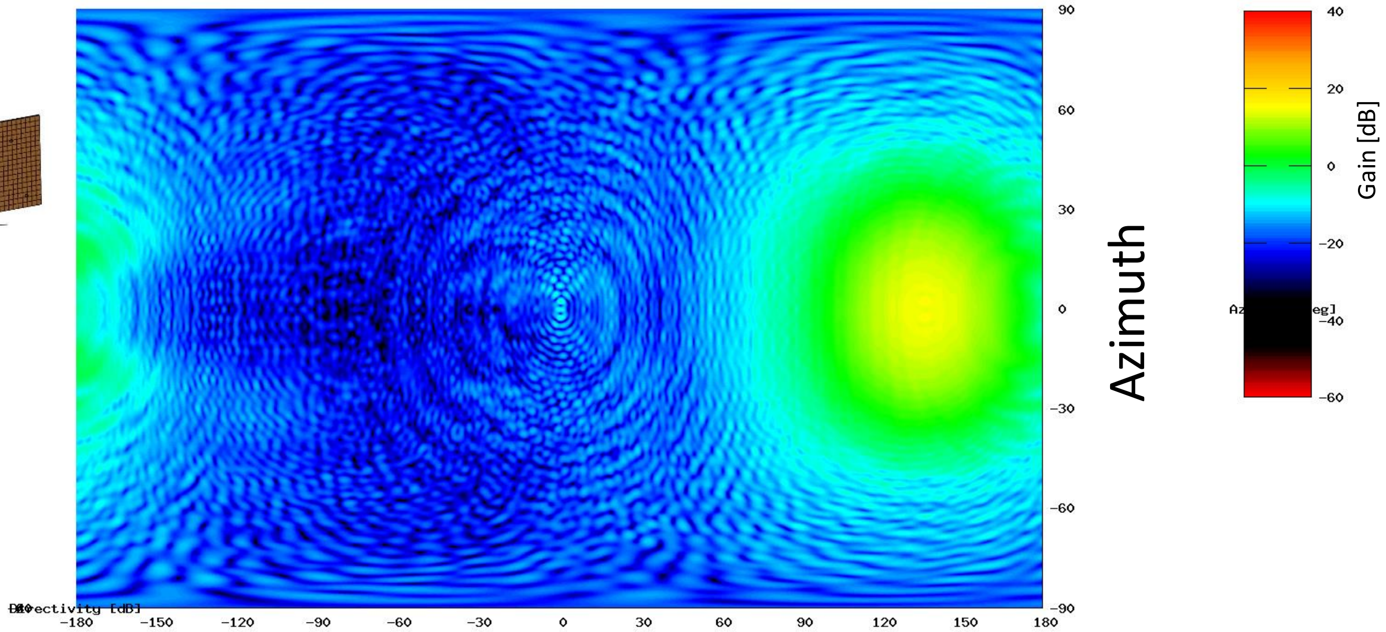
Elevation

Radiation Pattern Components

SAR V-Pol

Measured Feedhorn Pattern +
Scattering From S/C, Boom & Truss



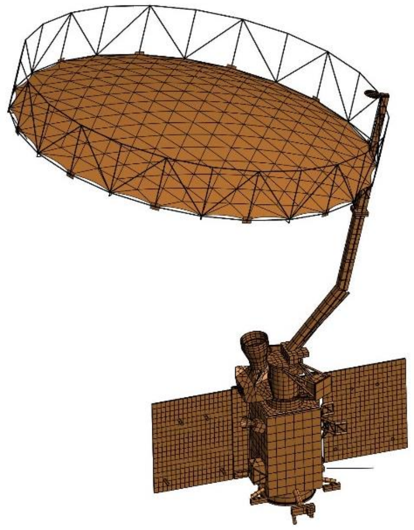


Azimuth

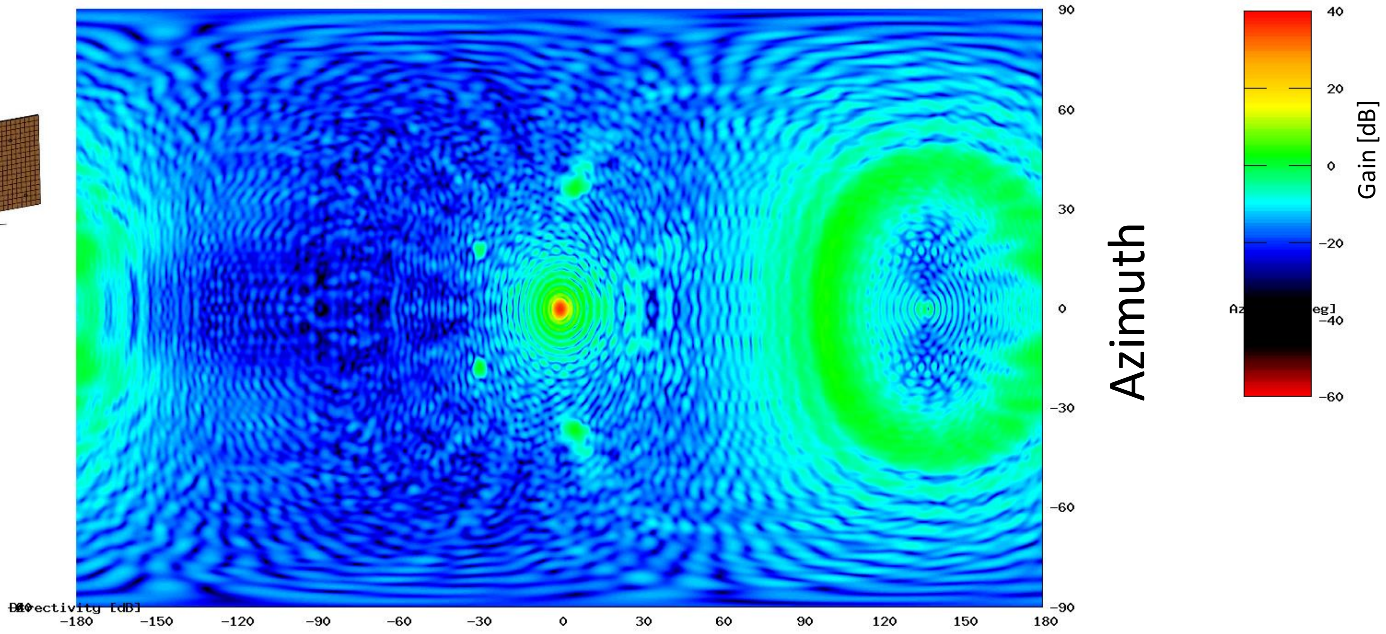
Elevation

Radiation Pattern Components

SAR V-Pol



Measured Feedhorn Pattern +
Scattering from S/C, Boom & Truss +
Reflector

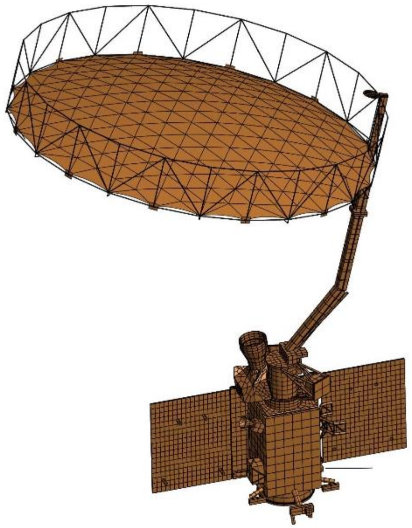


Azimuth

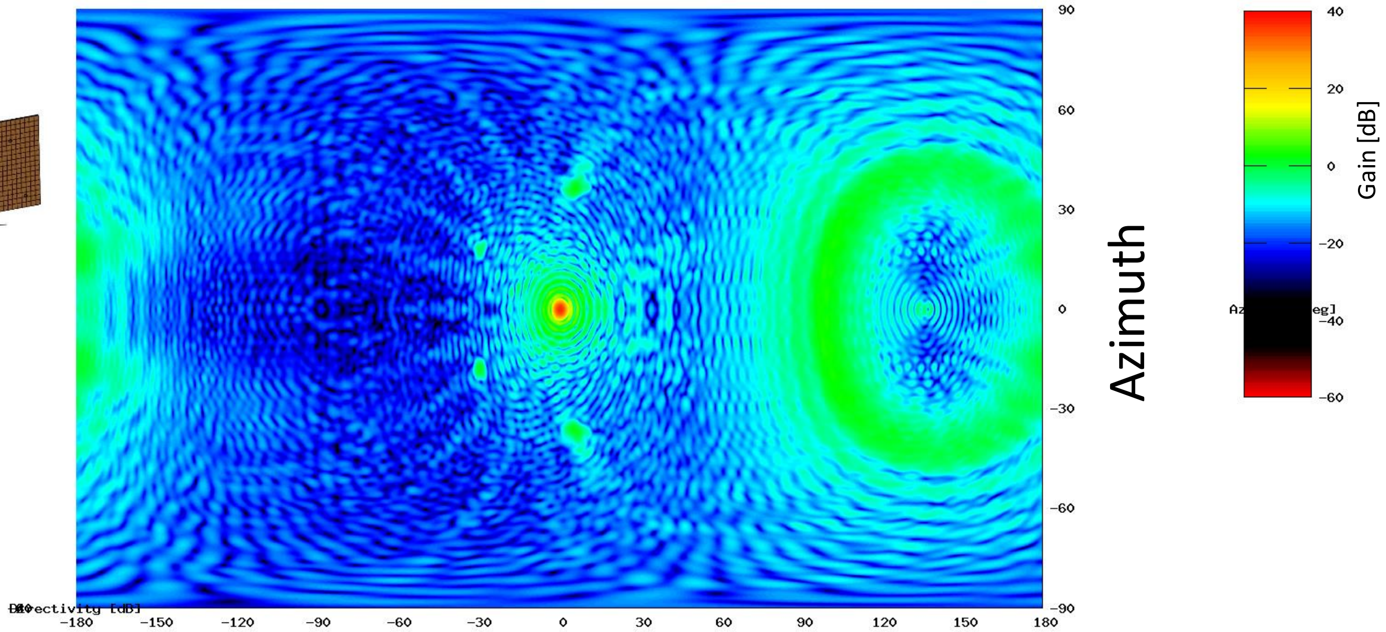
Elevation

Radiation Pattern Components

SAR V-Pol



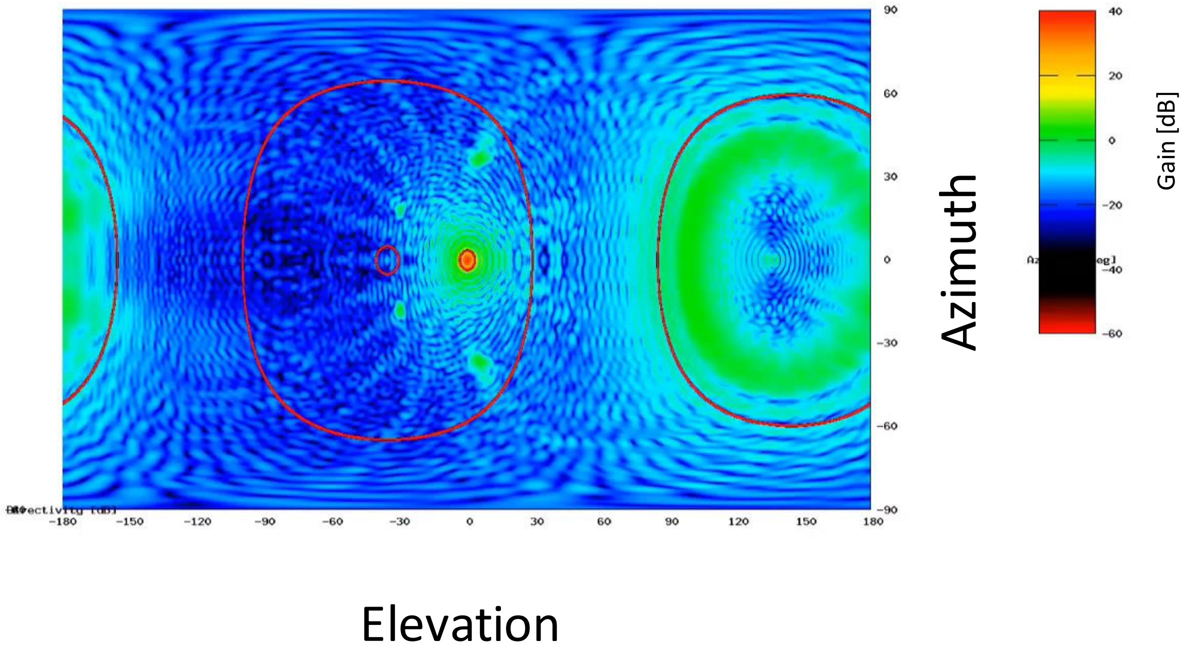
Measured Feedhorn Pattern +
Scattering From S/C, Boom & Truss +
Reflector + 2nd Order Scattering



Elevation

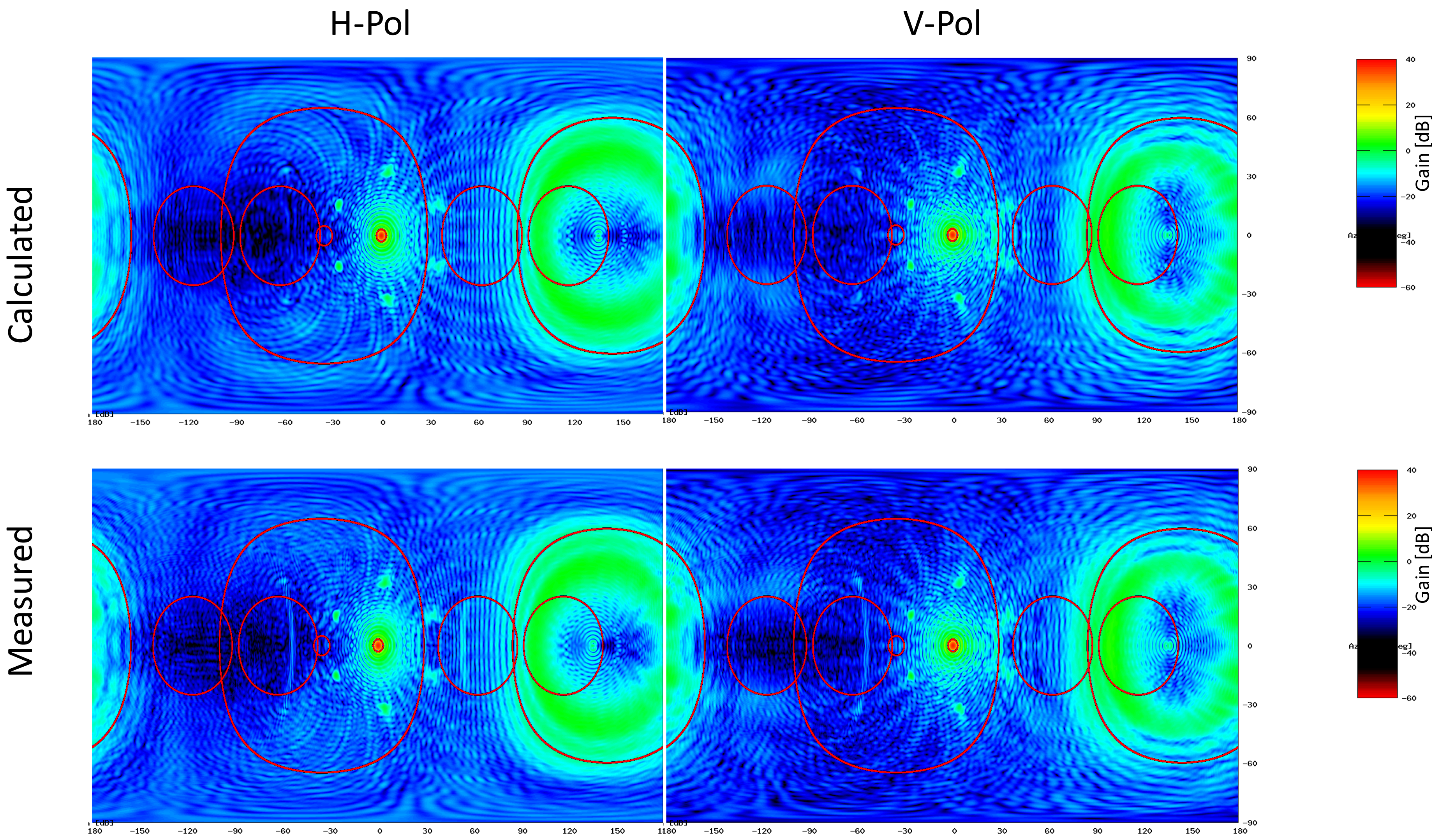
Effect of the Spinning Reflector

SAR V-Pol



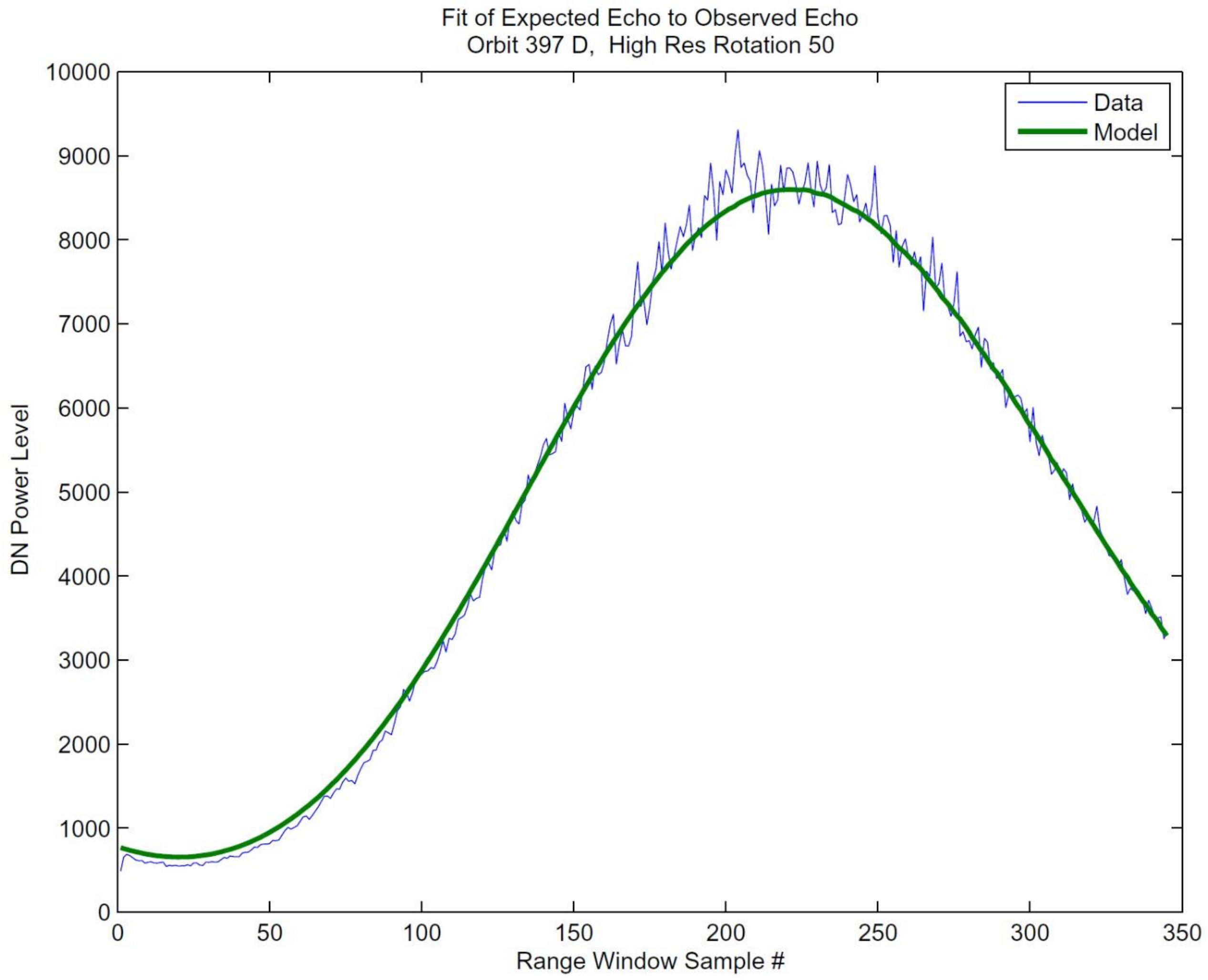
Radiation Pattern Comparison: RAD, 000

This document has been reviewed and determined not to contain export controlled CUI.



