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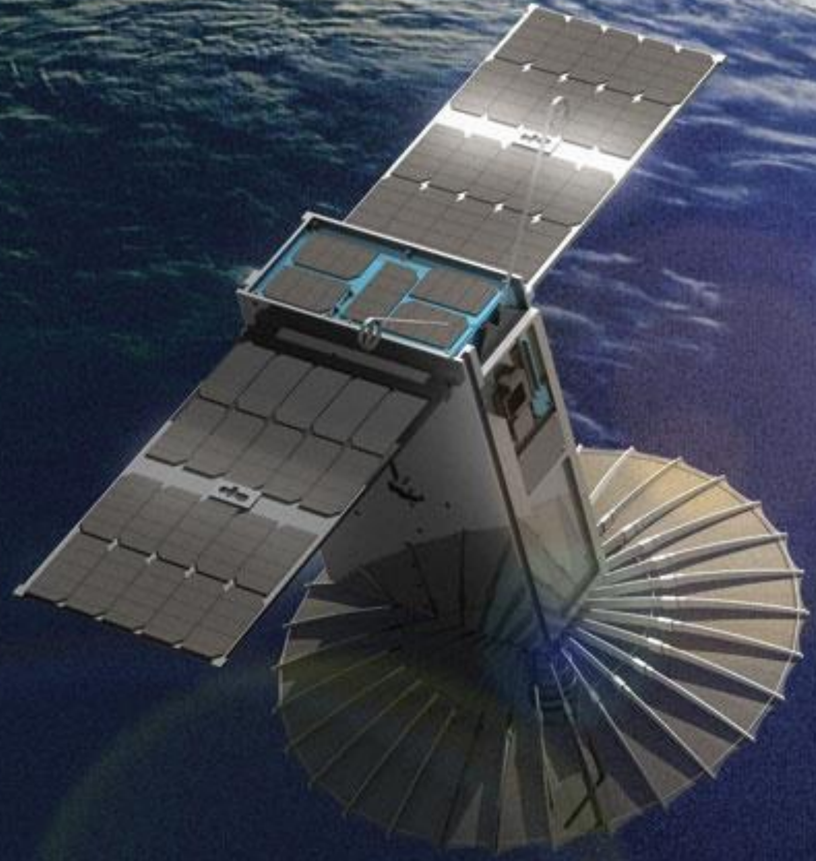


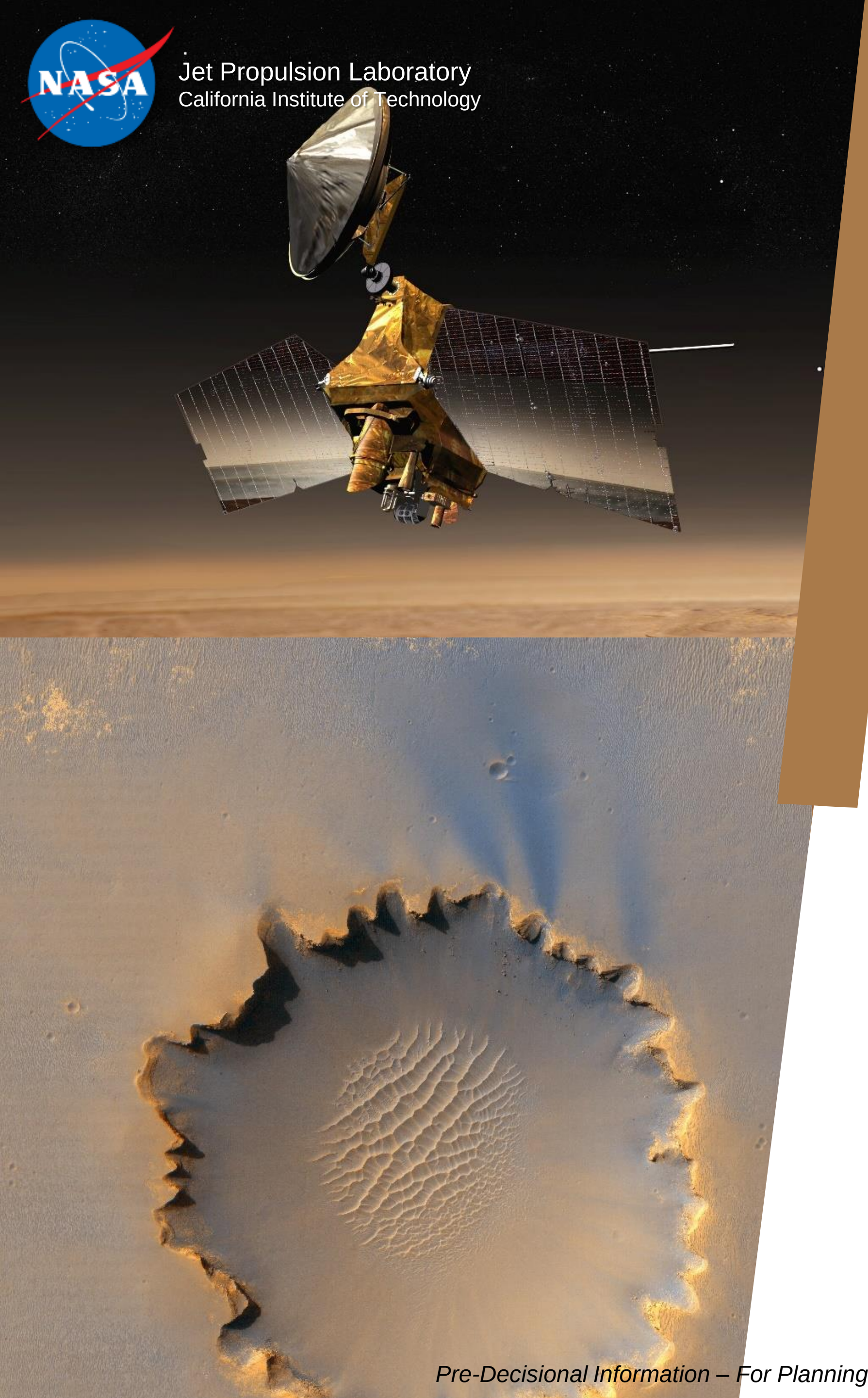
Mars Helicopter Communication Link and Innovative Antennas for Cubesats, Landers and Rovers

Nacer Chahat, Gaurangi Gupta
NASA Jet Propulsion Laboratory / California Institute of Technology

Jet Propulsion Laboratory
California Institute of Technology

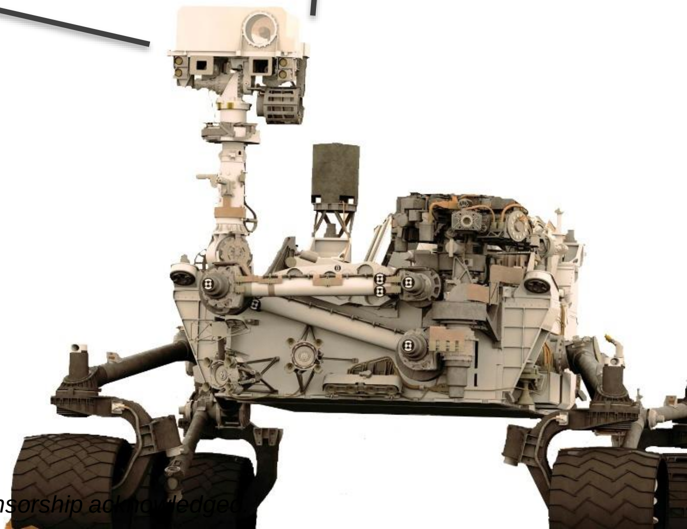
Artist's Concept

MARS HELICOPTER

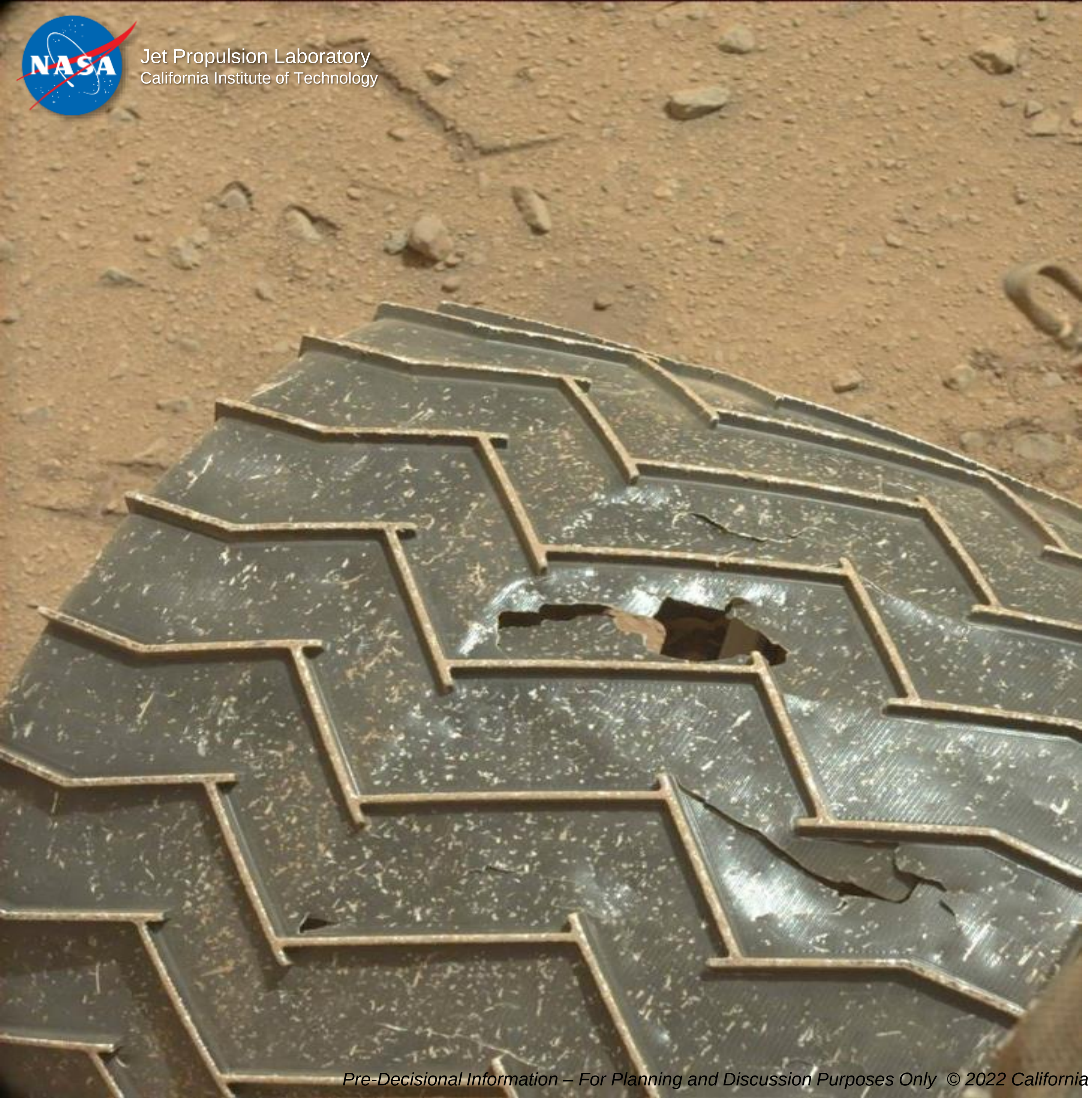


Satellites Orbiting Mars Provide Large Scale Maps of the Surface from an Altitude of 200 Miles, But Finer Features Are Not Detectable.

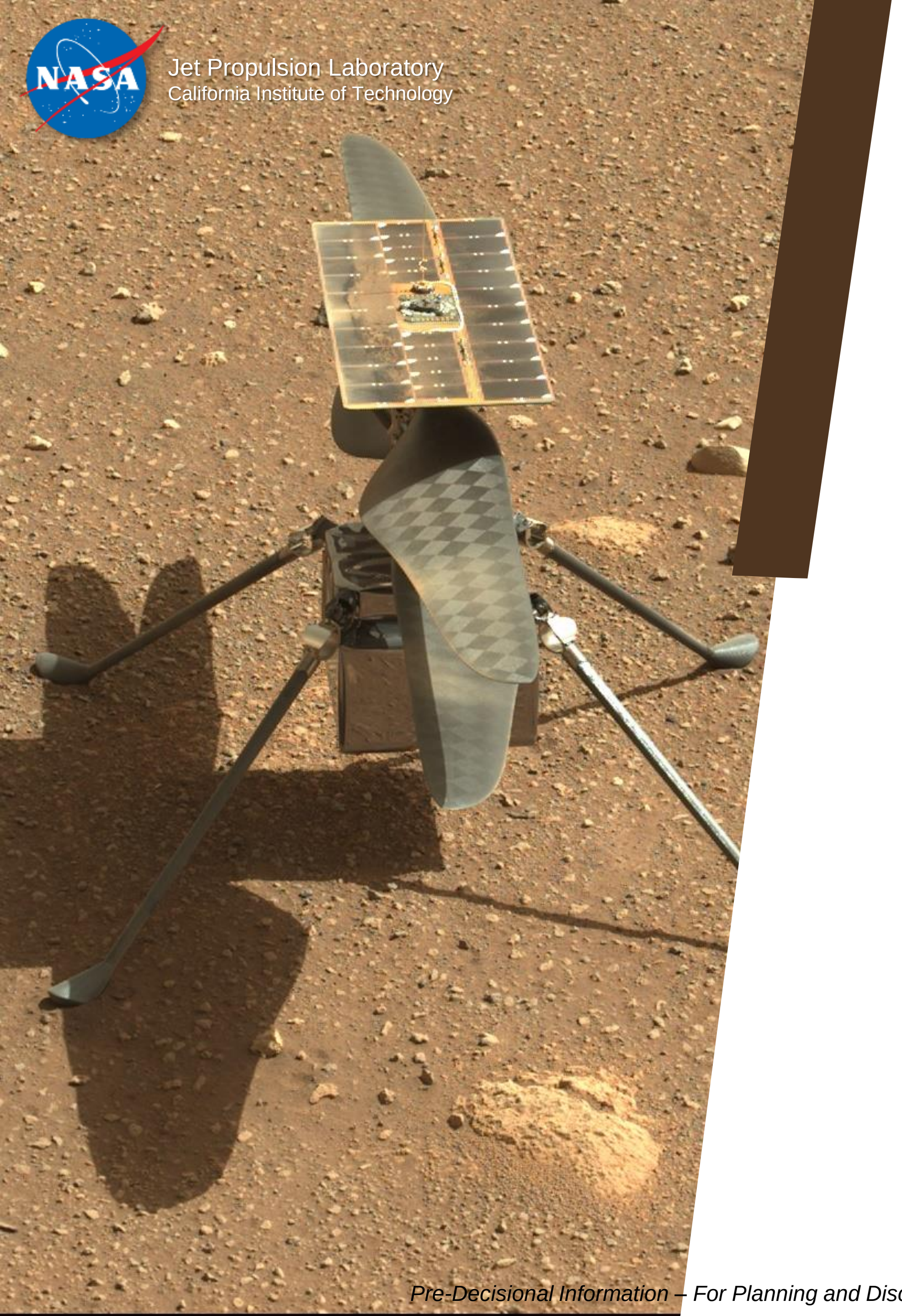
Cameras on the "Neck" of the Rover Provide More Detailed Ground Level Imagery ……. But Are Limited to Unblocked Line of Sight.



Opportunity Rover Spent 100 Days Roaming the Perimeter of this Crater in Search of Safe and Interesting Entry Point



Curiosity Rover …
Roving Over Terrain
that Should Have
Been Avoided ….. If
One Knew



FEW THINGS TO KNOW

1. **First test of powered flight on another planet.**

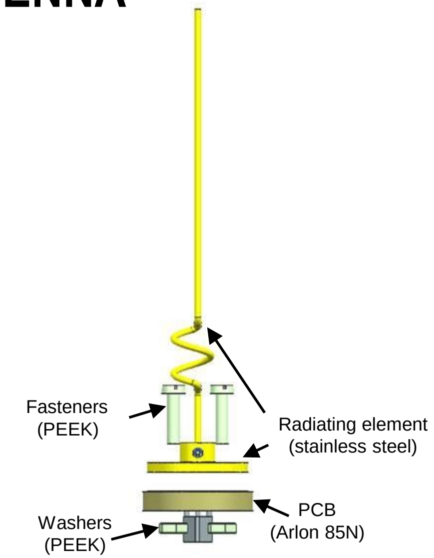
2. **Built to be light and strong** enough to stow away under the rover while on the way to Mars, and survive the harsh Martian environment after arriving on the surface. The helicopter weighs less than 4 pounds (1.8 kilograms).

3. **Powerful enough to lift off in the thin Mars atmosphere.** The atmosphere of Mars is very thin: less than 1% the density of Earth's.

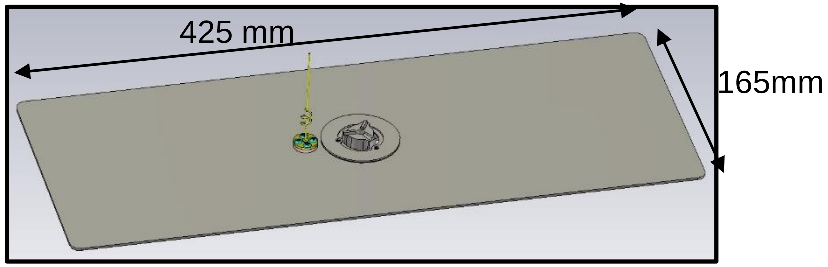
4. **The helicopter may fly for up to 90 seconds**, to distances of almost 980 feet (300 meters) at a time and about 10 to 15 feet from the ground. That's no small feat compared to the first 12-second flight of the Wright Brothers' airplane.

5. **The helicopter flies on its own, without human control.** It must take off, fly, and land, with minimal commands from Earth sent in advance.

