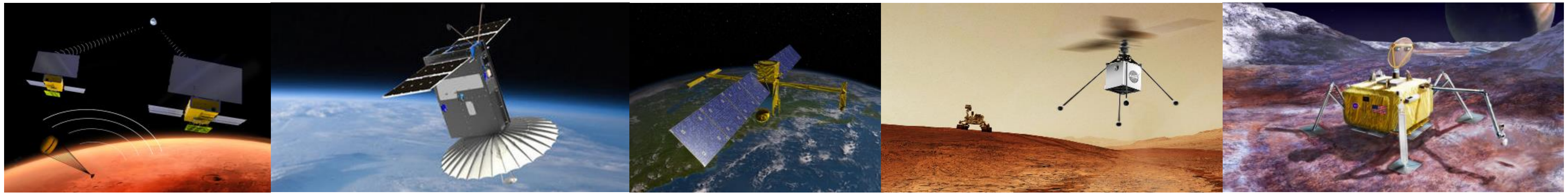
Pushing the Limits of Space Exploration One Antenna at a Time



Dr. Nacer Chahat
Jet Propulsion Laboratory / California Institute of Technology

Outline

- Innovative Deployable CubeSat Antennas
  - Mars Cube One (MarCO)
  - Raincube – Radar in a CubeSat
  - OMERA – One meter reflectarray
- SWOT
  - X-band Telecom for multipath mitigation
- The first Mars Helicopter – Antenna design and Telecommunication
  - Helicopter antenna
  - Mars Rover antenna
  - Link between Rover and Helicopter
- Europa Lander
  - Mission concept
  - Telecommunication antenna

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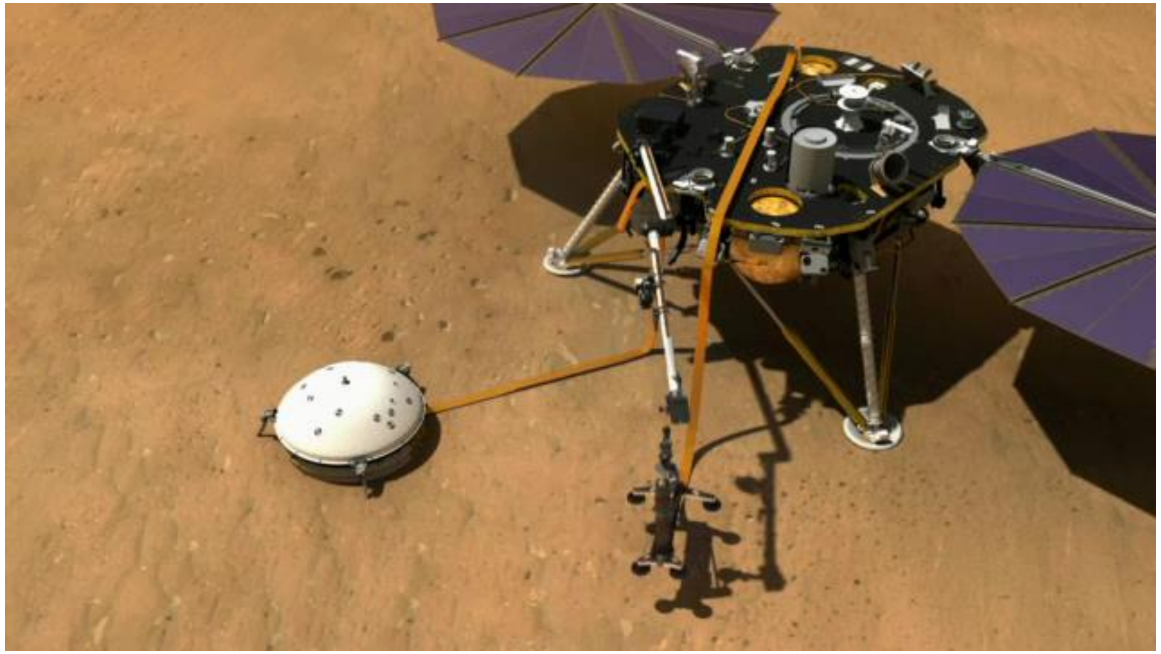
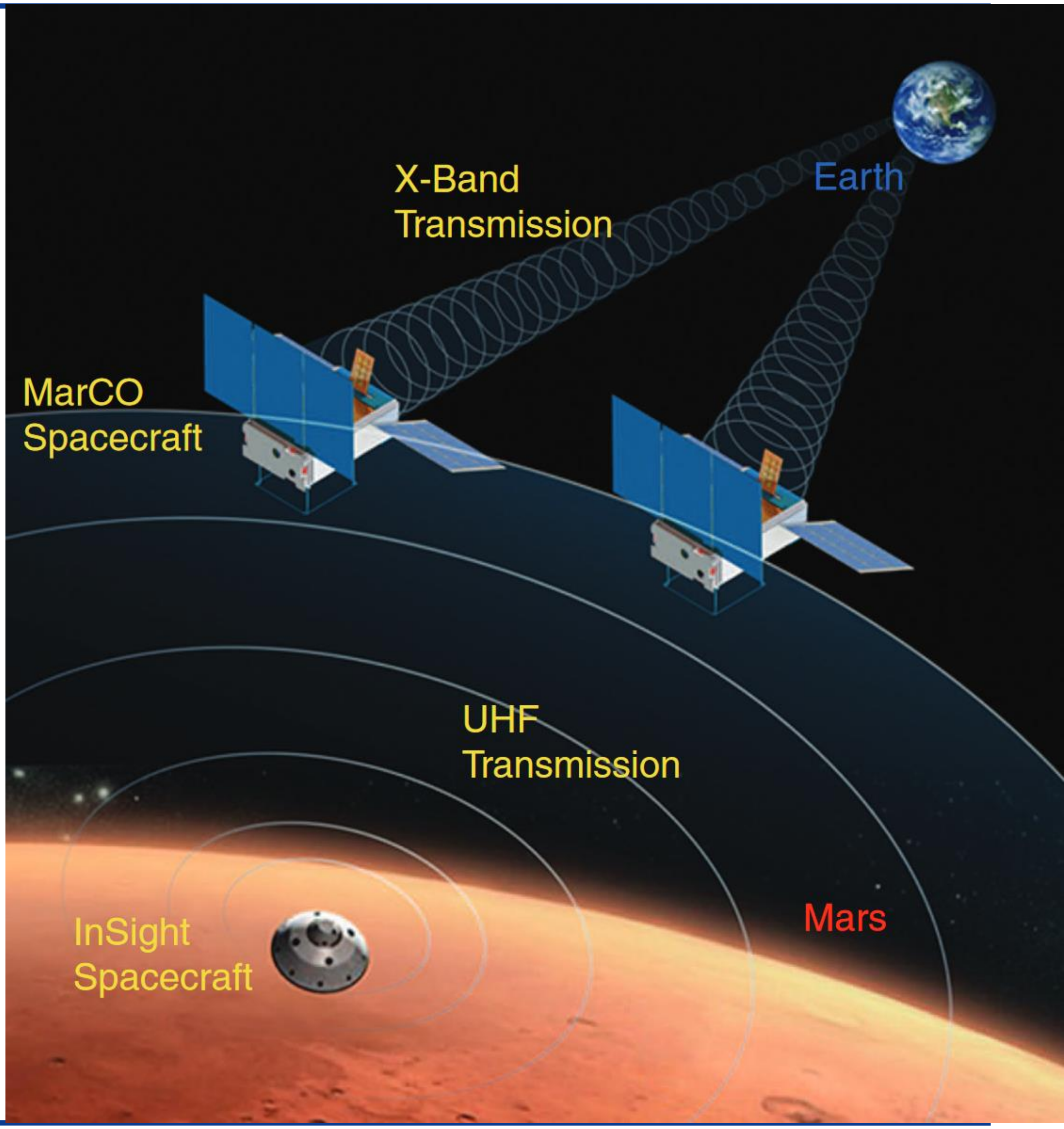
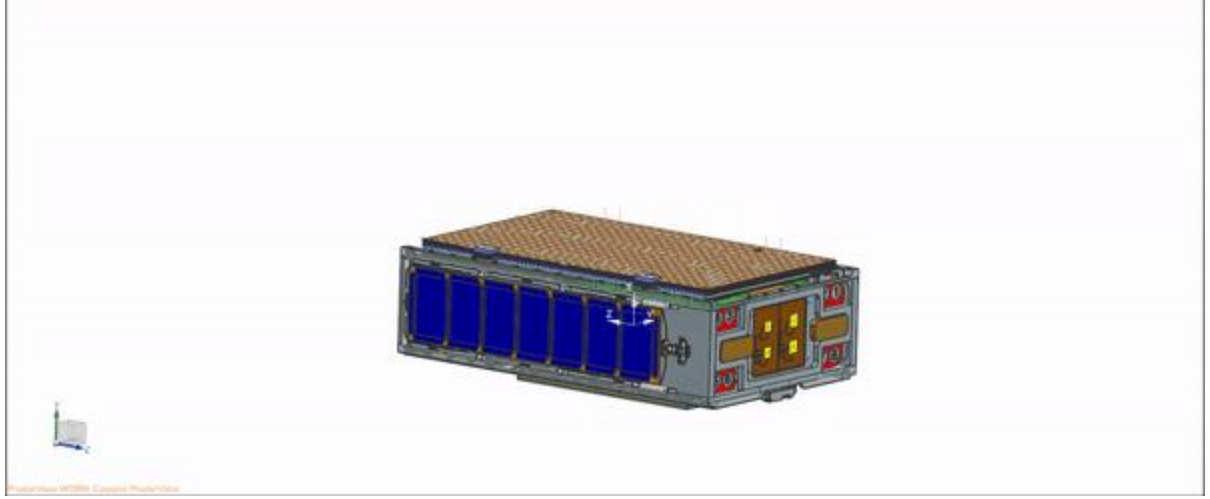
Mars Cube One (MarCO)

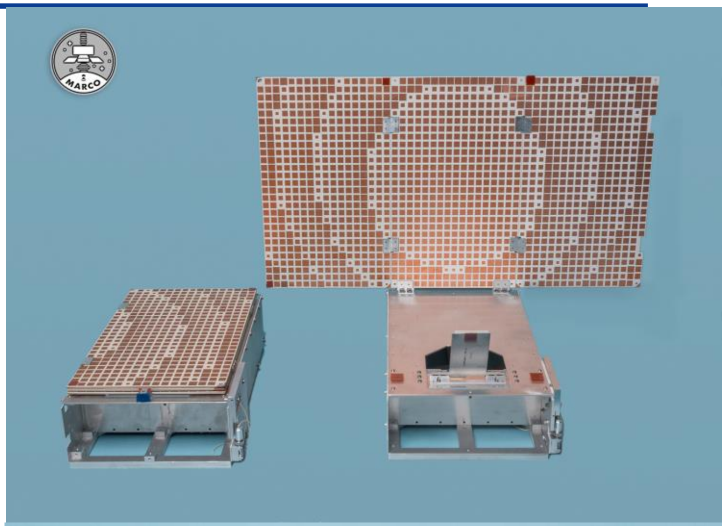


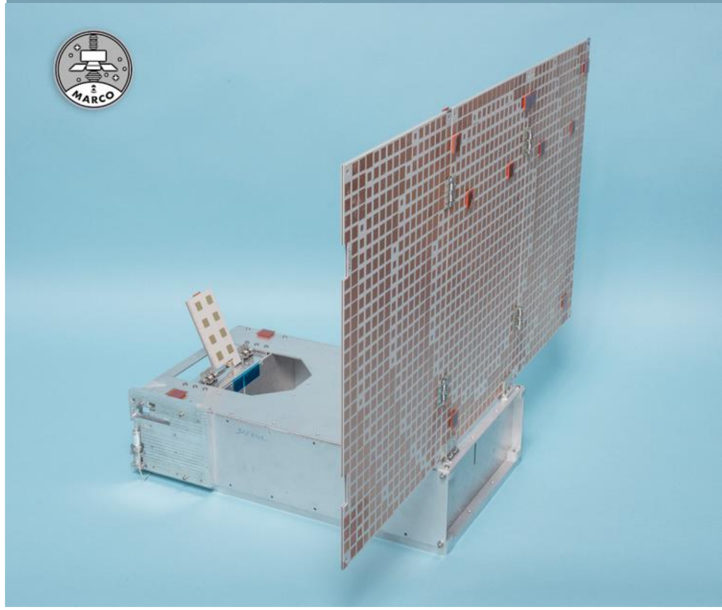


Mars Cube One (MarCO)

- **Challenge**: bent pipe communication at 1.04AU from Earth – i.e. receive and transmit at the same data rate (8kbps)
- **Main requirements**:
  - Stowage volume: 12.5mm × 210mm × 345mm
  - Gain of at least 28dBic
- **Required aperture**: 335mm × 587mm
- **Solution: foldable reflectarrray**



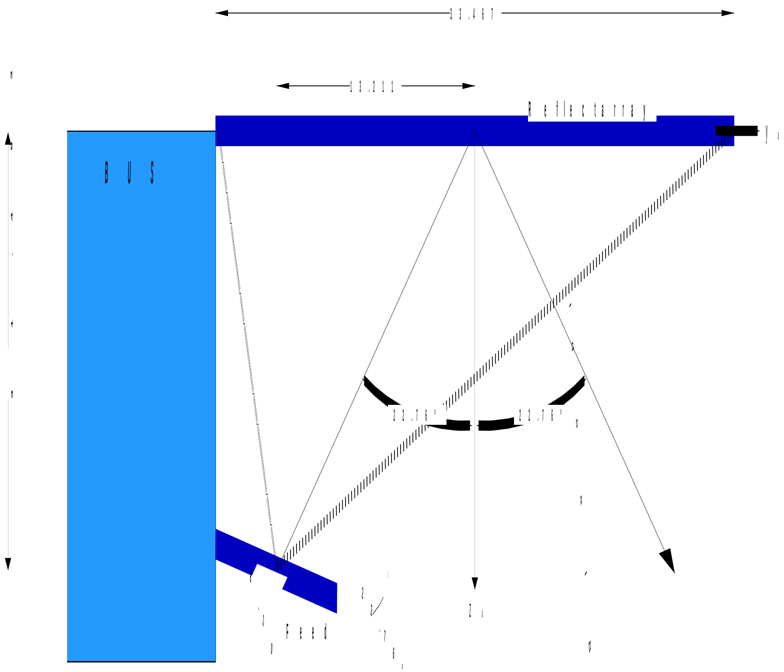




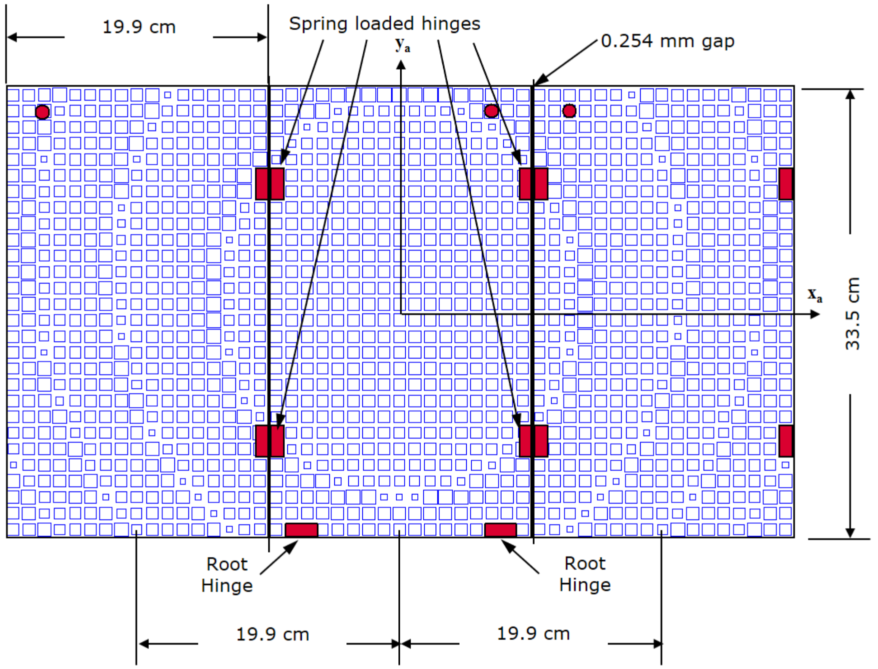
Pre-Decisional Information – For Planning and Discussion Purposes Only