Measurement of Radar Echo From Space

- Calculated radiation pattern could 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.

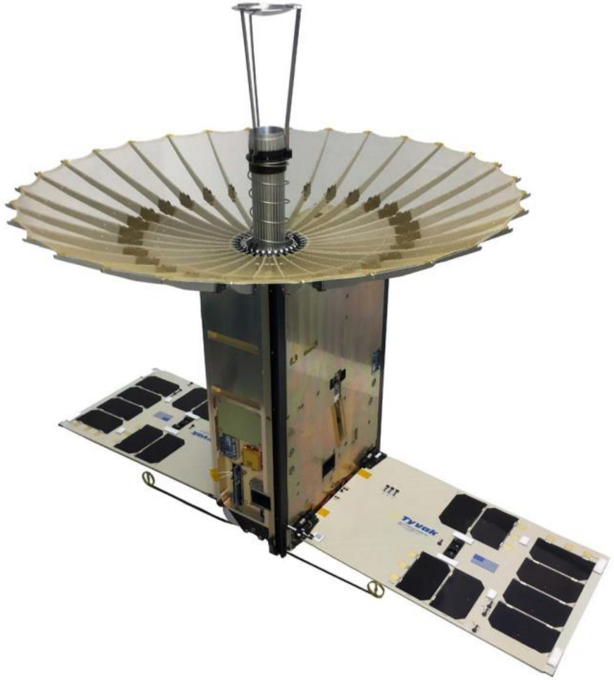


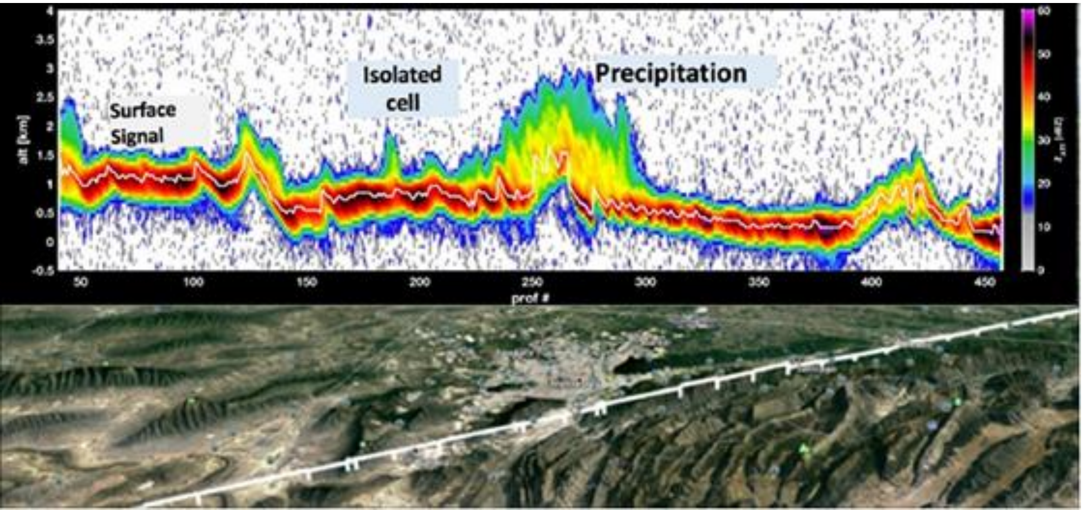
Raincube, 2018

Raincube Antenna
- 0.5m Cassegrain reflector
- Ka-band operations

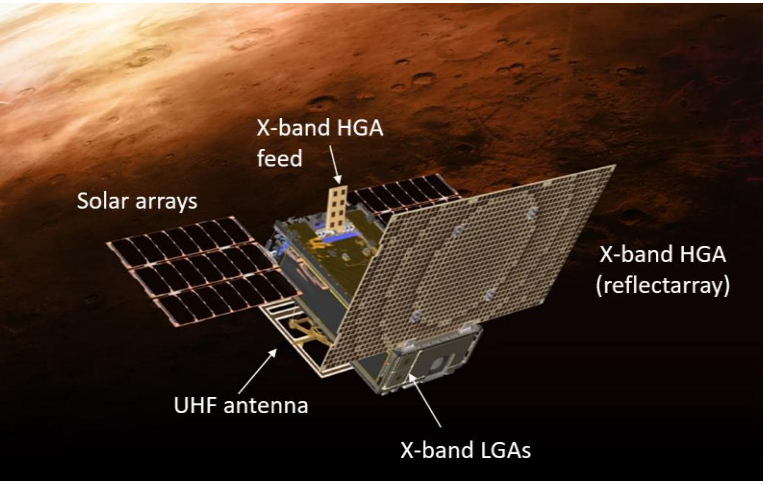
This document has been reviewed and determined not to contain export controlled CUI.

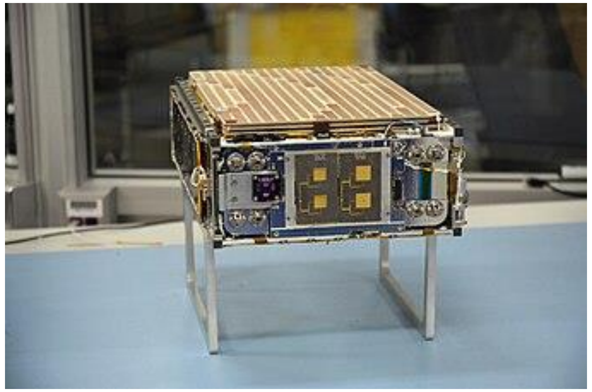
(a) (b) (c) (d)

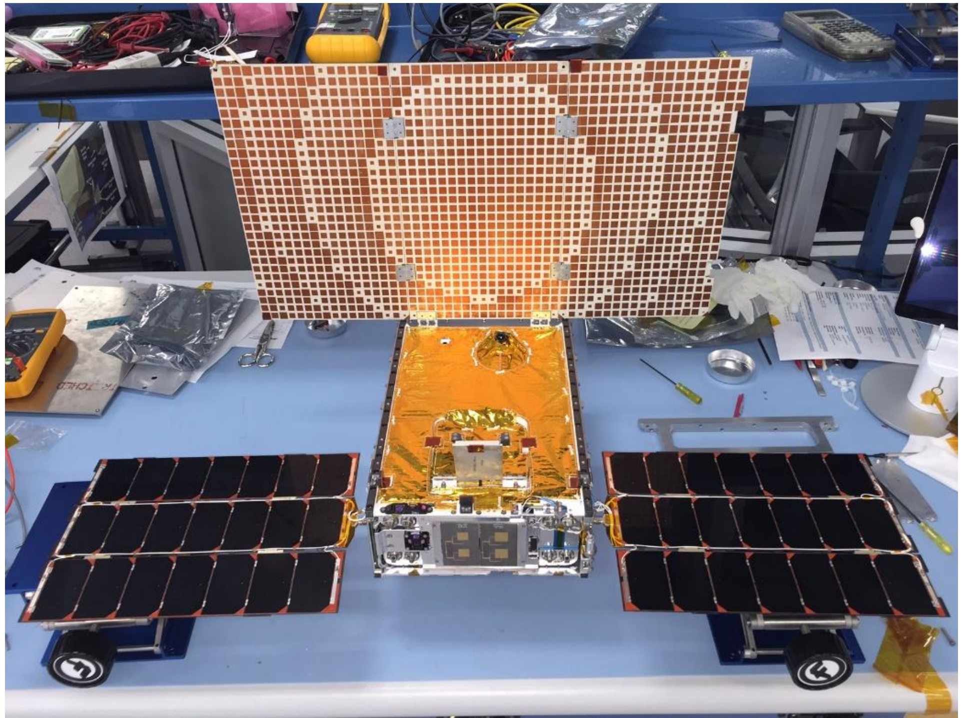


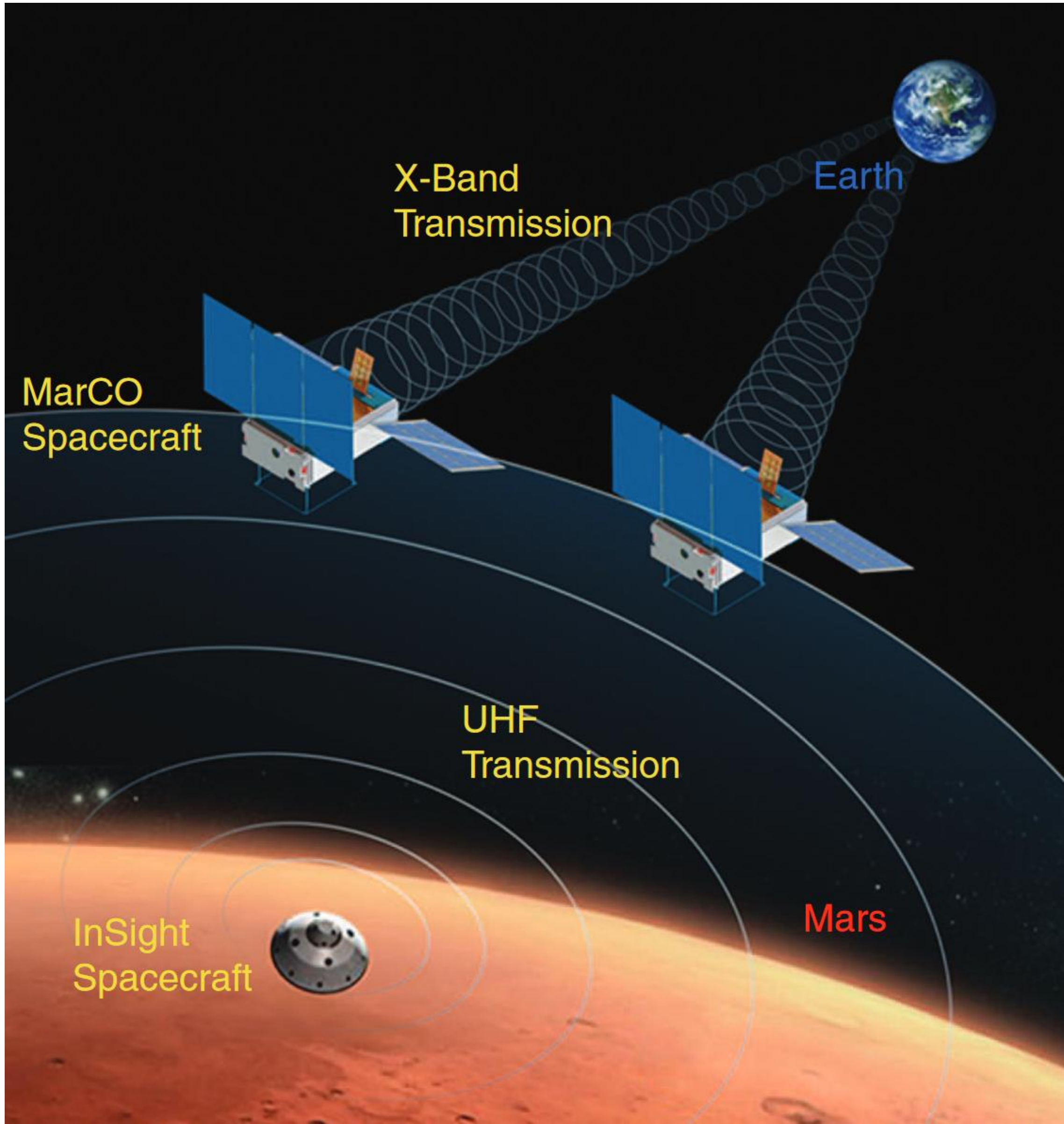


MarCO, Mars Cubesat One, 2018



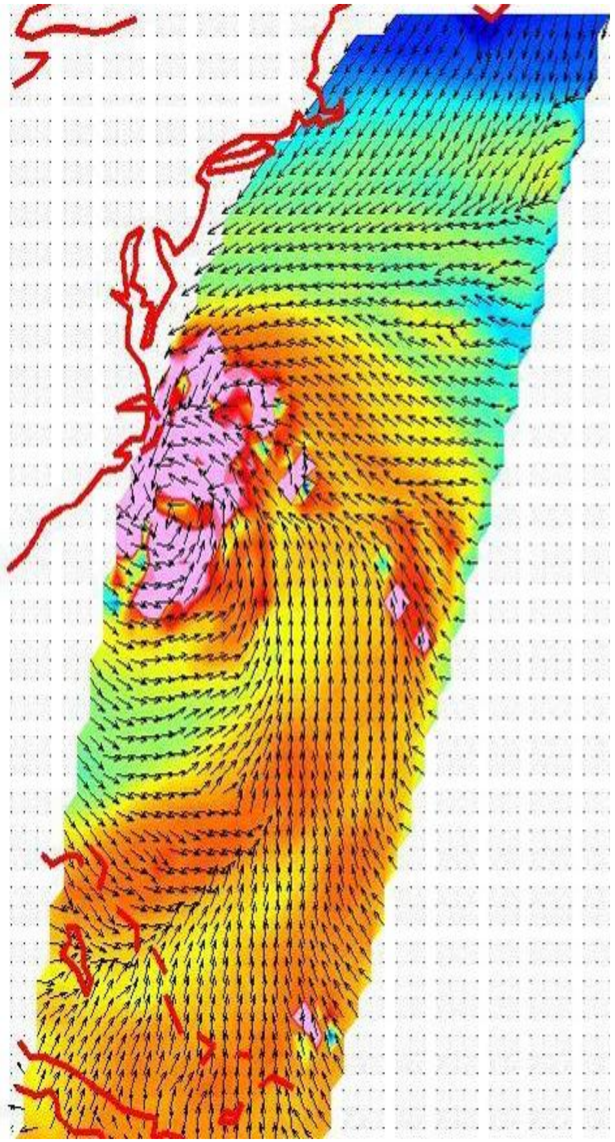


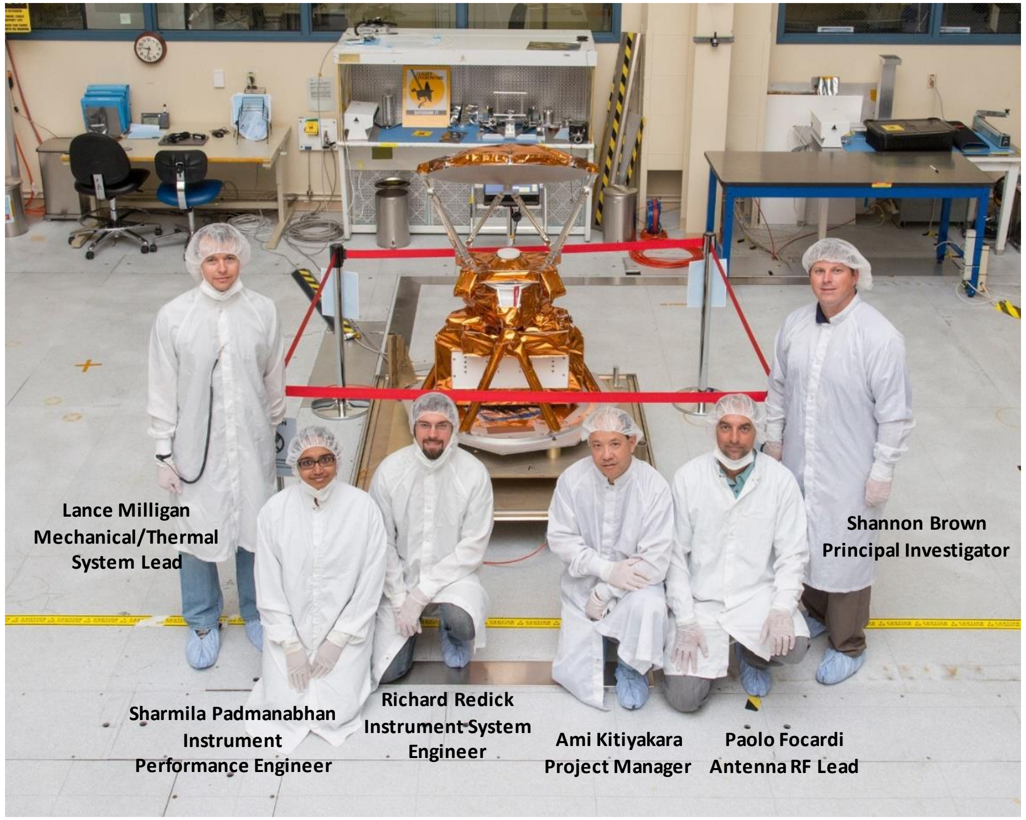


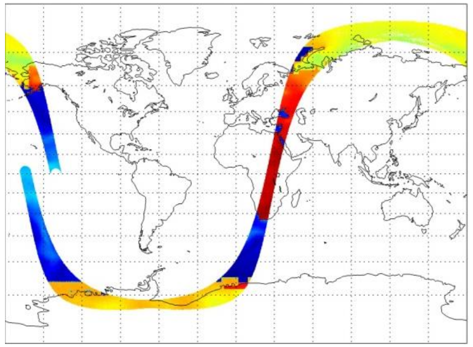


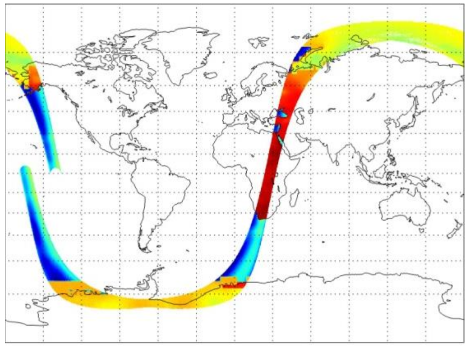
Compact Ocean Wind Vector Radiometer (COWVR), 2021

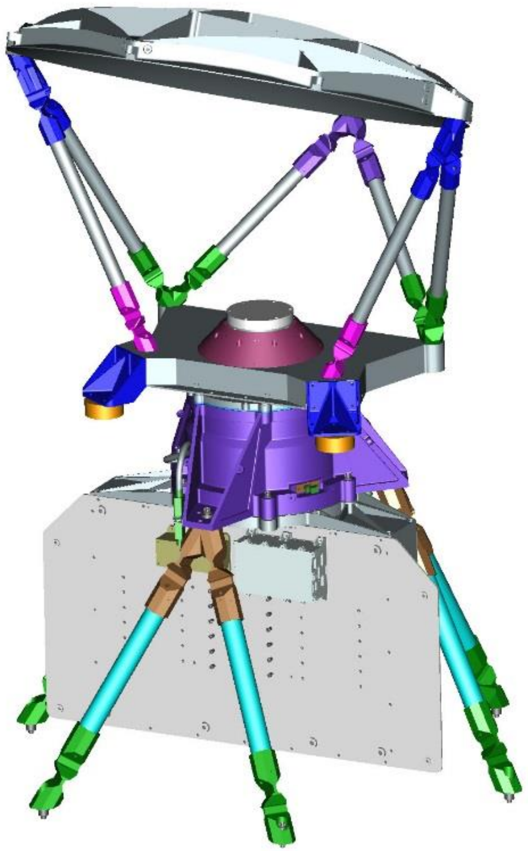
This document has been reviewed and determined not to contain export controlled CUI.



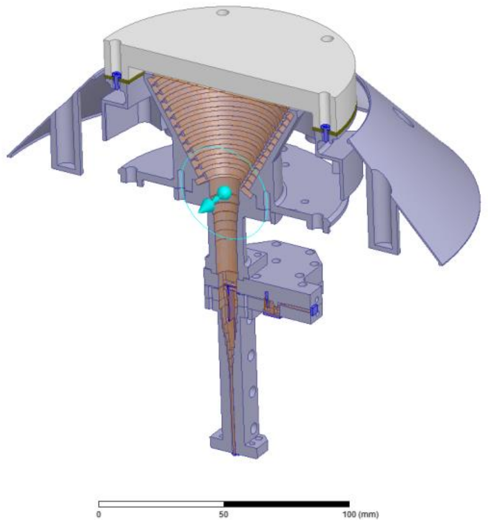


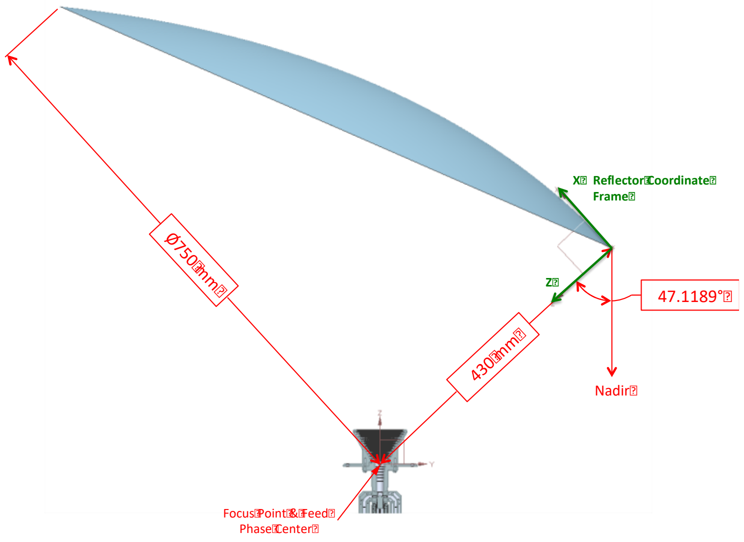






- COWVR’s mission is to measure the wind velocity vector over the ocean.
- Launched on December 21, 2021, it is currently operating on the ISS.
- The instrument consists of:
  - 75-cm offset solid reflector.
  - A single tri-band corrugated horn (18.7 GHz, 23.8 GHz, and 33.9 GHz).
  - Feed design was inherited from Jason 3.
  - Feed horn and radiometer are fixed; reflector spins around feed axis.