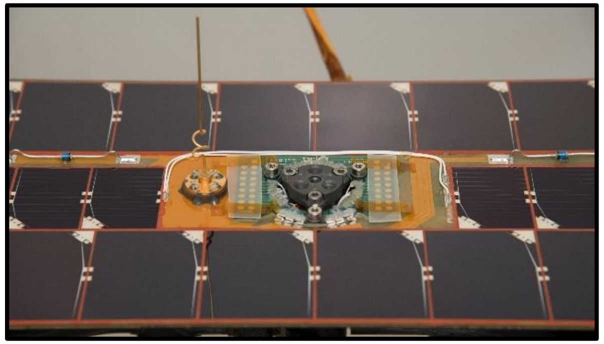
HELICOPTER ANTENNA



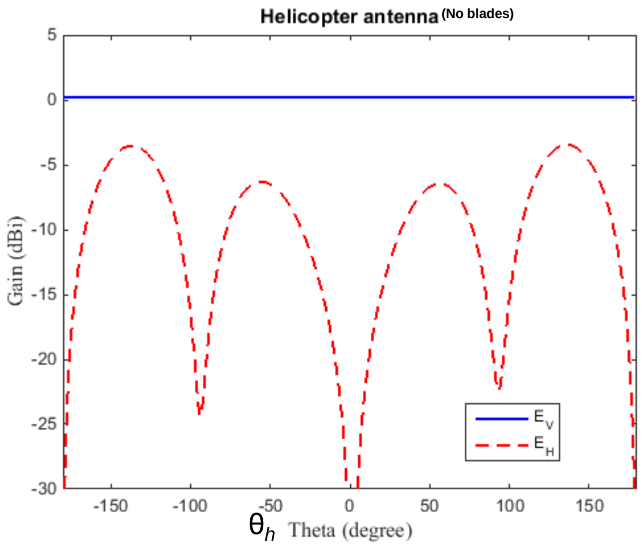
Antenna design

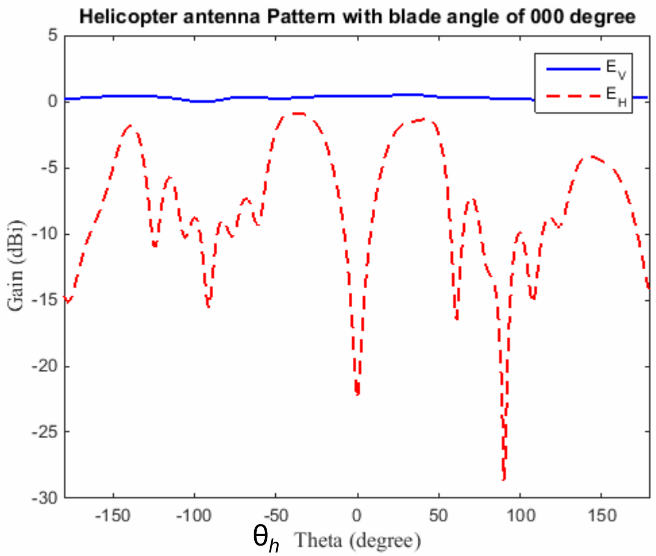


Helicopter antenna on its solar panel

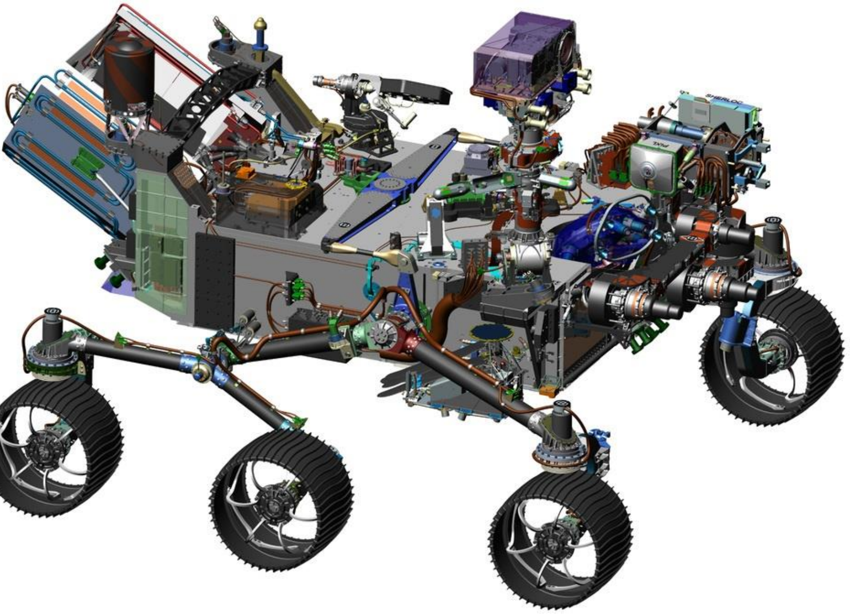


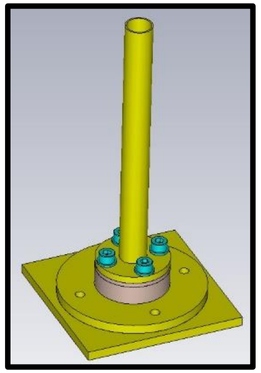
FM Helicopter antenna



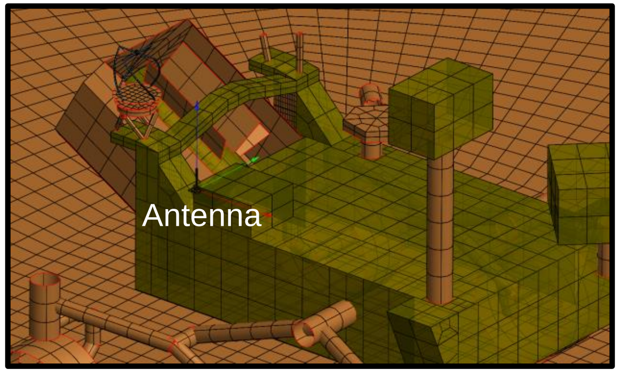


ROVER ANTENNA





Antenna design

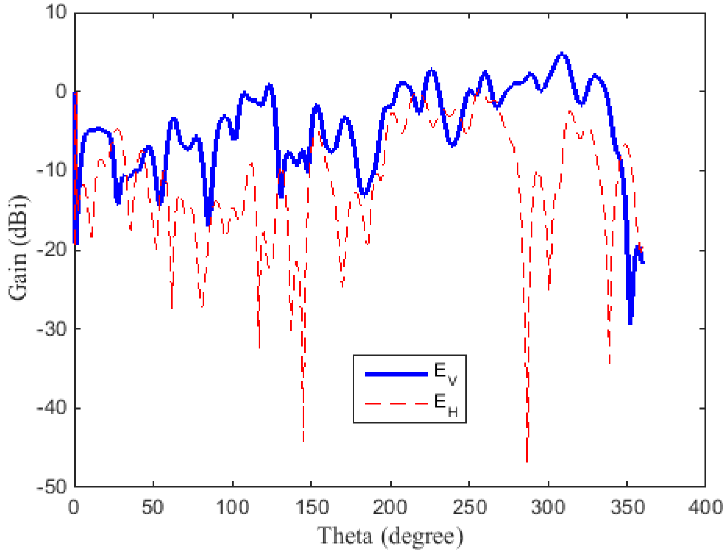


Antenna on M2020 Rover

Antenna testing on M2020 Rover mockup

FM Antenna

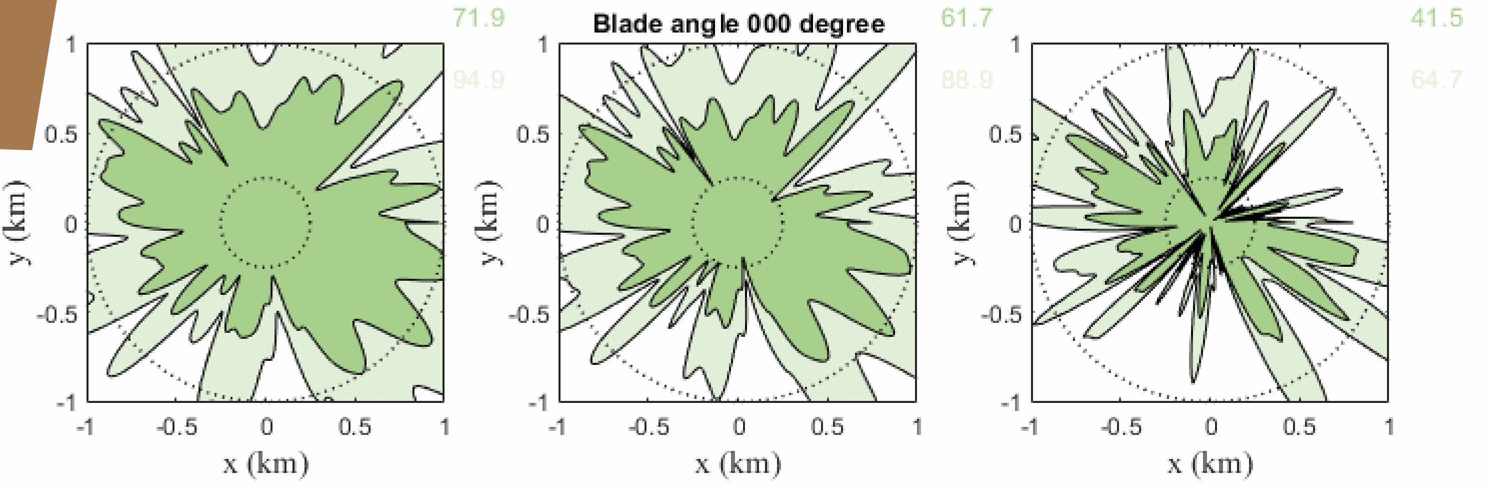
Helicopter Base Station Antenna (HBA) radiation pattern

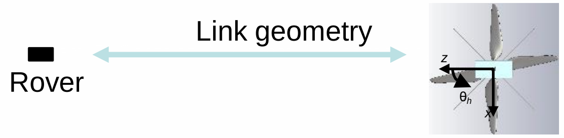


LINK BUDGET CALCULATION

Propagation Link while the helicopter is on the ground:

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





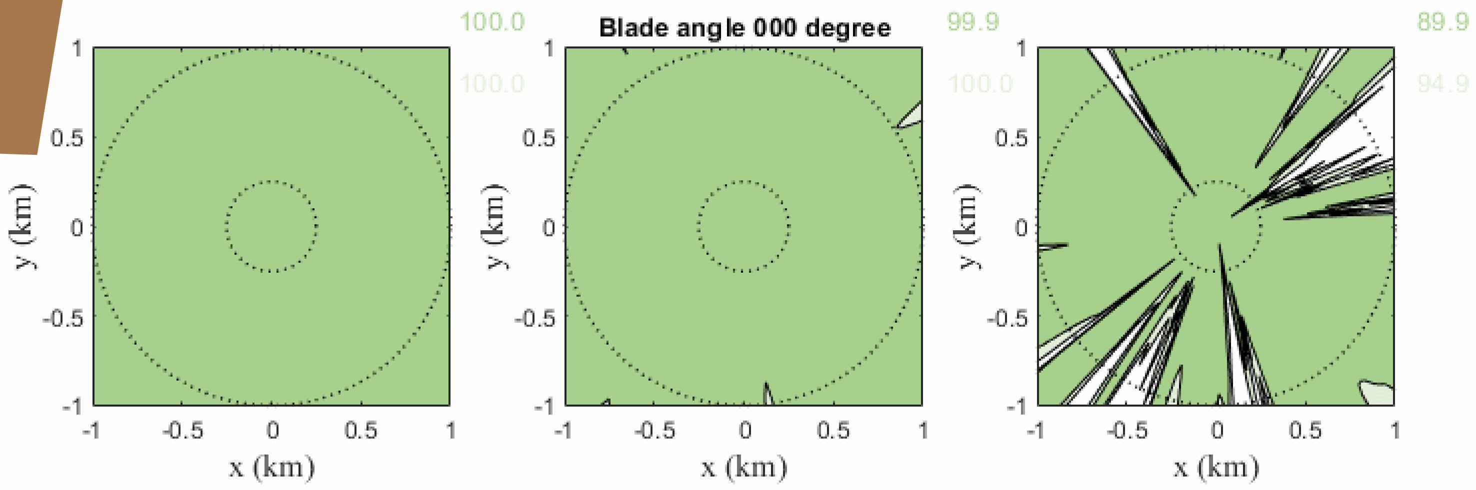
Azimuth angle θ_h = [0°-359°]

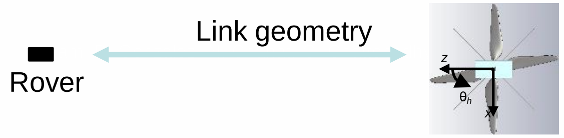
- Received power of >-99dBm ⇔ 250kbps
- Received power of [-108, -99] dBm ⇔ 20kbps
- No link

LINK BUDGET CALCULATION

Propagation Link while the helicopter is flying:

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

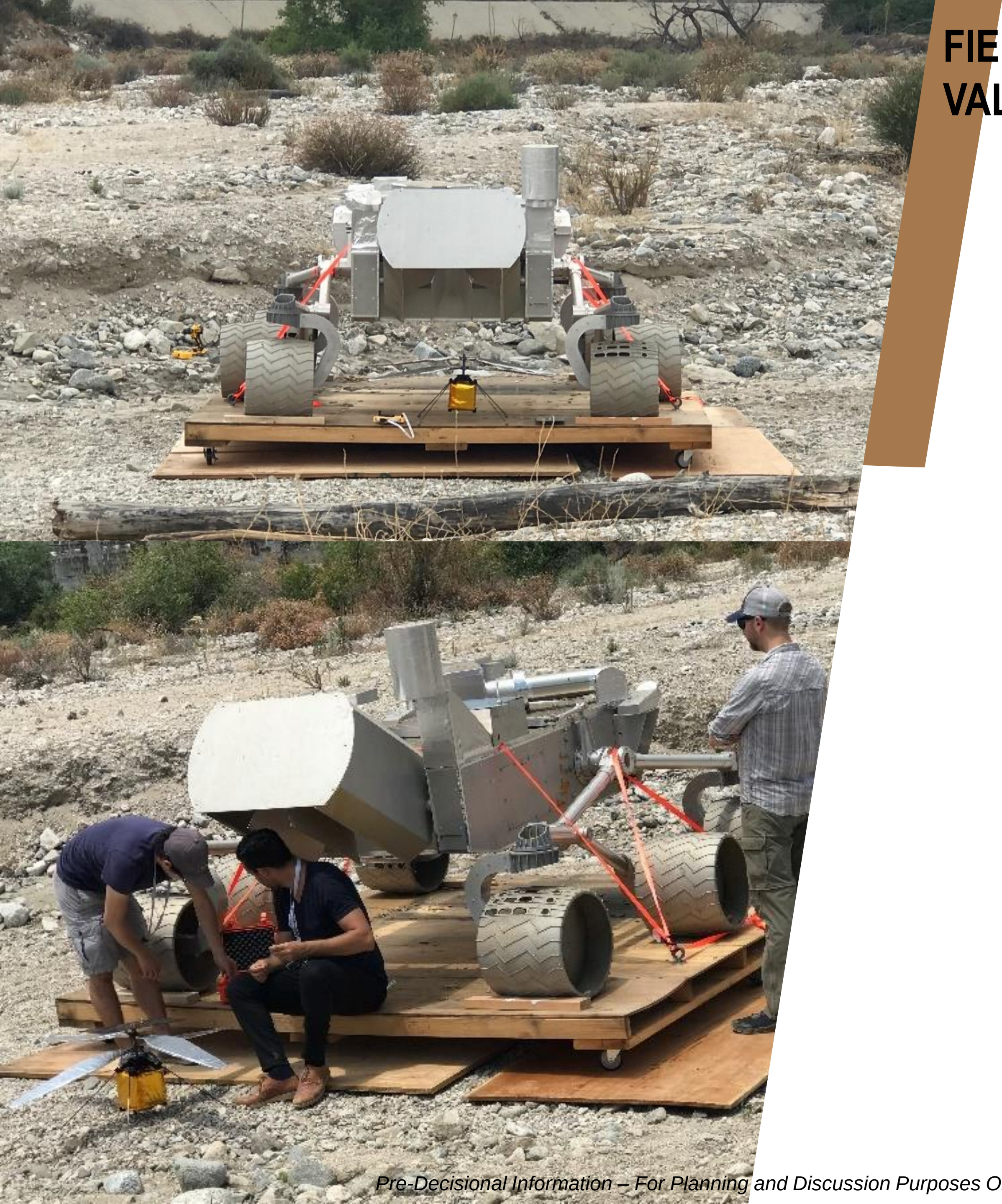


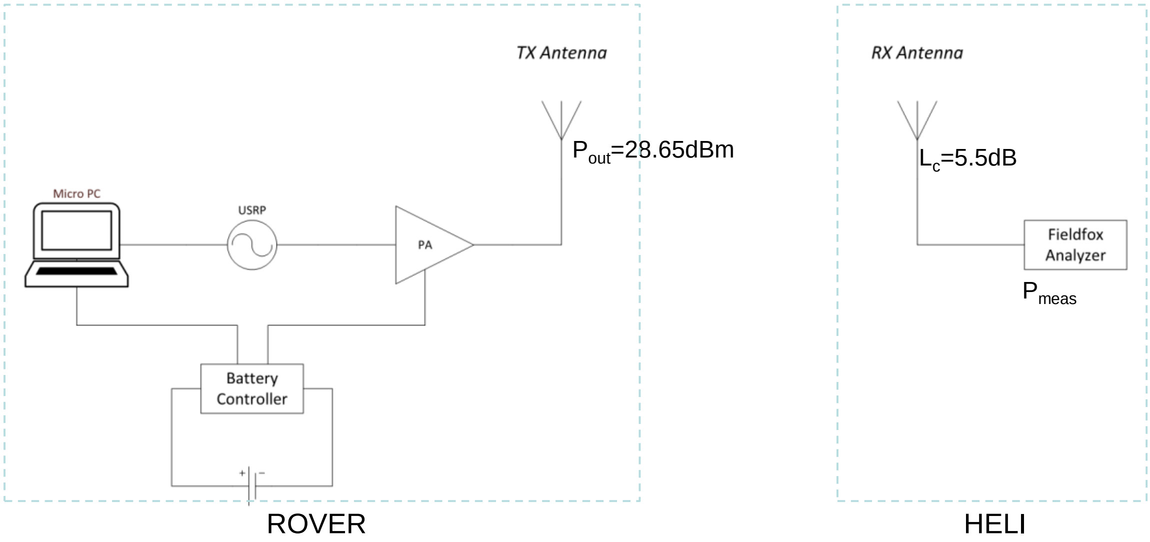


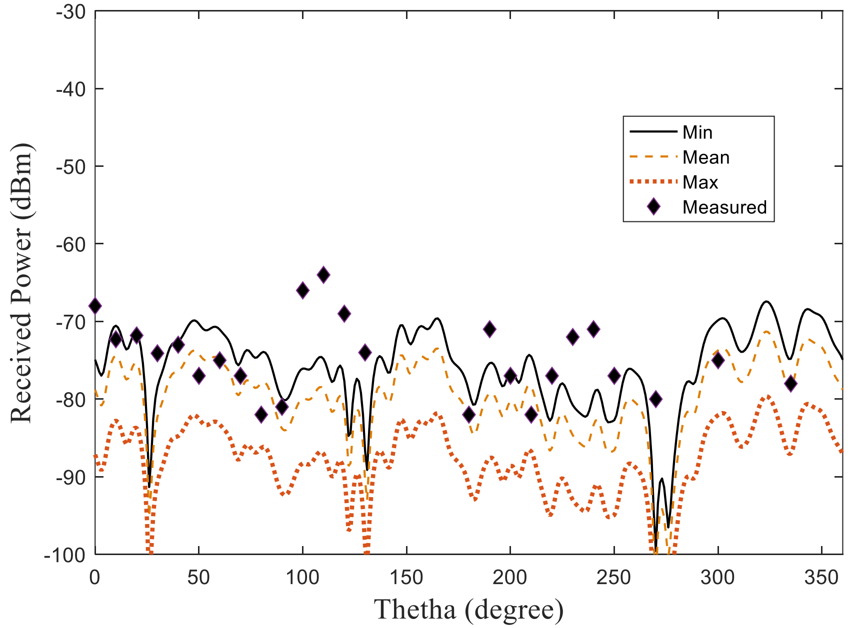
Azimuth angle θ_h = [0°-359°]

(green)	Received power of >-99dBm ⇔ 250kbps
(light green)	Received power of [-108, -99] dBm ⇔ 20kbps
(white)	No link