Mars Cube One (MarCO)

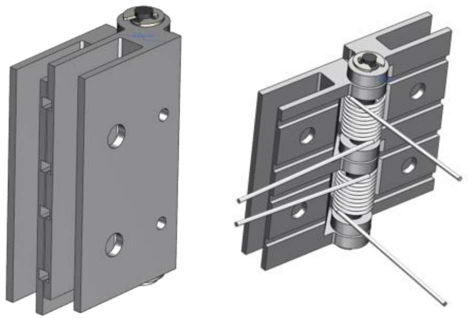
- **Reflectarray:**



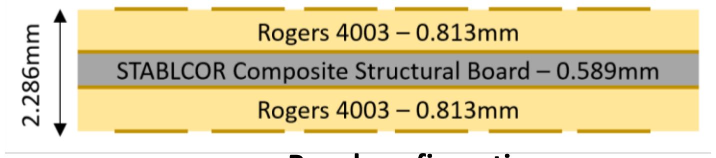
Reflectarray optics



Panel Layout



Custom made hinges

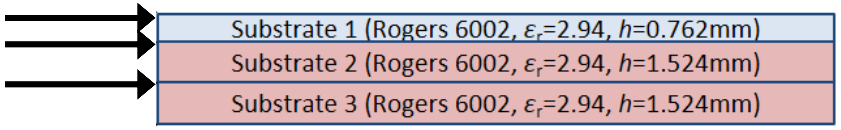


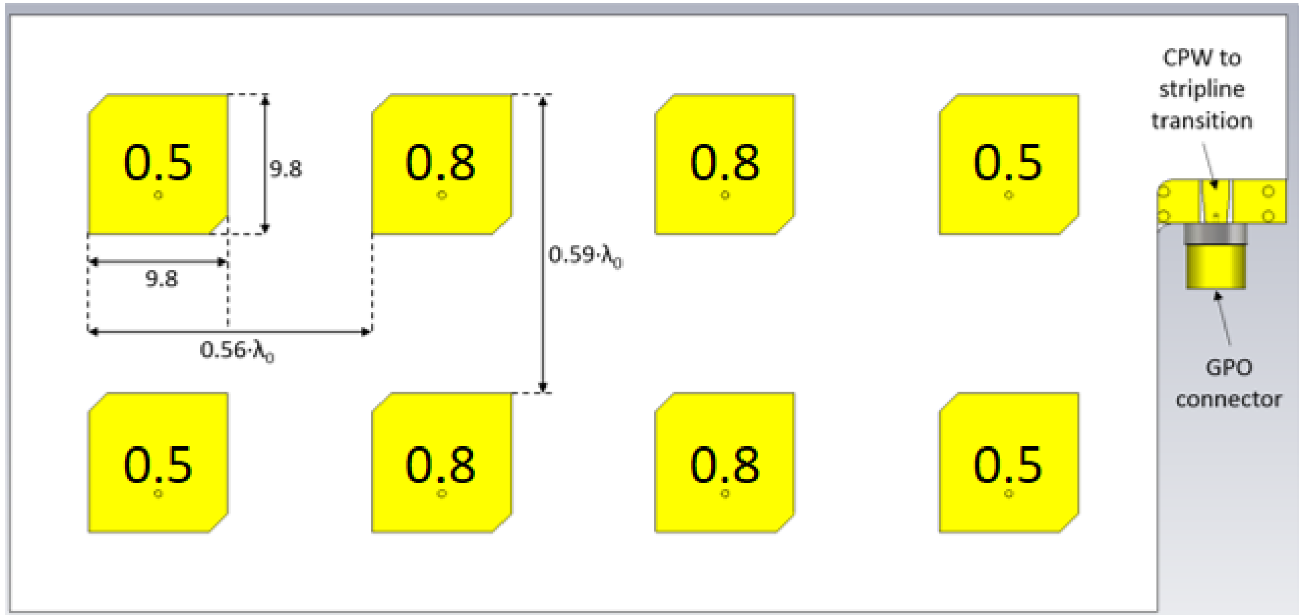
Panel configuration

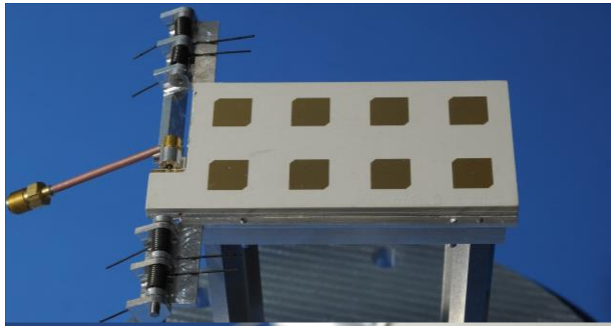
R. E. Hodges, N. Chahat, D. J. Hoppe, J. D. Vacchione, "The Mars Cube One deployable high gain cubeSat antenna," *IEEE Antennas Propag. Mag.*, vol. 59, no. 2, pp. 39-49, April 2017.

Mars Cube One (MarCO)

- **Reflectarray feed:**







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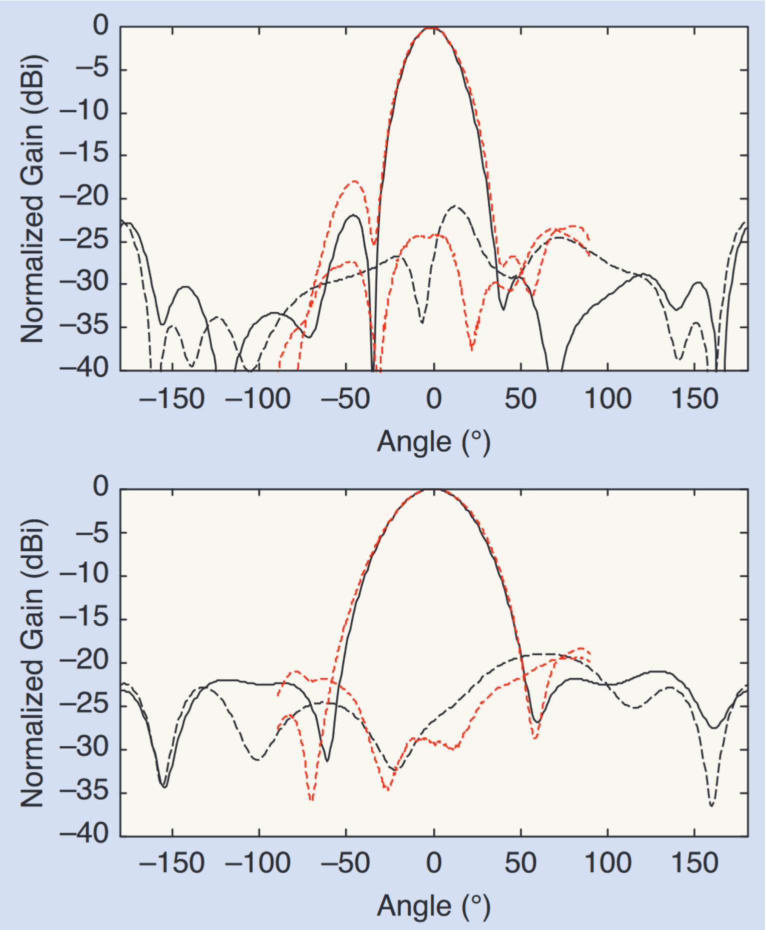
Mars Cube One (MarCO)

- **Reflectarray feed:**



	Gain (dBi)		Axial ratio (dB)	
Frequency (GHz)	Calculated	Measured	Calculated	Measured
8.375	13.8	13.90	2.0	2.76
8.400	13.96	13.96	1.2	1.53
8.425	13.97	13.93	0.3	0.55
8.450	13.87	13.92	1.6	1.33
8.475	13.78	13.87	3.0	2.60

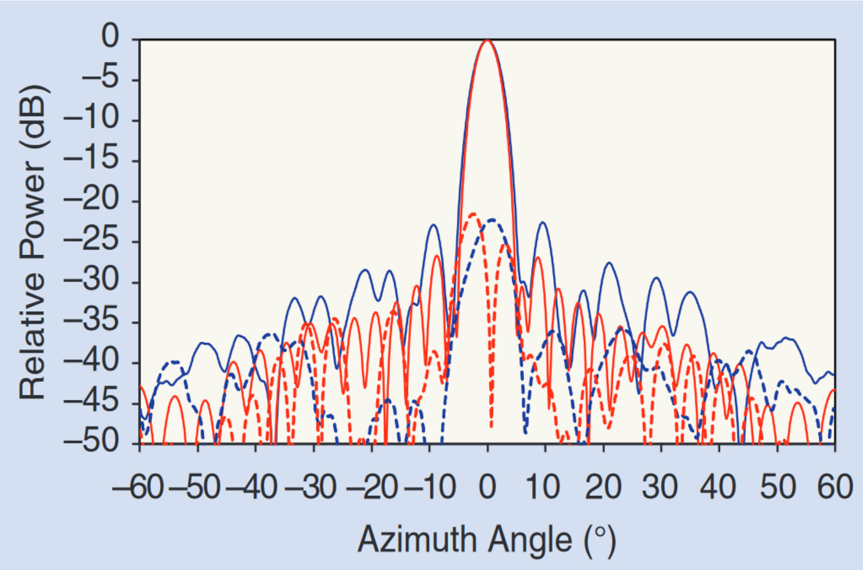
➔ Excellent agreement between calculation and measurements

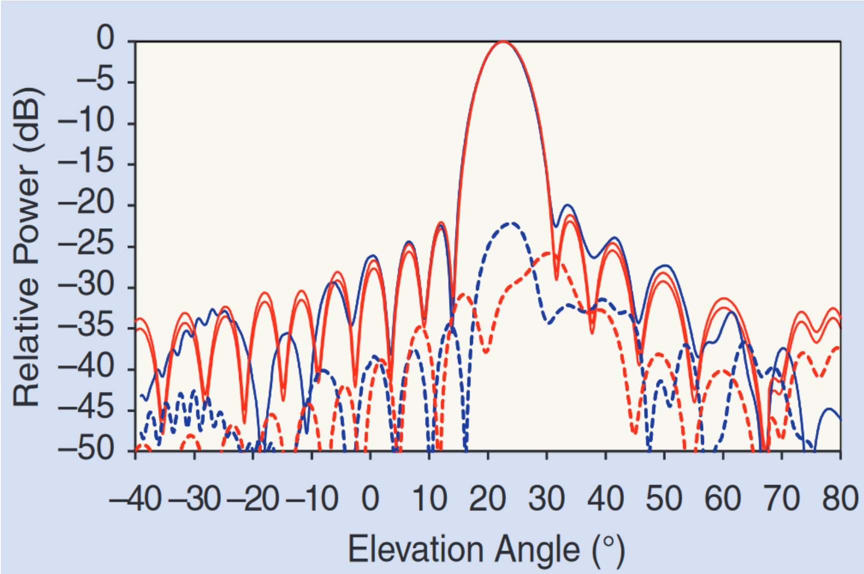
➔ Measured results are within 0.1dB

➔ AR is excellent across the entire frequency band

Mars Cube One (MarCO)

- **Measured reflectarray performance:**





	S/N 001	S/N 002
Computed directivity	**30.56**	**30.50**
Feed loss	–0.74	–0.74
Patch dielectric loss	–0.25	–0.25
Patch conductor loss	–0.04	–0.04
Mismatch loss	–0.14	–0.14
Hinge mounting area loss	–0.15	–0.15
Total loss	**–1.32**	**–1.32**
GAIN predict	**29.24**	**29.18**

→ Excellent agreement between calculation and measurements

→ Meets all project requirements

R. E. Hodges, N. Chahat, D. J. Hoppe, J. D. Vacchione, "The Mars Cube One deployable high gain cubeSat antenna," *IEEE Antennas Propag. Mag.*, vol. 59, no. 2, pp. 39-49, April 2017.

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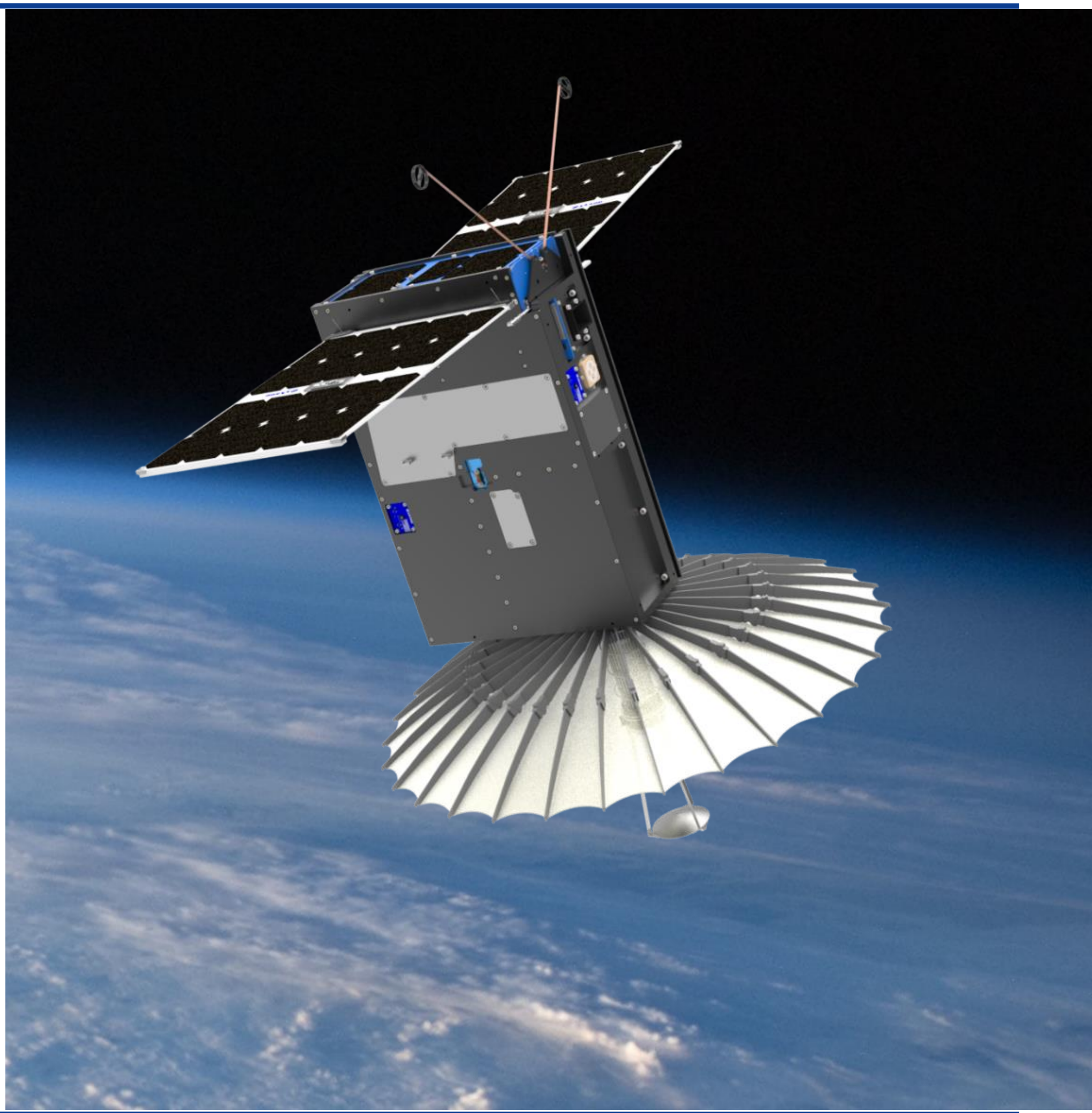
Raincube – Radar in a CubeSat