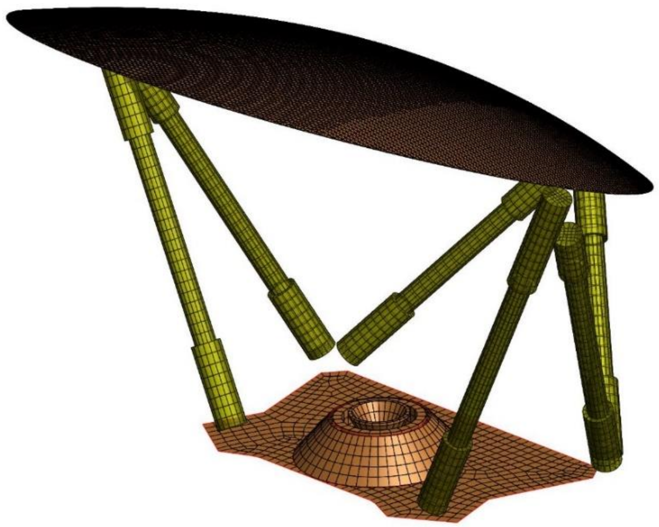


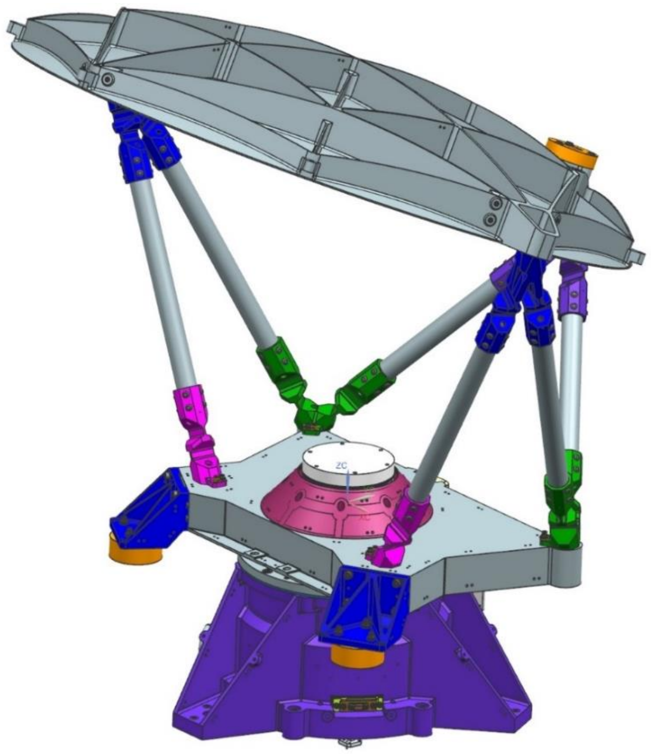


Initial RF Model

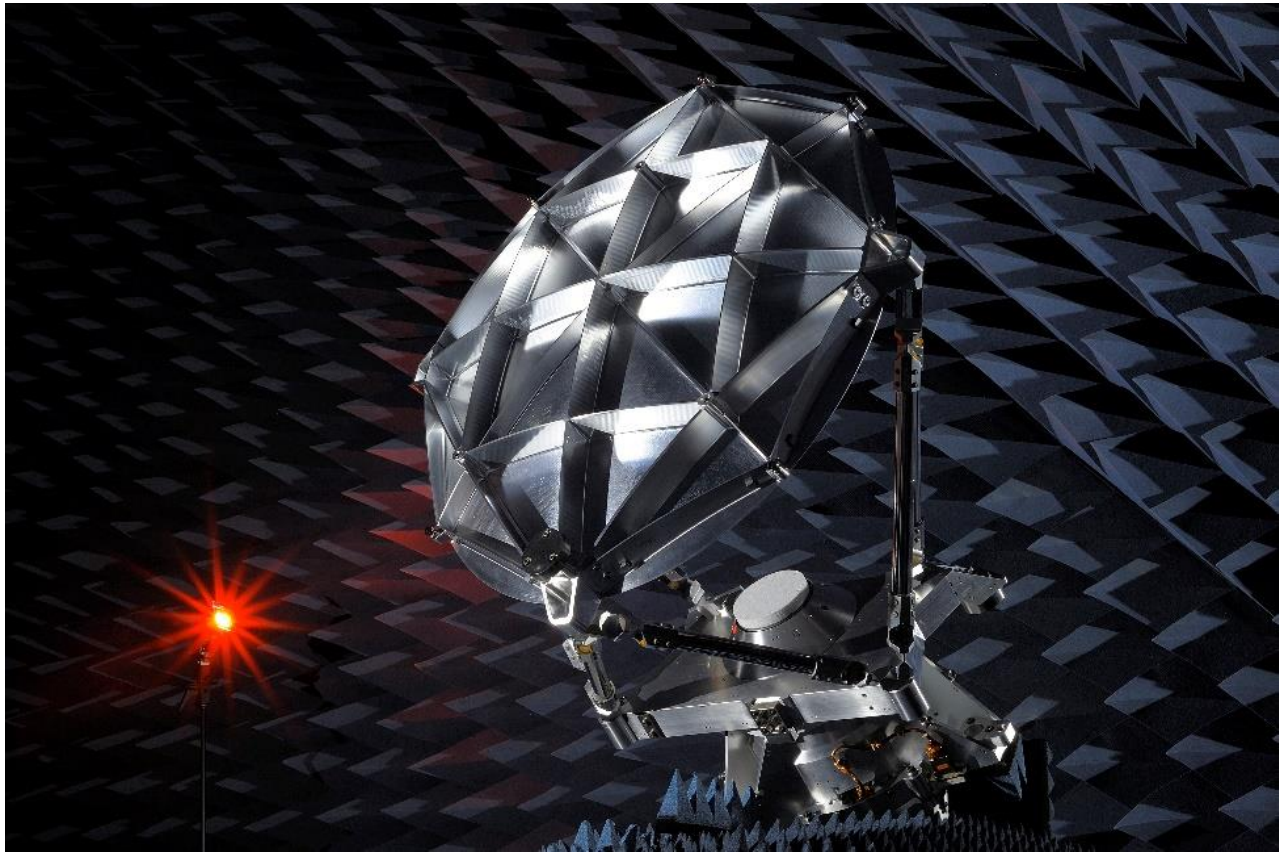
The initial RF Model in GRASP included:

- 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

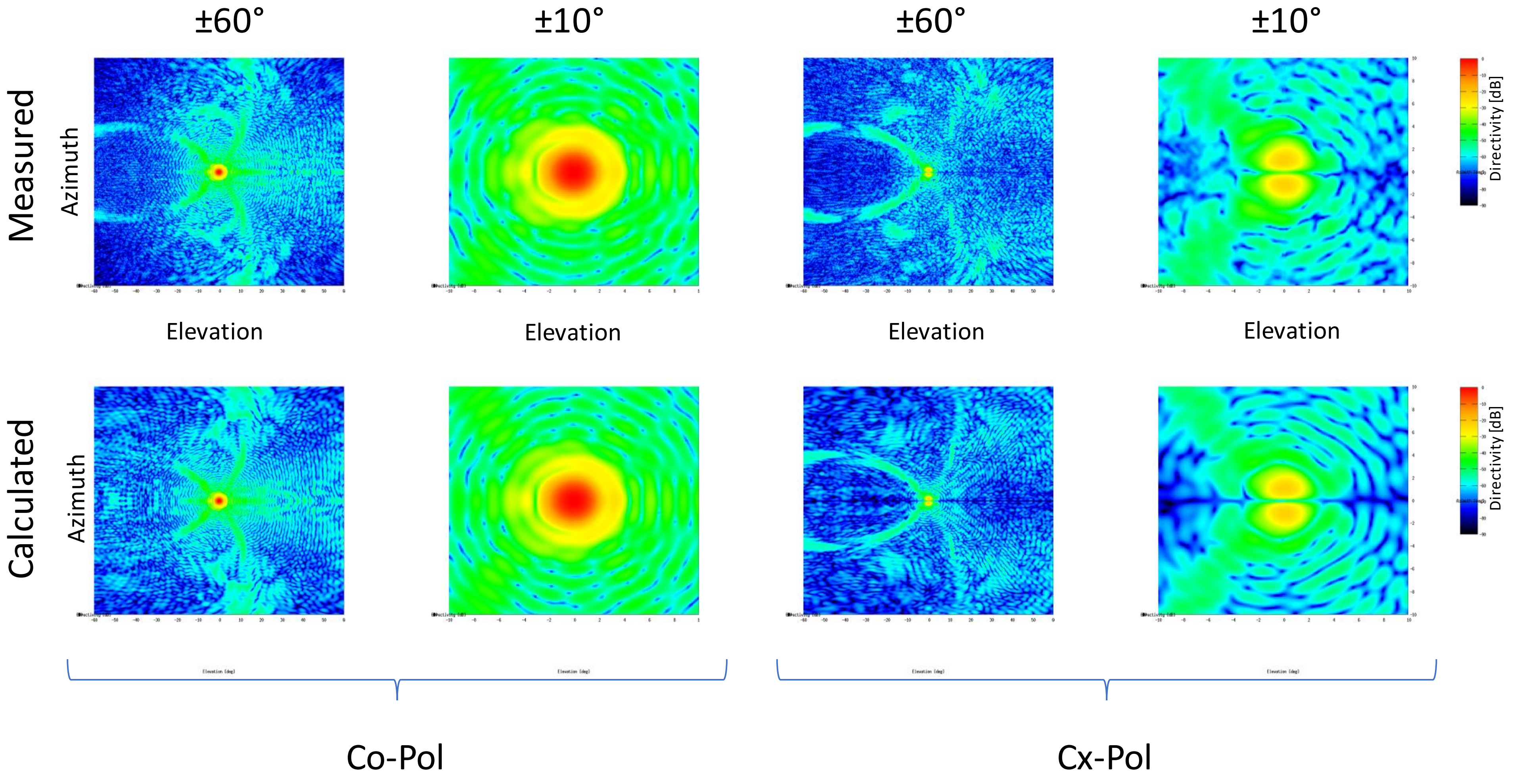




COWVR Instrument During RF Tests

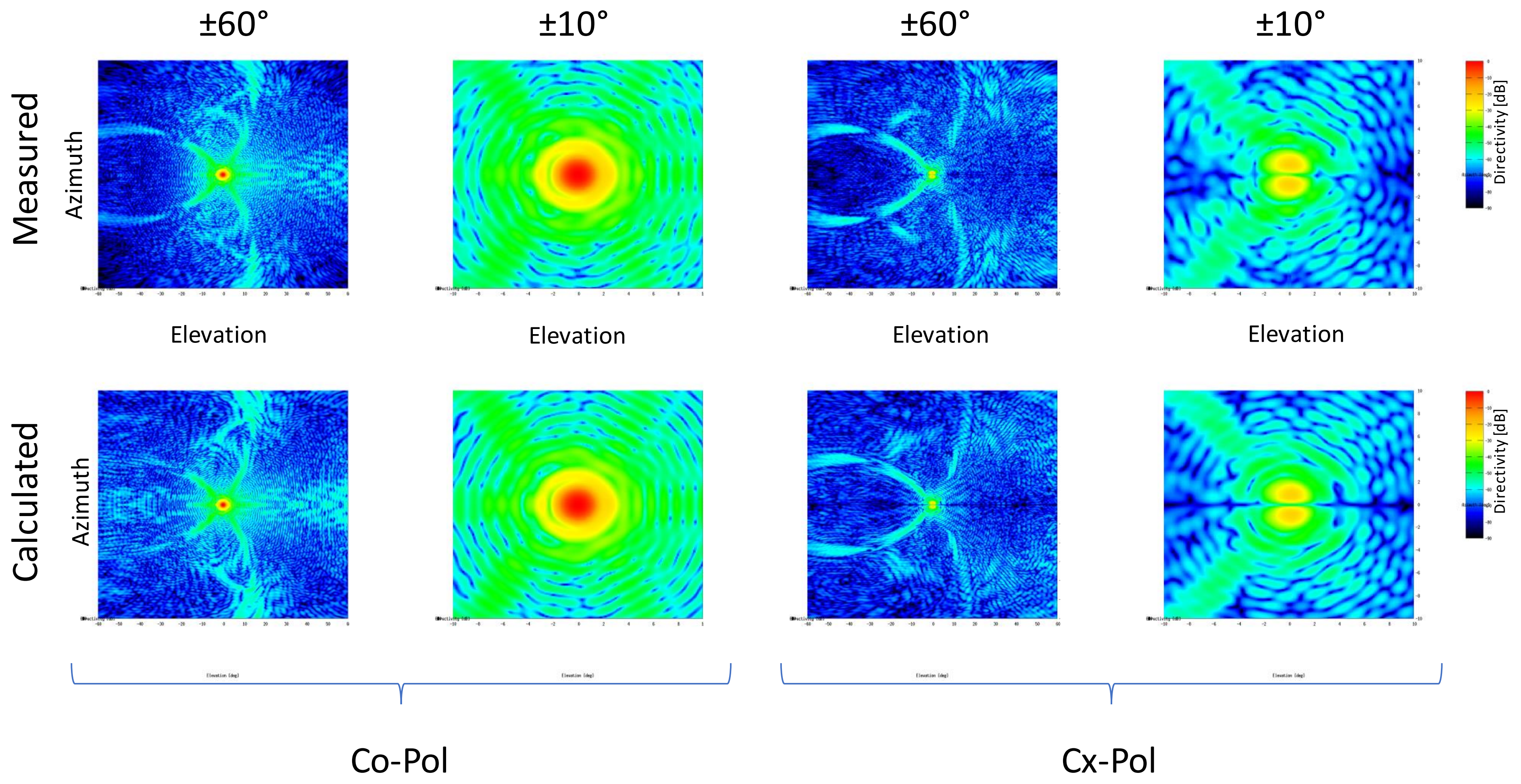


H-Pol Results, 180°, 18.7 GHz



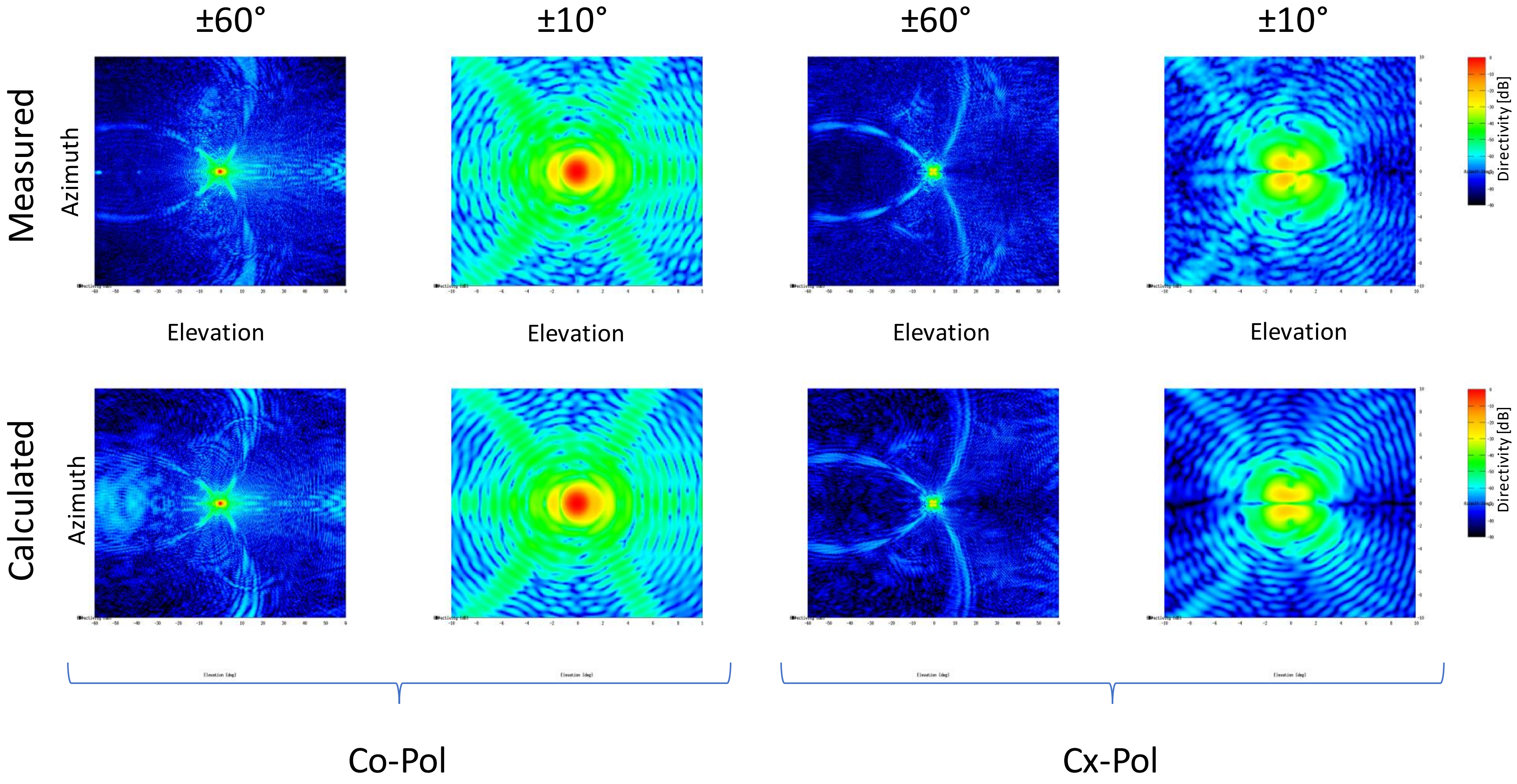
For reference: green = -45dB, light blue = -60dB