FIELD TEST FOR VALIDATION

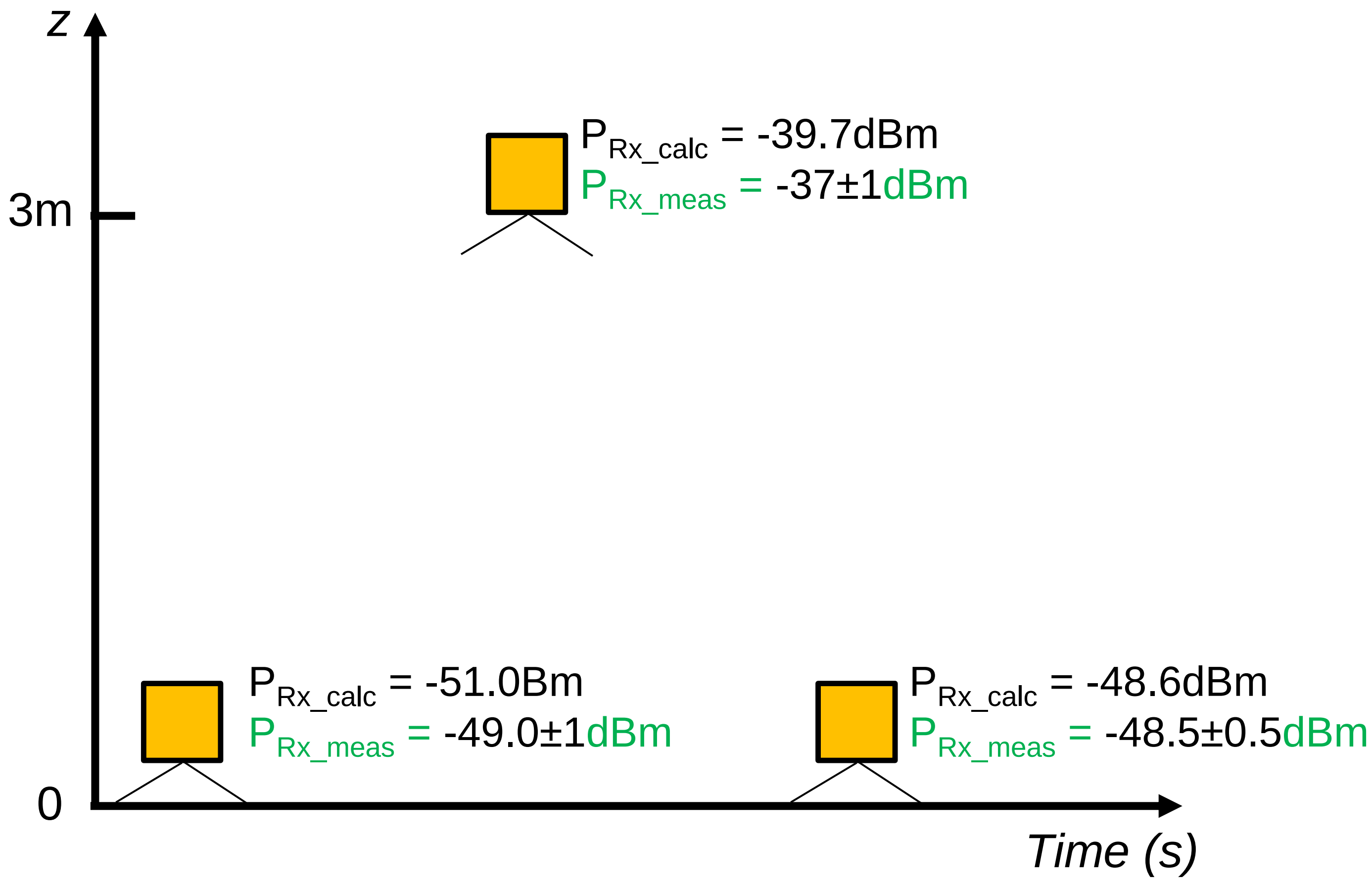






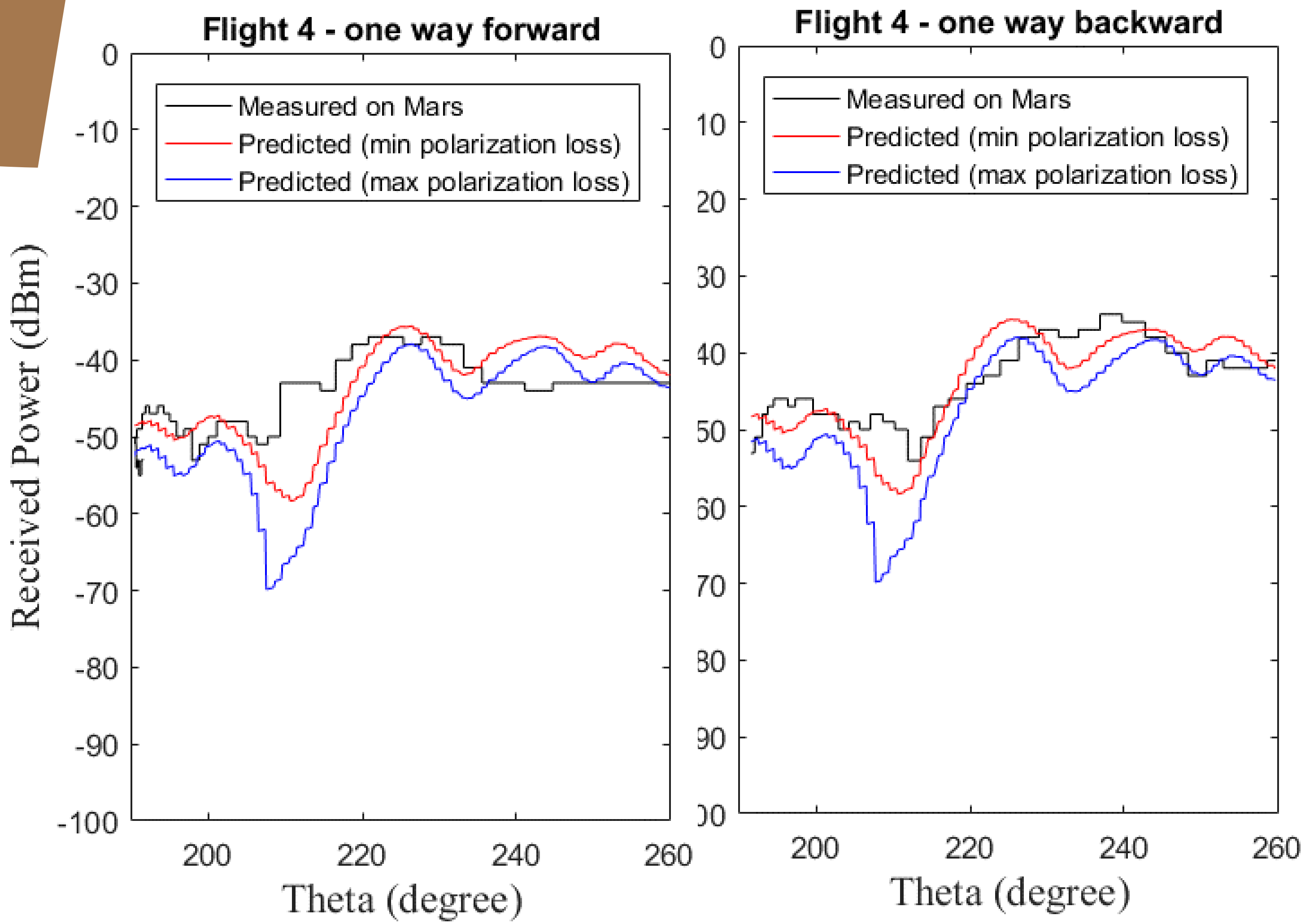
WHAT ABOUT ON MARS?

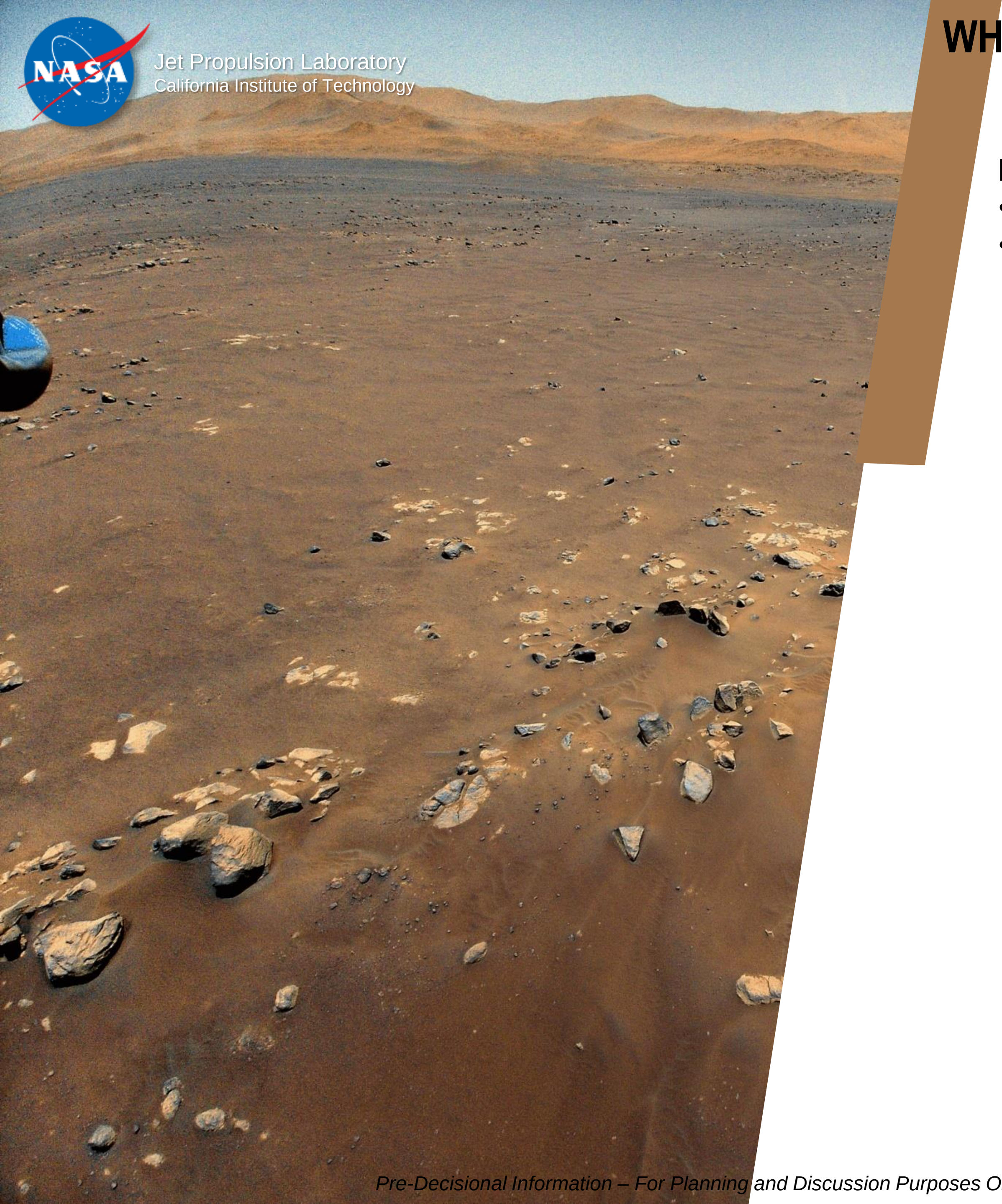
First Flight performed at 63m:



WHAT ABOUT ON MARS?

Flight 4 (in flight):
- Min distance (start and end) at 67m
- Max distance (in air) at 141m

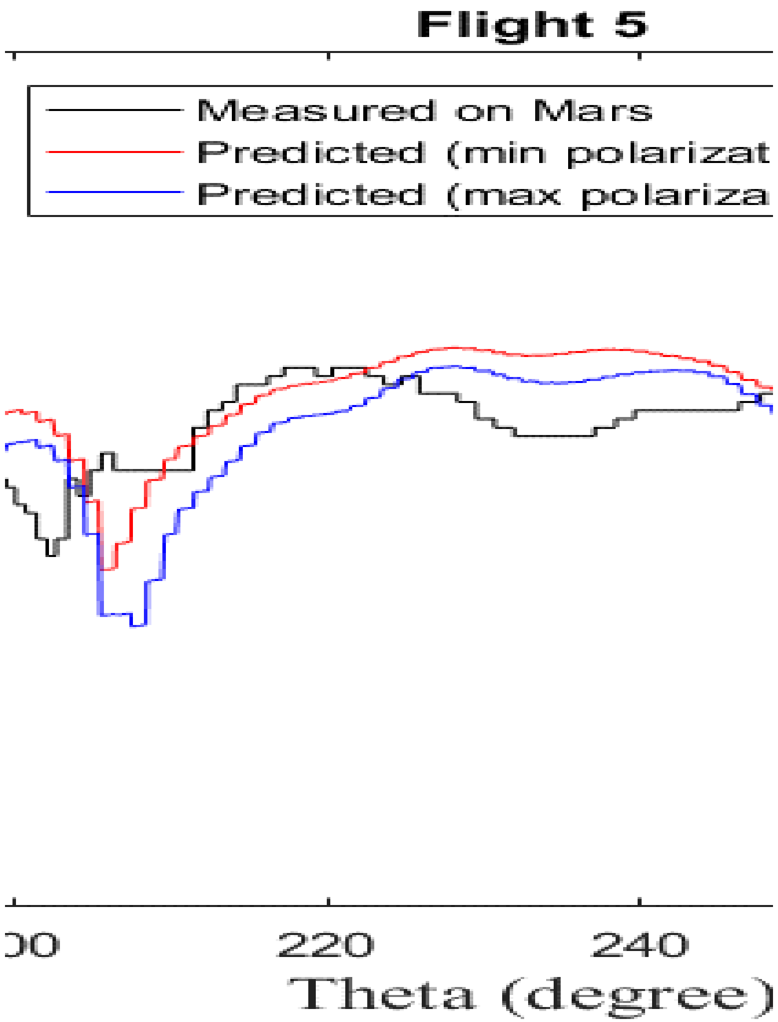




WHAT ABOUT ON MARS?

Flight 5 (in flight):

- Start distance of 92m
- Max distance (end) of 128m



Toward more accurate predictions

The Problem:

- Altair Winprop tool accounting for topology using the following methods:
  - **Parabolic Equation** (PE): uses numerical algorithms to consider propagation phenomena like reflection, diffraction, and forward-scattering. It accounts for the properties of the ground by the following parameters: (1) conductivity of the ground and (2) dielectric permittivity of the ground.
  - Inputs to this tool are the surface topology who needs to be generated (Matlab codes) and the antenna radiation pattern for the Rover and Helicopter which is generated using FEKO.

Background:

- Antenna modelling of Rover and Helicopter is critical for the validity of these analysis.
- Antenna patterns were characterized using Altair Feko as required as input for Winprop.

Summary:

- This tool was introduced to improve future telecommunication predictions in adverse scenarios by accounting for the Mars topology.
- This method was verified using the first 18 flights.
- It was then used for the rest of Ingenuity Mission Op.

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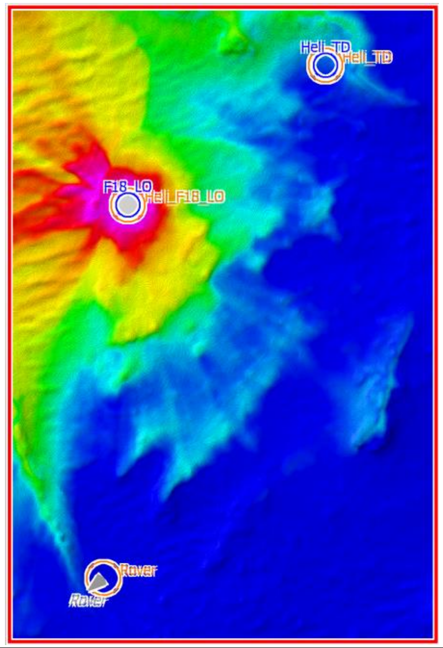
Validation Using Flight 18

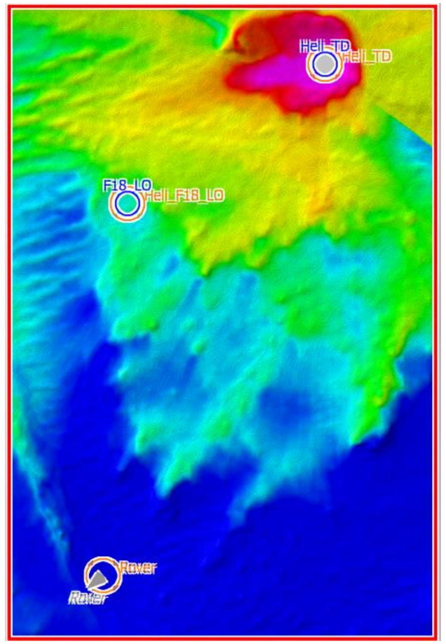
Flight 18:

- Take off distance of 358m
- Landing distance of 534m



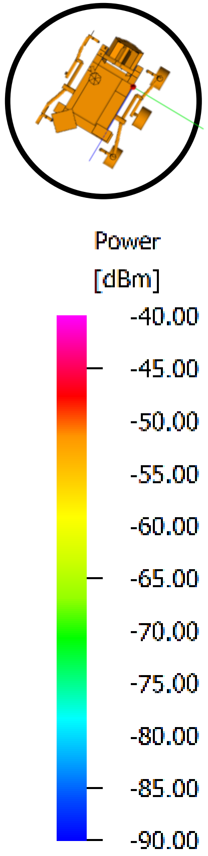
Liftoff – PE at 914MHz

914MHz:
P_{Rx_meas} = -99±1dBm
P_{PE} = -96.7 dBm



Touchdown – PE at 914MHz

914MHz:
P_{Rx_meas} = -96dBm
P_{PE} = - 95.1 dBm

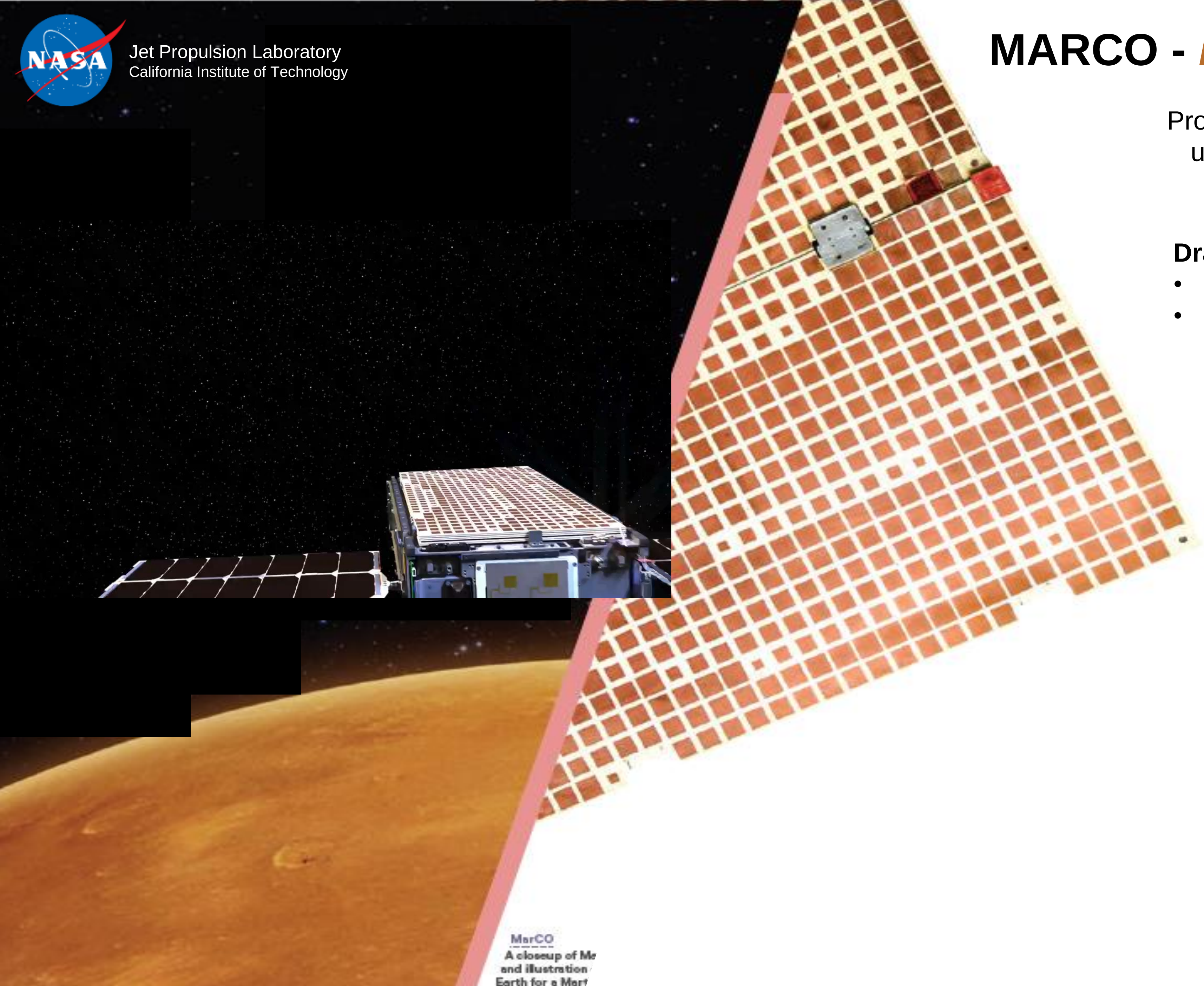


Flight #18	X	Y
Pt A (liftoff)	-686.1	-177.9
Pt B (touchdown)	-497.1	-44.1

Flight #18	X	Y	Yaw
Rover location	-709.3	-534.8	-129.1

CUBESAT ANTENNAS

MARCO - *First Deep Space CubeSat*



Provided bent pipe communication at 1AU at 8kbps using an innovative UHF deployable antenna and the first reflectarray in Space.