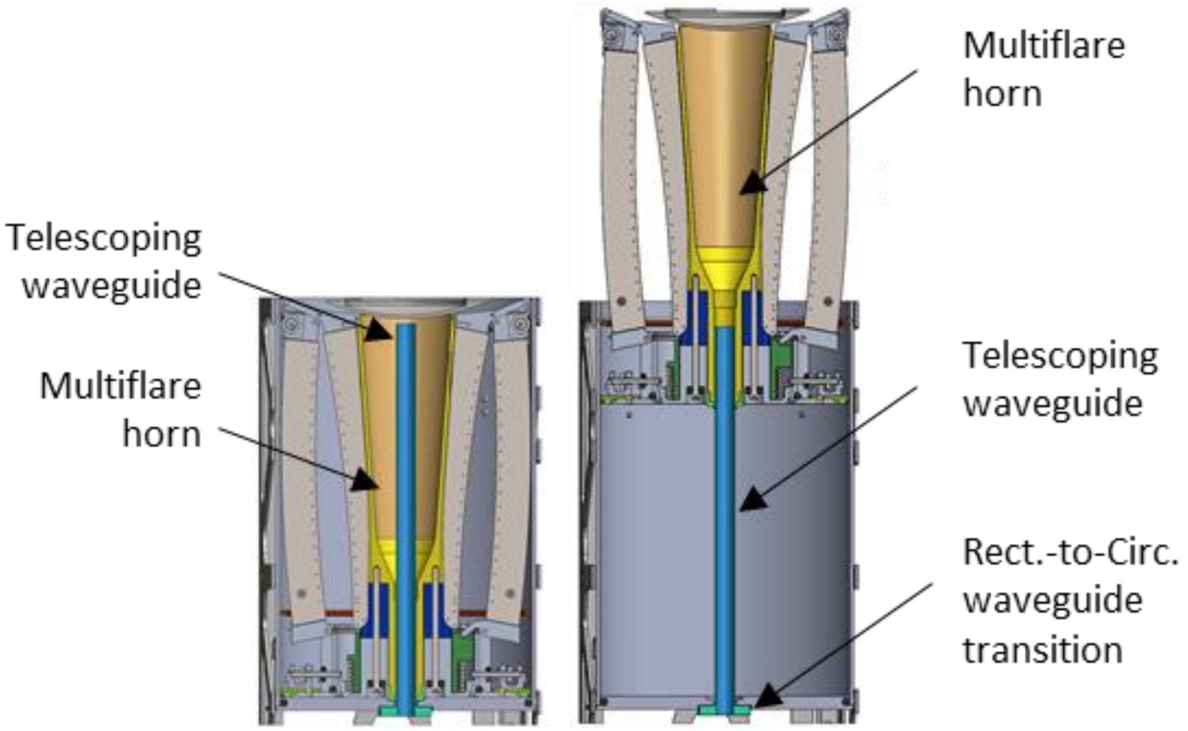
- First radar in a CubeSat (6U)
  - 3U for the entire radar + antenna
  - 1.5U for the folded antenna
- Ka-band antenna operating at 35.75GHz
- Linear polarization
- Efficiency of 55%
- Cassegrain antenna:
  - 40 OPI mesh
  - 30 ribs
  - Uses a telescoping waveguide
  - Subreflector is held by three struts
  - Achieved surface accuracy of ±0.22mm
  - Surface aberration compensated by optimizing the subereflector



N. Chahat, R. E. Hodges, J. Sauder, M. Thomson, E. Peral and Y. Rahmat-Samii, "CubeSat Deployable Ka-Band Mesh Reflector Antenna Development for Earth Science Missions," *IEEE Trans. Antennas & Propag.*, vol. 64, no. 6, pp. 2083-2093, June 2016.

Raincube – Radar in a CubeSat

- Antenna description:



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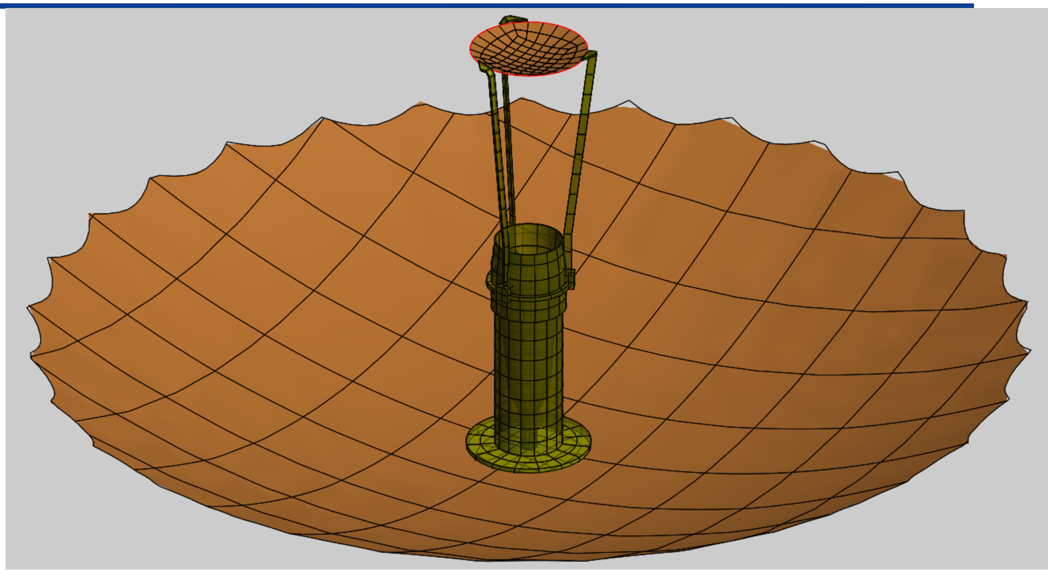
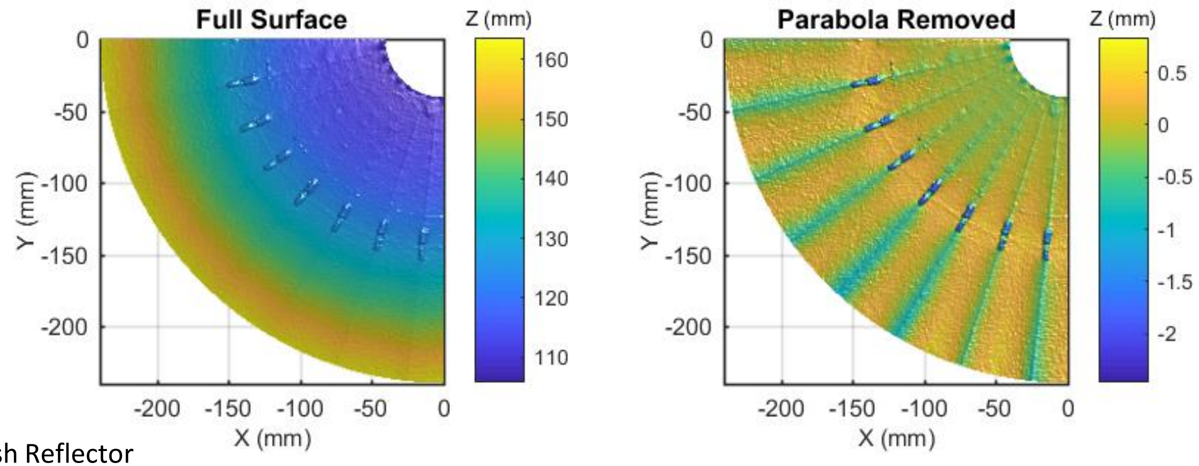
Raincube – Radar in a CubeSat

- Ticra GRASP is employed:
  - MoM for the feed, struts, and subreflector.
  - PO + PTD for the main reflector
  - The horn is a BoR object
  - The 3 struts are represented using a tabulated mesh
  - Mesh is represented by a Wire mesh object
- The reflector is represented by an unfurlable surface with 30 ribs, and a focal length of 0.25m
- Rim is defined using tabulated rim
- CST MWS is used to calculated the feed insertion loss and S_{11}.
- The subreflector was redesigned to compensate for the surface aberration due to the limited number of ribs. See to the right the measurement of the surface mesh.





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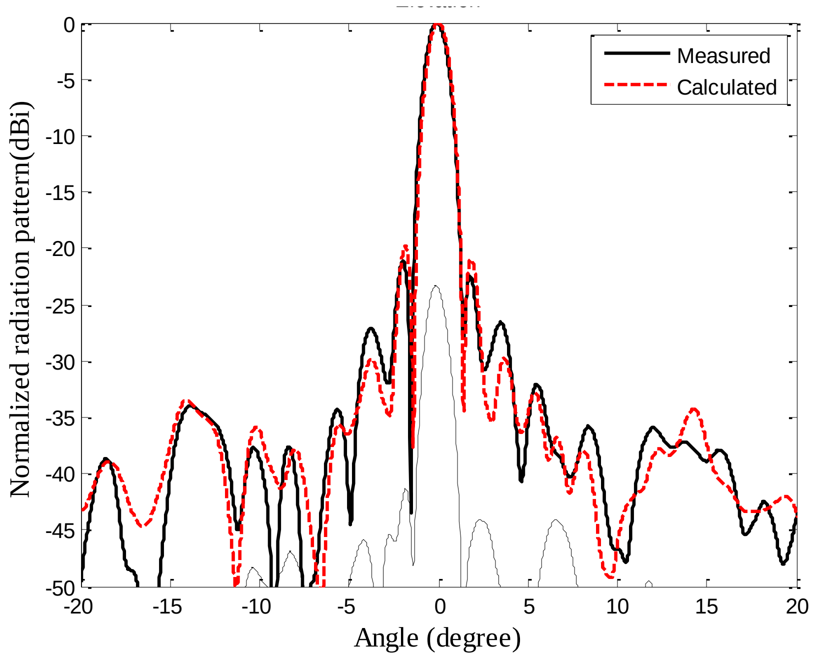
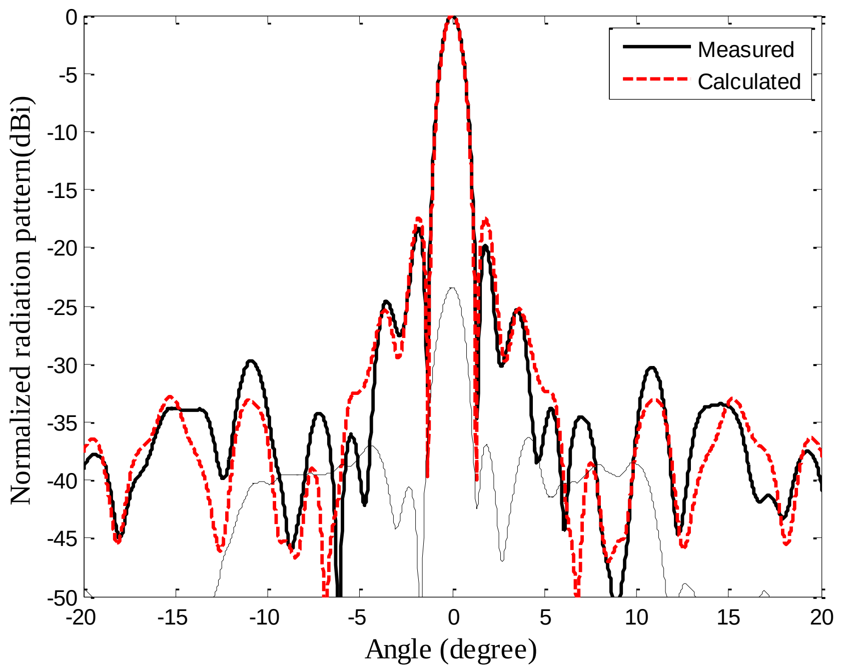
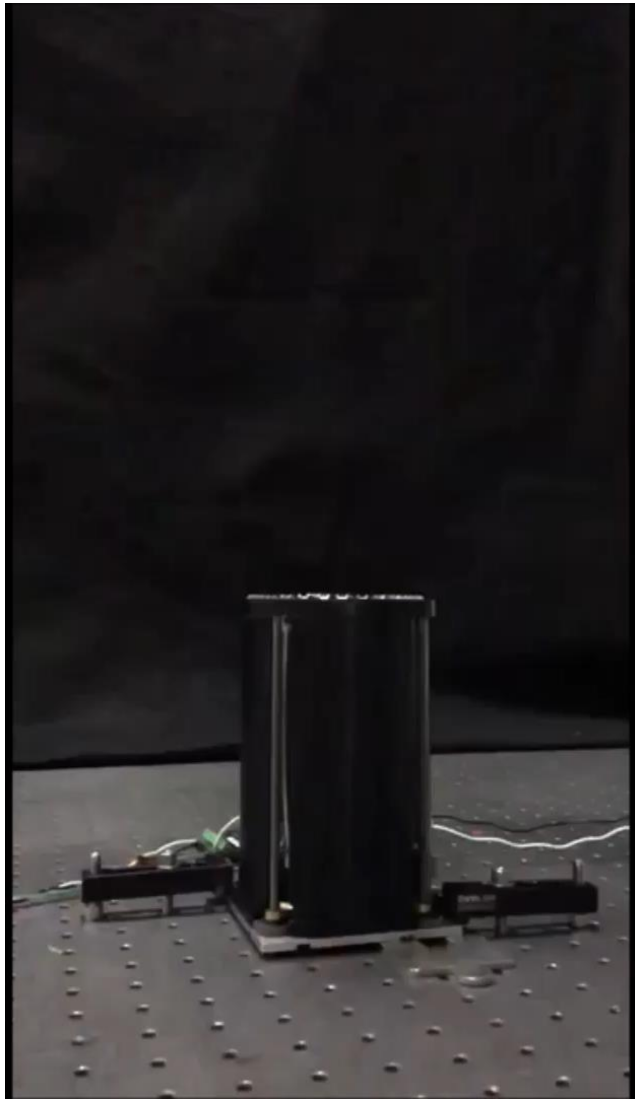
Raincube – Radar in a CubeSat

- Calculated vs Measured results







	Directivity (dBi)		Gain (dBi)		Loss (dB)*		Peak SLL (dB)	
	Calc.	Meas.	Calc.	Meas.	Calc.	Meas.	Calc.	Meas.
Solid	43.6	43.55	43.3	43.24	0.3	0.31	-17.45	-17.75
Mesh	-	43.28	42.61	42.48	-	0.8	-16.8	-18.33