H-Pol Results, 180°, 23.8 GHz



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

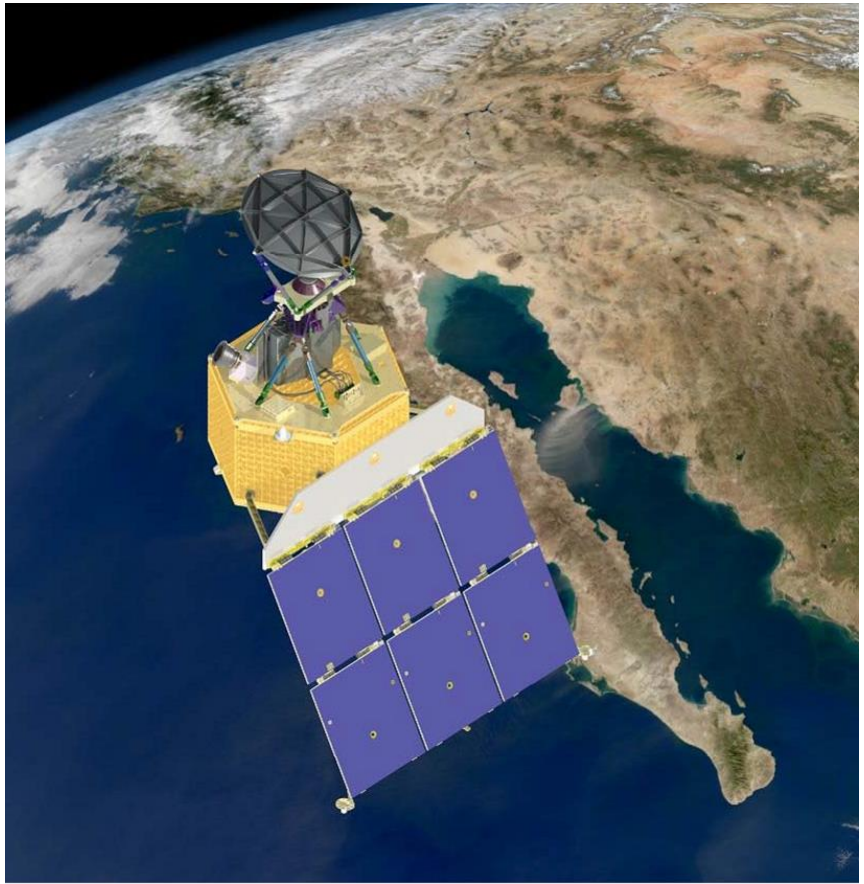
H-Pol Results, 180°, 33.9 GHz

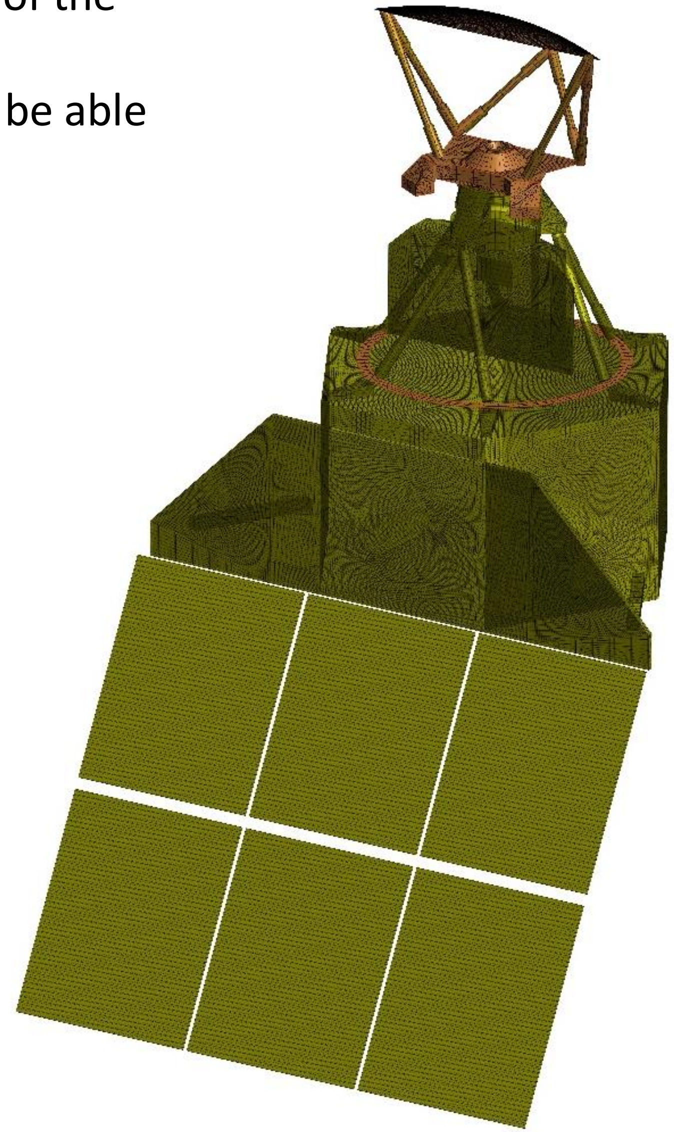


For reference: green = -45dB, light blue = -60dB

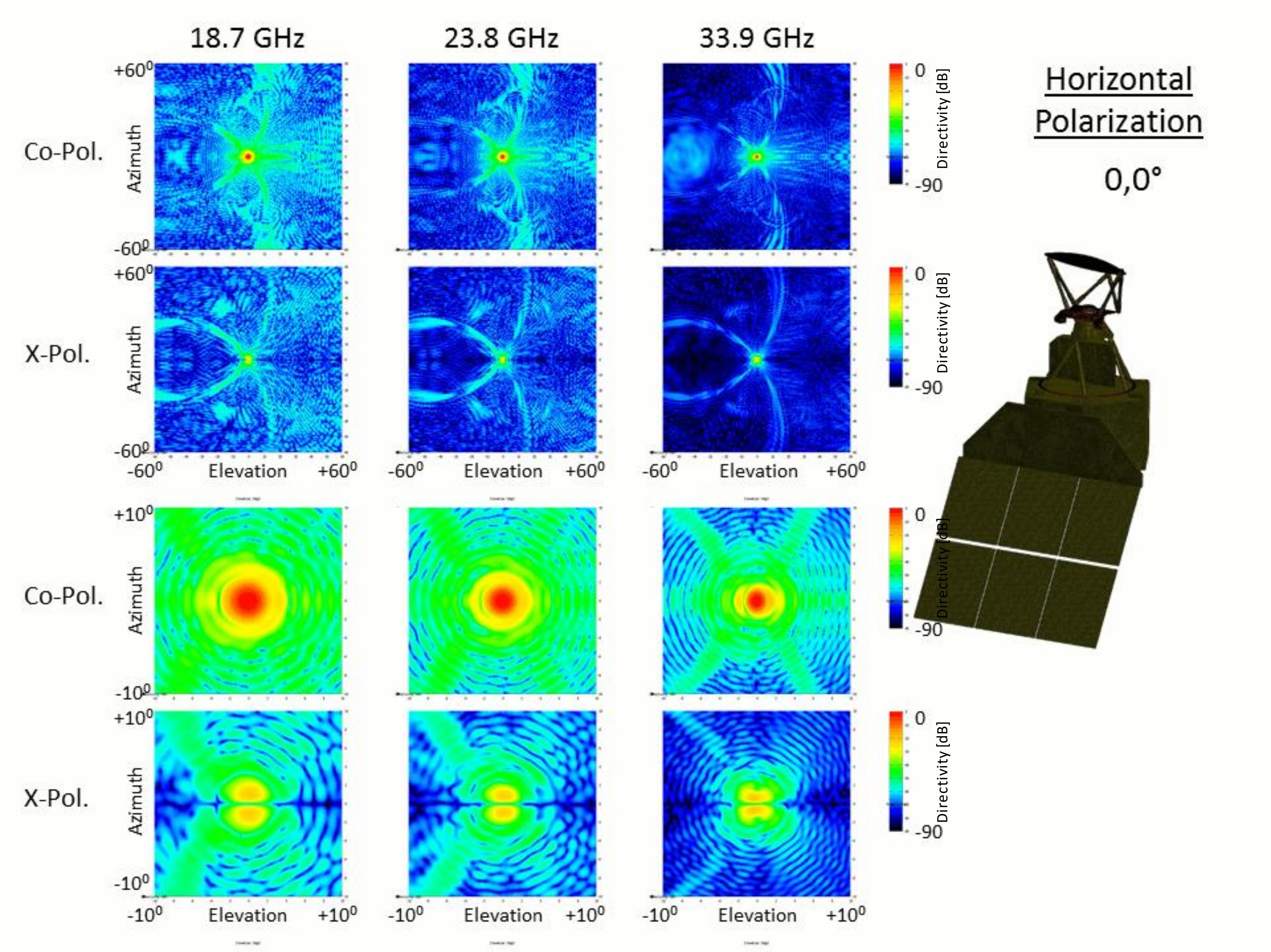
Improved RF Model

- A larger RF model was also made in GRASP to test the effect of the solar array on the instrument's performance.
- TICRA's help was instrumental in optimizing the RF model to be able to run it on a single machine.

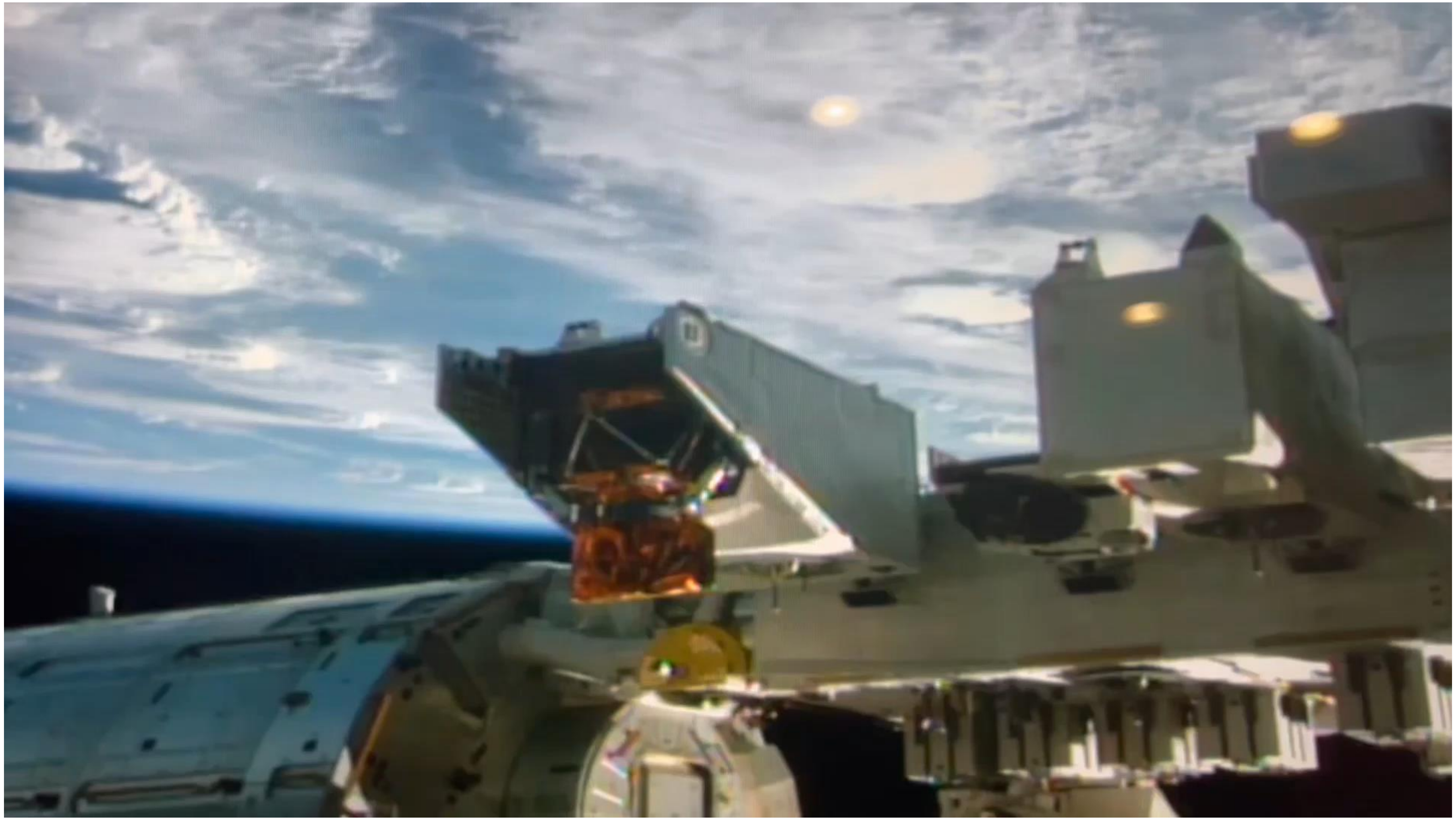




H-Pol Data


18.7 GHz
23.8 GHz
33.9 GHz
Co-Pol.
X-Pol.
Co-Pol.
X-Pol.
Azimuth
Elevation
+60°
-60°
+10°
-10°
Directivity [dB]
0
-90
Horizontal Polarization
0,0°

Deployment on ISS – 1

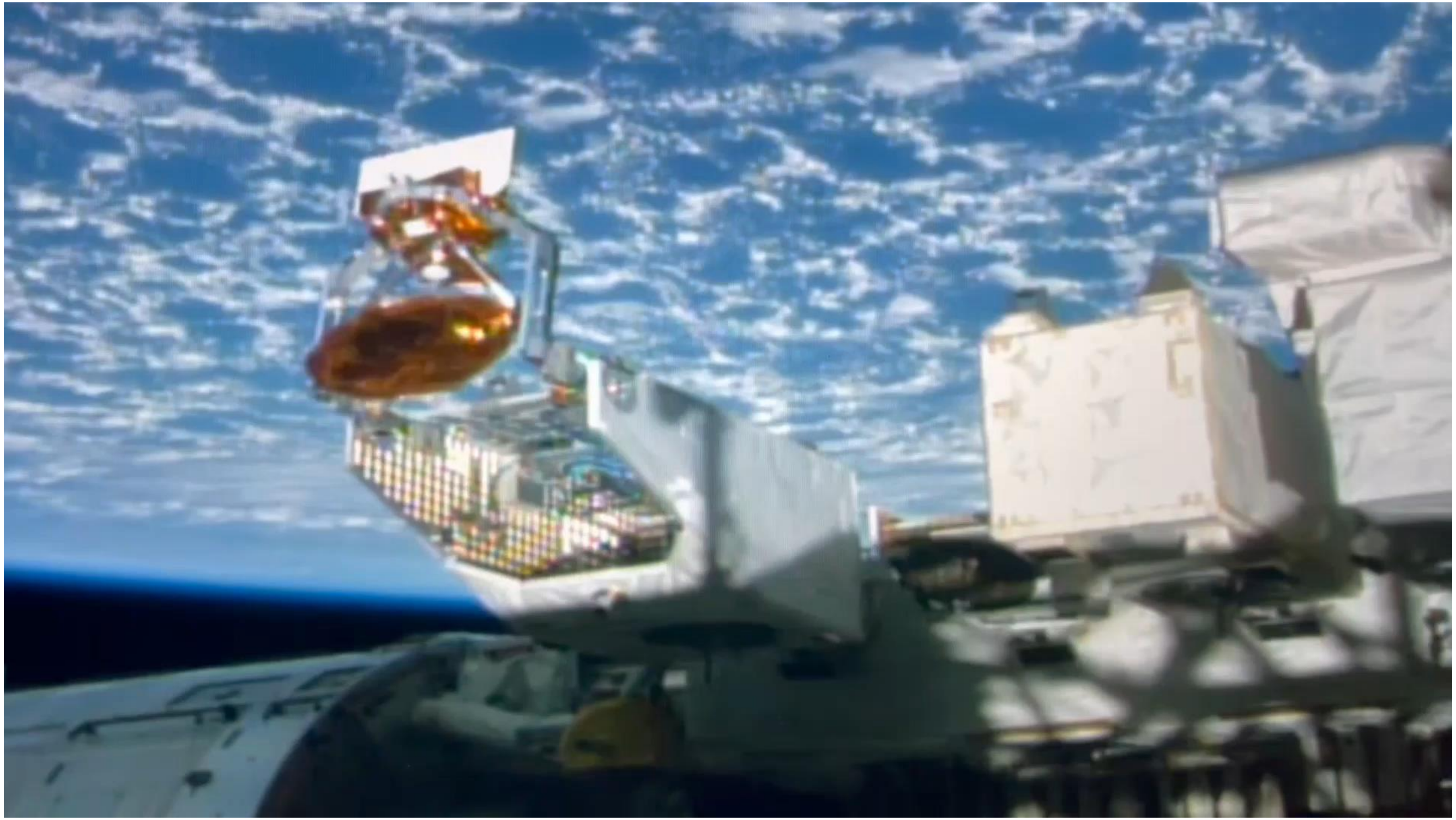


Deployment on ISS – 2

Deployment on ISS – 3

Deployment on ISS – 4

Deployment on ISS – 5



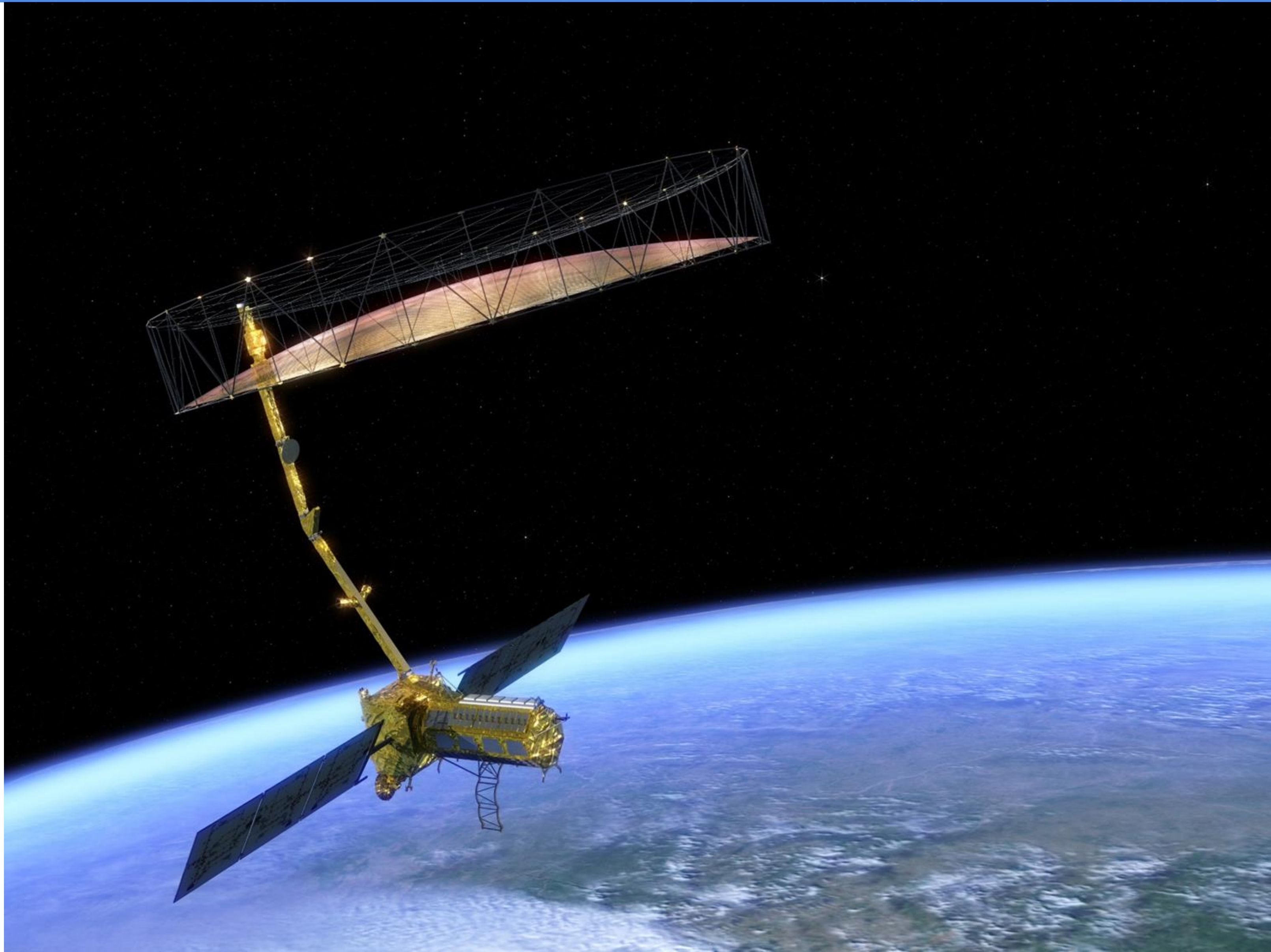
NISAR, NASA ISRO SAR

- NISAR is a collaboration between:

Jet Propulsion Laboratory
California Institute of Technology

ISRO
Indian Space Research Organization

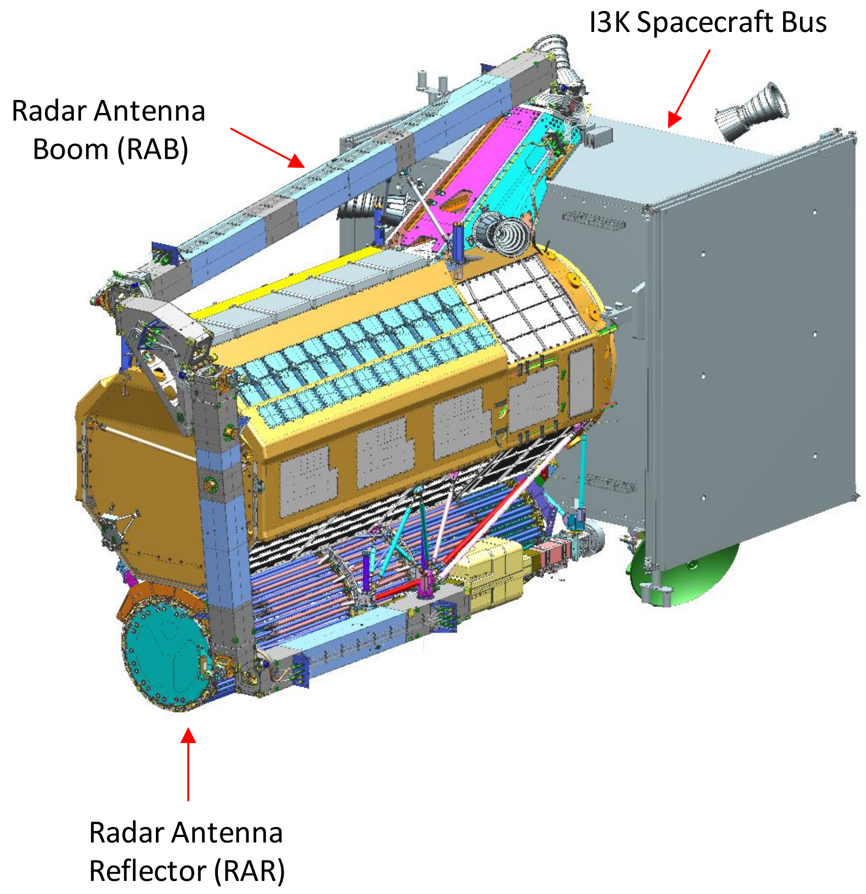
- NISAR's mission is to measure how Earth's environment changes over time.
- It will be launched in early 2024 from India.
- The instrument consists of:
  - 12-m deployable mesh offset reflector
  - An L-band 2x12 element patch feed array (JPL)
  - An S-band 2x24 element patch feed array (SAC/ISRO)
  - An L-band radar (JPL)
  - An S-band radar (SAC/ISRO)
- The observatory can be operated both in left and right looking configurations.
- Sweep-SAR technique.
- 12-day repeat cycle.