Drastic requirements:

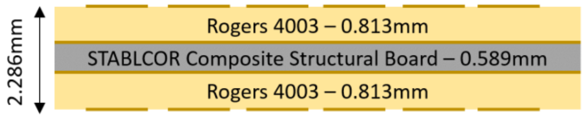
- Stowage volume: 12.5mm × 210mm × 345mm
- Gain of at least 28dBic (required aperture: 335mm × 587mm)

Constraints:

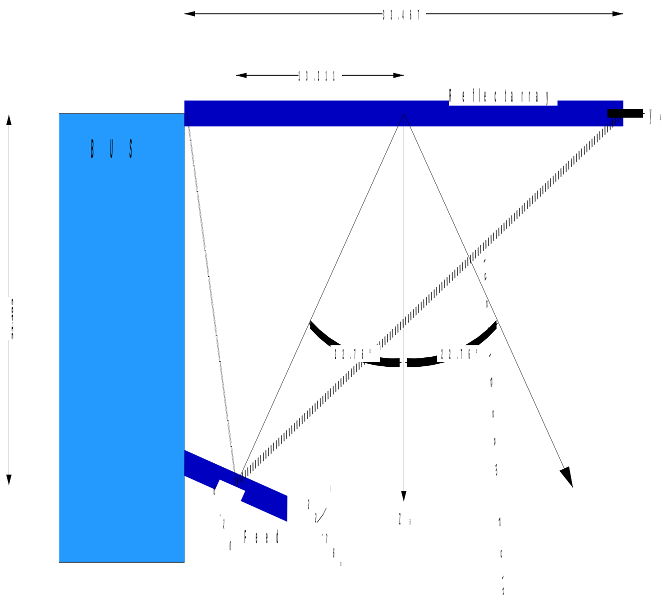
- No internal stowage volume
- Limited RF output power

MARCO - *First Deep Space CubeSat*

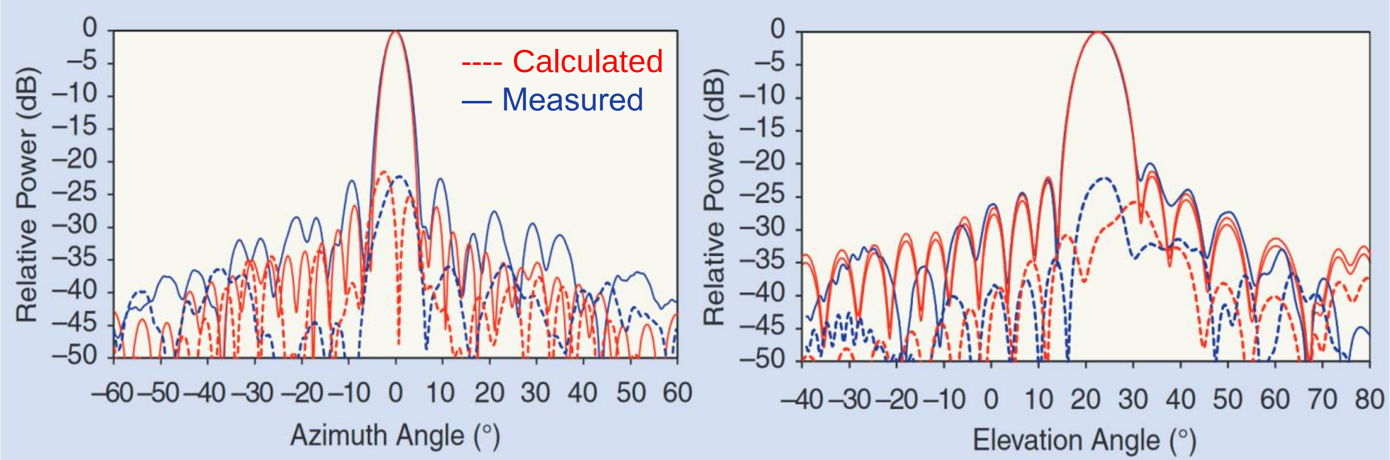
Reflectarray design:



Panel configuration



	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**



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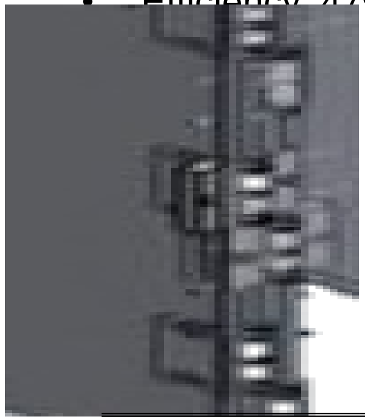
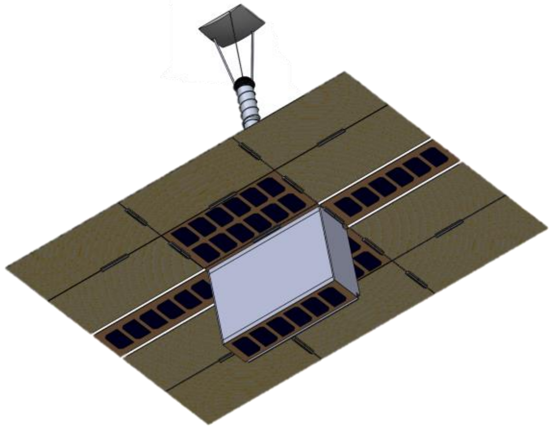
OMERA – *Larger Deployable Reflectarray*

Ka-band deployable reflectarray:

- 1-m reflector Ka-band antenna (98.6cm×82.1cm)
- Polarization: V-polarization
- Gain: > 47.0 dBi
- Efficiency: 47%





	Gain (dBi)	Loss (dB)
Ideal directivity	51.58	-
Spillover	50.67	0.91
Taper	49.95	0.72
Blockage	49.67	0.28
Struts	49.37	0.3
Gap loss	49.22	0.15
Patch dielectric / conductivity loss	48.97	0.25
Surface accuracy *	47.77	1.2
Feed loss / telescoping waveguide / transition	47.47	0.3
Feed mismatch (RL=17dB)	47.38	0.09
Overall performance	47.38	4.2

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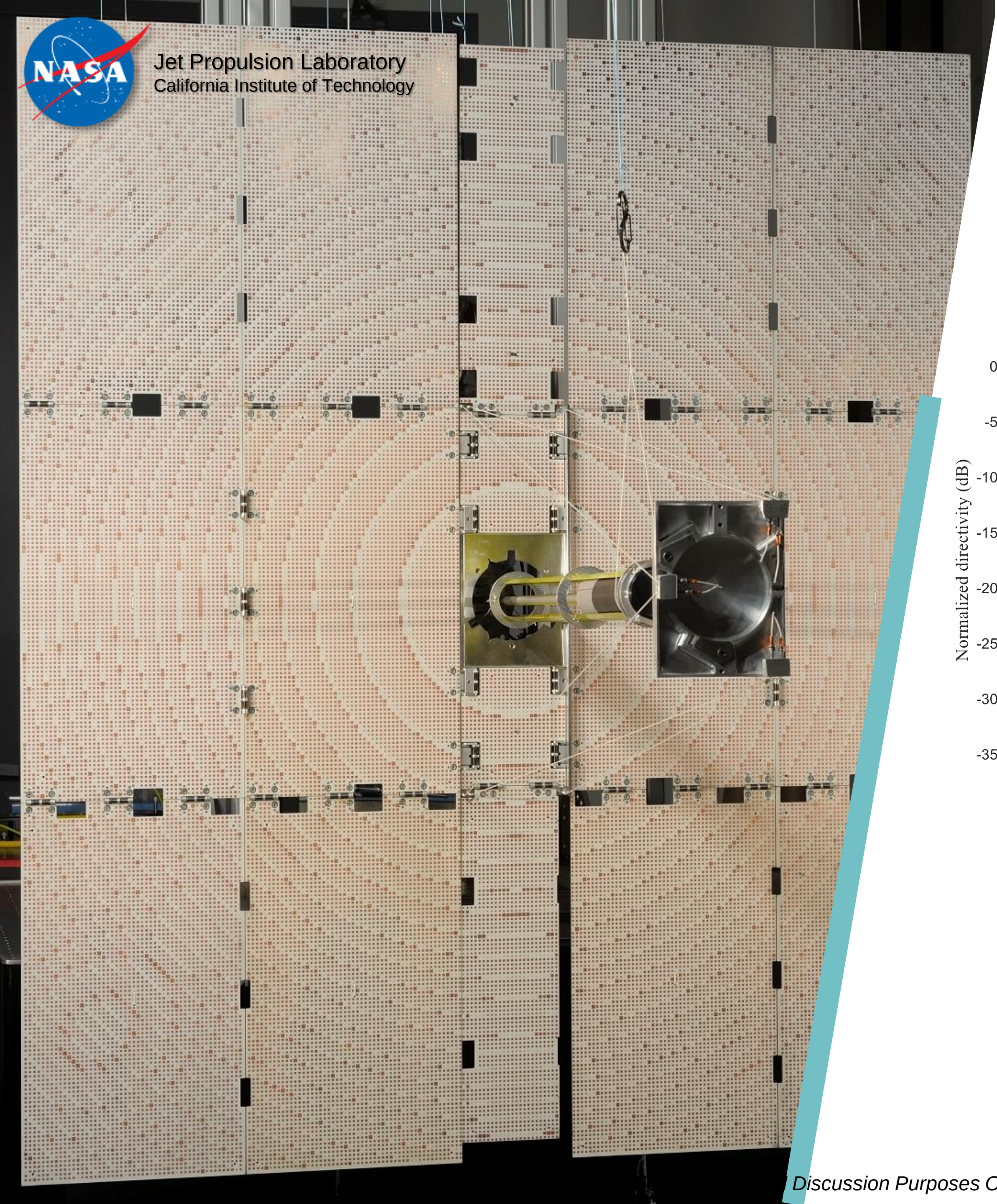
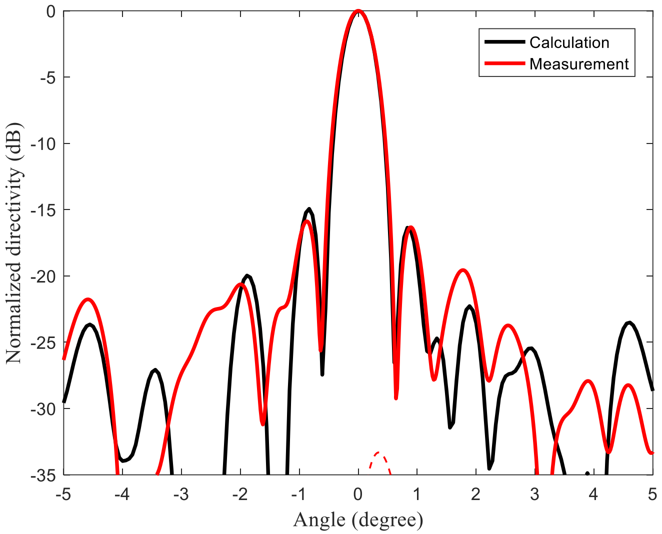
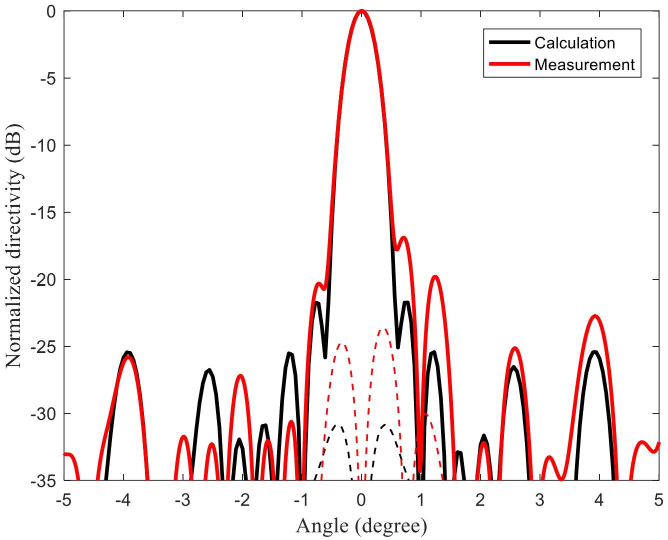
OMERA – *Larger Deployable Reflectarray*



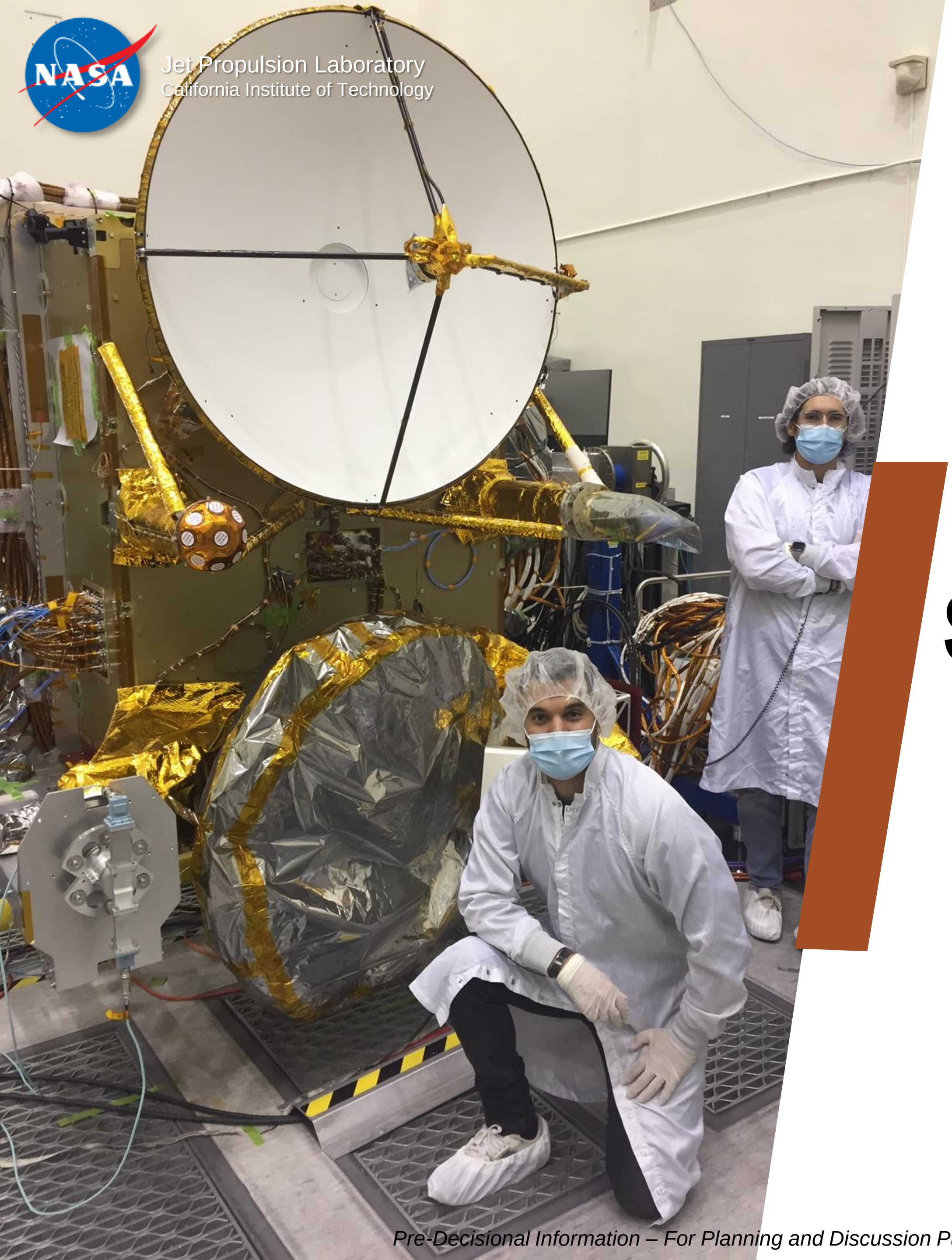
Ka-band deployable reflectarray:

- 1-m reflector Ka-band antenna (98.6cm×82.1cm)
- Polarization: V-polarization
- Gain: > 47.0 dBi
- Efficiency: 47%