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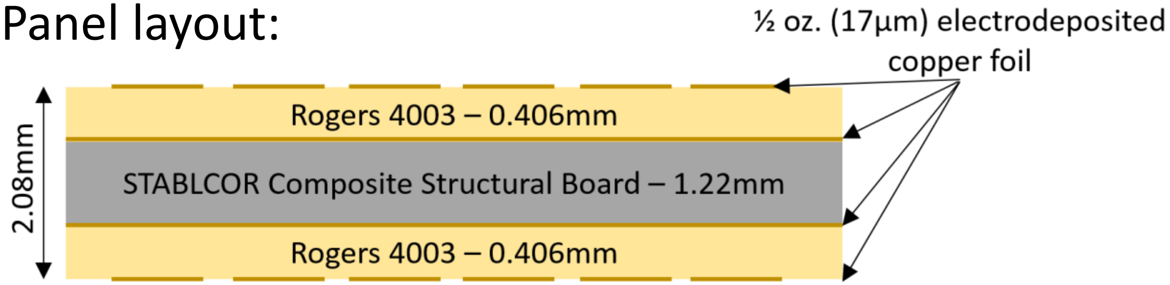
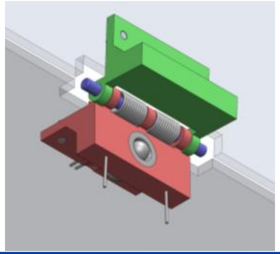
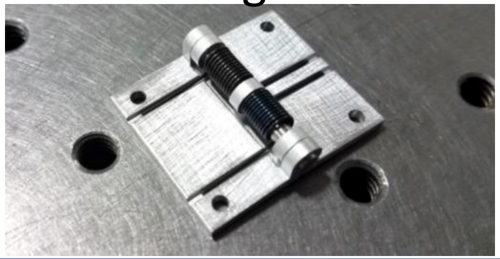
OMERA

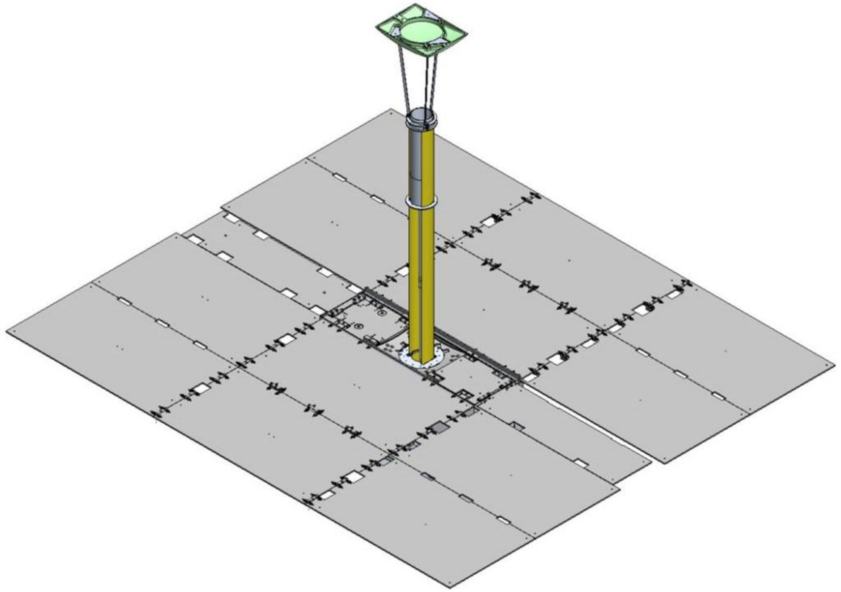
- On-going JPL's technology development
- Largest Ka-band deployable antenna for 6U CubeSat
  - Frequency: 35.75GHz
  - Polarization: linear
  - Dimensions: 1049.2mm × 922.5mm
- Deployable reflectarray antenna with 14 deployable panels
- Panel layout:

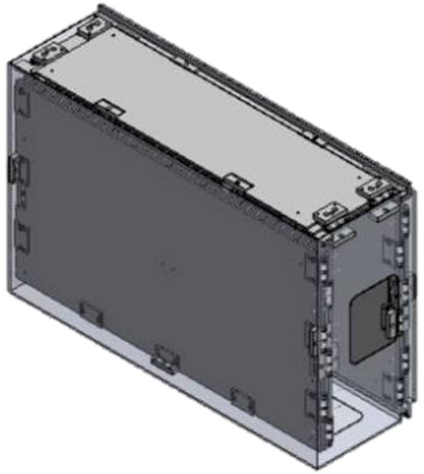


- Adjustable custom-made hinges to meet the deployment accuracy of ±0.04degree



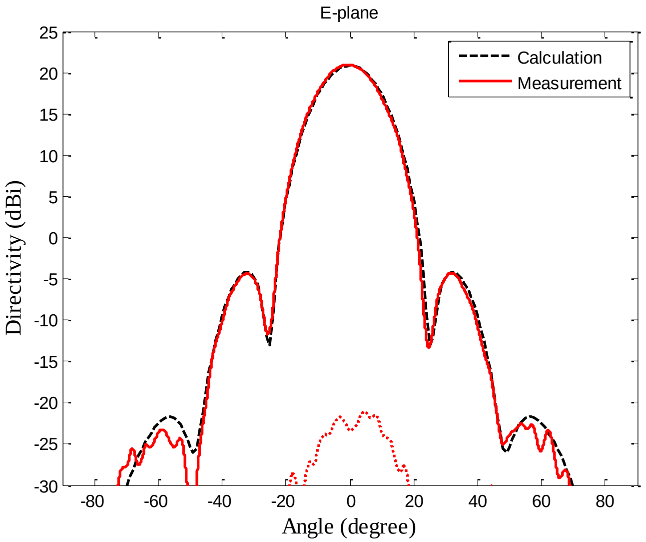


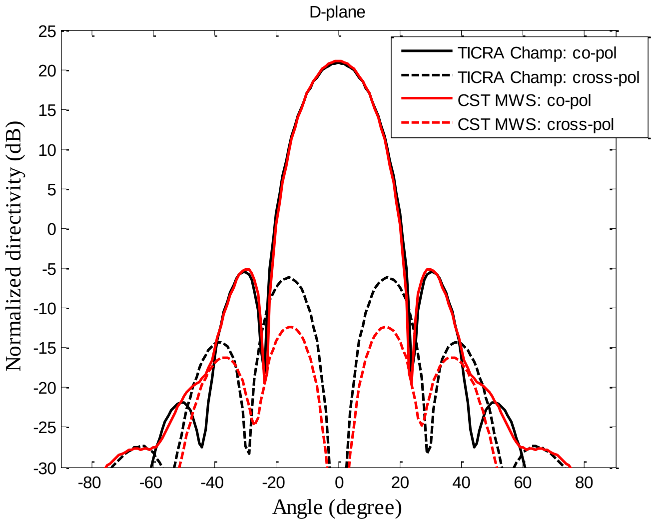


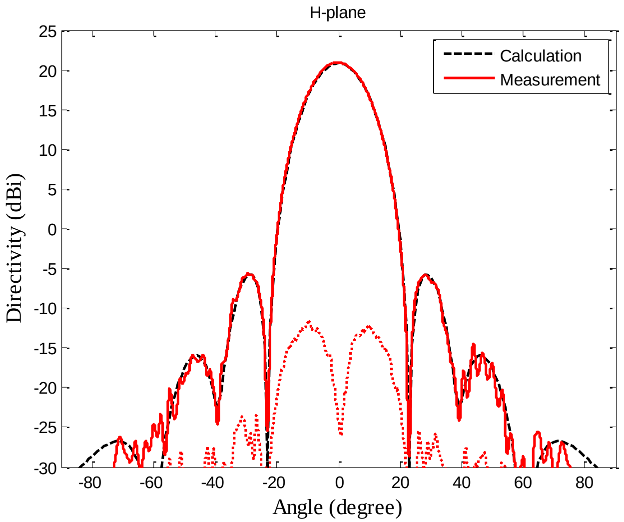


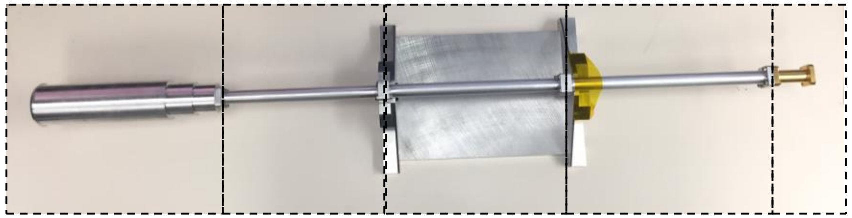
OMERA

- Characterization of feed RF performance with its three telescoping waveguides







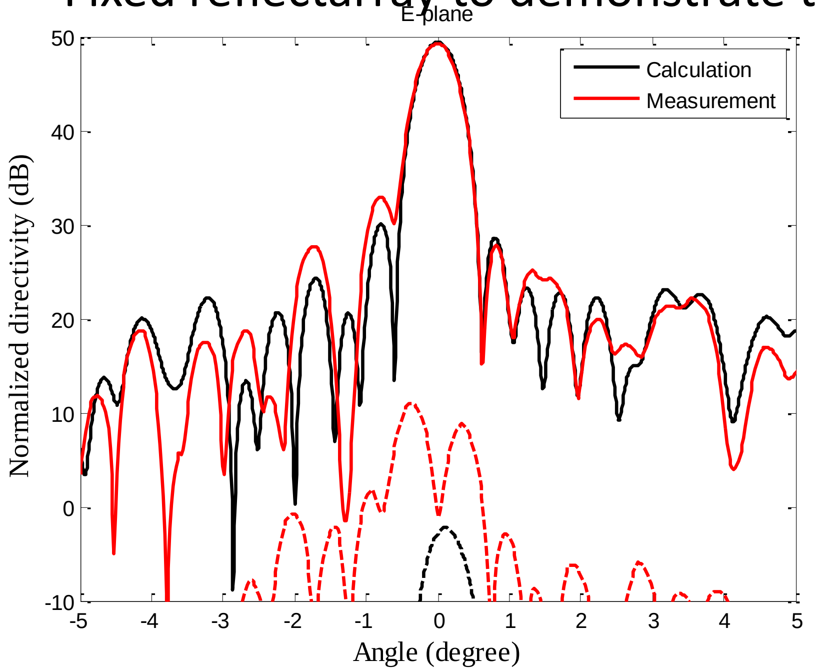


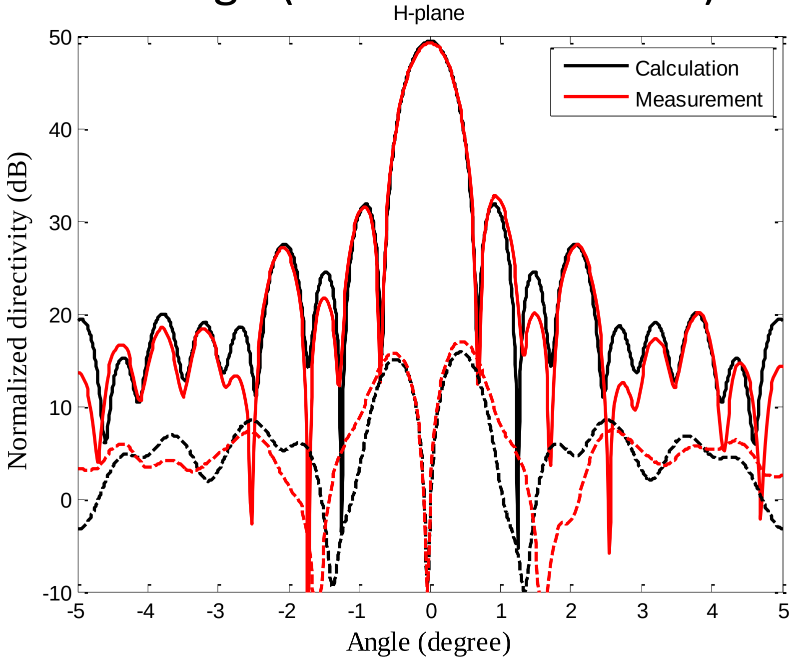
Horn Wg1 Wg2 Wg3 Transition Rect-to-Circ

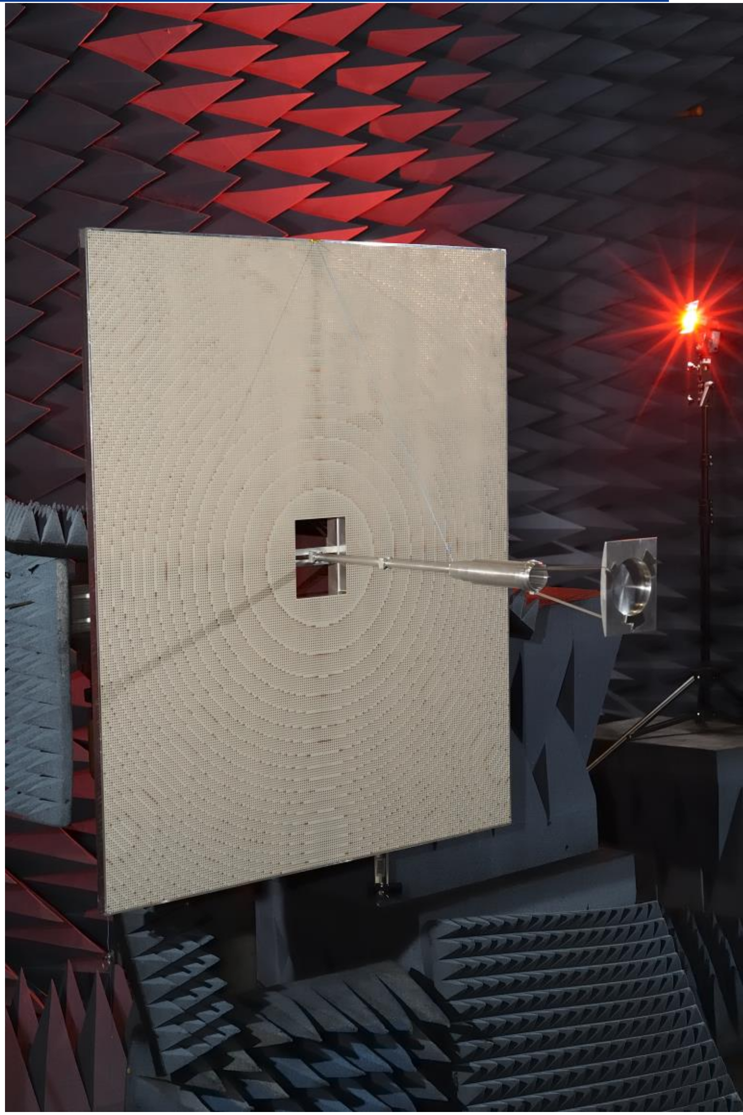
	Directivity (dBi)	Gain (dBi)
Calc.	20.82	20.52
Meas.	20.95	20.4

OMERA

- Fixed reflectarray to demonstrate the RF design (size: 98.4 x 81.8cm)





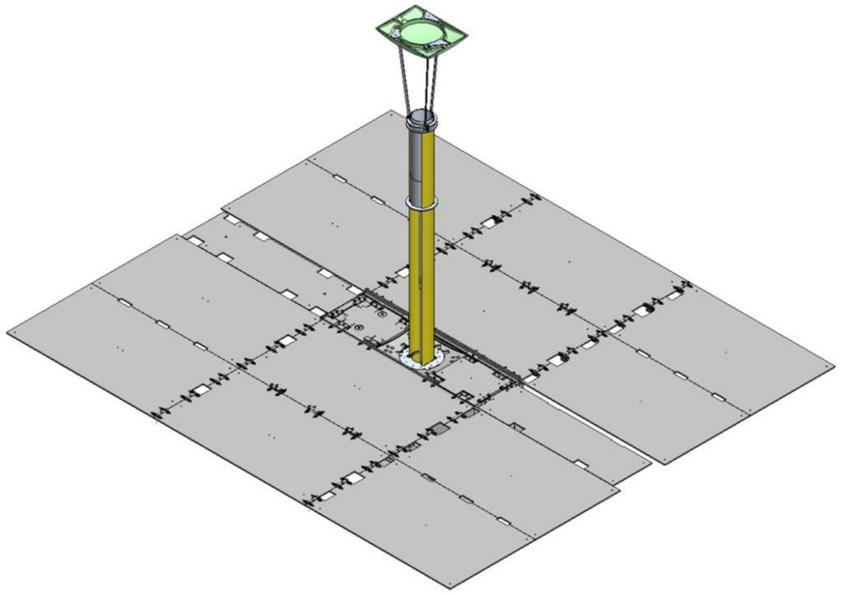


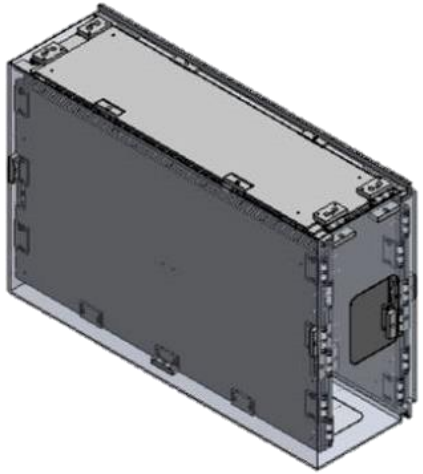
	Directivity (dBi)		Gain (dBi)		Loss (dB)*		Efficiency (%)	
	Calc.	Meas.	Calc.	Meas.	Calc.	Meas.	Calc.	Meas.
Fixed	49.28	49.27	48.31	48.5	0.97	0.77	47.10	49.20