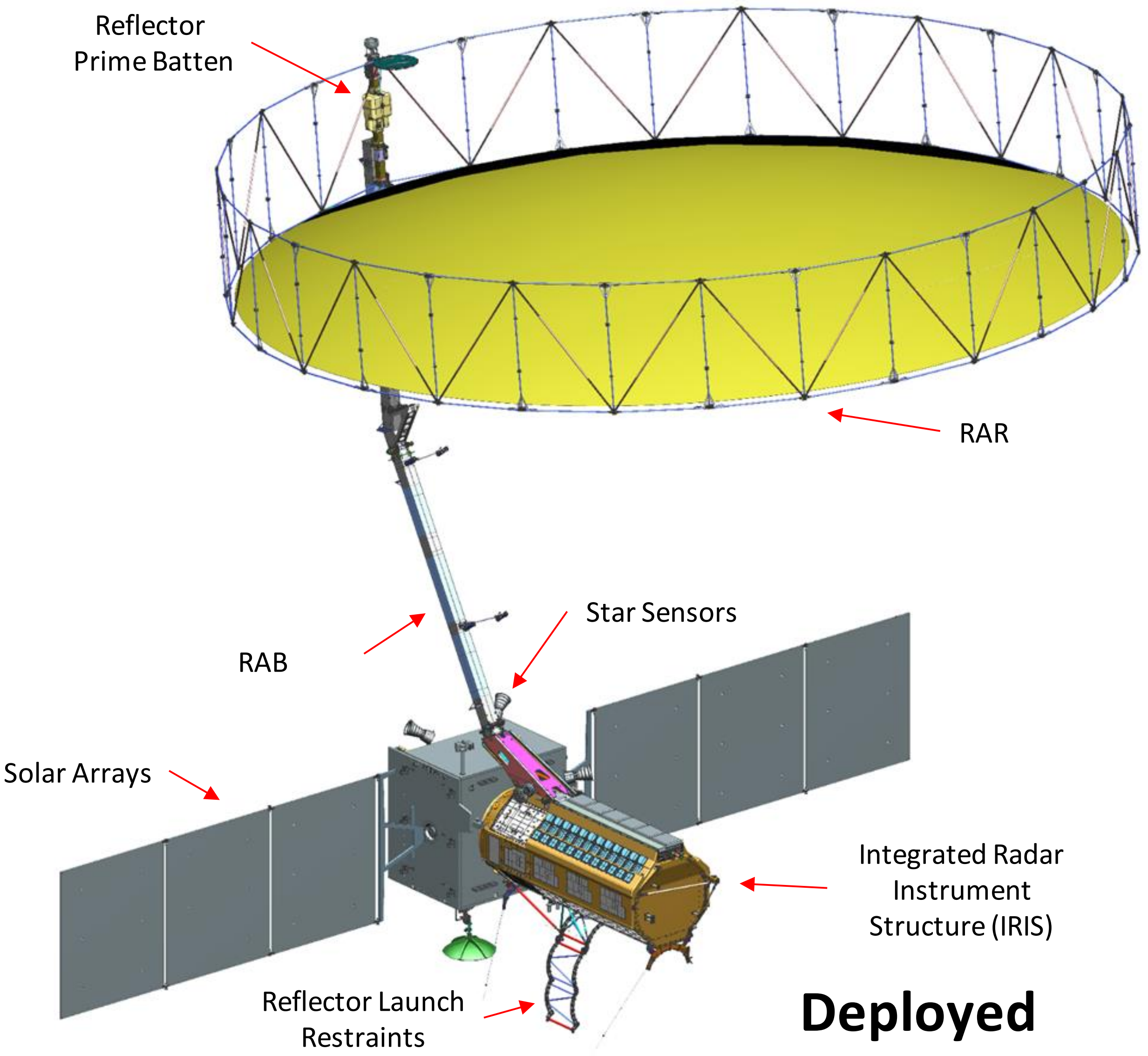


Observatory Configuration

This document has been reviewed and determined not to contain export controlled CUI.

Stowed



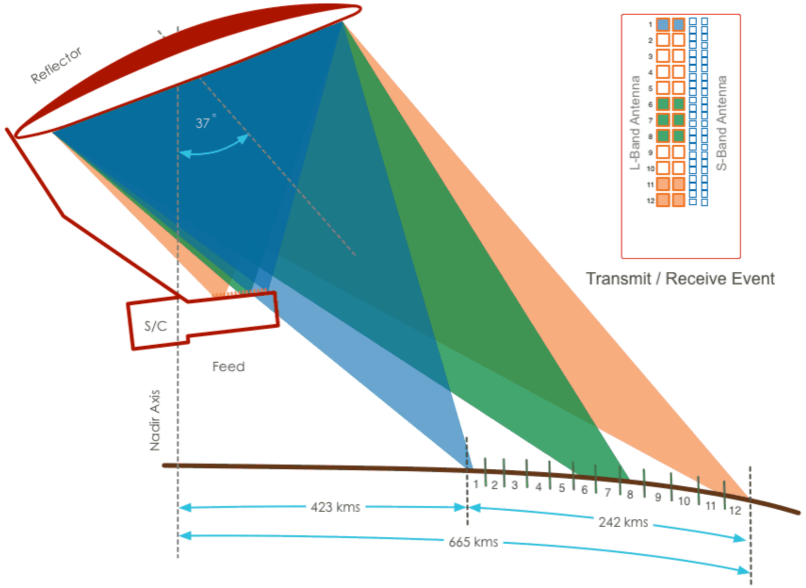


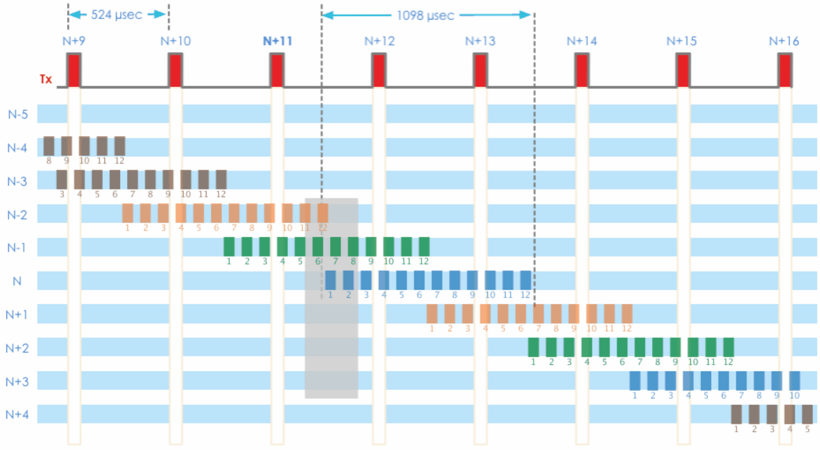
Deployed

At JPL Before Being Shipped to India

Sweep-SAR Measurement Technique

- **Sweep-SAR 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 interpulse period
- **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
  - Onboard processing is not reversible – requires onboard calibration before data is combined to achieve optimum performance

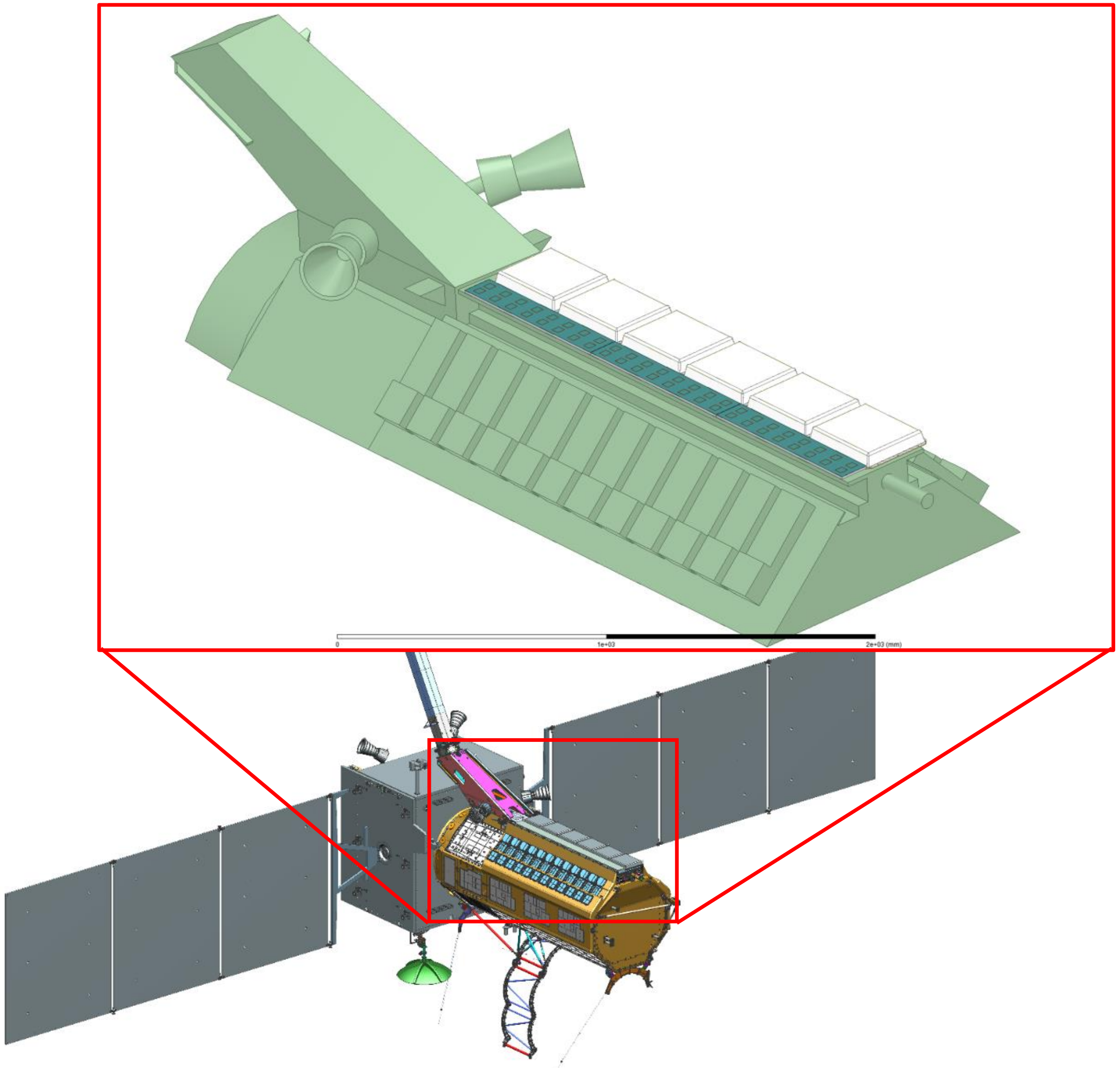




PRF = 1910 Hz, PRI = 524 μsec. Echo time difference between 423 km to 665 km swath = 1098 μsec

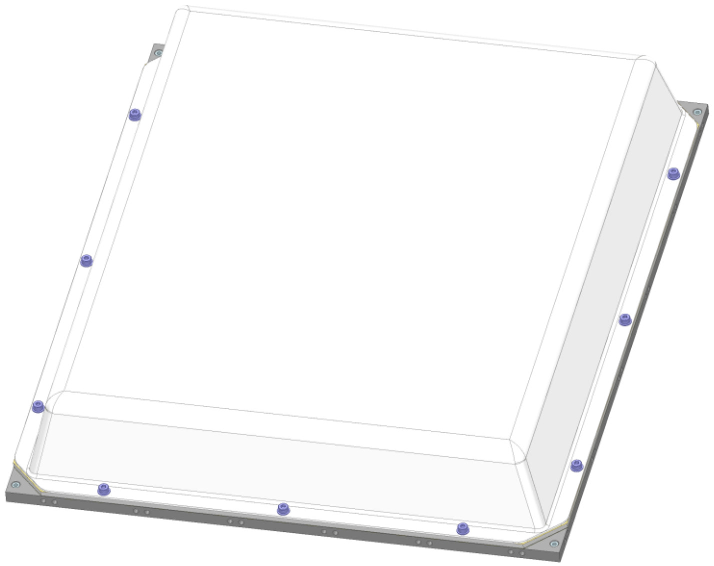
L-Band Feed RF Aperture (L-FRAP) RF Model

- Latest Ansys HFSS RF model includes:
  - Complete L-FRAP
  - Simplified version of:
    - S-FRAP
    - Radar antenna system
    - Top 3 panels of IRIS
    - Boom base
    - Star sensors
- This RF model is used to generate radiation patterns to feed the TICRA GRASP analysis that includes the entire spacecraft.
- Each LFTA is 358 x 310 mm.
- L-FRAP is 2,158 x 310 mm.

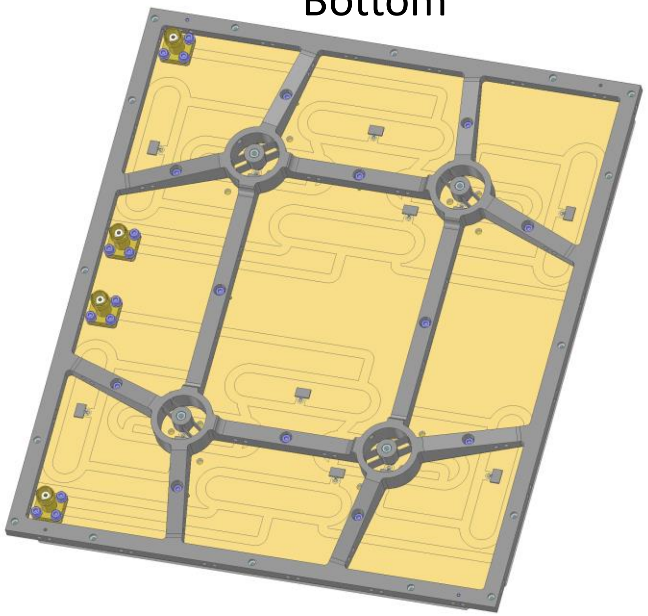


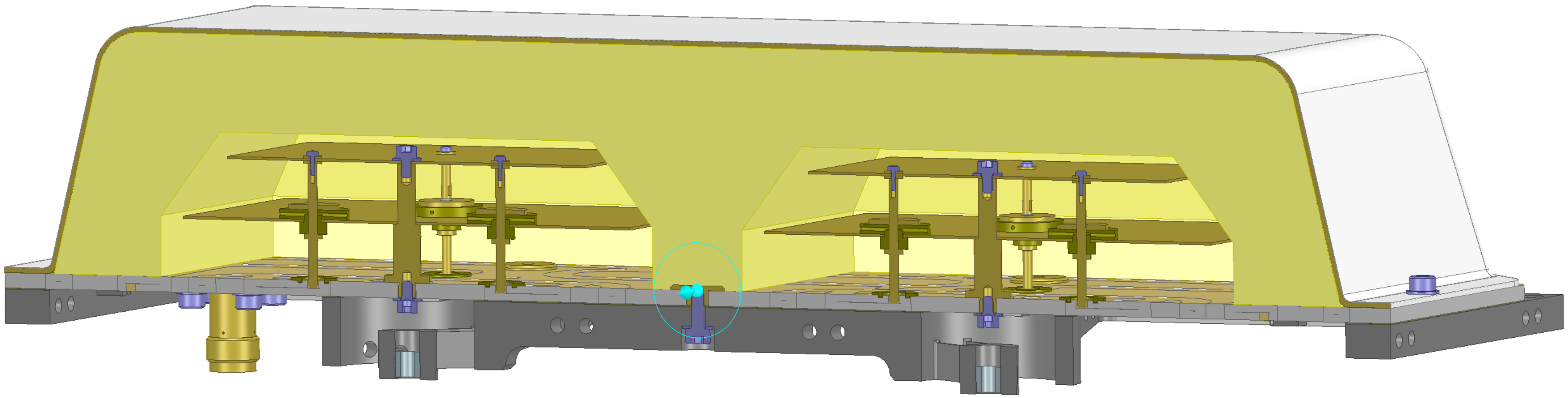
L-Band Feed Tile Assembly (LFTA) RF Model

Top



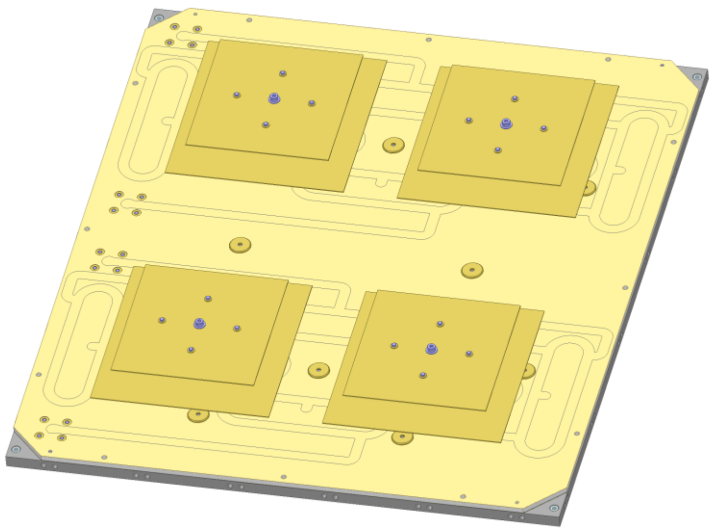
Bottom



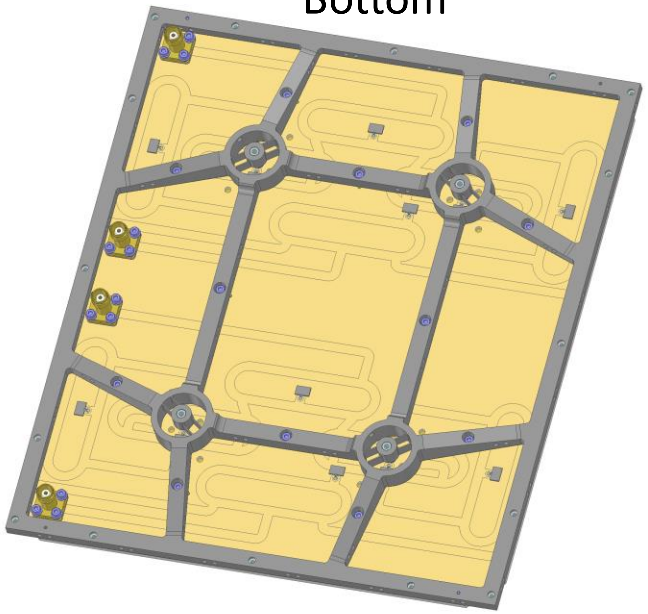


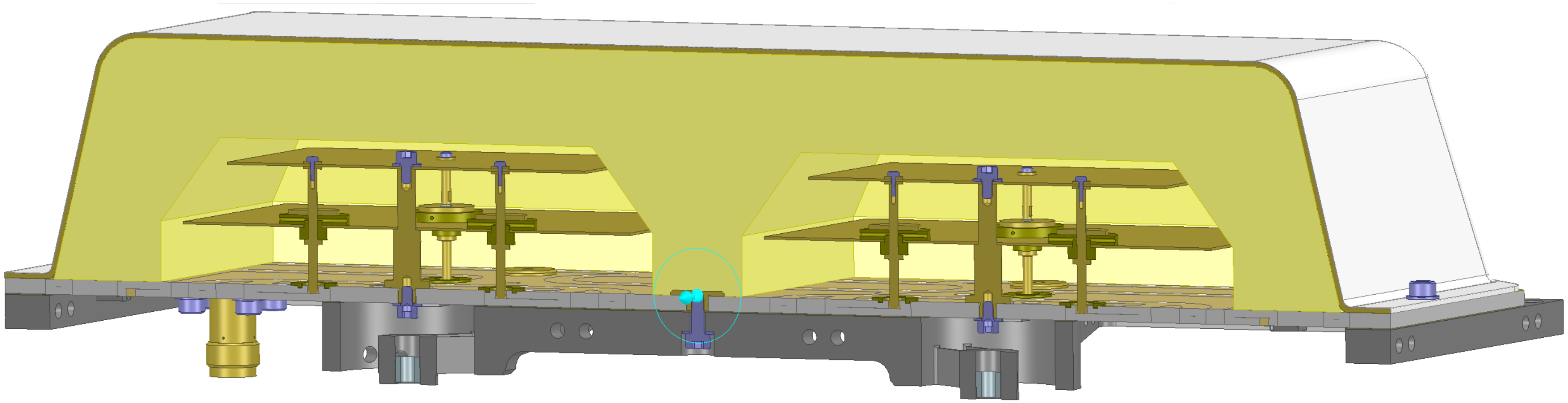
L-Band Feed Tile Assembly (LFTA) RF Model