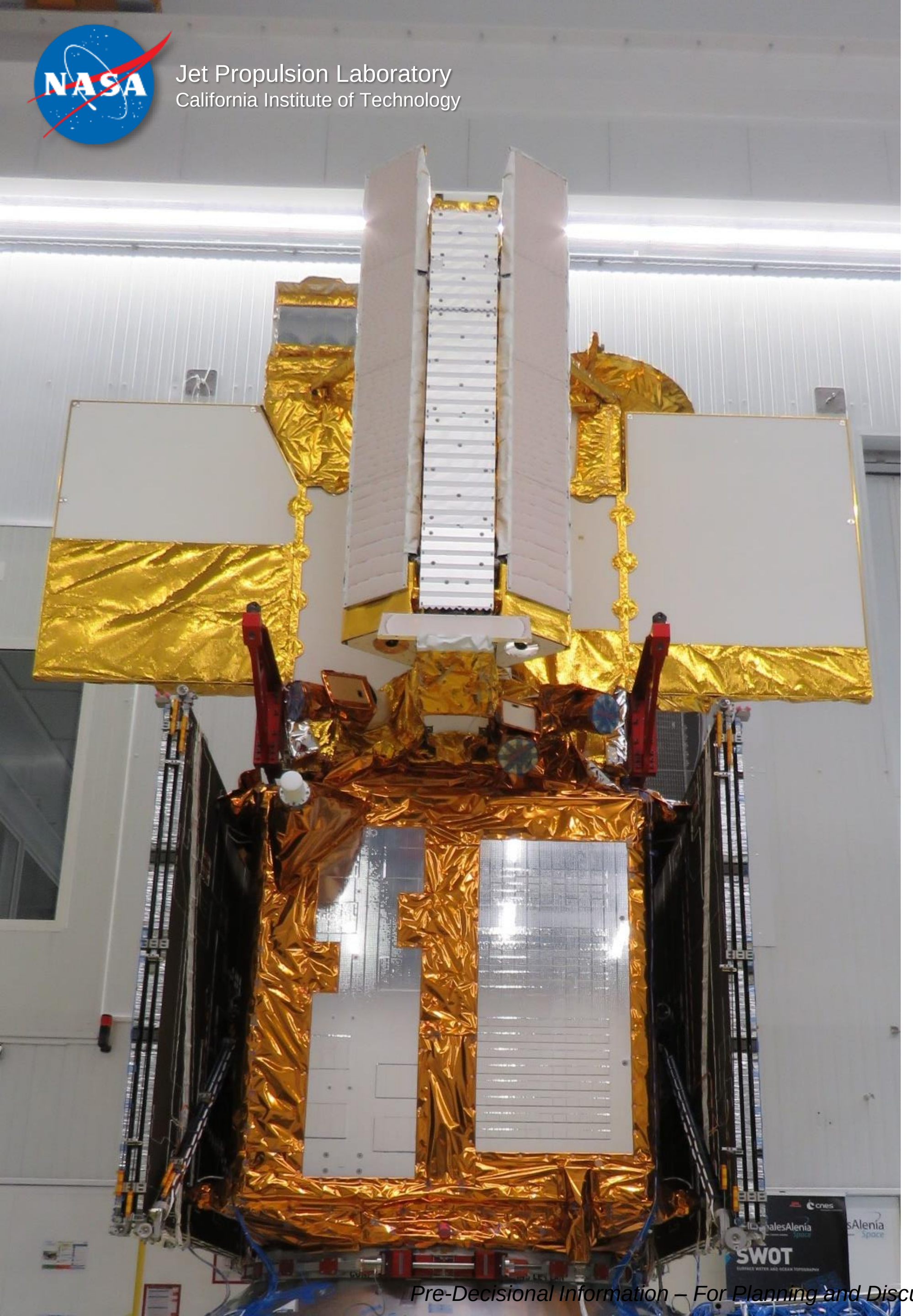


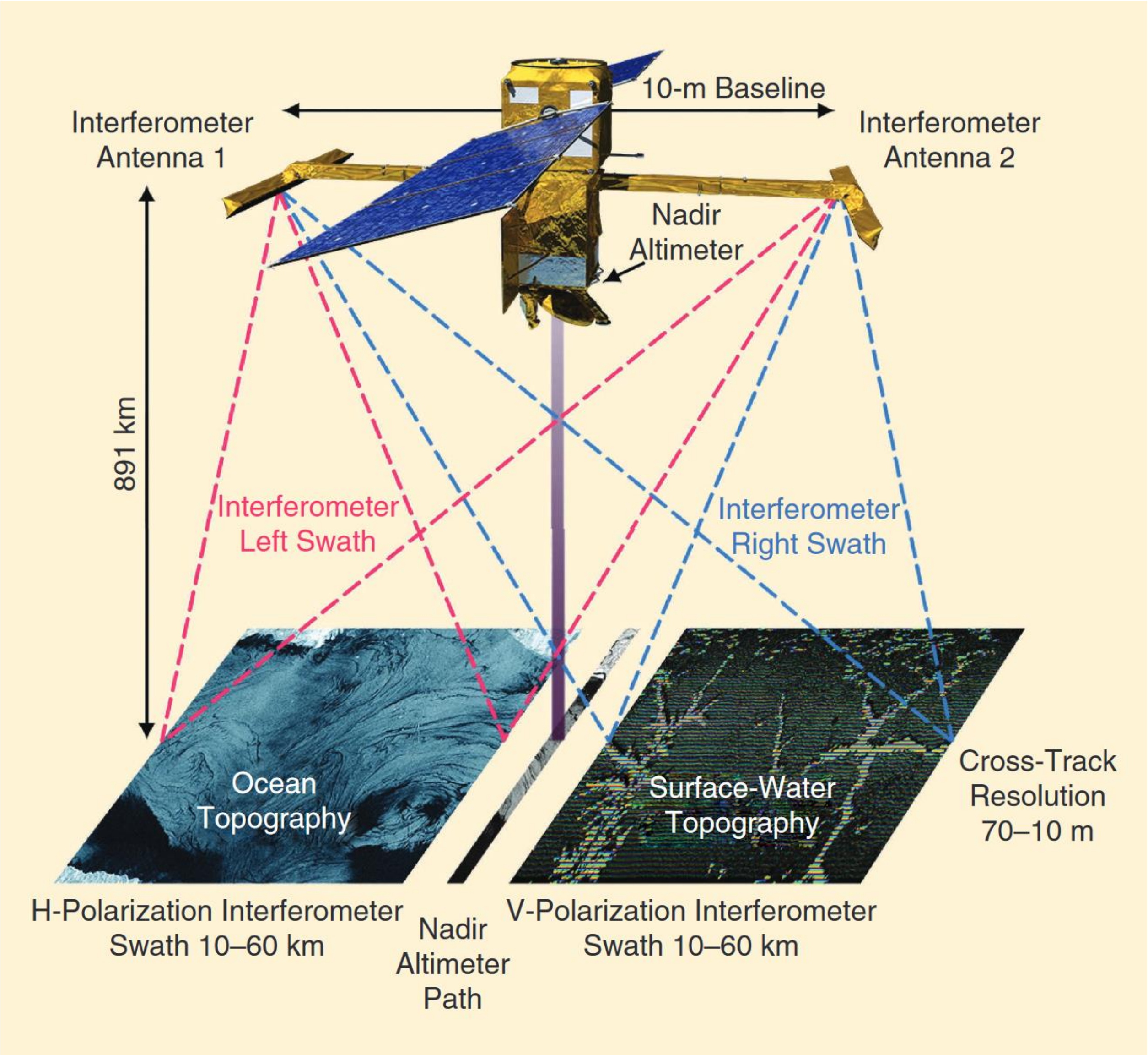
Gain = 47.1dBi at 35.75GHz

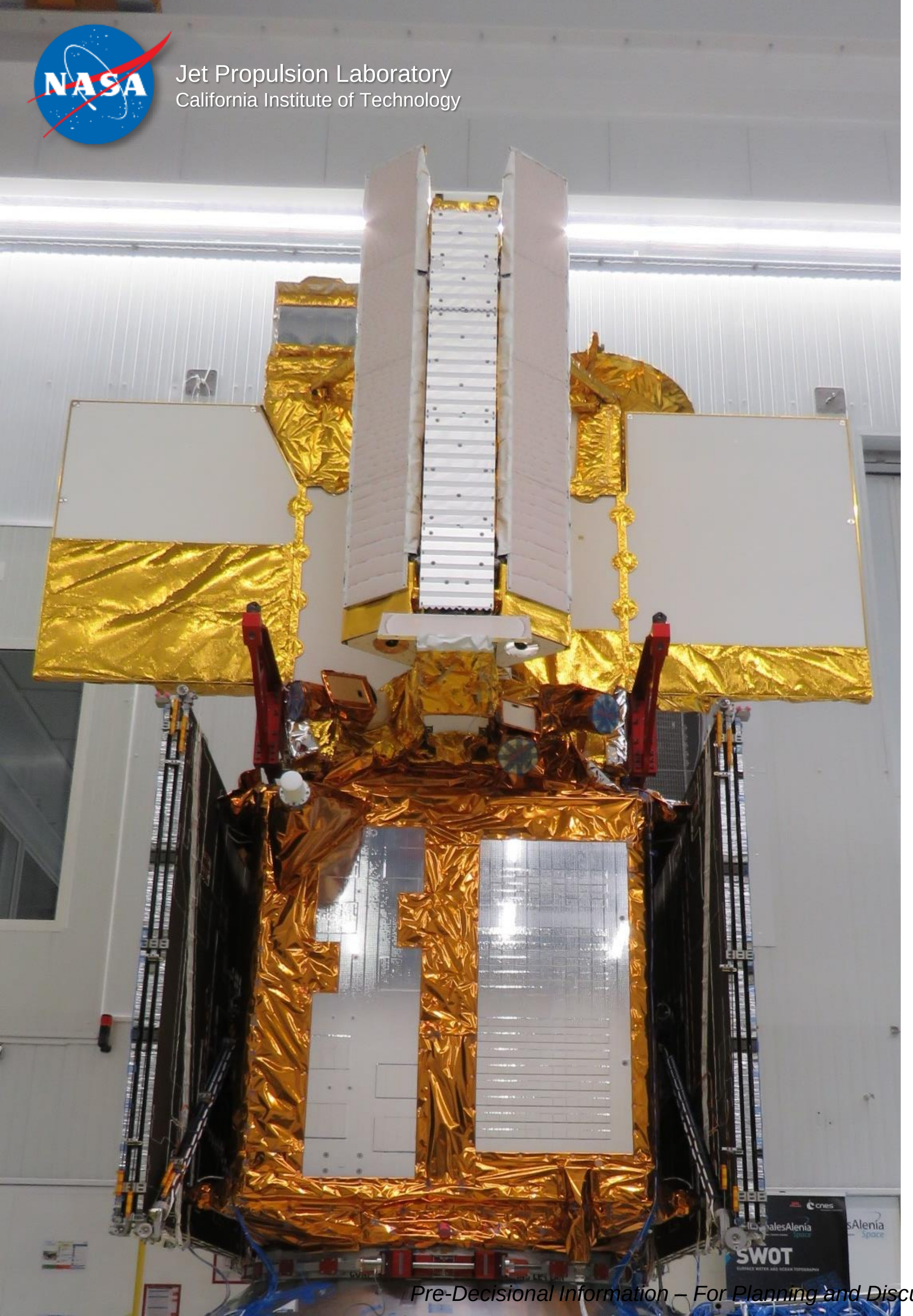


SWOT Mission

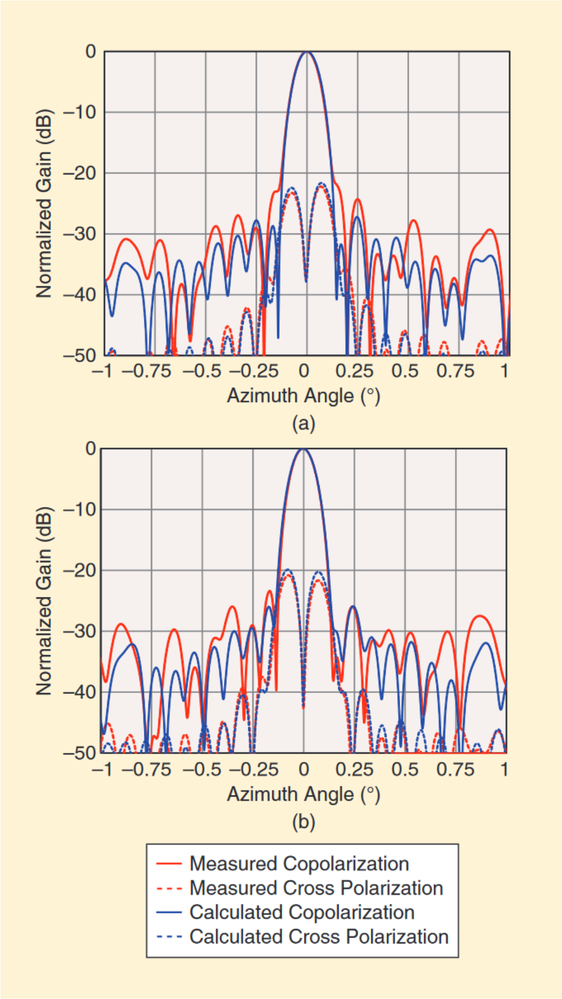
Surface Water and Ocean Topography (SWOT)



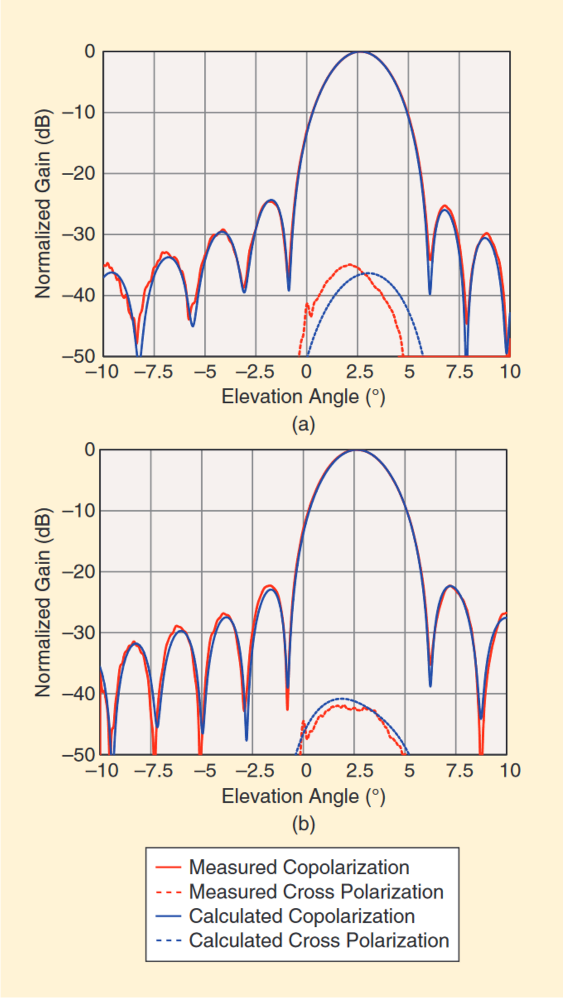




Surface Water and Ocean Topography (SWOT)



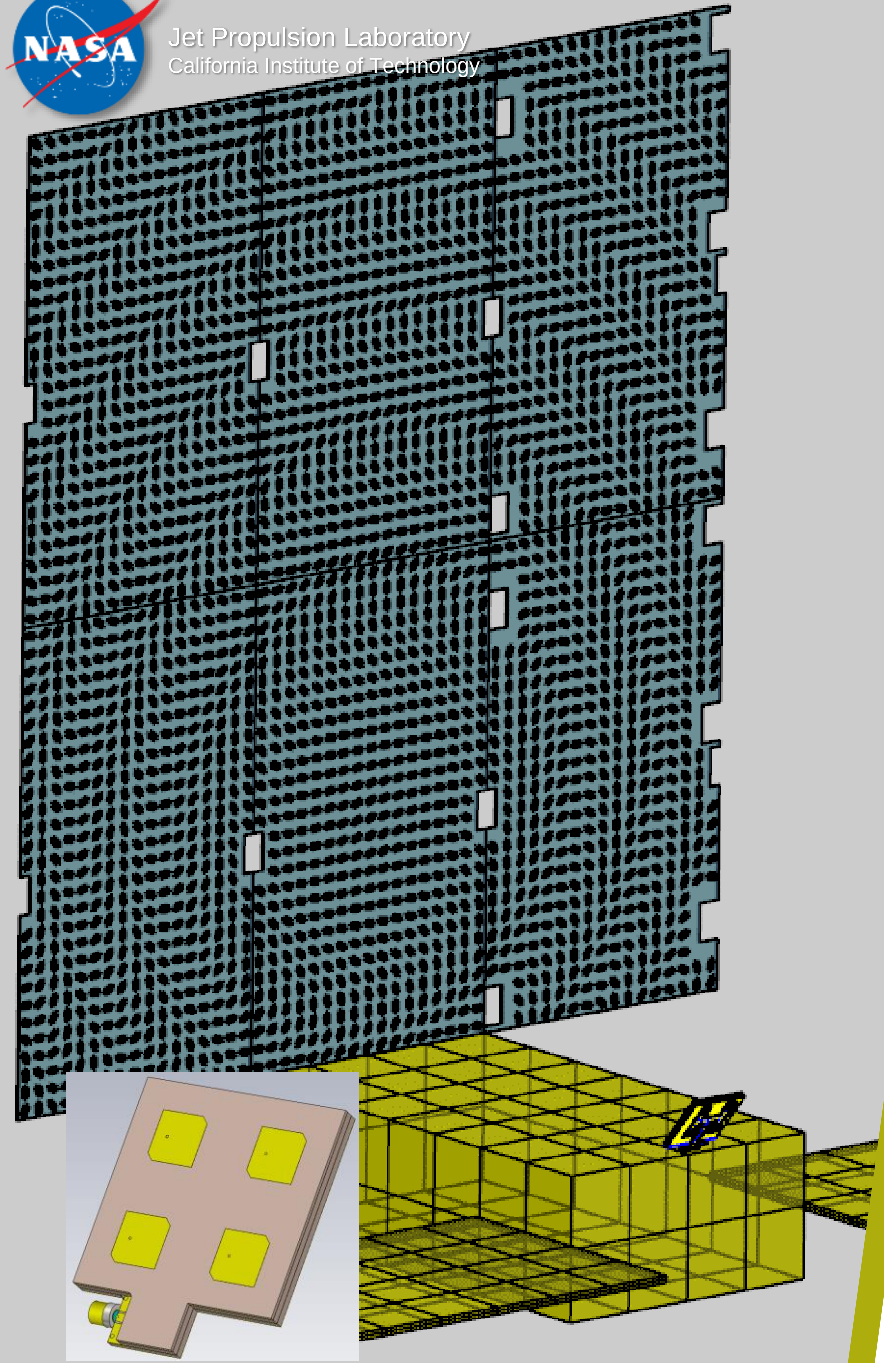
V-polarization azimuth reflectarray radiation patterns at 35.75 GHz: (a) antenna 1 and (b) antenna 2.



V-polarization elevation reflectarray radiation patterns at 35.75 GHz: (a) antenna 1 and (b) antenna 2.

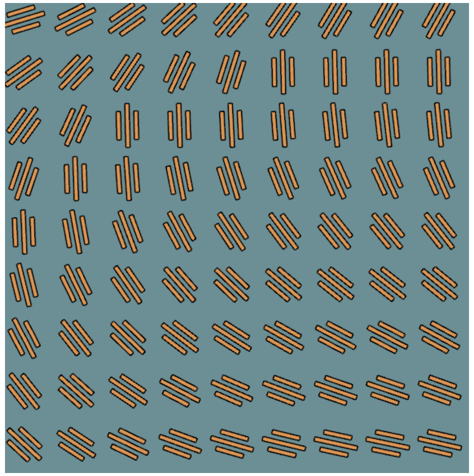
R. E. Hodges, *et al.*, "An Extremely Large Ka-Band Reflectarray Antenna for Interferometric Synthetic Aperture Radar: Enabling Next-Generation Satellite Remote Sensing," in *IEEE Antennas and Propagation Magazine*, vol. 62, no. 6, pp. 23-33, Dec. 2020, doi: 10.1109/MAP.2020.2976319.