OMERA

- Calculated performance of the deployable reflectarray
  - Directivity: 51.6dBi
  - Gain: 47.75dBi
  - Efficiency: 41.4%

	Gain (dBi)	Loss (dB)
Ideal directivity	51.58	-
Spillover	50.67	0.91
Taper	49.95	0.72
Blockage	49.67	0.28
Struts	49.27	0.4
Gap loss	**49.12**	**0.15**
Patch dielectric / conductivity loss	48.87	0.25
Surface accuracy (±0.2mm)*	**48.47**	**0.4**
Angle deployment accuracy	**48.14**	**0.33**
Feed loss / telescoping waveguide / transition	47.84	0.3
Feed mismatch (RL=17dB)	47.75	0.09
Overall performance	**47.75**	3.75





OMERA

- **Panel deployment demonstration**
  - The test is made using aluminum panels and only one side is tested
  - Accurate deployment will be made using the reflectarray panels and measurements of surface accuracy will be made.
  - The hinges can be adjusted to obtain requested surface flatness

- **Feed deployment demonstration**
  - The feed uses three telescoping waveguide
  - The horn is a multiflare horn
  - The subreflector is maintained in place using three struts
  - The deployment is performed using two tapes controlled by a motorized system

- **On-going exciting work!!**

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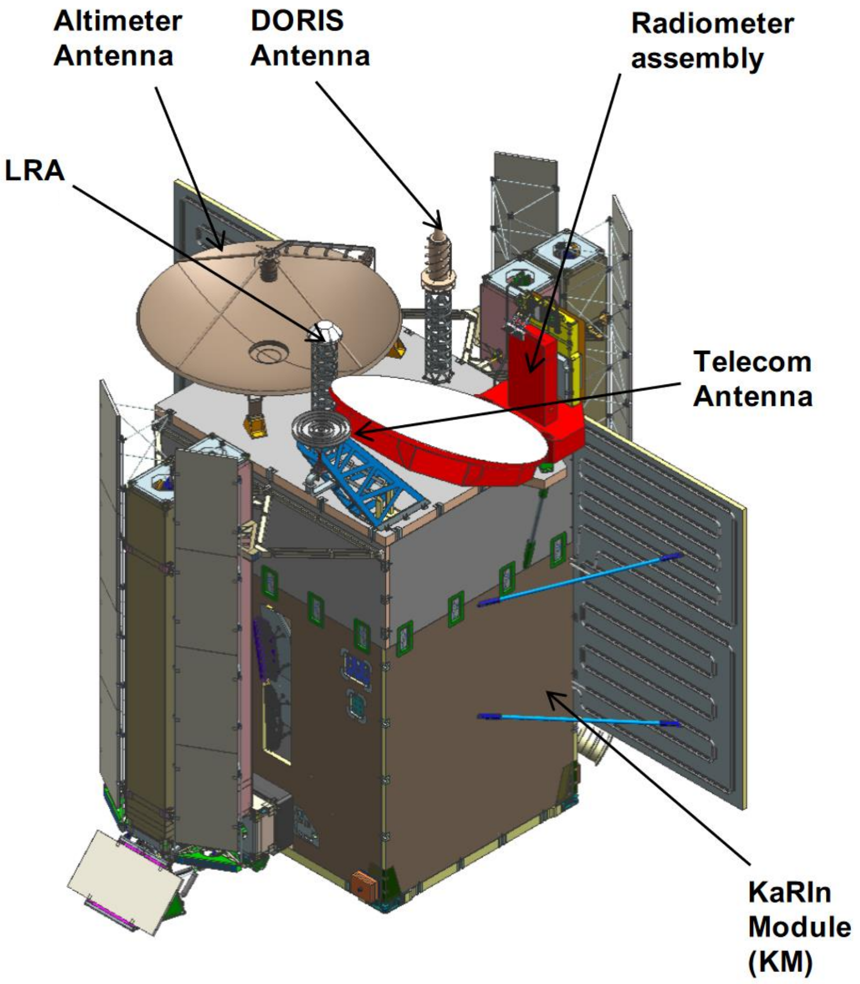
SWOT

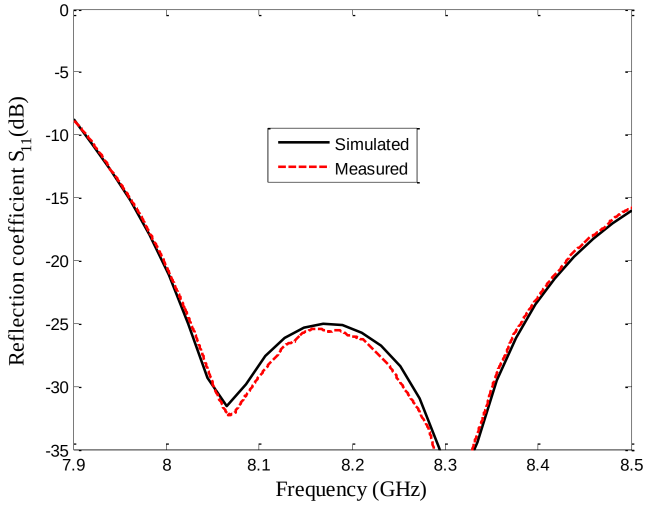


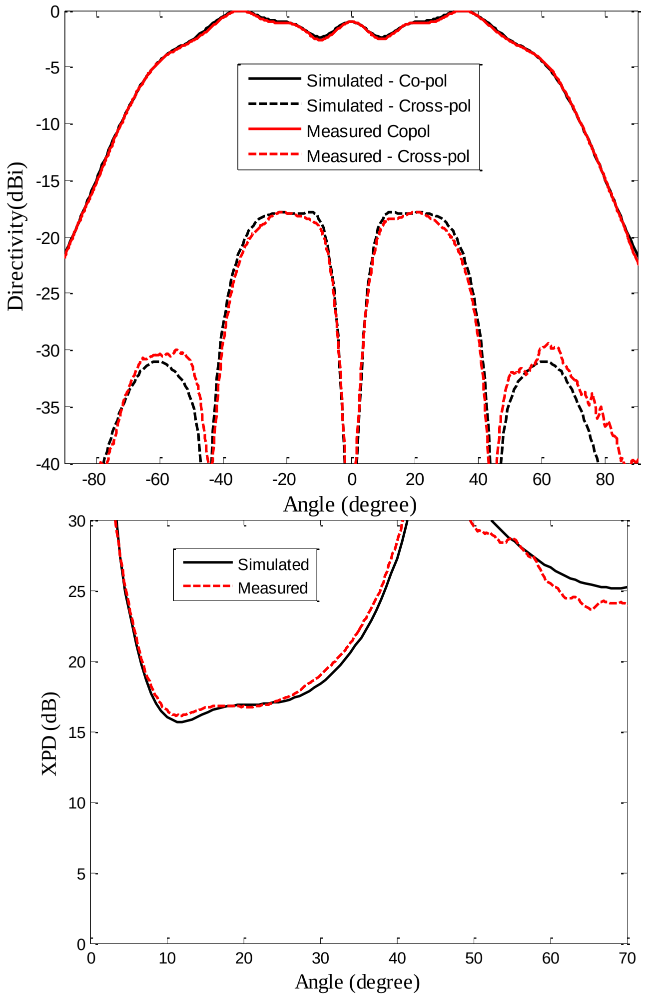
- SWOT telecommunication scheme uses dual polarization link (RHCP and LHCP) within 8.025-8.4GHz
- The crowded nadir deck causes multipath and cross-polarization loss
- We designed an antenna to adequately mitigate cross-polarization and multipath loss
    - ➔ Excellent XPD (>20dB) at 60degree off-boresight is required to minimize cross-polarization loss
    - ➔ Rapid roll-off is required to mitigate multipath (backward radiation <-15dB)
- Solution is an in-house choke ring horn antenna

Pre-Decisional Information – For Planning and Discussion Purposes Only

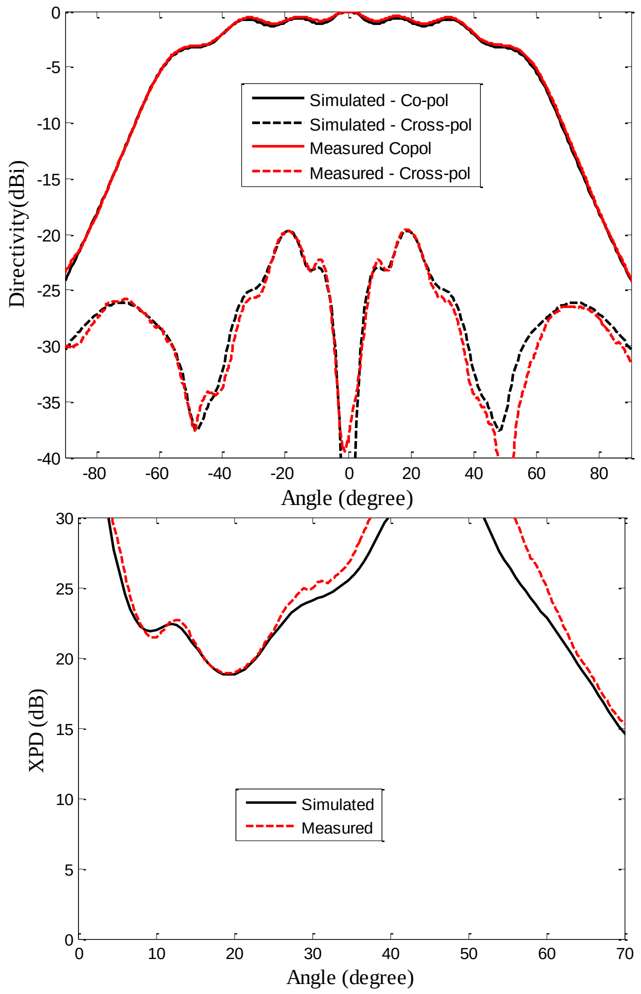
SWOT

- **Choke ring horn antenna RF performance in free space:**
  - The performance were first optimized in free space in terms of reflection coefficient and radiation pattern (gain and XPD)
  - Excellent agreement between calculation and simulation was obtained.





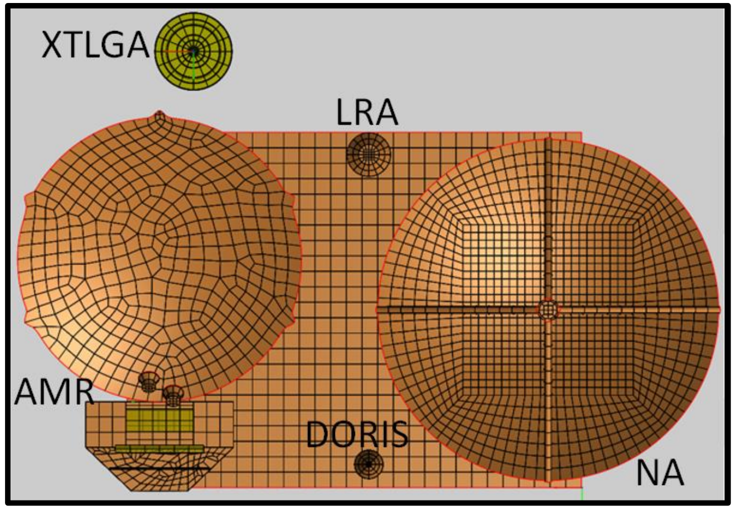
f = 8.025GHz



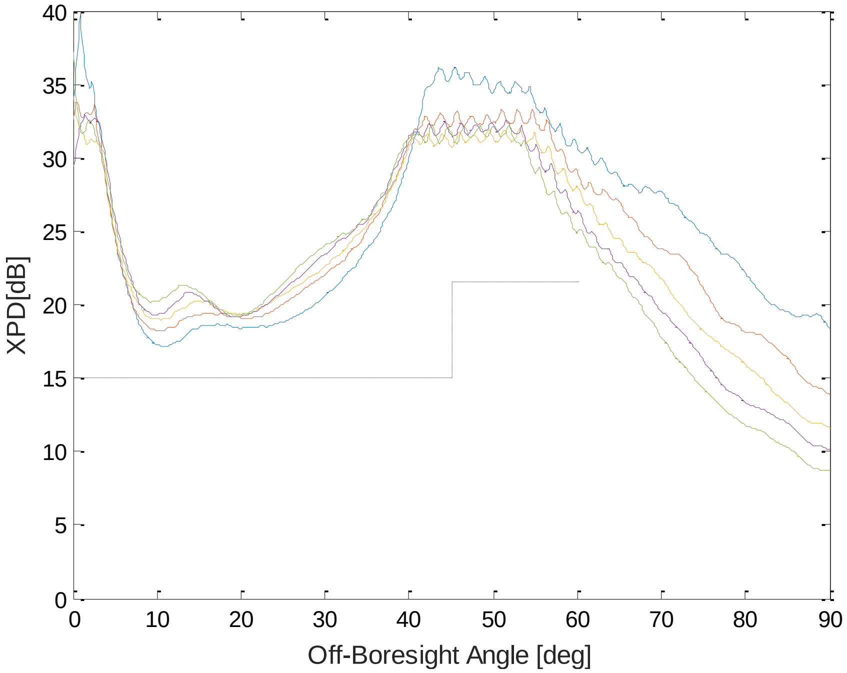
f = 8.4GHz

SWOT

- **Choke ring horn antenna RF performance on the Nadir deck:**
  - The performance were first verified on the spacecraft to validate multipath mitigation using MoM MLFMM.
  - Performance over temperature range were also assessed analytically.
  - Gain is very stable (~±0.3dB). XPD requirement is met.