Top

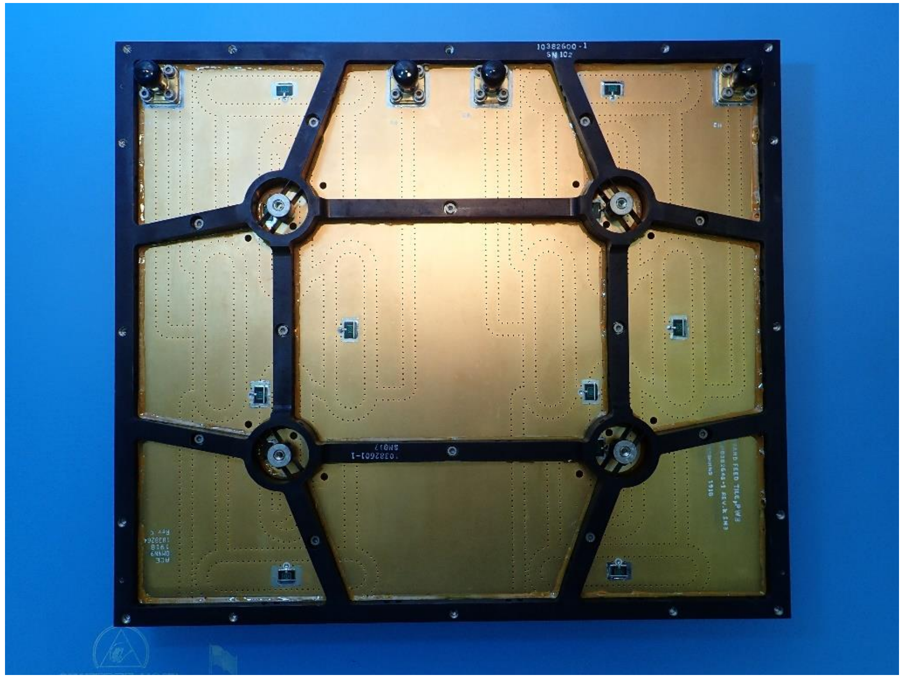


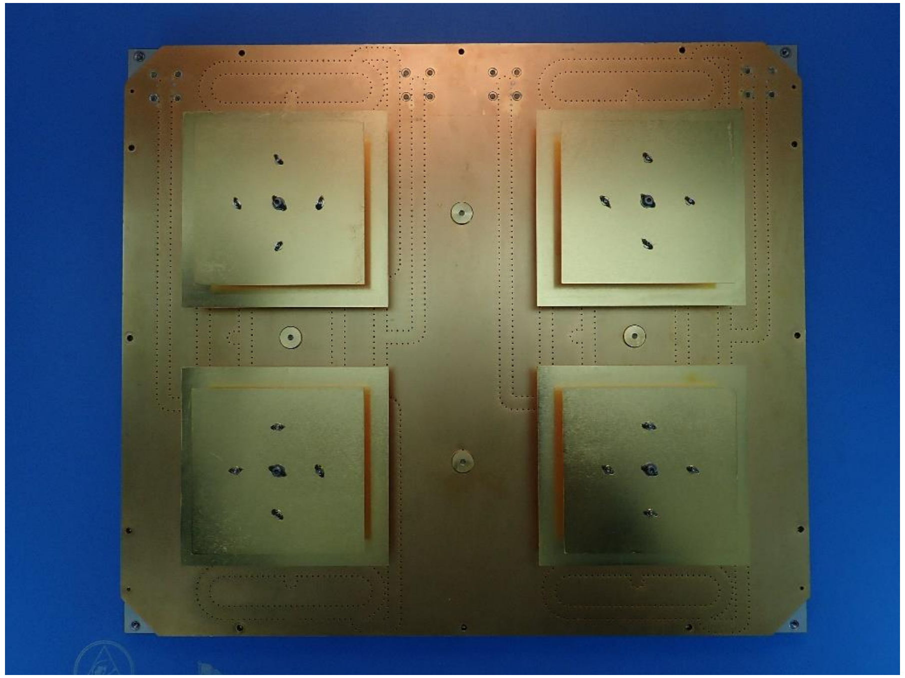
Bottom



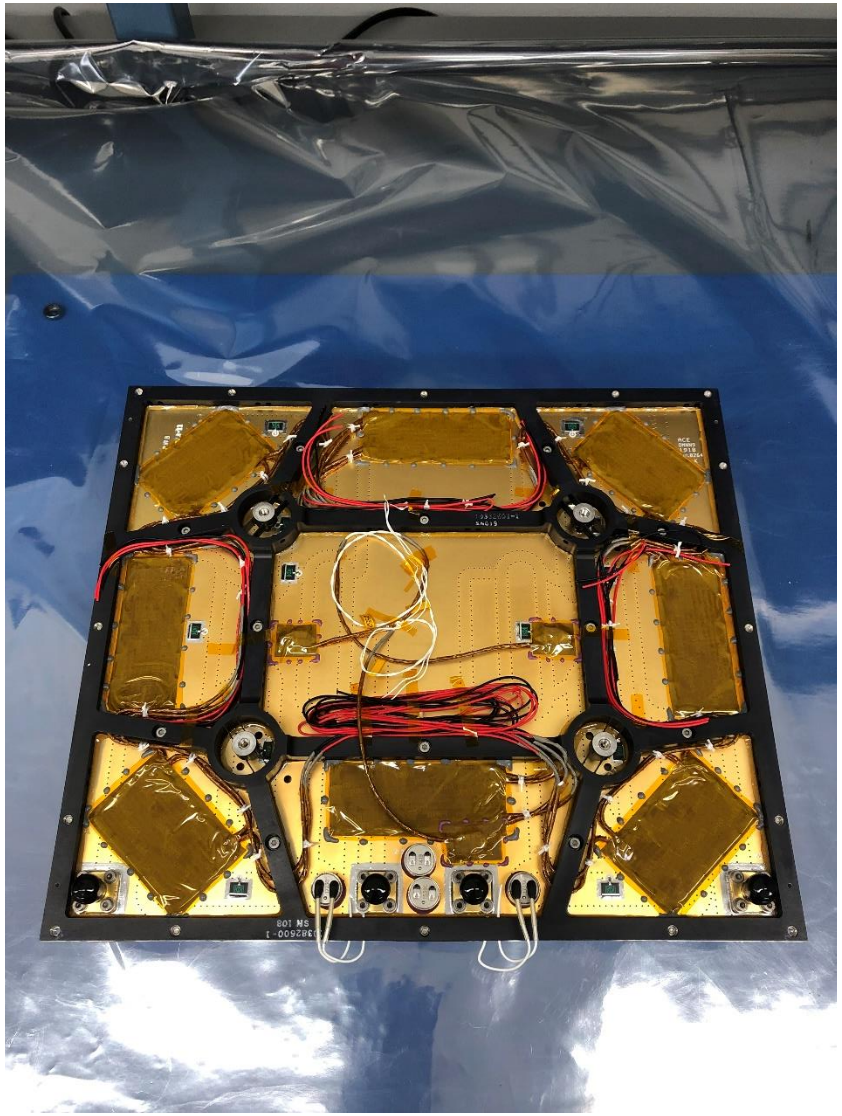


Flight Unit Without Radome, PN 10382600-1

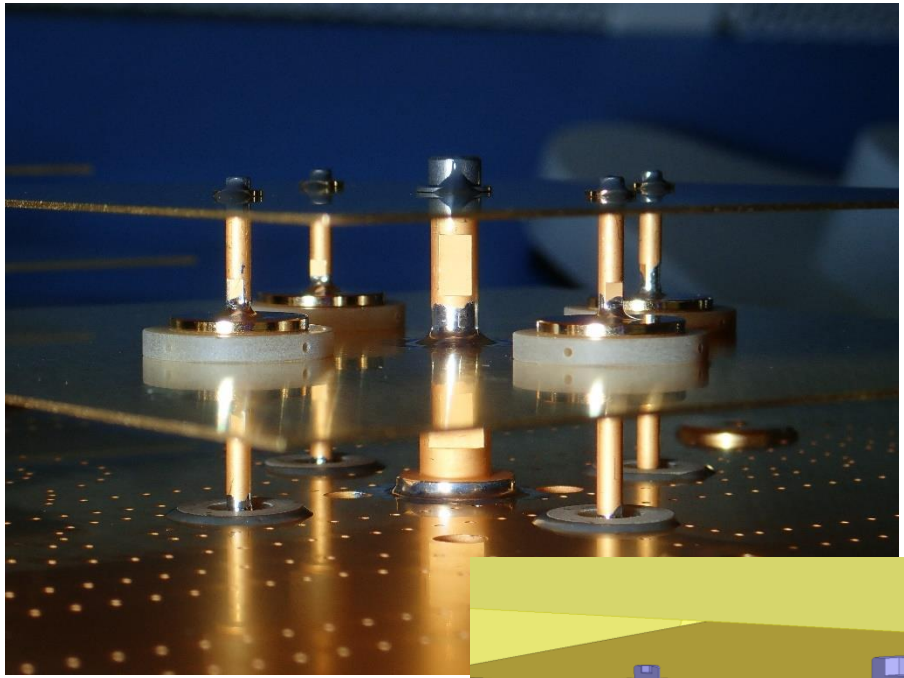


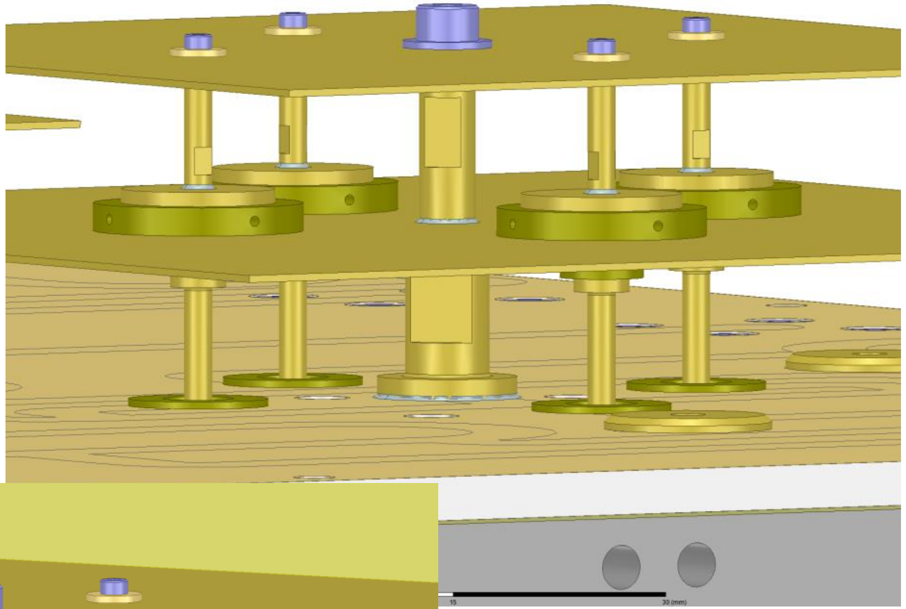


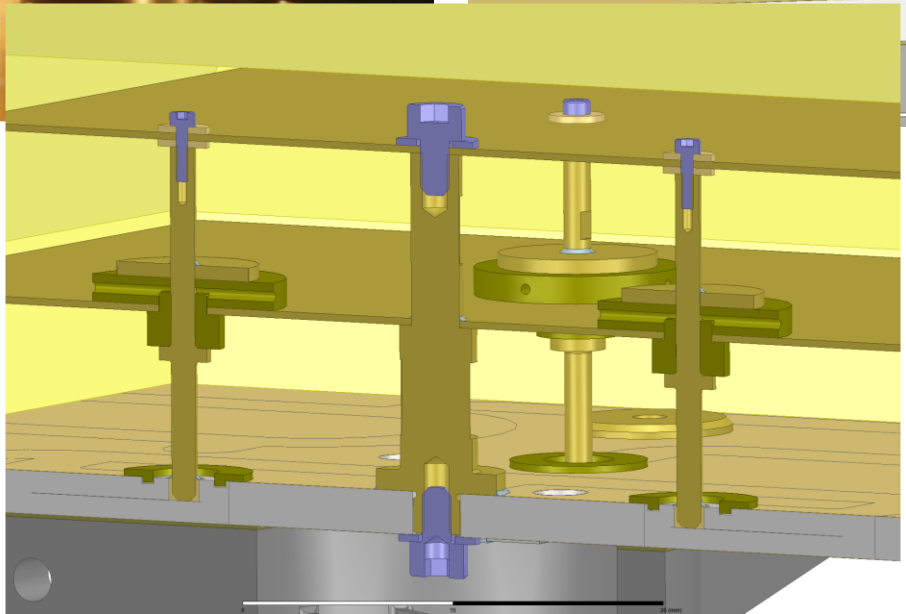
Complete FM LFTA, PN 10380071-1



Detail of the Patch Assembly

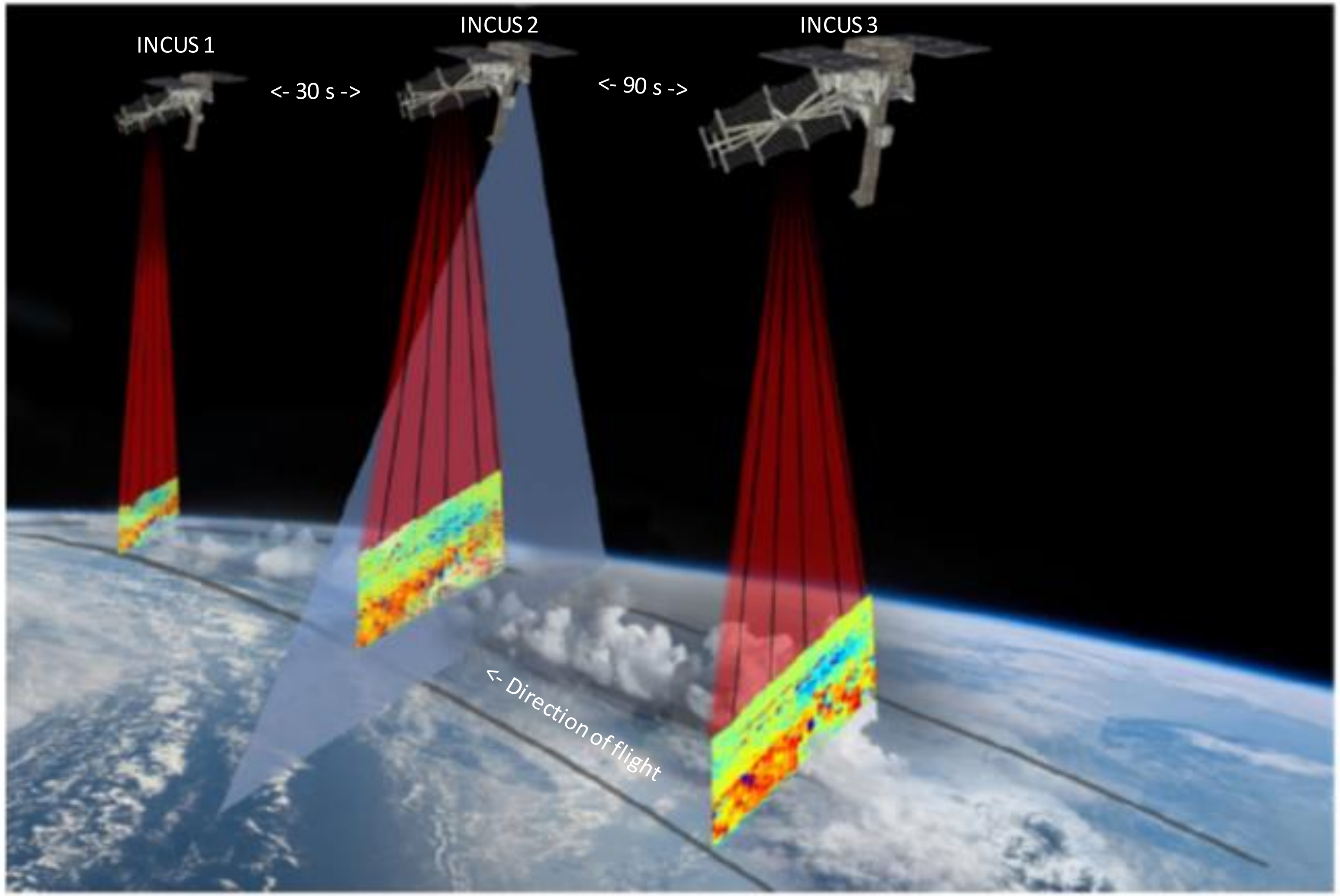






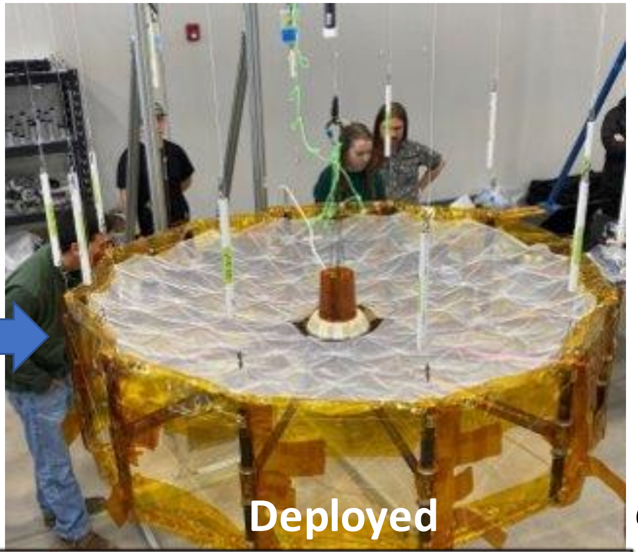
INCUS, Investigation of Convective Updrafts

- Low Earth Orbit
  - 450-550 km, ~9 km radar swath made of 7 individual 3-km beams
- Three almost identical observatories to measure time-differenced profiles of radar reflectivity
  - Satellites are 30 and 90 seconds apart
- Each observatory has:
  - 1.6-m deployable mesh KaTENna, provided by Tendeg
    - F/D = 0.7, 20 cm offset
  - **7-beam Ka-band feed assembly, developed at JPL**
  - Ka-band radar (dynamic atmospheric radar), heritage of Rain-Cube
- Middle observatory has a dynamic microwave radiometer with 4 channels between 150 GHz and 190 GHz, heritage of TEMPEST-D
  - 500-km swath
  - The other two observatories have mass mockups
- Commercial satellite bus provided by Blue Canyon Technologies