More Reflectarrays – X-band

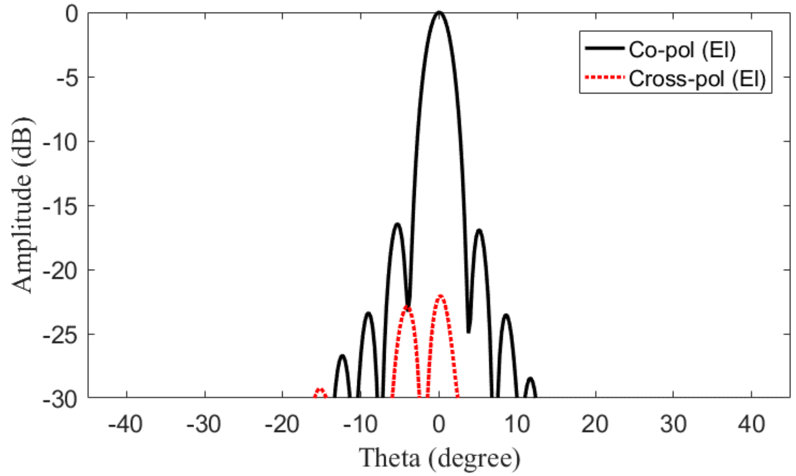


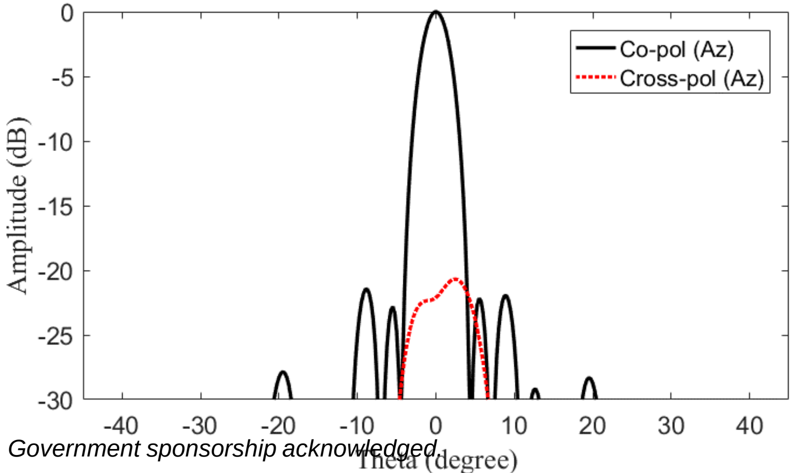
Feed with MarCO heritage

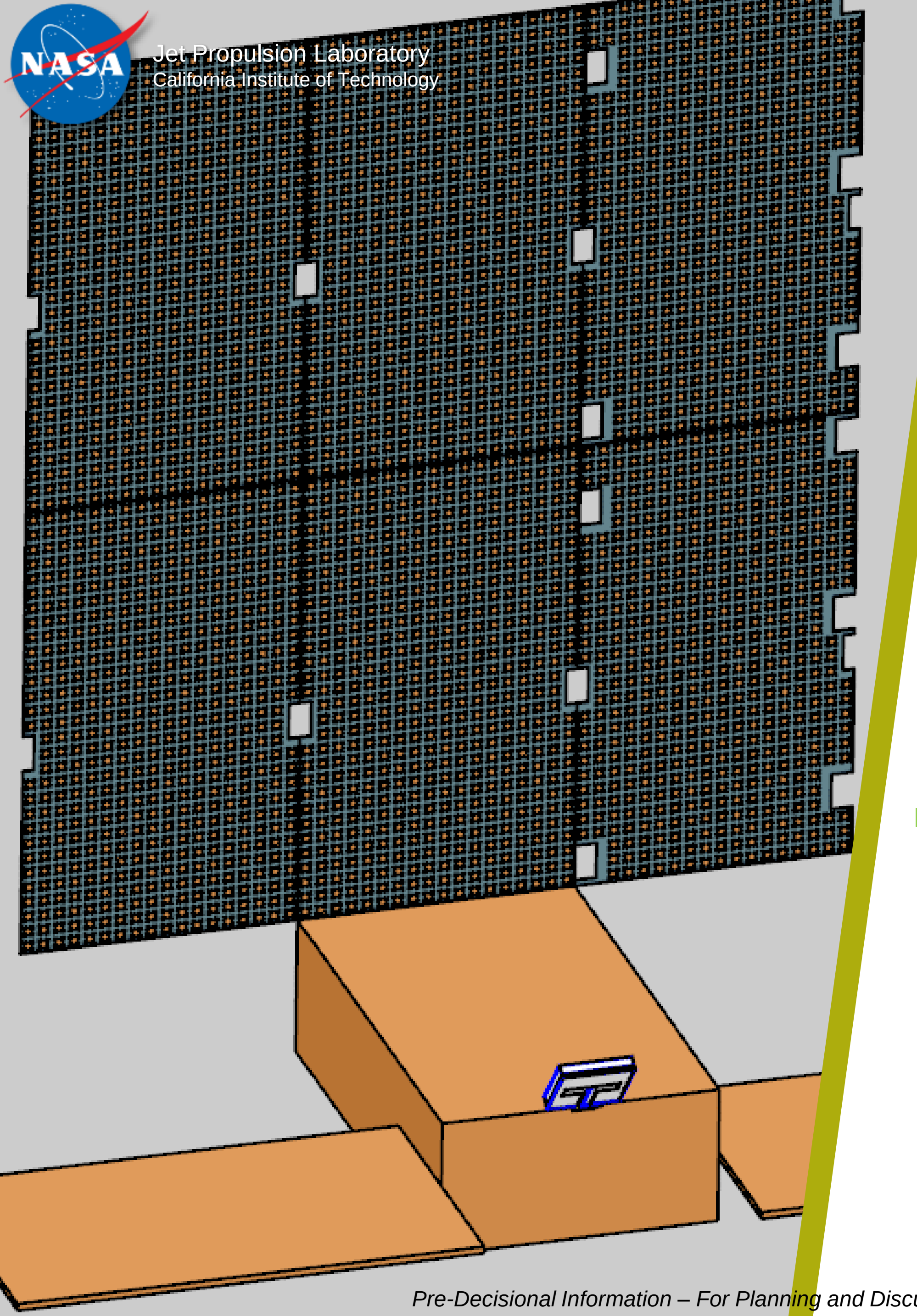
- **Features:**
  - Compatible with 6U CubeSat
  - X-band design for Telecom
  - Transmit only
  - Deployed area: 600mm × 670mm
  - Gain of 32.5dBic between 8.4-8.45GHz



Triple Dipole using the variable rotation technique (VRT) technique





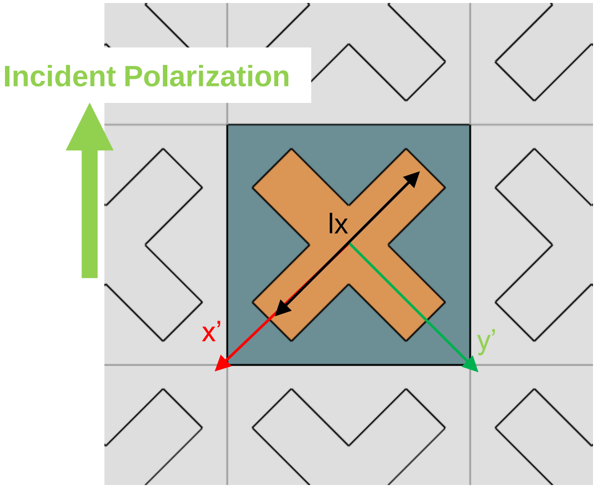


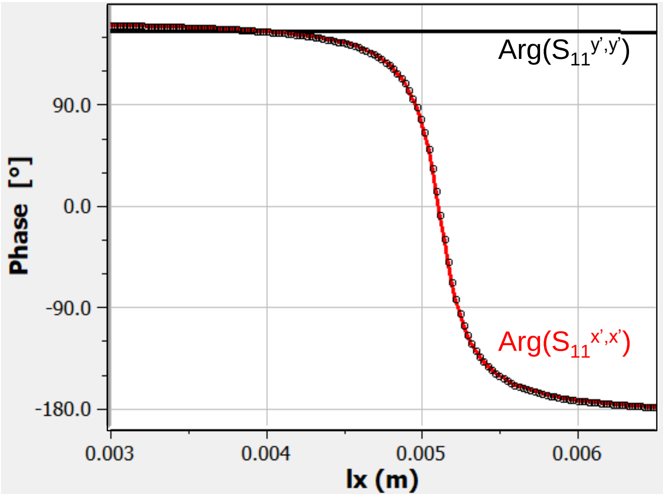
More Reflectarrays – X-band

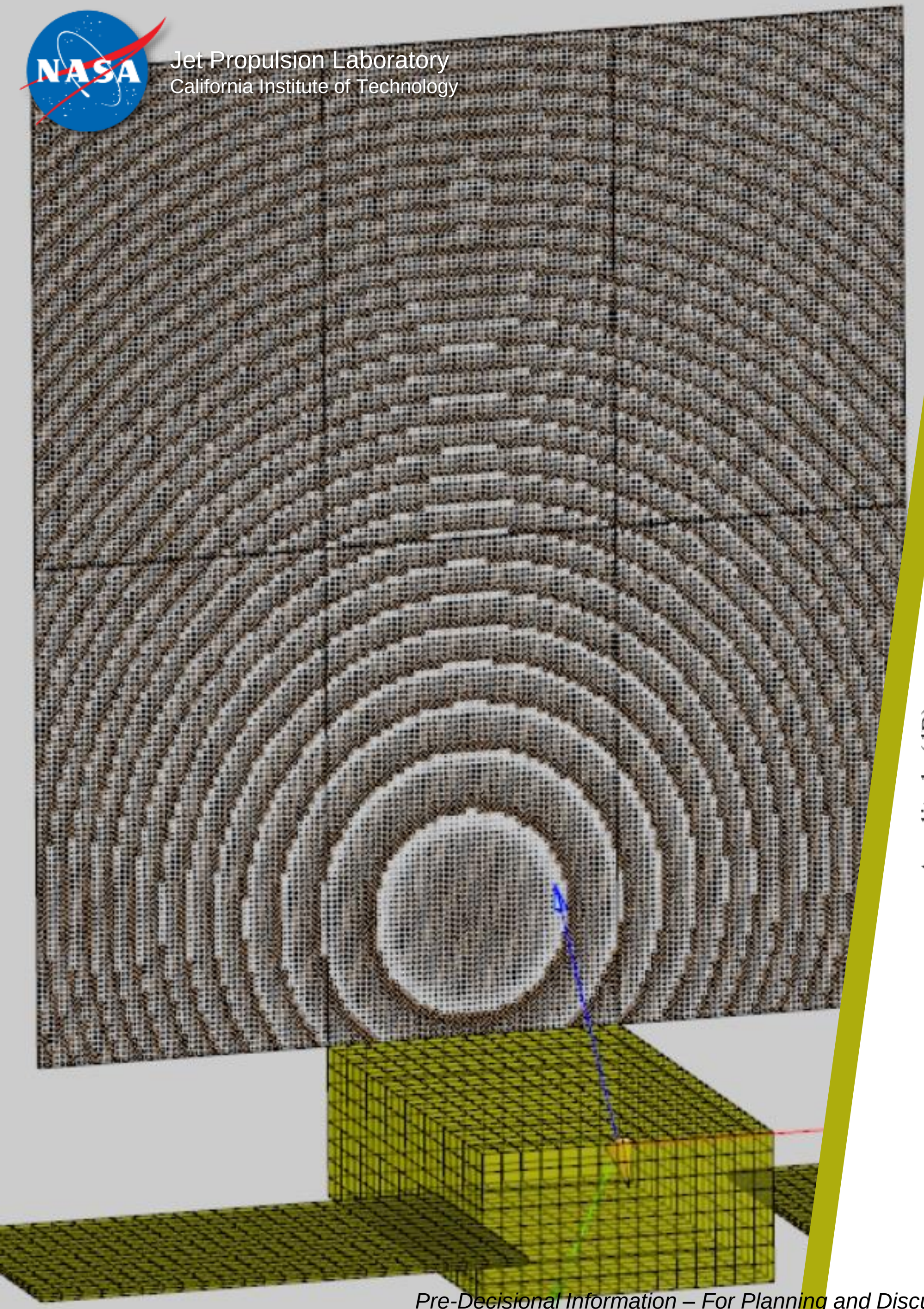
- **Features:**
  - Compatible with 6U CubeSat
  - X-band design for Telecom
  - Transmit only
  - Deployed area: 600mm × 670mm
  - Gain of 32.5dBic between 8.4-8.45GHz

Dual Frequency:

- PL dual frequency feed
- Convert LP to CP by utilizing a reflectarray element that provides a relative phase shift of ±90

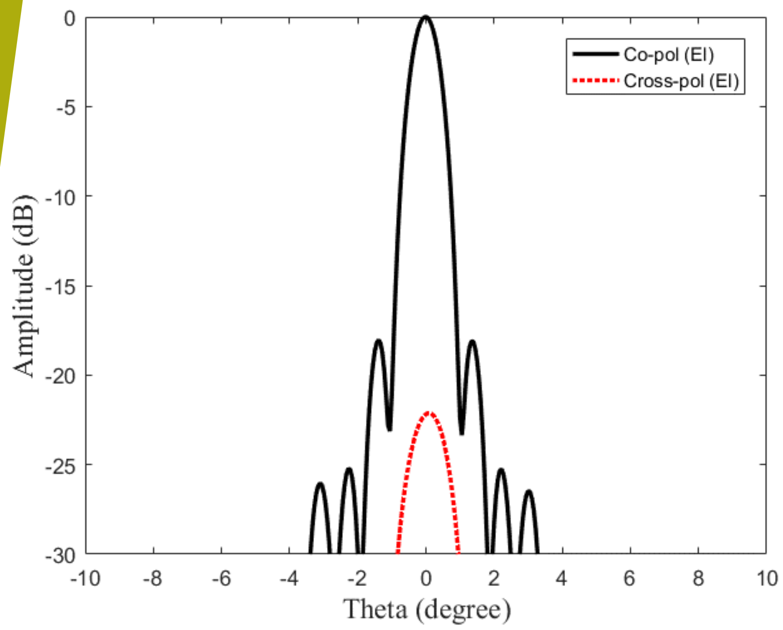


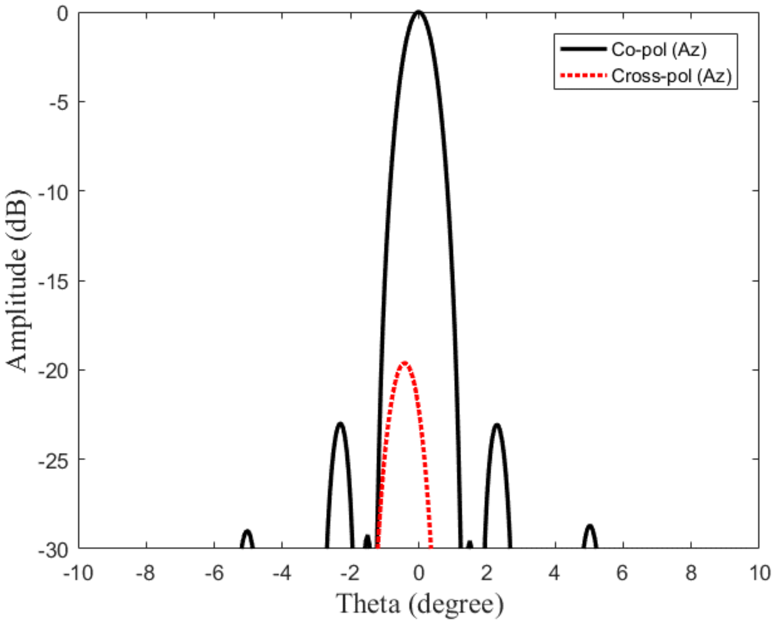


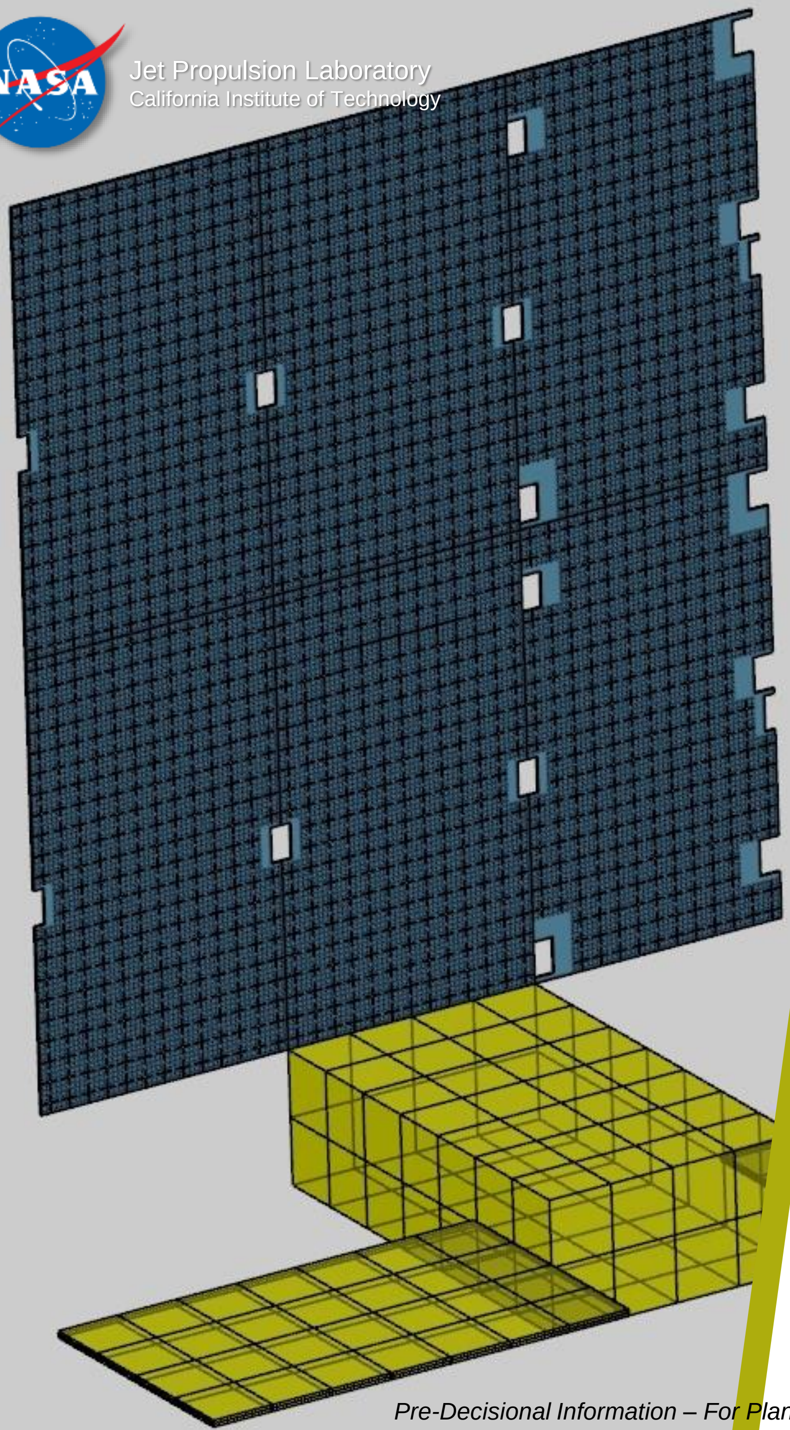


More Reflectarrays – Ka-band

- **Features:**
  - Compatible with 6U CubeSat
  - Ka-band design for Telecom
  - Transmit only
  - Deployed area: 600mm × 670mm
  - Gain of 43.2dBic between 31.8-32.3GHz

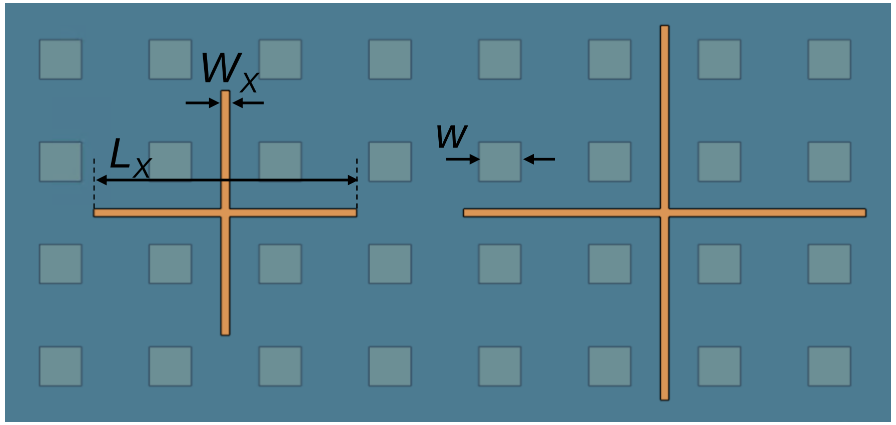


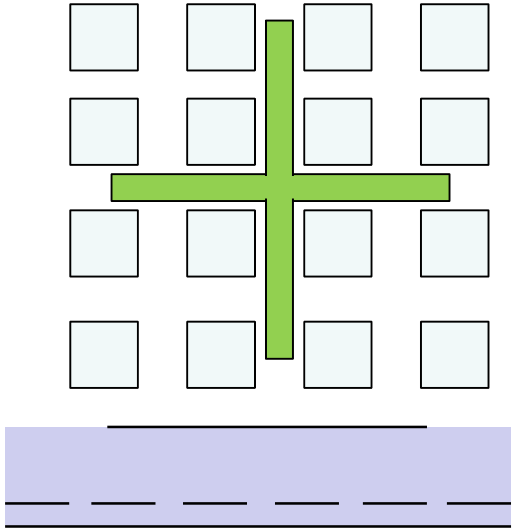




More Reflectarrays – X/Ka-band

- **Features:**
  - Compatible with 6U CubeSat
  - X- and Ka-band design for Telecom
  - Transmit only
  - Deployed area: 600mm × 670mm
  - Gain of 32dBic between 8.4-8.45GHz
  - Gain of 43.5.0dBic between 31.8-32.3GHz
  - Co-located feed with identical beam-pointing