GRASP model of the nadir deck



f = 8.025GHz to 8.4GHz

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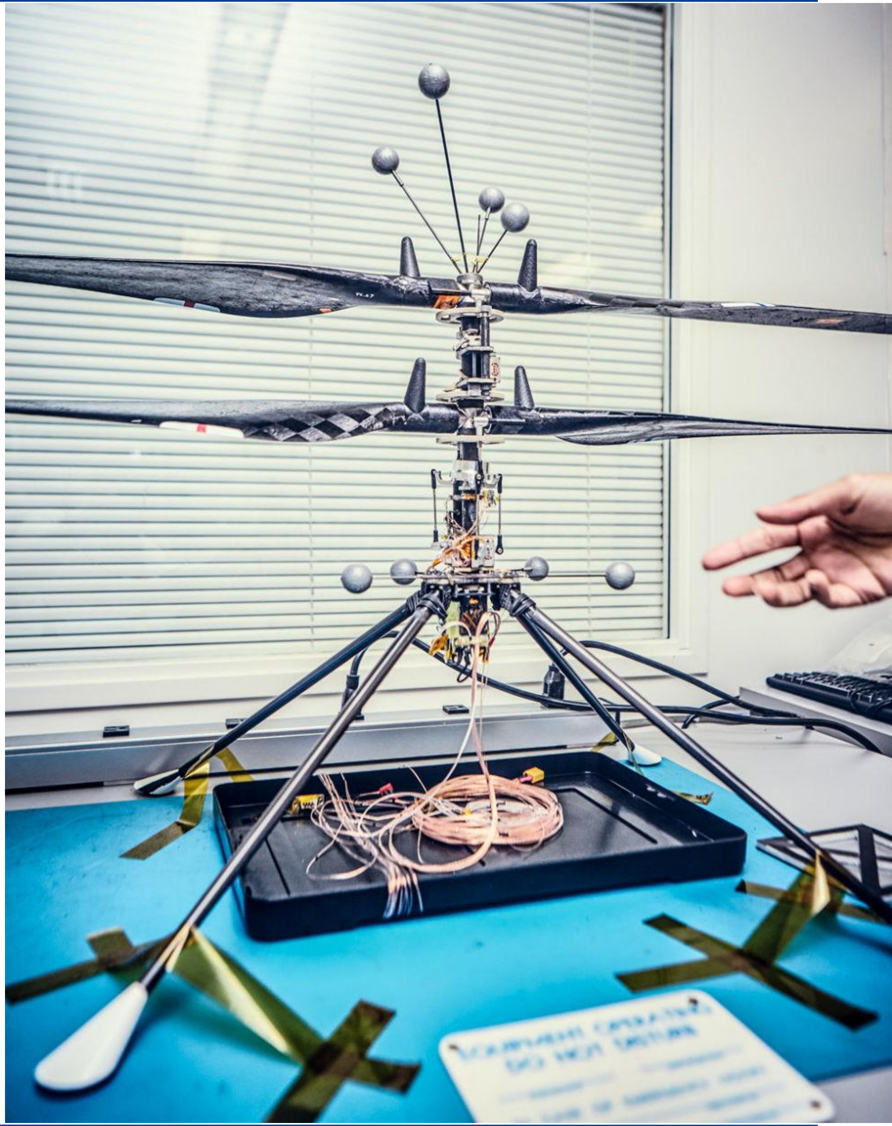
Mars Helicopter (mission concept)

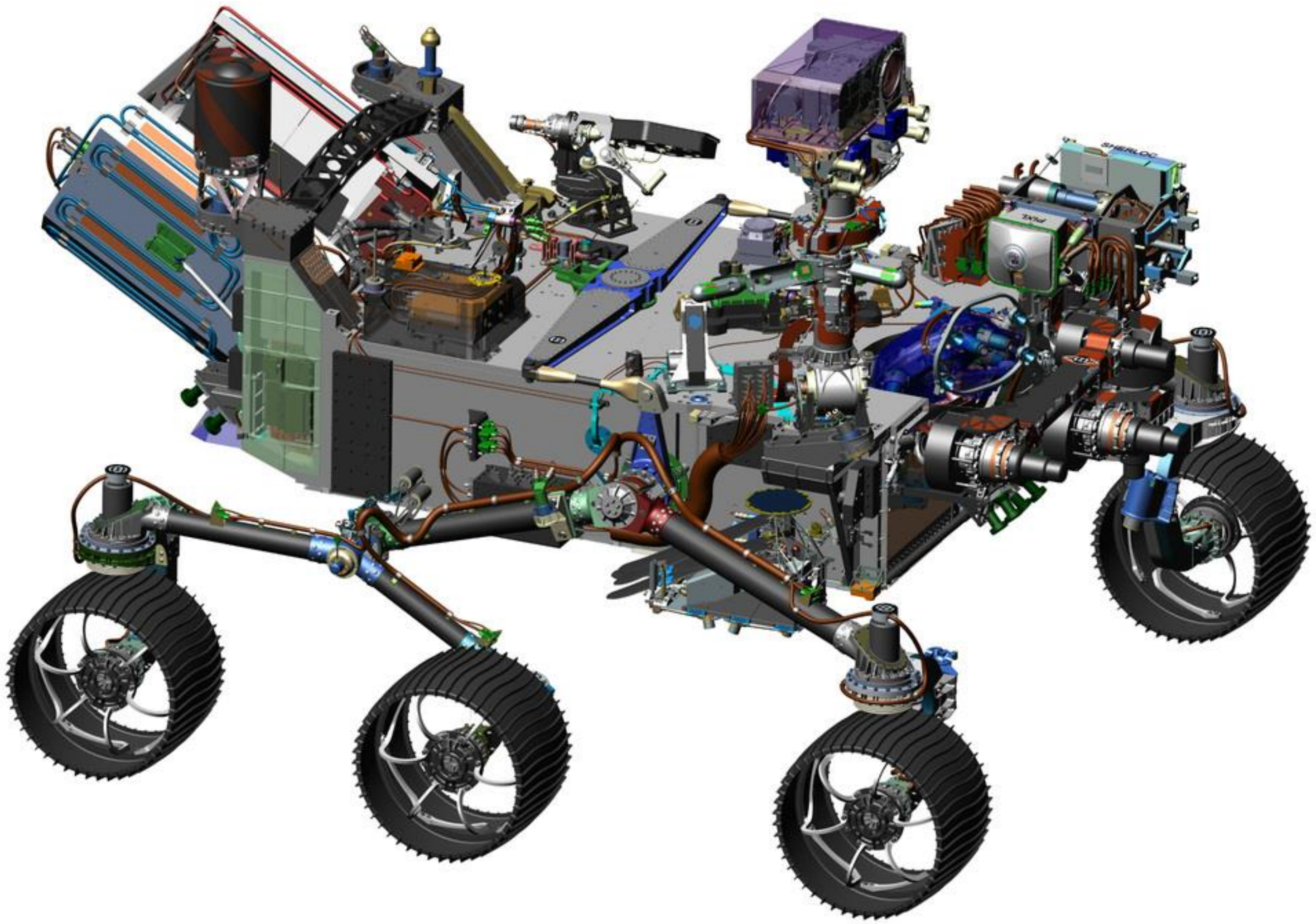
- **Nominal flights**
  - 2-3 minute duration
  - 600 meter range
  - 40 meter above ground
  - Up to one flight per sol
- **High-resolution colors images of terrain**
- **Helicopter**
  - Rotor blades: 1.1meter diameter
  - Blade speed: 2600 rpm (vs 400 to 650 rpm on Earth)
  - Chassis: 14cm × 14cm × 14cm
  - Max mass: ~1.4kg
  - Power ~220W (solar cells)
- **Fully autonomous:**
  - Using gyroscope accelerometer, a camera, an altimeter, and on-board computer
- **Telecommunication:**
  - Transmit data from helicopter to interface box on Rover
  - During flight but primarily while landed



Mars Helicopter (mission concept)

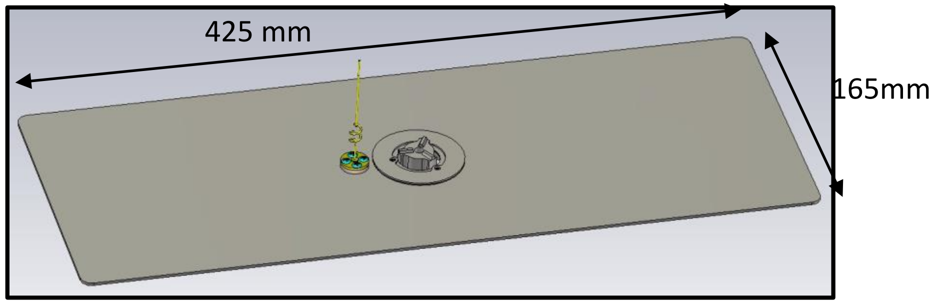
- Frequency: 914MHz

Mars Helicopter (mission concept)

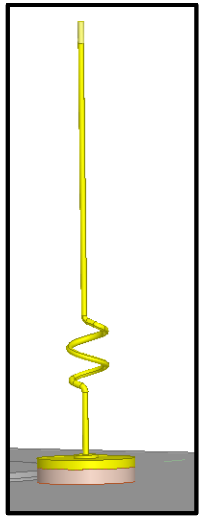


Mars Helicopter (mission concept)

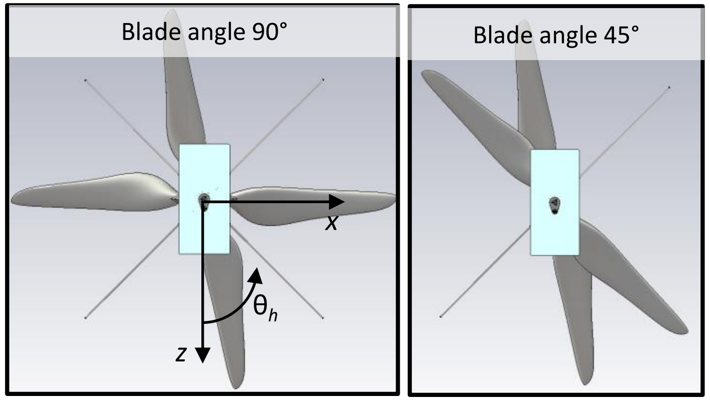
- **Antenna on Helicopter:**



Helicopter antenna on its solar panel

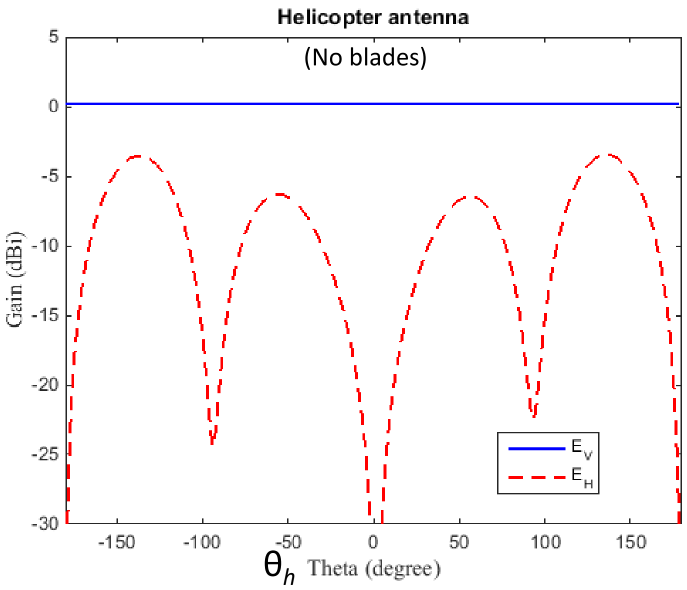


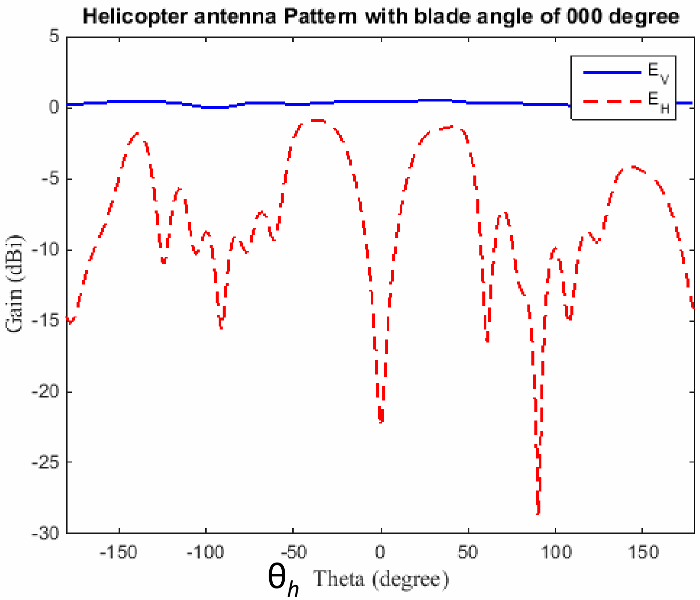
Antenna design



Helicopter antenna on its solar panel (includes blades)

HBA radiation pattern

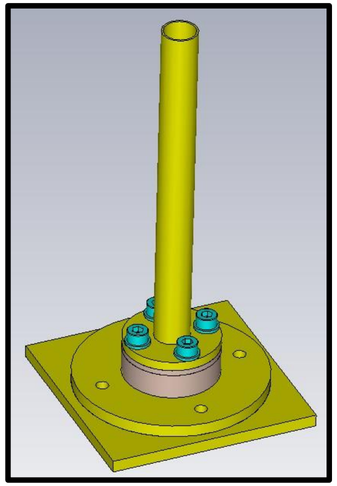




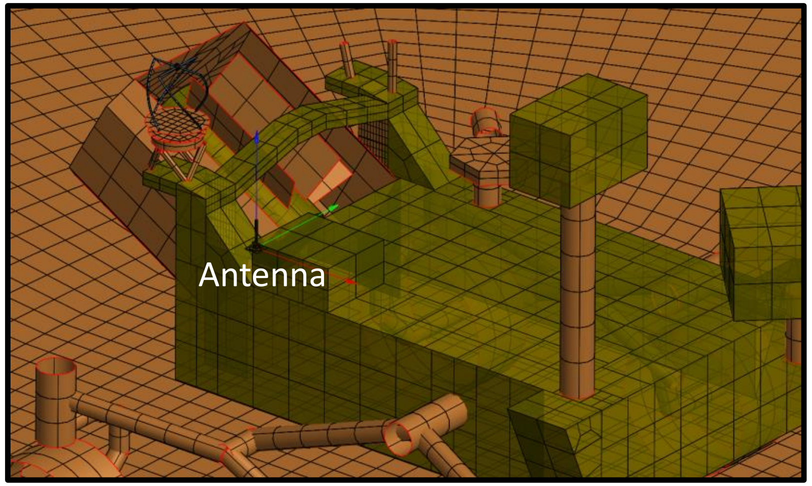
- The blades are made of carbon fiber and are therefore reflective surfaces.
- The cross-polarization component varies as the blades rotates. This needs to be taken into account as it will affect the polarization loss.