Tendeg KaTENna Design & RF Model

1.5-m Tendeg KaTENna Design, Stowed

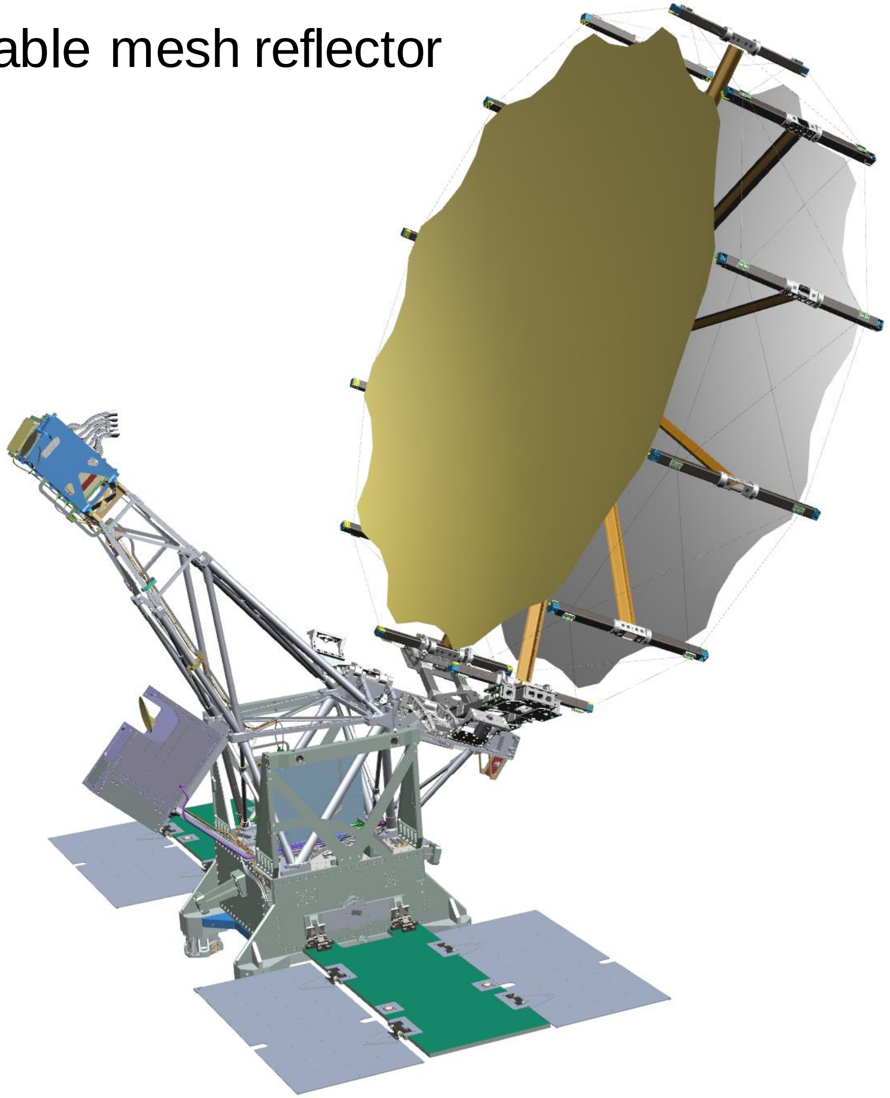


Deployed

(Source: Courtesy of Tendeg)

3-m Tendeg KaTENna Design

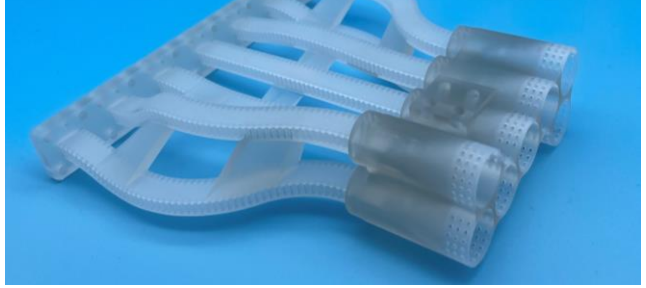
- Tendeg KaTENna, Tendeg proprietary Ka-band design
- 1.6-m deployable mesh reflector
- F/D = 0.7
- 20-cm offset



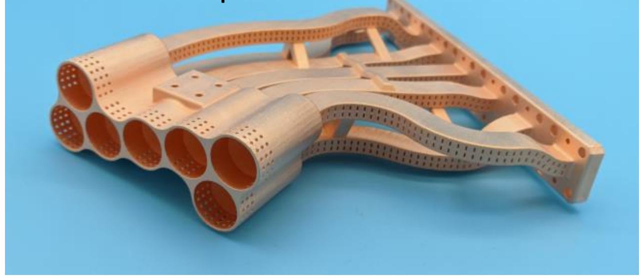
(Source: Courtesy of Tendeg)

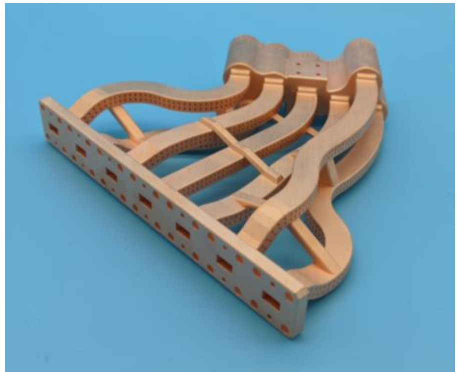
Golden Devices’ Feed Assembly Prototypes

SLA or SLS Polyimide models

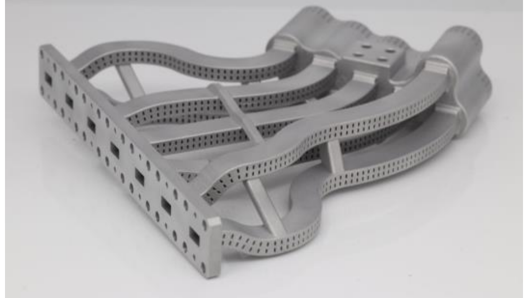


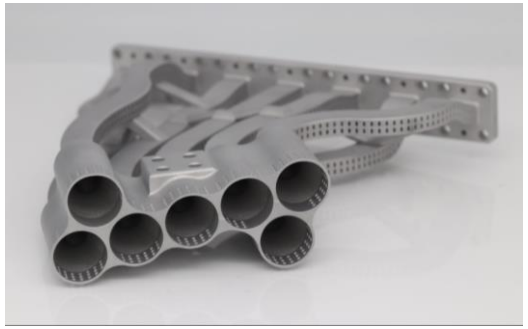
Cu or Cu+Ni plated SLS and SLA models

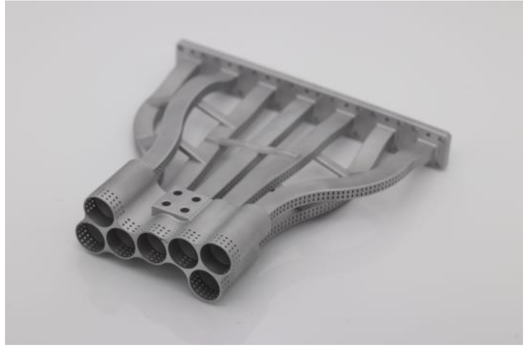




Cast Al models based on SLA mold

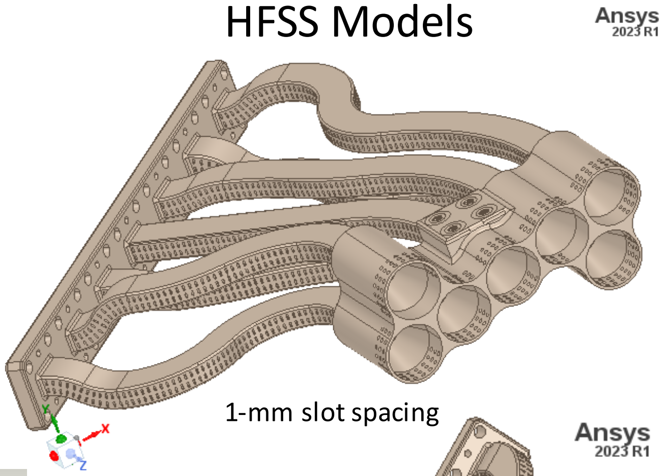




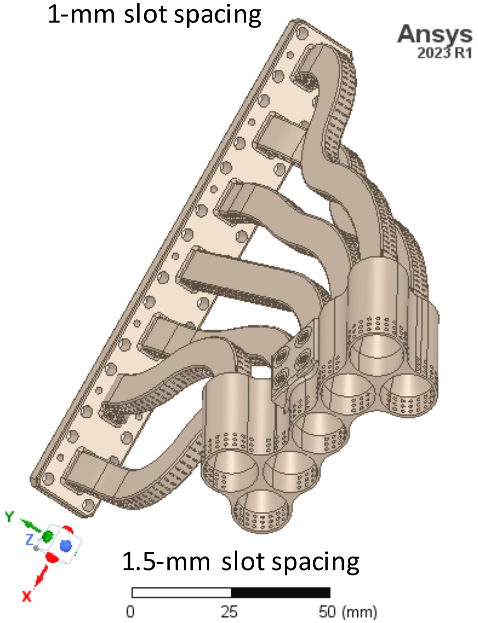


New Cast Al models

HFSS Models

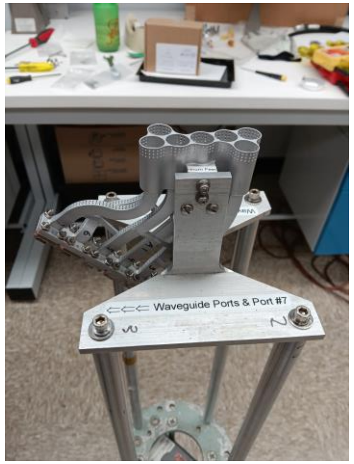


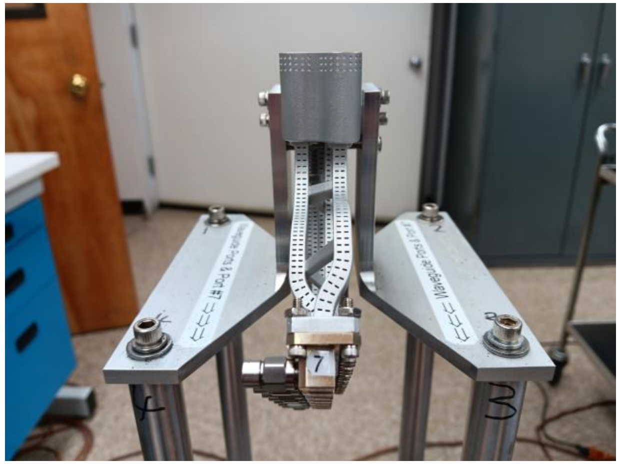
1-mm slot spacing

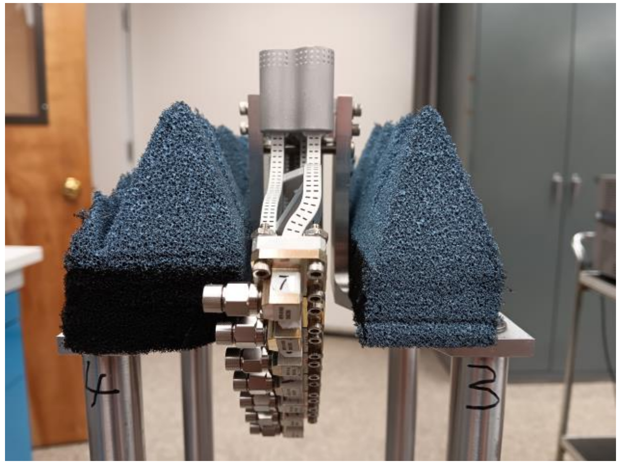


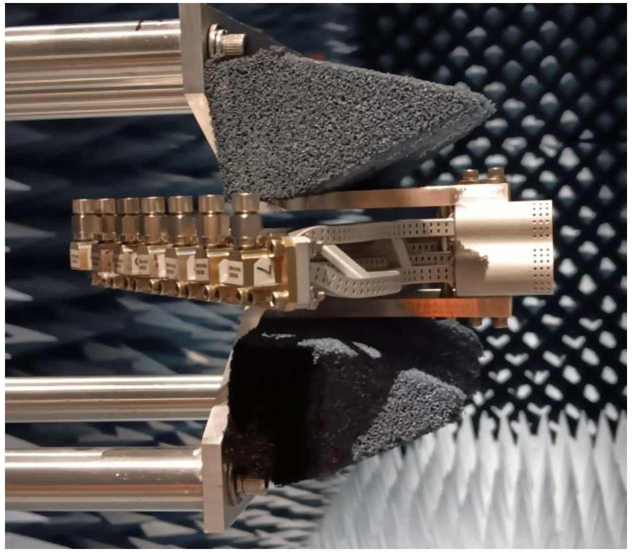
1.5-mm slot spacing

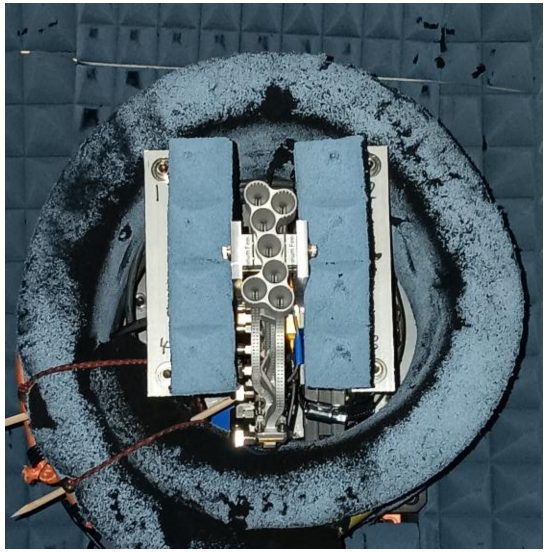
Radiation Pattern Measurements

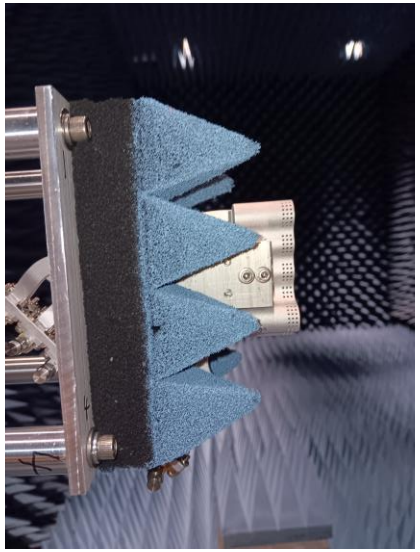


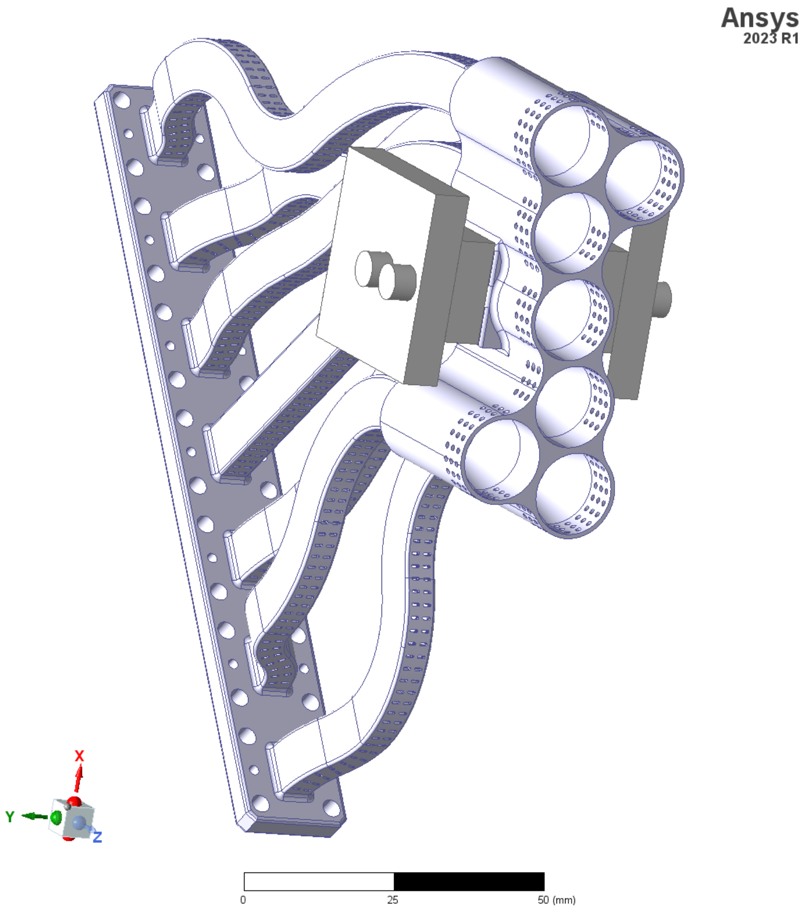






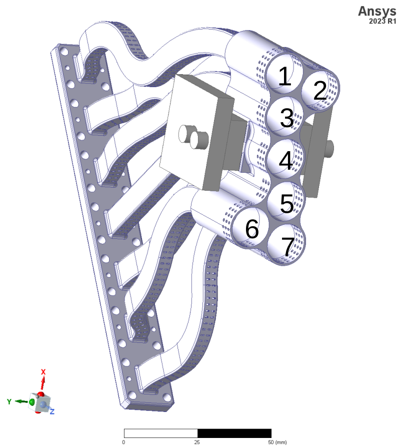






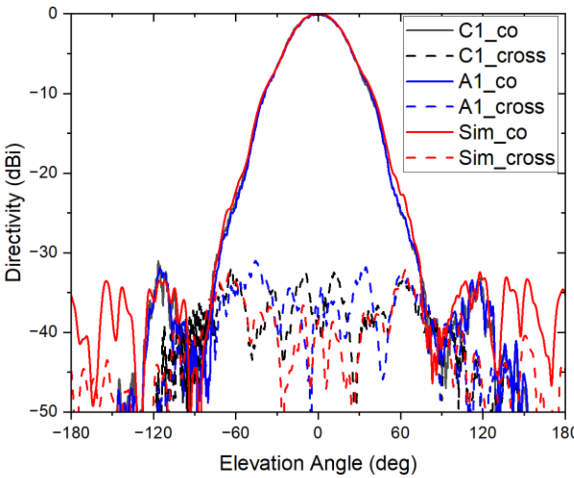
HFSS model used to compare with measurements

Port 4 Patterns

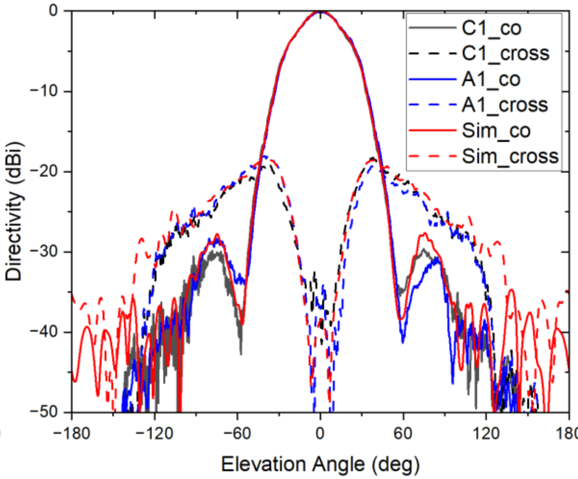


Reflector subtended angle is 34°.