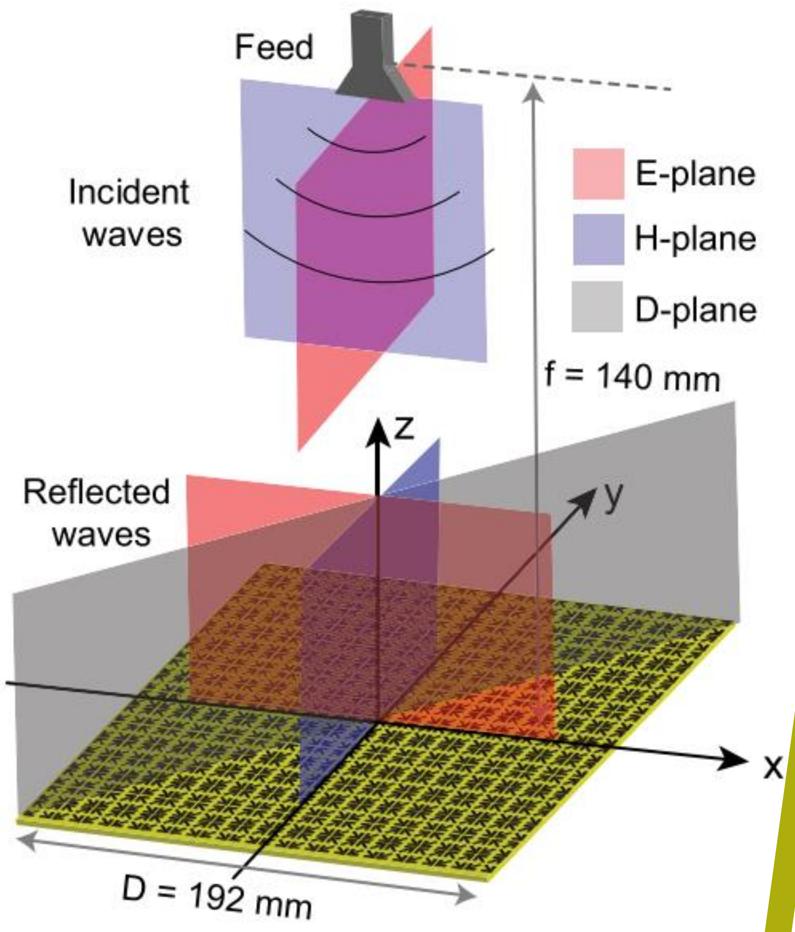
X-band elements in green (h_X=1.5mm)
Ka-band elements in blue (h_{Ka}=0.406mm)

Beam Steering Reflectarrays

Jet Propulsion Laboratory
California Institute of Technology

Beamsteering Reflectarrays

Reflectarray antennas, Wiley 2018



Beam Steering Approaches

Feed tuning

1. Single feed
2. Multiple feeds
3. Switched array
4. Phased Array

For single or dual reflectors

Aperture Tuning

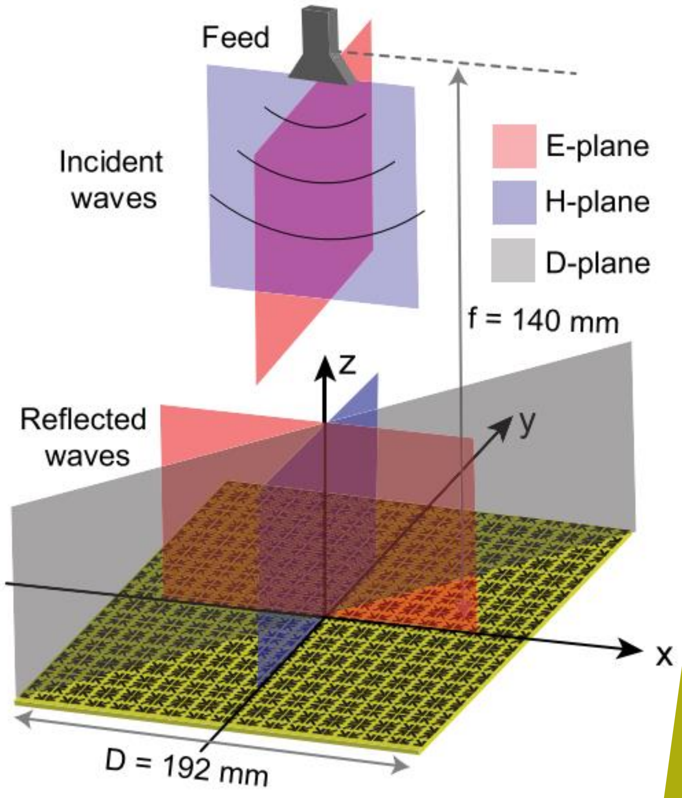
1. Mechanical Tuning (Motors, Actuators)
2. Electronic Devices (PIN, Varactors, MEMS)
3. Functional materials (Liquid crystal, ferroelectric)

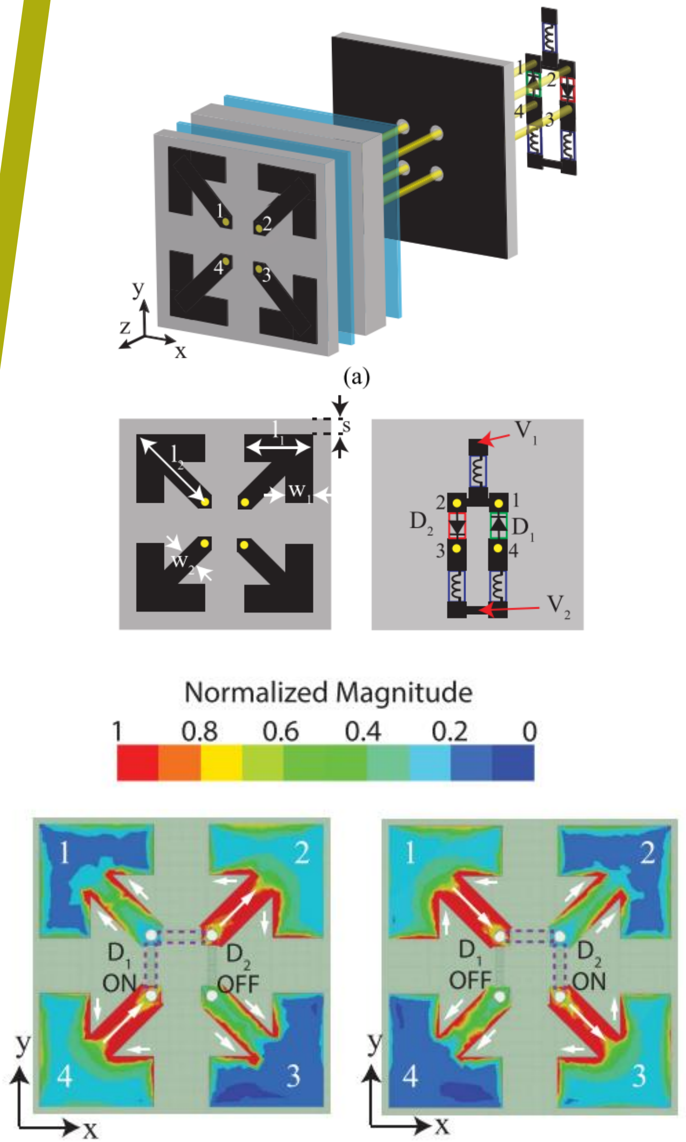
Phase distribution on each element of reflectarray

$$\varphi(x_i, y_i) = -k_0 R_i + \varphi_R(x_i, y_i)$$

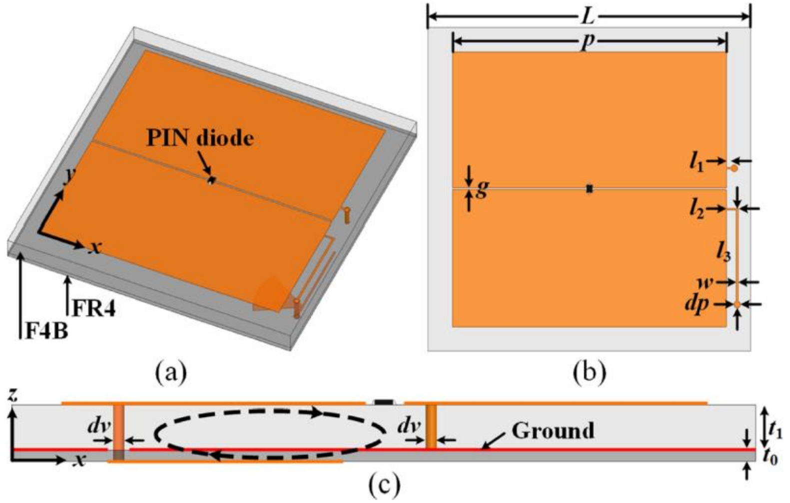
1st term- Spatial delay between phase center of feed and element on reflectarray
2nd term- Reflection phase of i^{th} element on aperture

Electronically Reconfigurable Unit cells

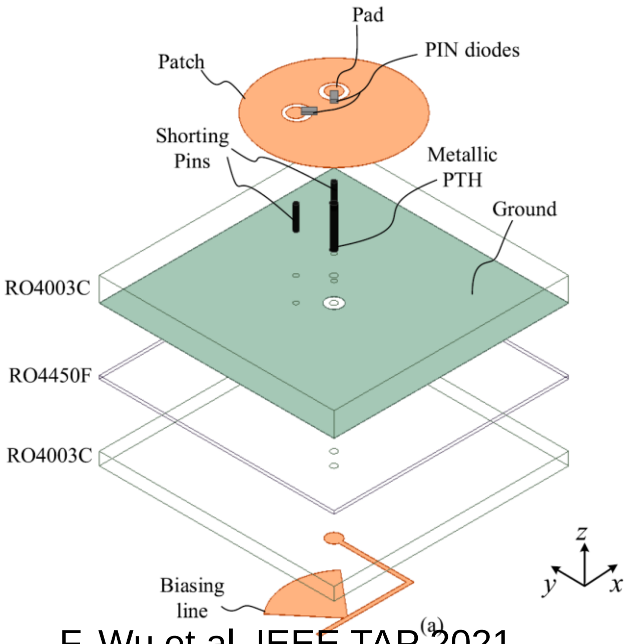




H. Luyen et.al, IEEE TAP 2022



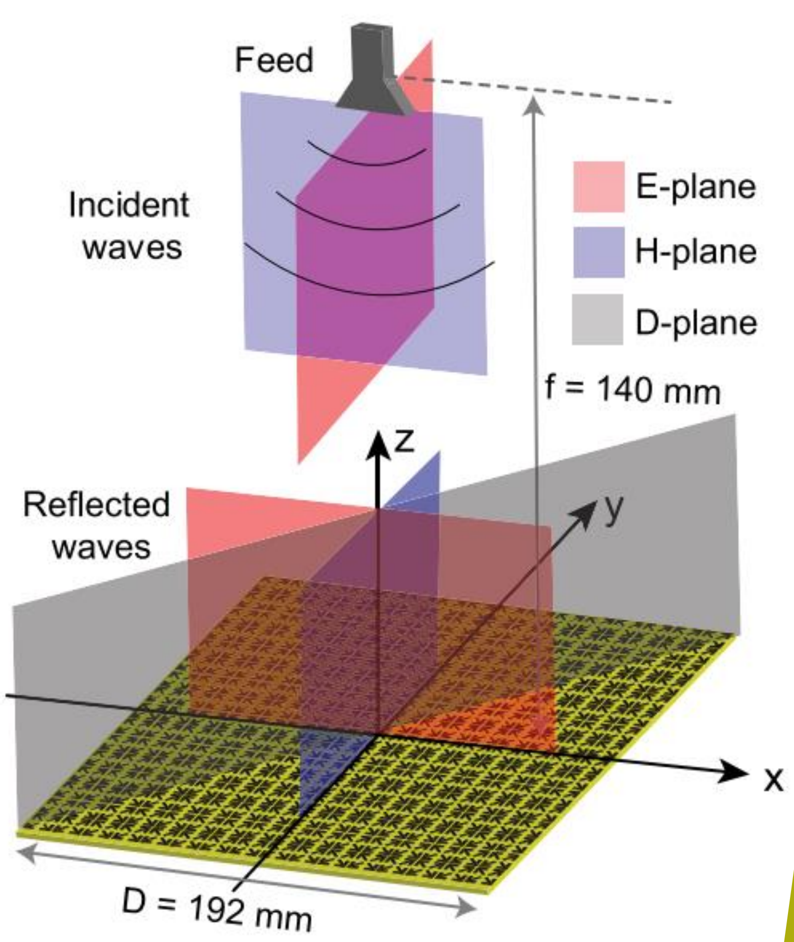
J. Han et.al, IEEE AWPL 2019



F. Wu et.al, IEEE TAP 2021

Electronic Beamsteering Reflectarrays

H. Luyen et.al, IEEE TAP 2022



$$\Phi_{out}(m,n) = -\frac{2\pi}{\lambda} r_{mn}\ \sin(\theta_0)\ \cos(\phi_{mn} - \phi_0) + \phi_{ref}$$

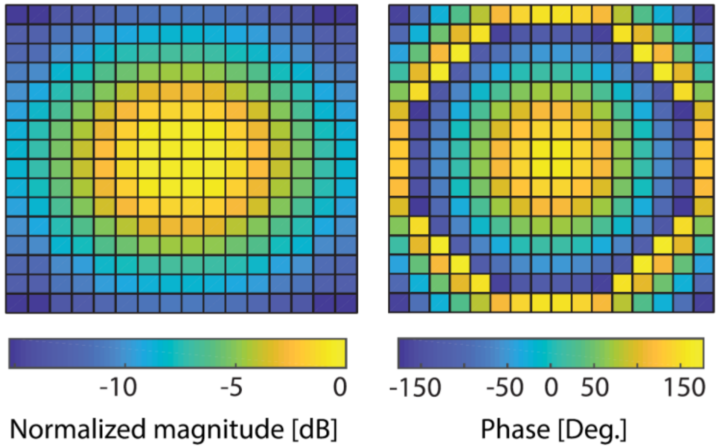
Desired outgoing phase — Direction of main beam (θ_0, φ_0)

$$\Phi_{cell}(m,n) = \Phi_{out}(m,n) - \Phi_{inc}(m,n)$$

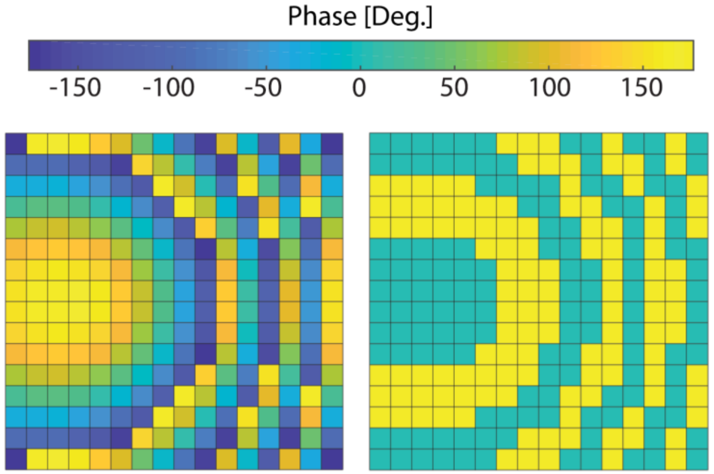
Phase shift of unit cell — Incident E field phase

For 1 bit operation

$$\text{Mode} = \begin{cases} 1, & \text{if } -90° \le \Phi_{cell}(m,n) < 90° \\ 2, & \text{if } 90° \le \Phi_{cell}(m,n) \text{ or } \Phi_{cell}(m,n) < -90° \end{cases}$$



Amplitude and phase distribution of incident E field from feed horn antenna on reflectarray

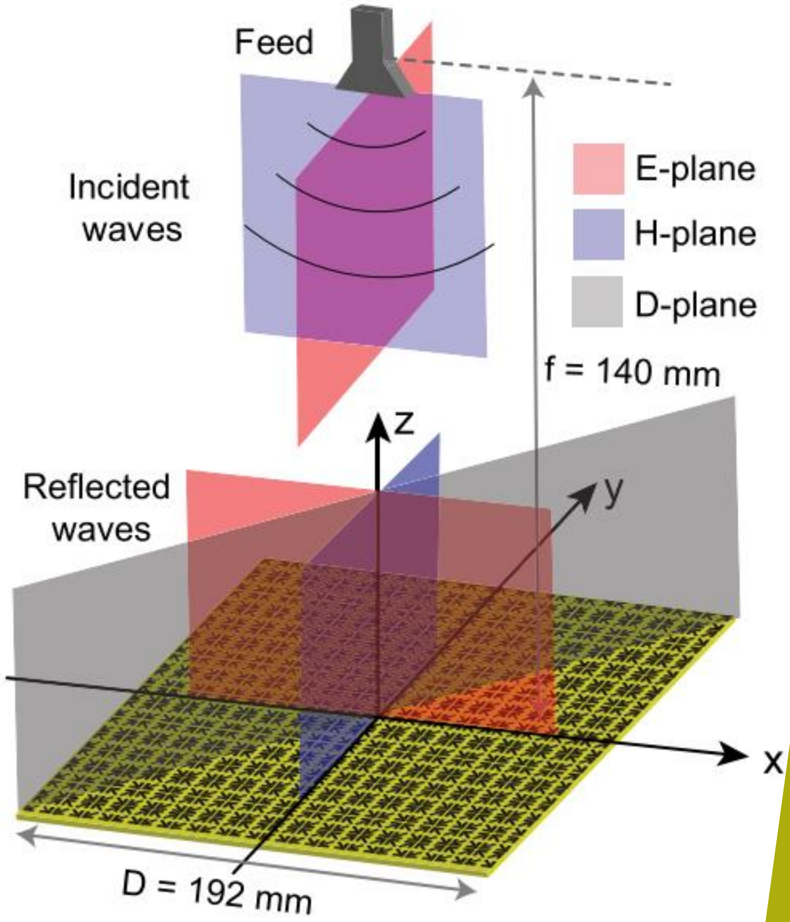


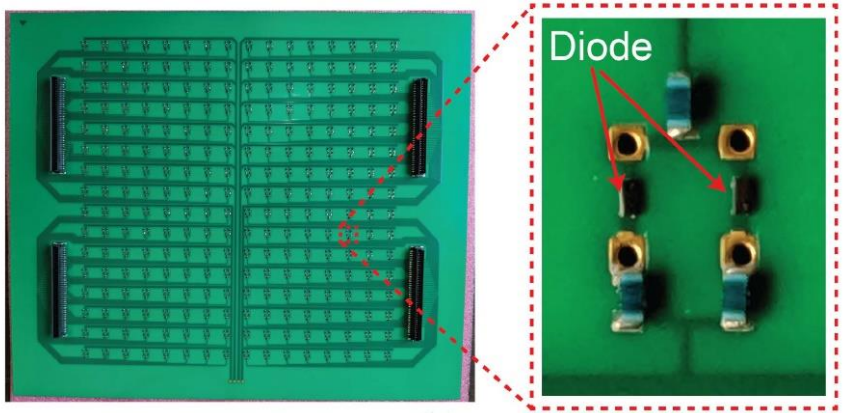
Non quantized and quantized phase distribution on unit cells for main beam at 30° in E plane

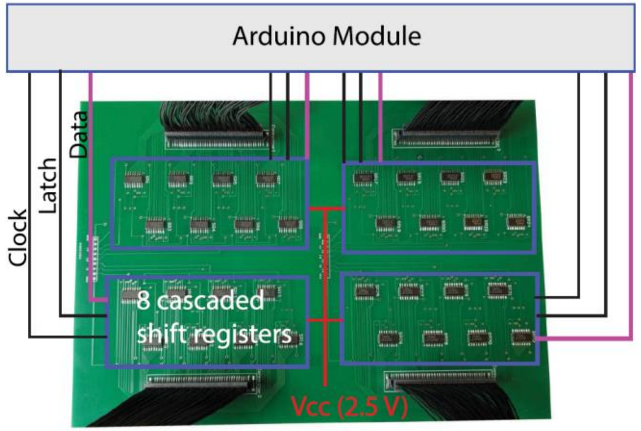
Jet Propulsion Laboratory
California Institute of Technology