Mars Helicopter (mission concept)

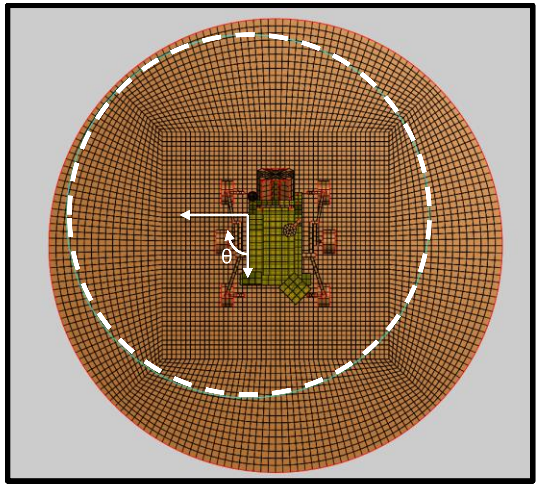
- **Antenna on Rover:**



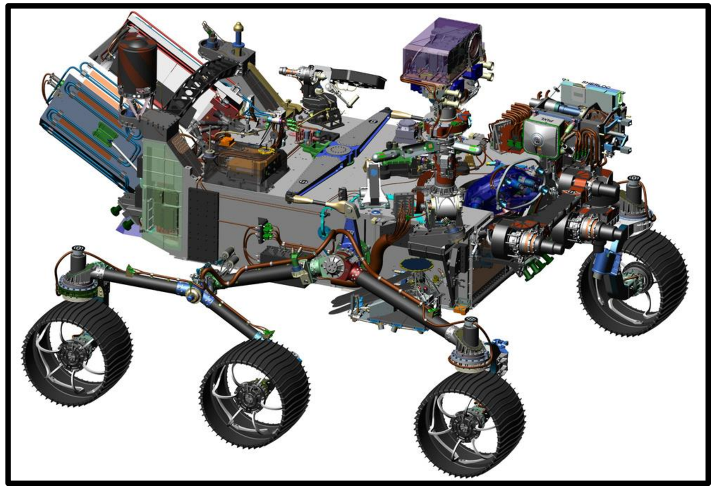
Antenna design



Antenna on M2020 Rover

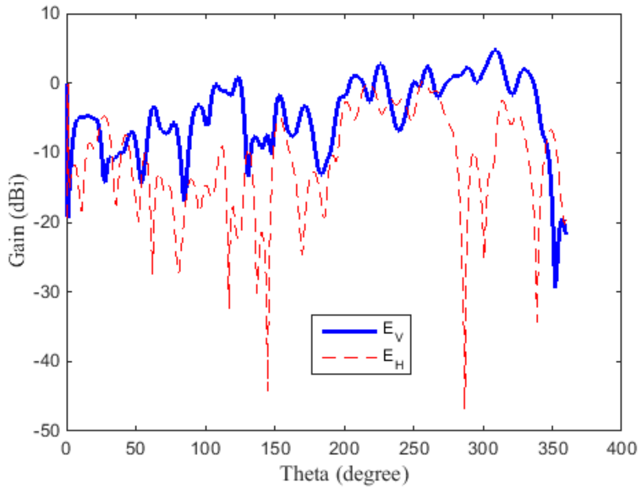


Coordinate system



Potential candidate

Helicopter Base Station Antenna (HBA) radiation pattern



Interpretation of results:

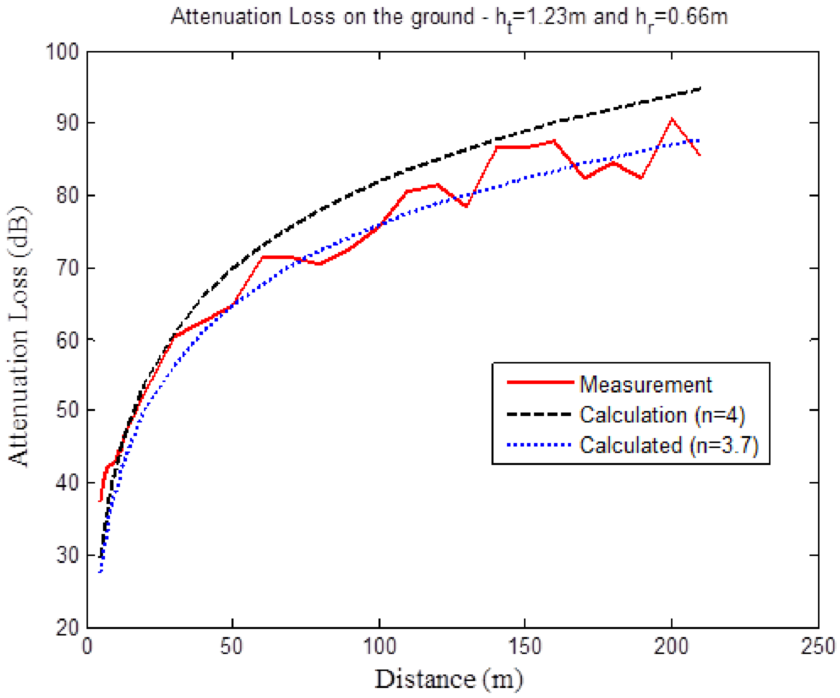
- Shadowing effects
- Multipath (reflections)
- Suffers from a very small ground plane
- Larger ground plane and/or location would improve the result

Mars Helicopter (mission concept)

Propagation loss:

The permittivity of the Mars surface is well known but Bullington has shown that for a large distance and a flat surface, the propagation, between two antennas at heights h_t and h_r, is independent from the ground permittivity. The total path loss for a surface communications link can be calculated as: $L_{FG} \equiv -10\log_{10} \ell_{FG}(d) = -20\log_{10}(h_t h_r) + 40\log_{10} d$

Validation:



Next step:

Measuring the link using a Rover Mockup and Helicopter using the EM antennas and radios. Shadowing from the Rover will be accounted for.

K. Bullington, "Radio Propagation Fundamentals," The Bell System Technical Journal, Vol. XXXVI, no. 3, May 1937.

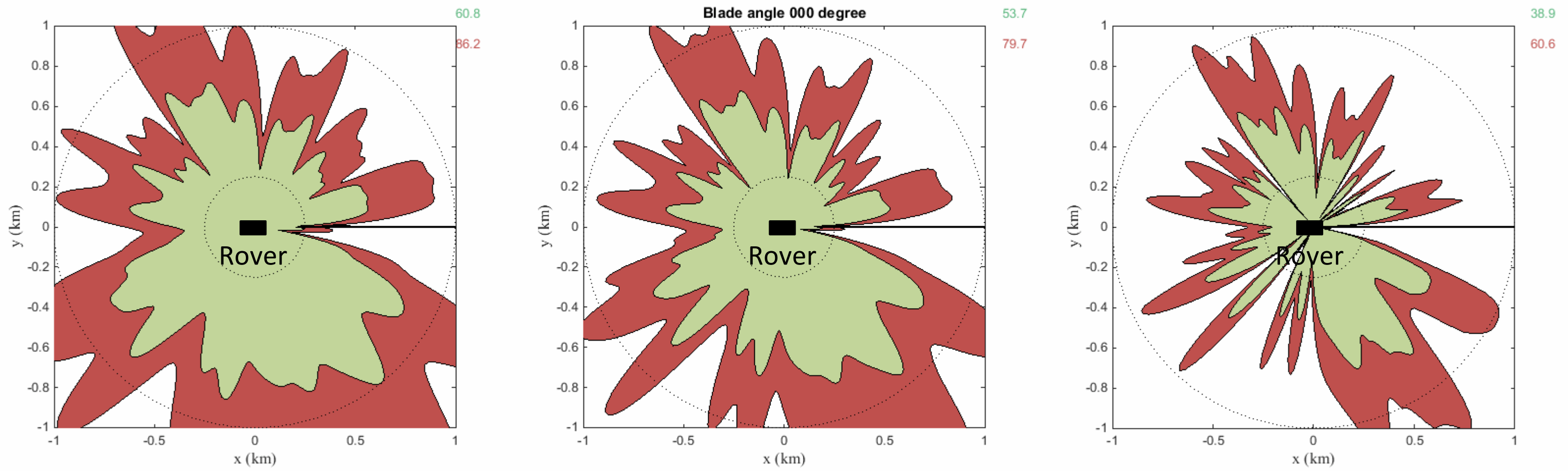
Mars Helicopter (mission concept)

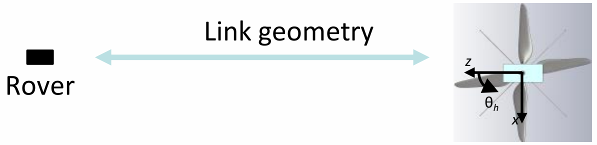
Propagation Link while helicopter is flying:

Map coverage assuming min, mean, max polarization loss with blade rotating.

The math is done for all azimuth angles around the helicopter.

These results were obtained using **Bullington** with $\boldsymbol{h_t}$**=0.48m** and h_r=1.23m.





Azimuth angle θ_h = [0°-359°]

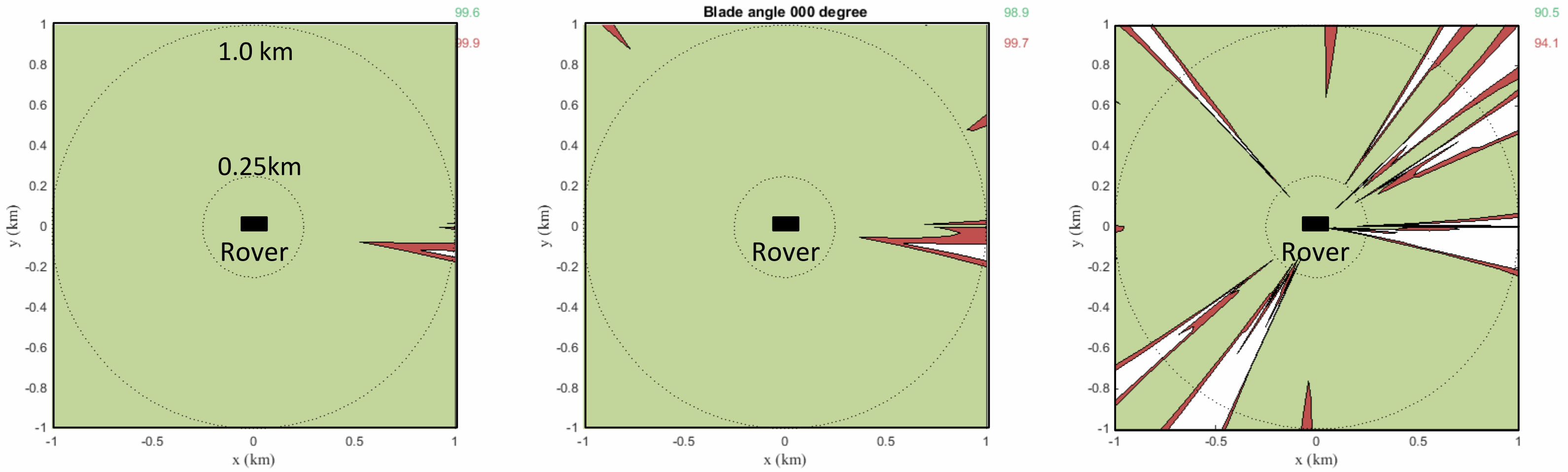
Received power of >-94dBm ⬄ 250kbps (no margin) – 40kbps (8dB margin)

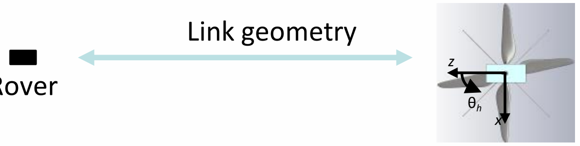
Received power of [-102, -94] dBm ⬄ 40kbps (no margin)

Mars Helicopter (mission concept)

Propagation Link while helicopter is flying:

Map coverage assuming min, mean, max polarization loss with blade rotating.
The math is done for all azimuth angles around the helicopter.
These results were obtained using **Bullington** with $\boldsymbol{h_t}$**=10m**, h_r=1.23m, and Req = [0.25 - 1] km.





Azimuth angle θ_h = [0°-359°]

Received power of >-94dBm ⬄ 250kbps

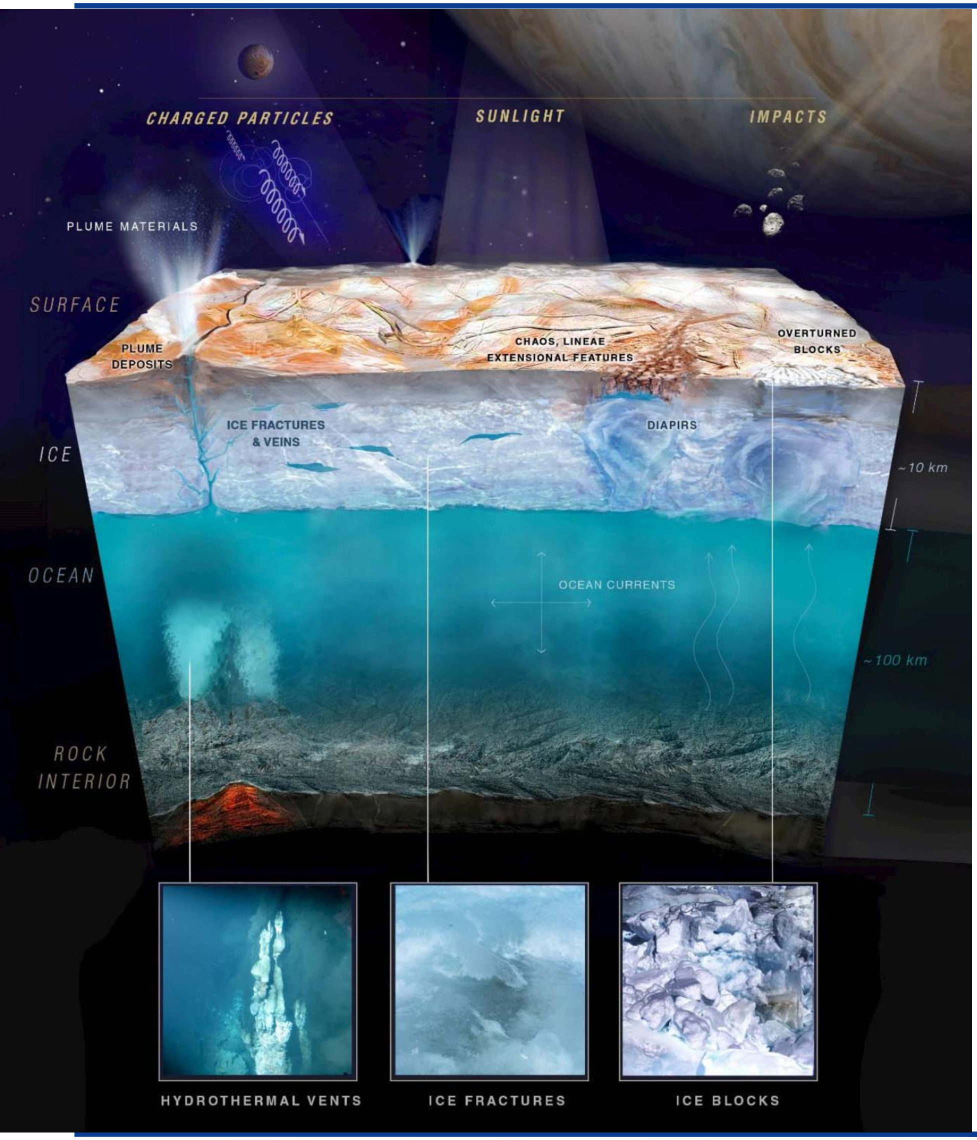
Received power of [-102, -94] dBm ⬄ 40kbps

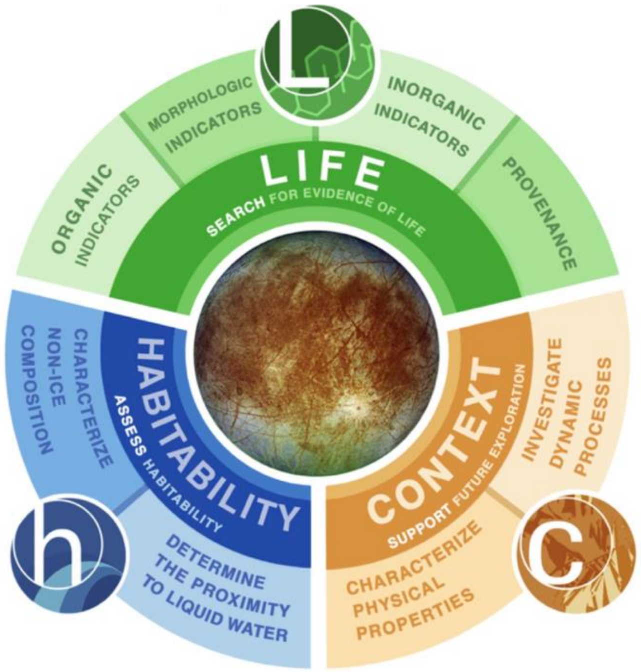
No link

Outline

- Innovative Deployable CubeSat Antennas
  - Mars Cube One (MarCO)
  - Raincube – Radar in a CubeSat
  - OMERA – One meter reflectarray
- SWOT
  - X-band Telecom for multipath mitigation
- The first Mars Helicopter – Antenna design and Telecommunication
  - Helicopter antenna
  - Mars Rover antenna
  - Link between Rover and Helicopter
- Europa Lander
  - Mission concept
  - Telecommunication antenna