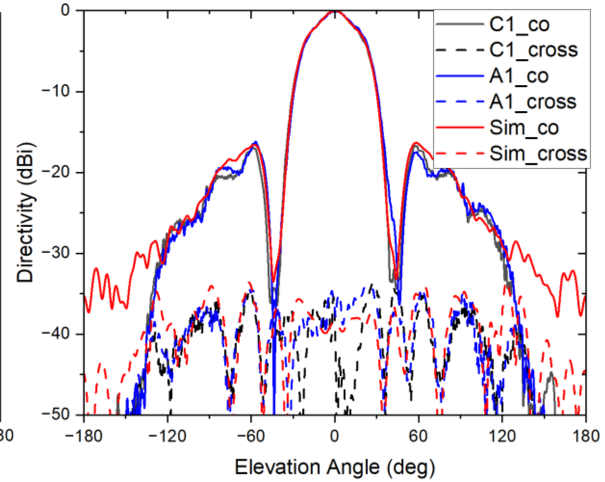
0° cut



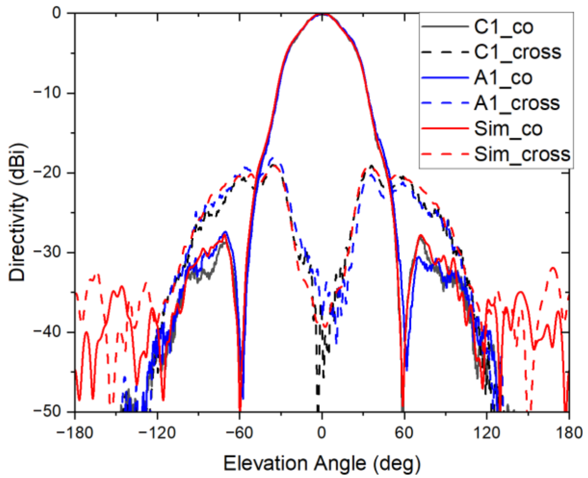
45° cut



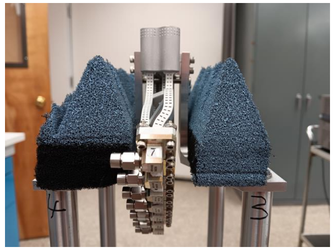
90° cut

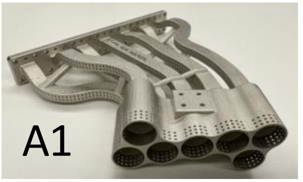


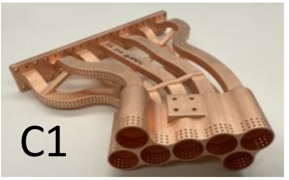
135° cut



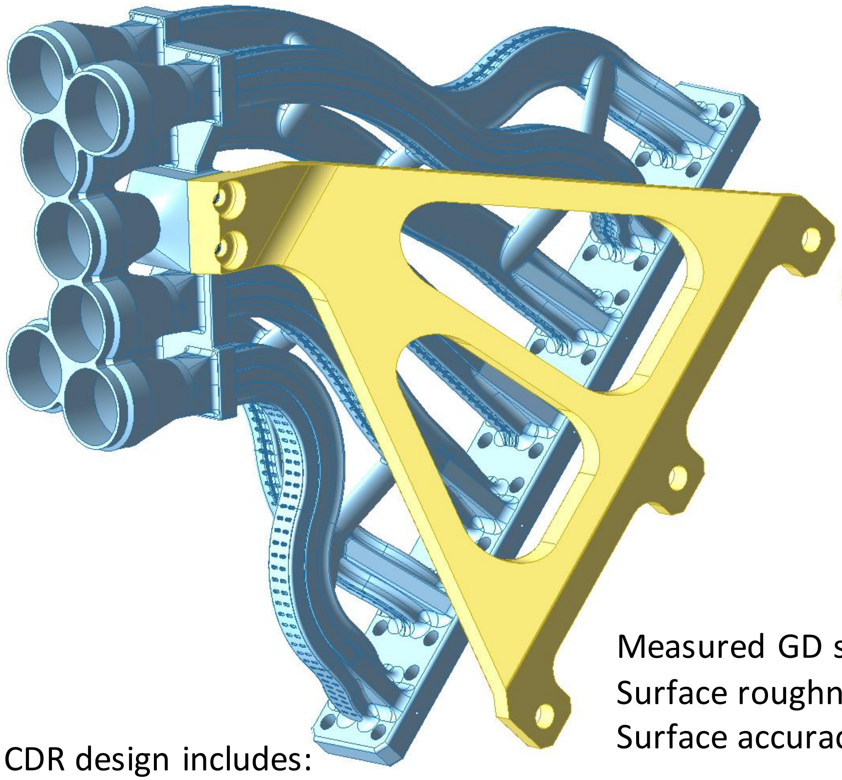
- All measurements were corrected for laser metrology.
- The scattering of the exposed supporting flanges is most visible on the results of this port, which is the center horn.
- The RF model predicted this effect with very good accuracy.

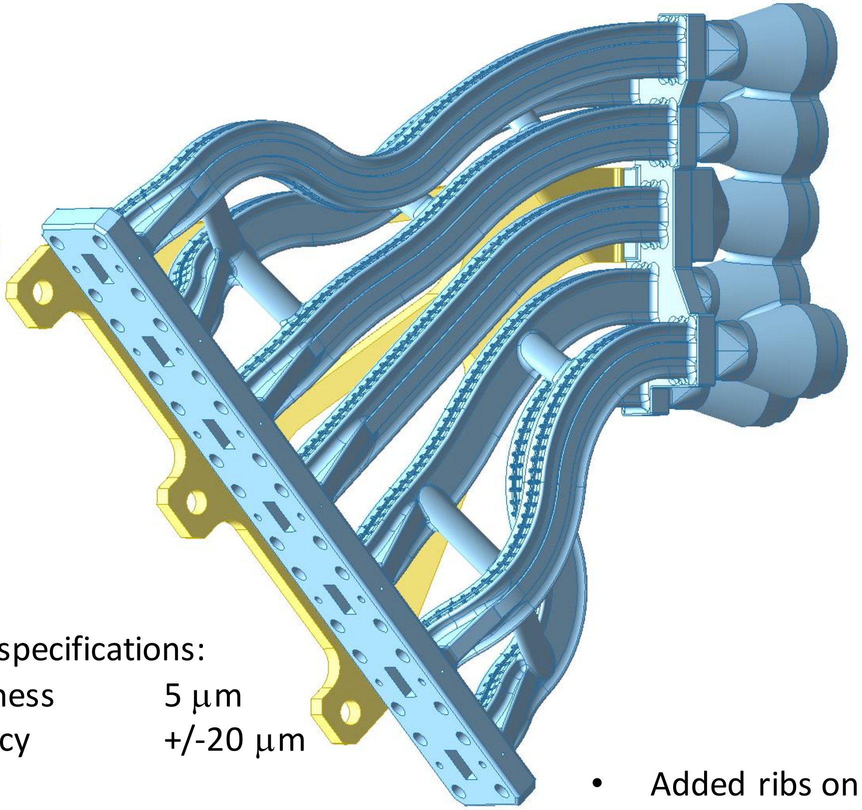


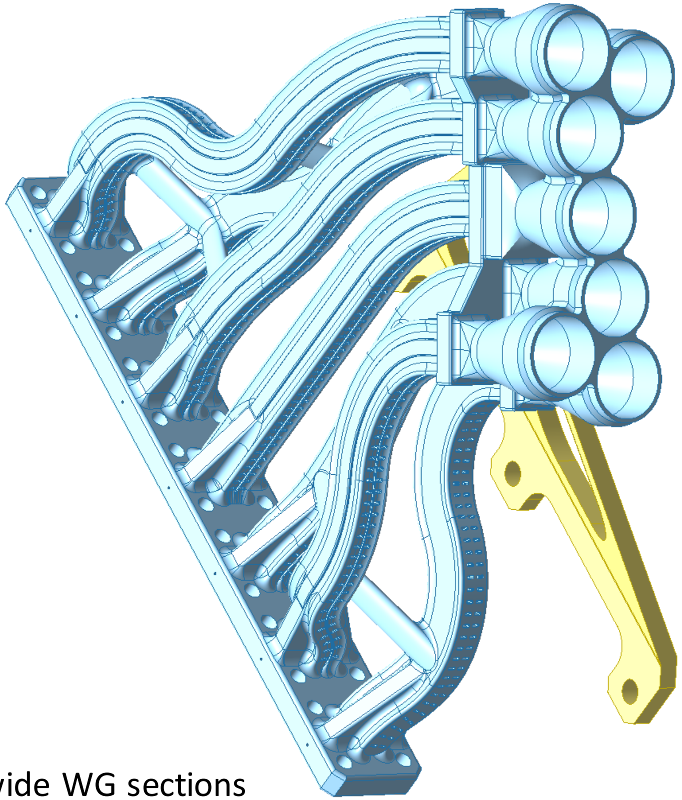




CDR Feed Design







Measured GD specifications:

Surface roughness	5 μm
Surface accuracy	+/-20 μm

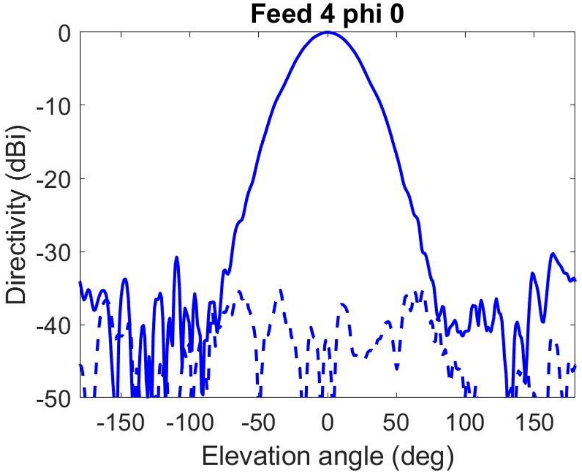
CDR design includes:

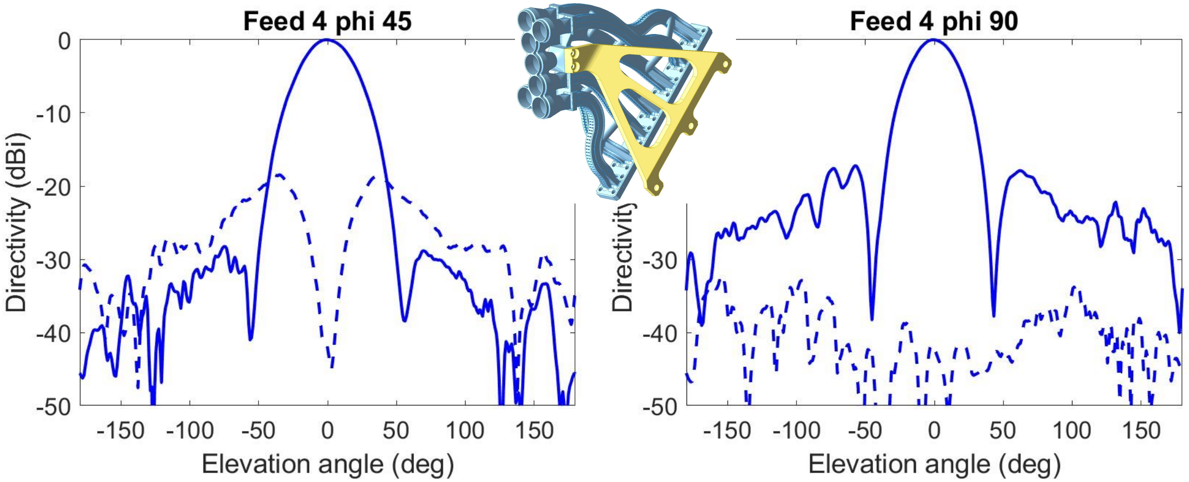
- Slimmed down horn section
- Single-sided bracket
- Larger fillets
- Better structural support at the FESA MB interface
- Larger bracing between WG

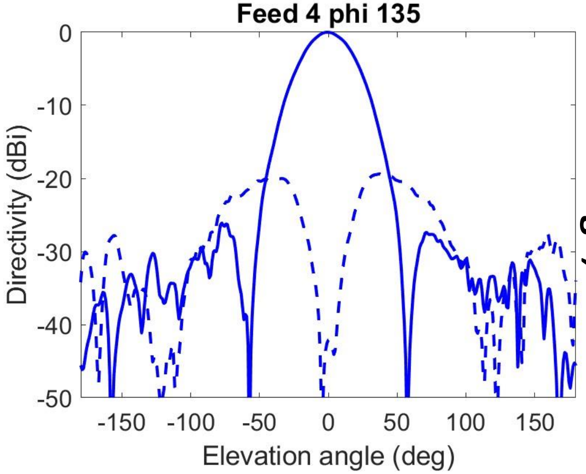
- Added ribs on wide WG sections
- Added ribs along the slotted WG sides
- Venting holes for alignment pins
- Simpler plate behind the horns
- Thicker side on WG 7

Feed 4

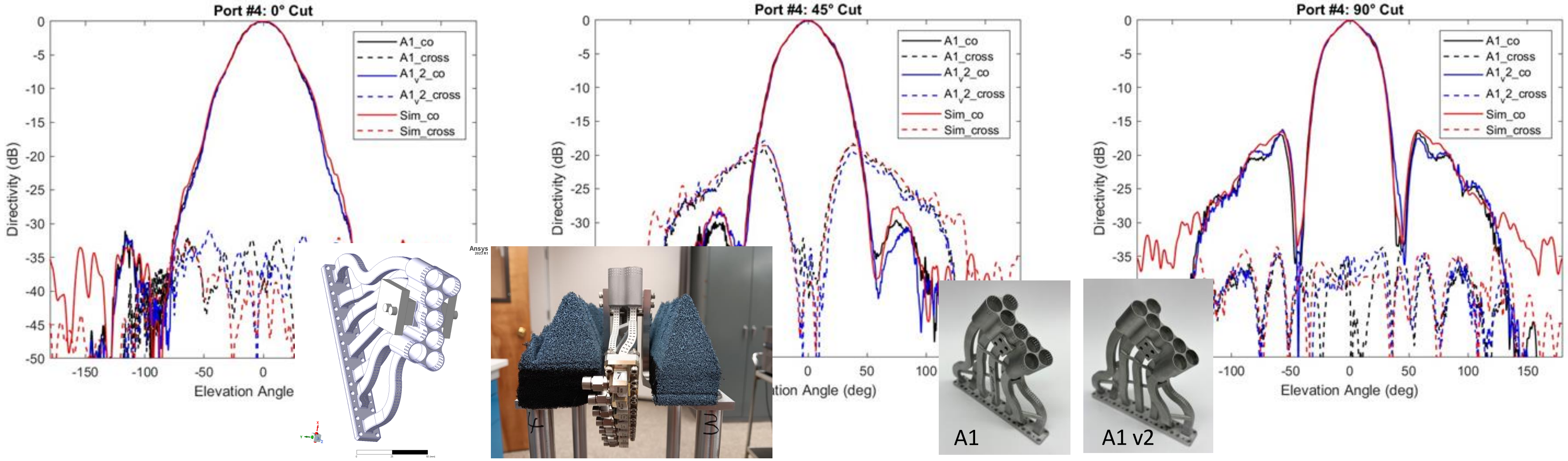
CDR Design, Calc.

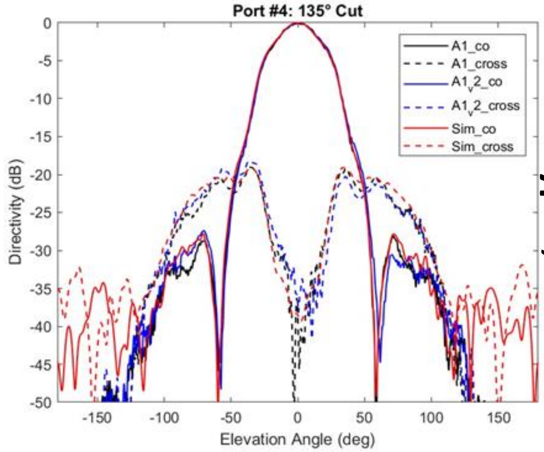




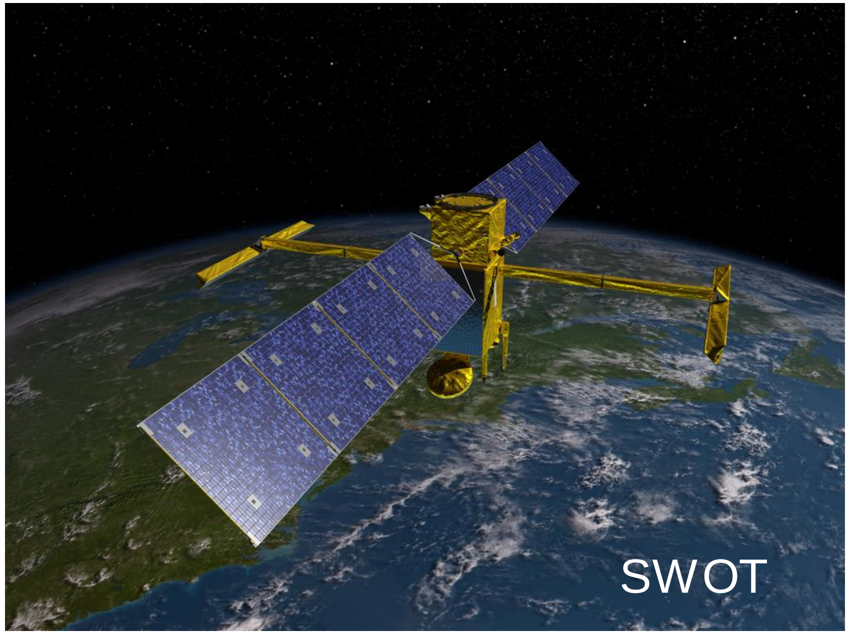


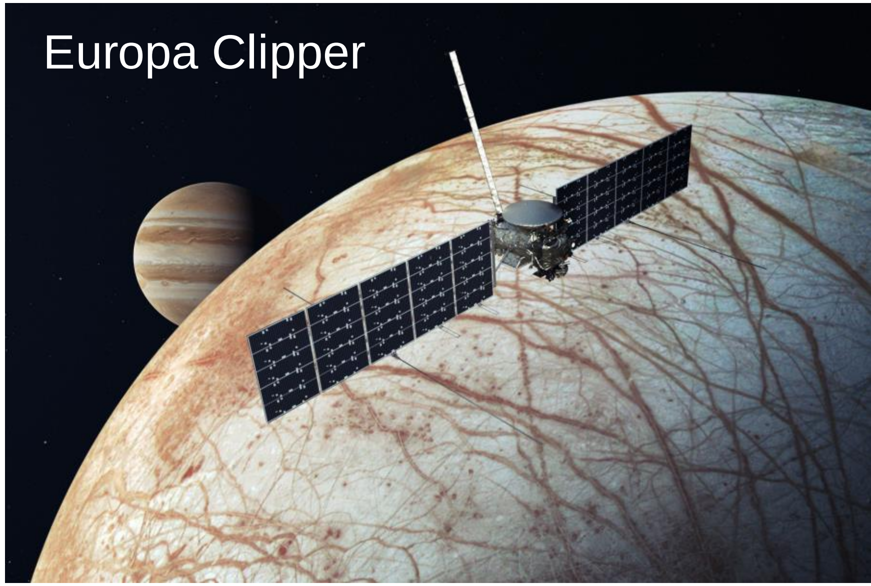
PDR Prototypes, Calc. & Meas.

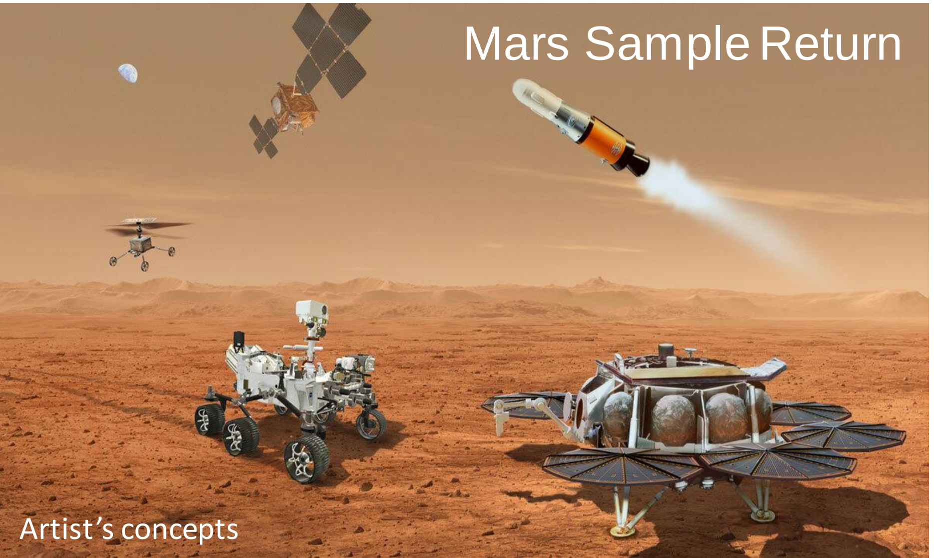




Other Important Flight Projects







Thank you!

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