Electronic Beamsteering Reflectarrays

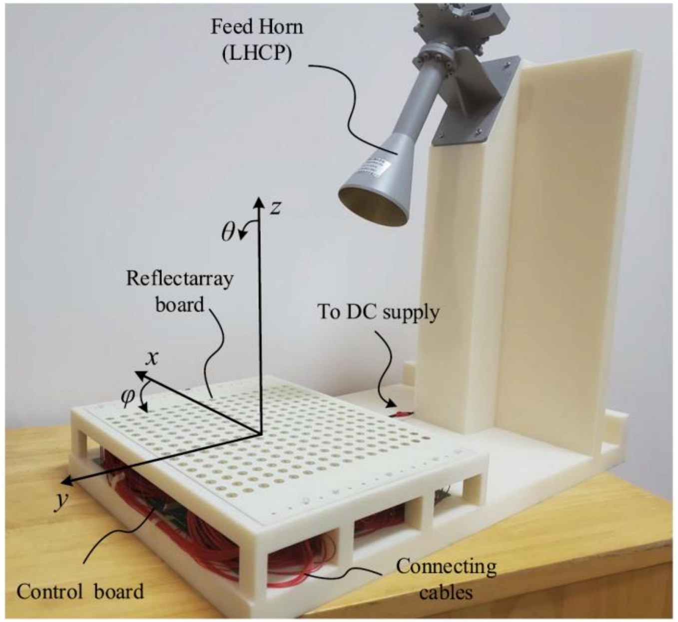
H. Luyen et.al, IEEE TAP 2022

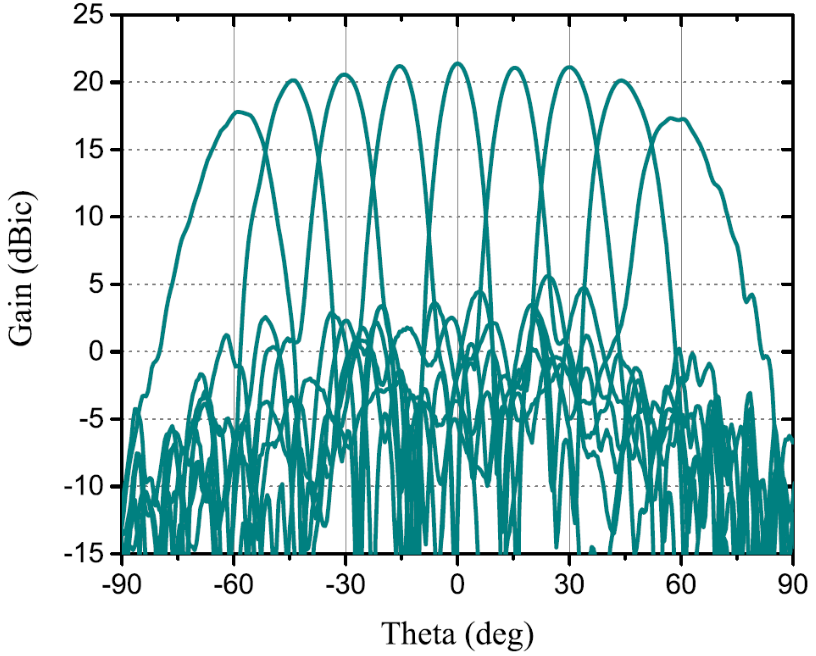






Control circuitry



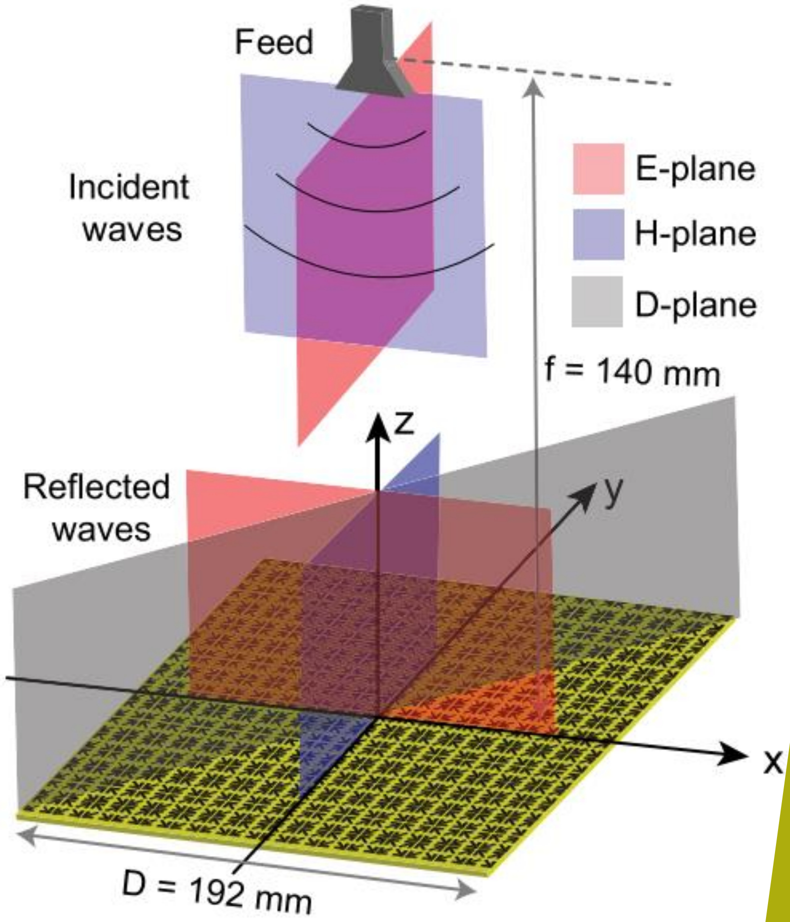


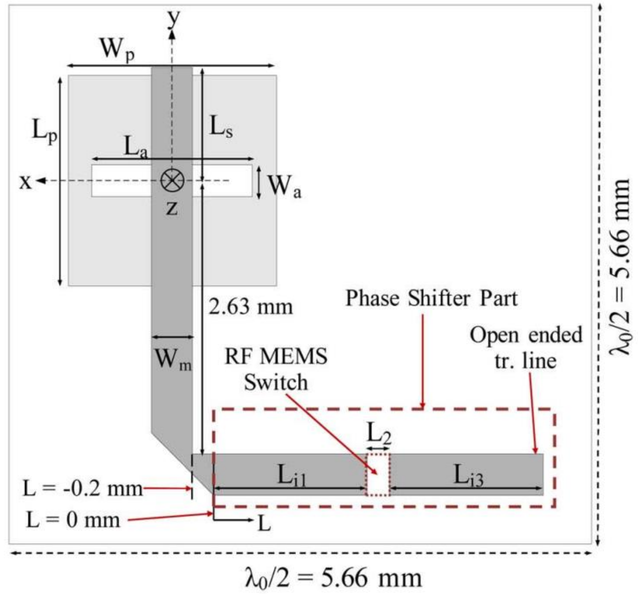
Beam steering performance

Jet Propulsion Laboratory
California Institute of Technology

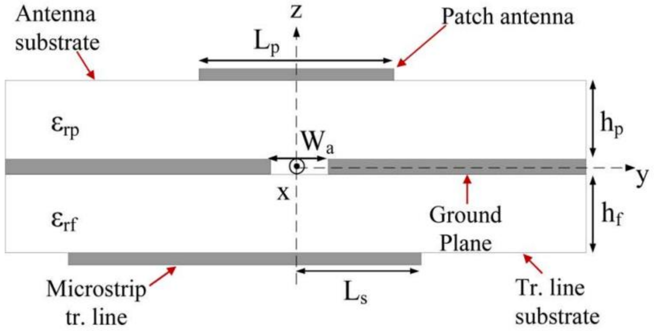
Beamsteering Reflectarrays using MEMS

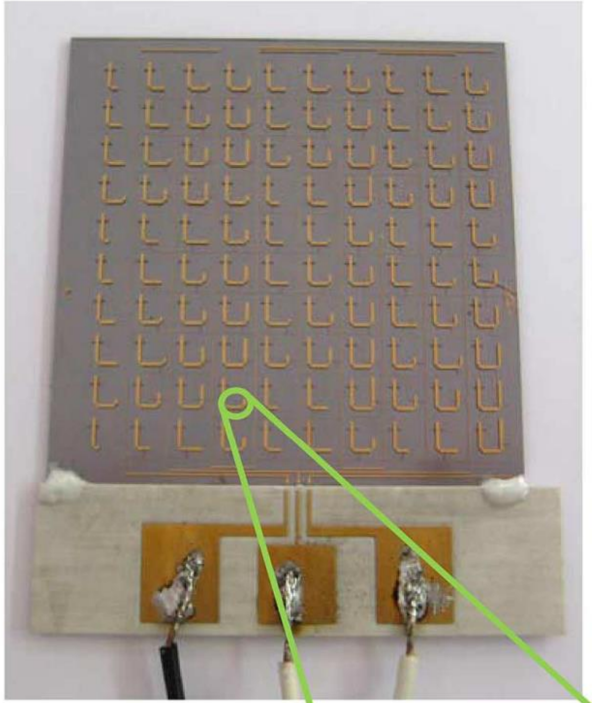
O. Bayraktar et.al, IEEE TAP 2012



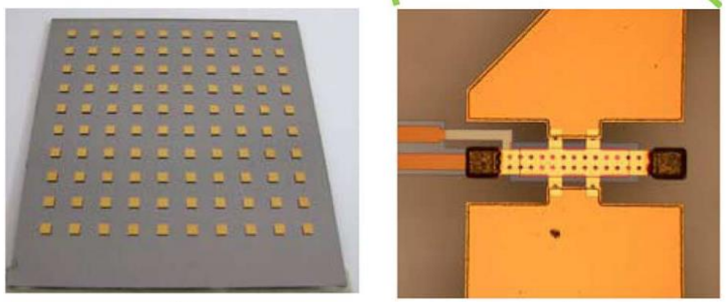


(a)





(a)



MEMS switch size 0.4 × 0.14 mm for Ka band

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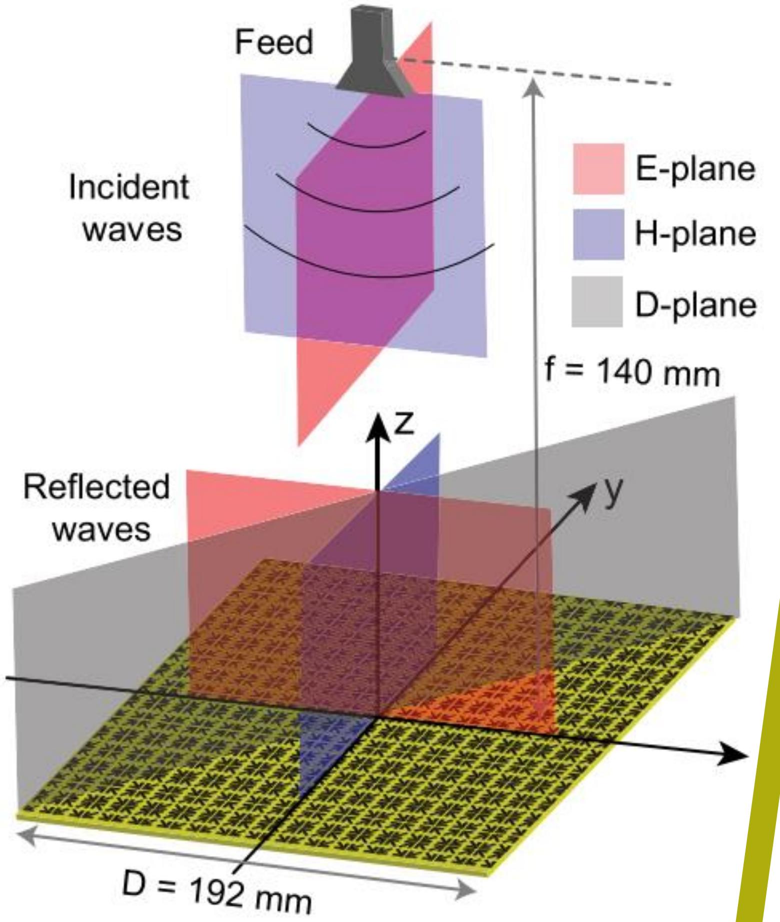
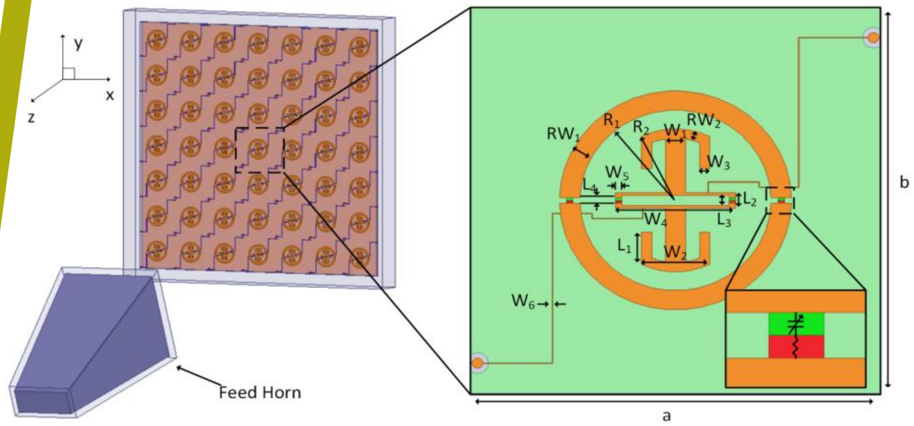
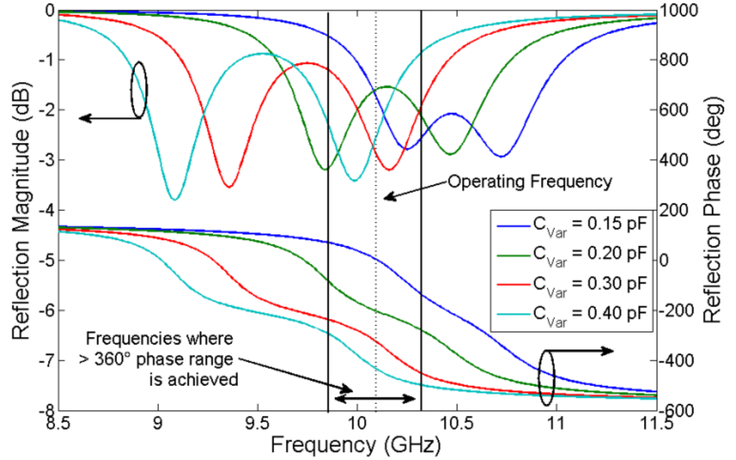
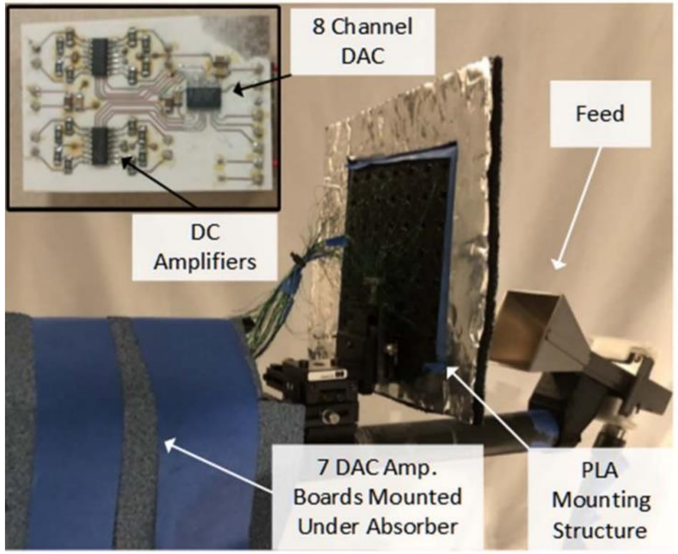
Continuous Electronic Beamsteering Reflectarrays

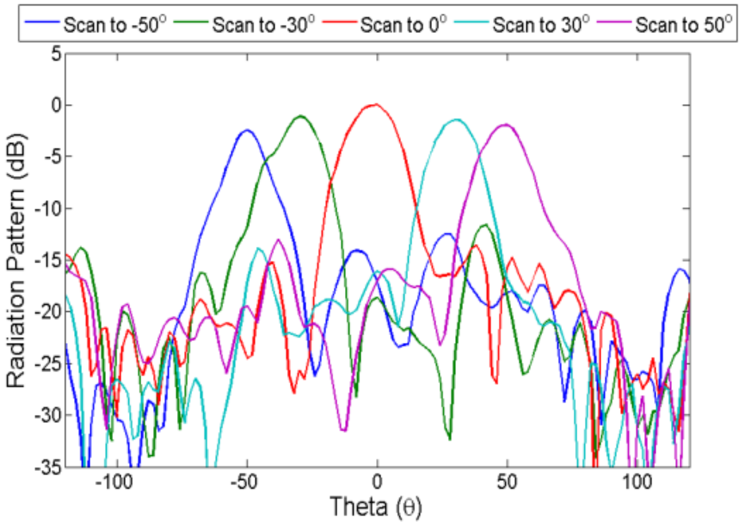
M. Trampler et.al, IEEE TAP 2020

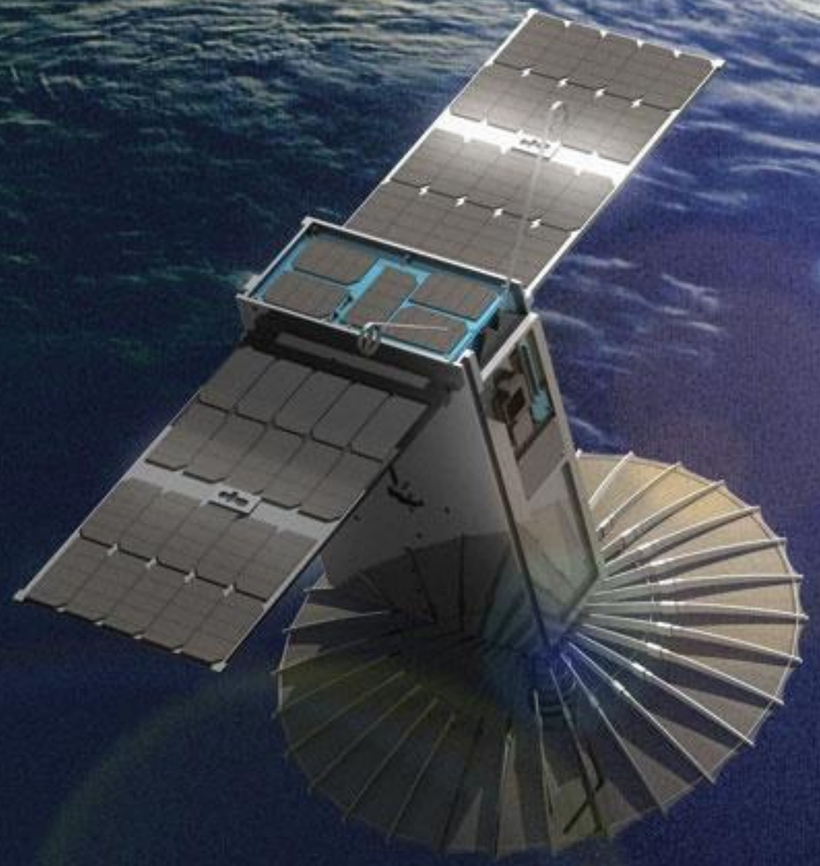












Mars Helicopter Communication Link and Innovative Antennas for Cubesats, Landers and Rovers

Nacer Chahat, Gaurangi Gupta
NASA Jet Propulsion Laboratory / California Institute of Technology

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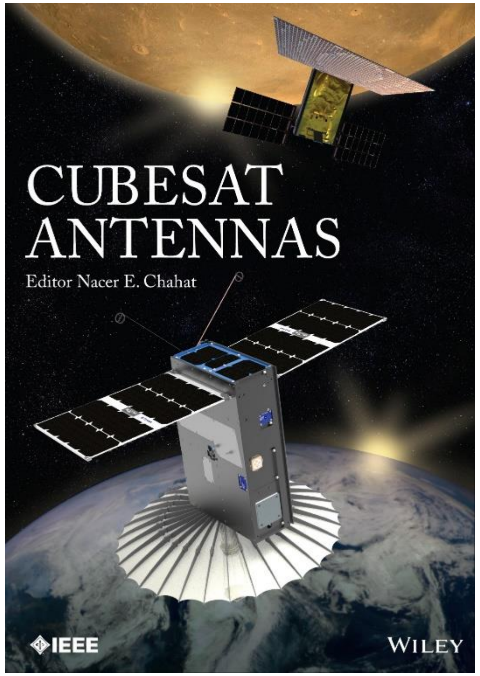

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