Europa Lander (mission concept)



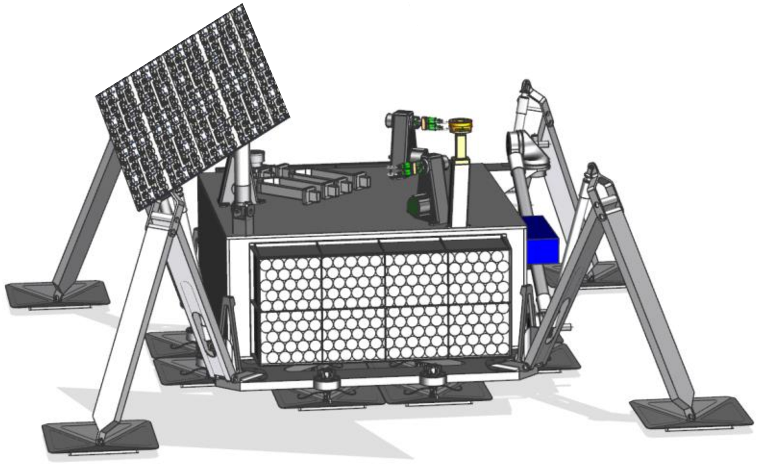


Pre-Decisional Information – For Planning and Discussion Purposes Only

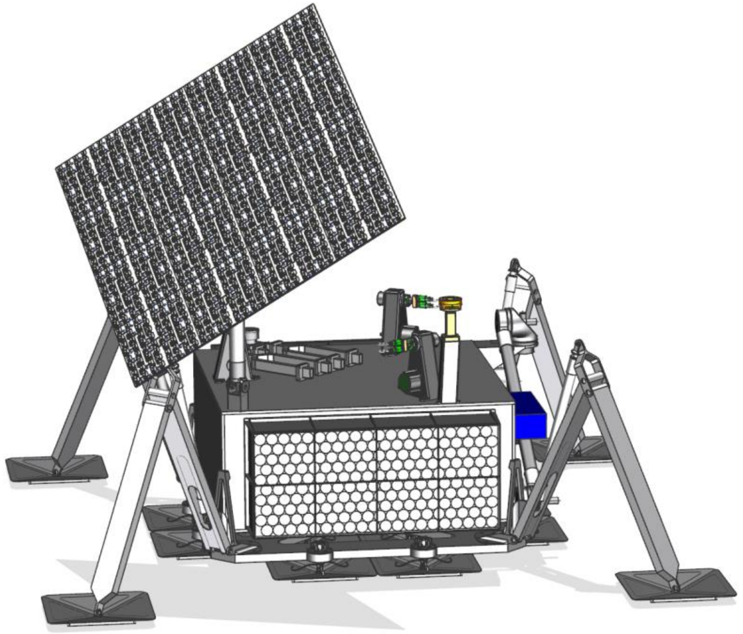
Europa Lander (mission concept)

New antenna concept:

- Meeting the drastic stowage volume constraints requiring the antenna to be flat
- Mostly made of aluminum to survive harsh environment (high radiation and wide range of temperature)
- Air strip line for high efficiency (>80%)
- Scalable design
- The building bloc is a 8x8 patch array
- 16x16 patch array consists of 4 building bloc interconnected by waveguides.



16x16 patch array

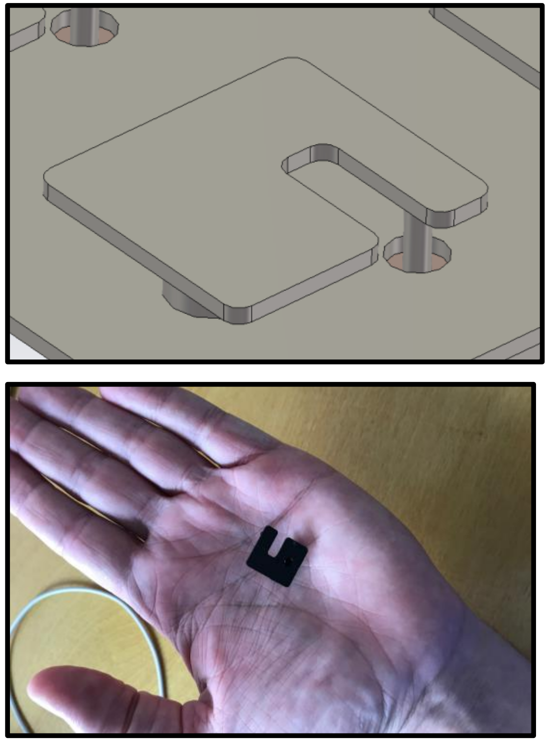


32x32 patch array

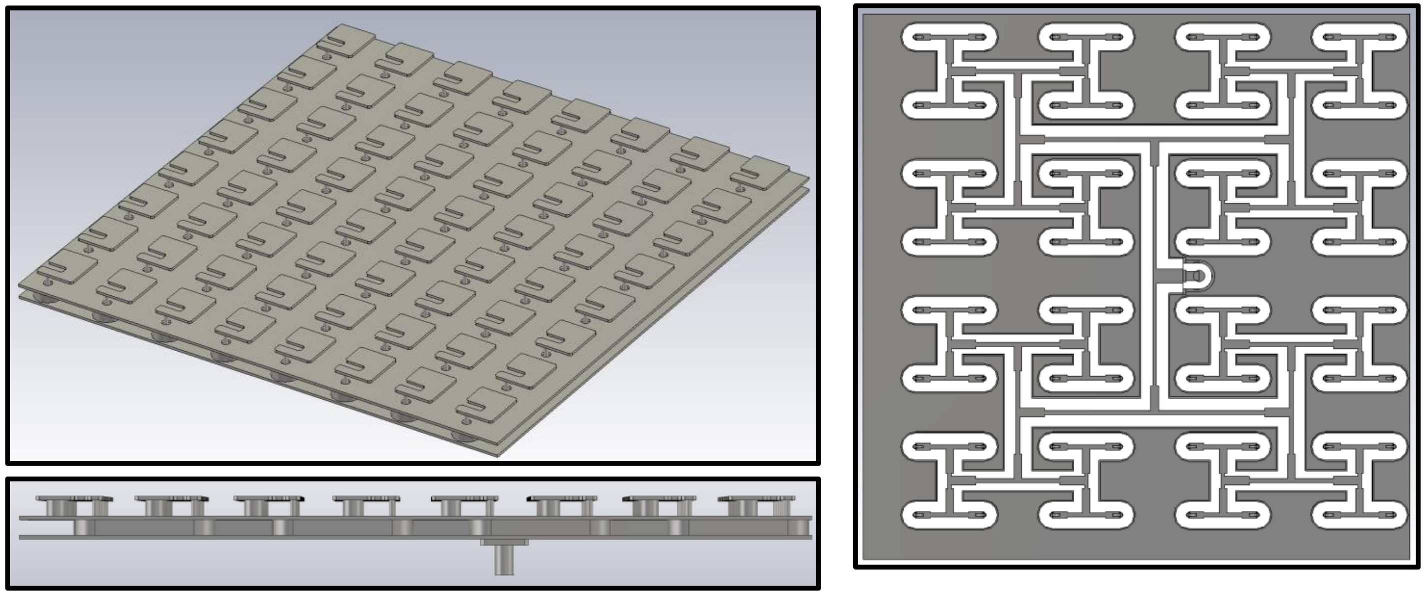
Europa Lander (mission concept)

Antenna demonstration:

- Single feed element covering both Uplink (7.145-7.19GHz) and Downlink (8.4-8.45GHz) DSN bands with RHCP polarization
- The radiating element has a single-fed point
- The building bloc (8x8 patch array) is shown below:



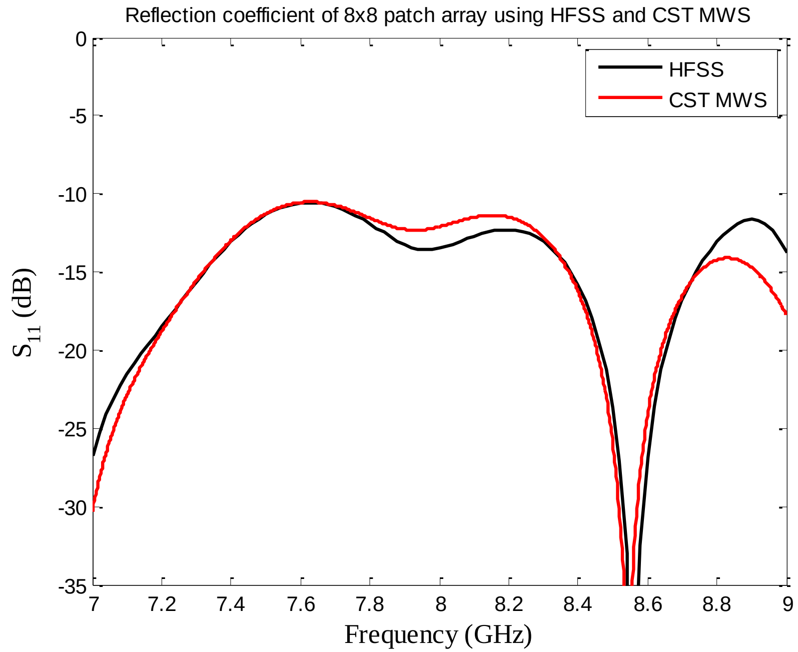
Single Element

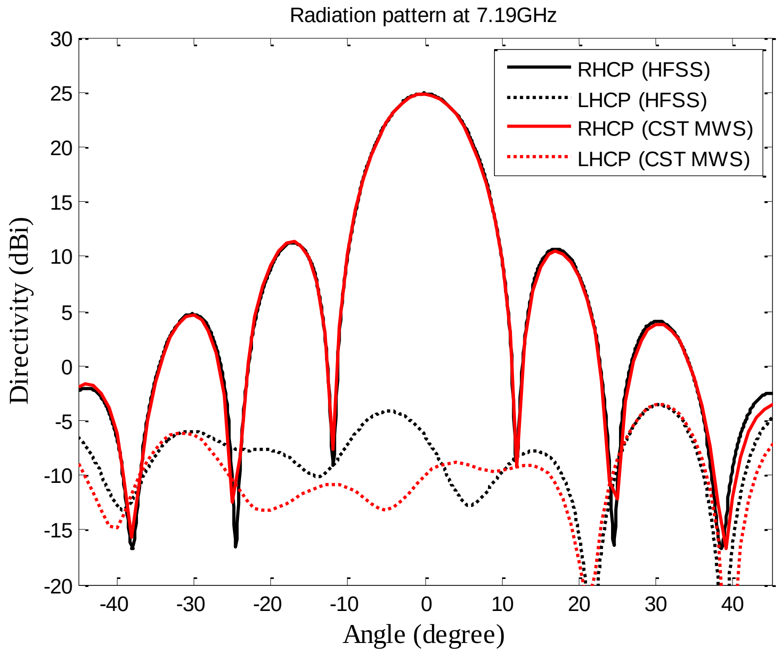


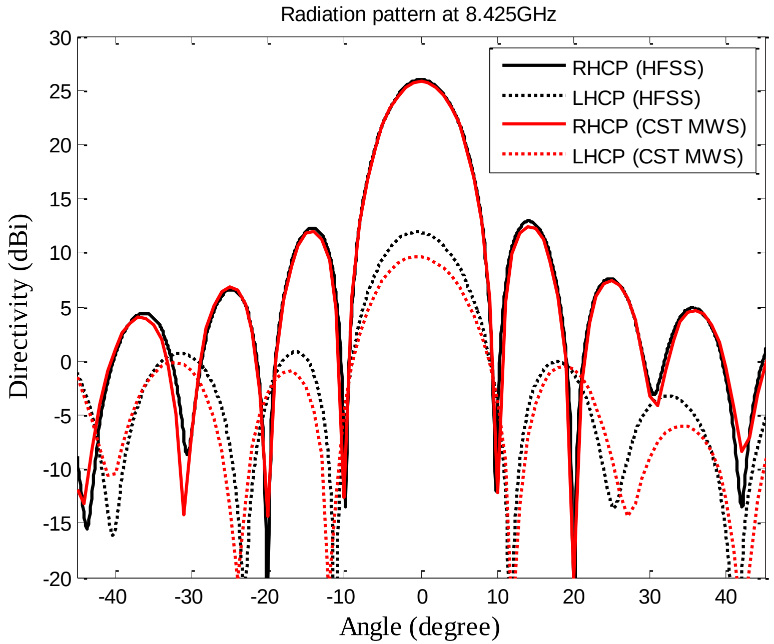
8×8 patch array

Europa Lander (mission concept)

Antenna demonstration:







	Directivity (dBi)		**Gain (dBi)**	
	CST MWS	HFSS	CST MWS	HFSS
7.19 GHz	24.8	24.9	24.6	24.8
8.425 GHz	25.9	26.0	25.6	25.9

➔ Fabrication on-going

Pre-Decisional Information – For Planning and Discussion Purposes Only

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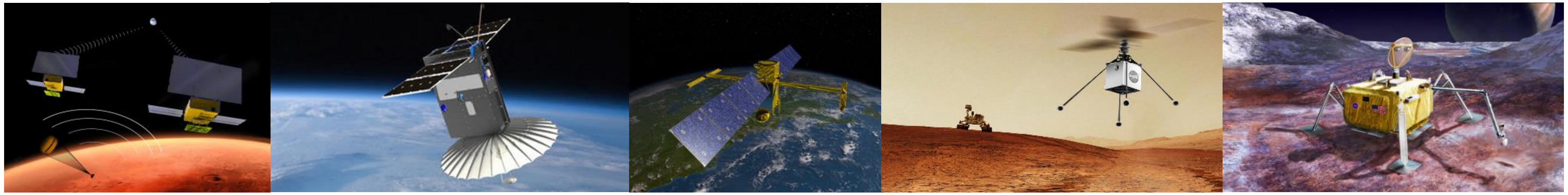

Acknowledgement:
This work was supported by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics of Space Administration.

Mars Helicopter (mission concept)

Polarization loss between two linear polarization:

- Both antenna shall ideally be vertically polarized
  - Not in practice: shadowing, multiple reflection, disturb the antenna radiation
  - Non perfectly linearly polarized antenna suffers from polarization loss
- Lets assume a receive antenna having the linear components:

$$E_r = E_h(\hat{x} + \hat{\rho}_{L1}\hat{y}) = E_h\hat{x} + E_v\hat{y} \qquad \hat{\rho}_{L1} = E_v / E_h$$

Note that in our coordinate system, if perfectly vertically polarized: $\rho_{L1} \rightarrow \infty$.

- The incident wave on the antenna is given by

$$E_i = E_{h2}(\hat{x} + \hat{\rho}_{L2}\hat{y}) = E_{h2}\hat{x} + E_{v2}\hat{y} \qquad \hat{\rho}_{L2} = E_{v2} / E_{h2}$$

Not that in our coordinate system, if perfectly vertically polarized: $\rho_{L2} \rightarrow \infty$.

- The polarization loss is express as:

$$\Gamma = 10 \cdot \log_{10}\left|\frac{E_i E_r^*}{|E_i|^2 |E_r|^2}\right| = 10 \cdot \log_{10}\left[\frac{1 + |\hat{\rho}_{L1}|^2 |\hat{\rho}_{L2}|^2 + 2|\hat{\rho}_{L1}||\hat{\rho}_{L2}|\cos(\delta_1 - \delta_2)}{(1 + |\hat{\rho}_{L1}|^2)(1 + |\hat{\rho}_{L2}|^2)}\right]$$

where δ_1 and δ_2 are the phases of the polarization ratios of the receive antenna and the incident wave. → we assume the worse case with $\delta_1 - \delta_2 = \pi$, best case $\delta_1 - \delta_2 = 0$.