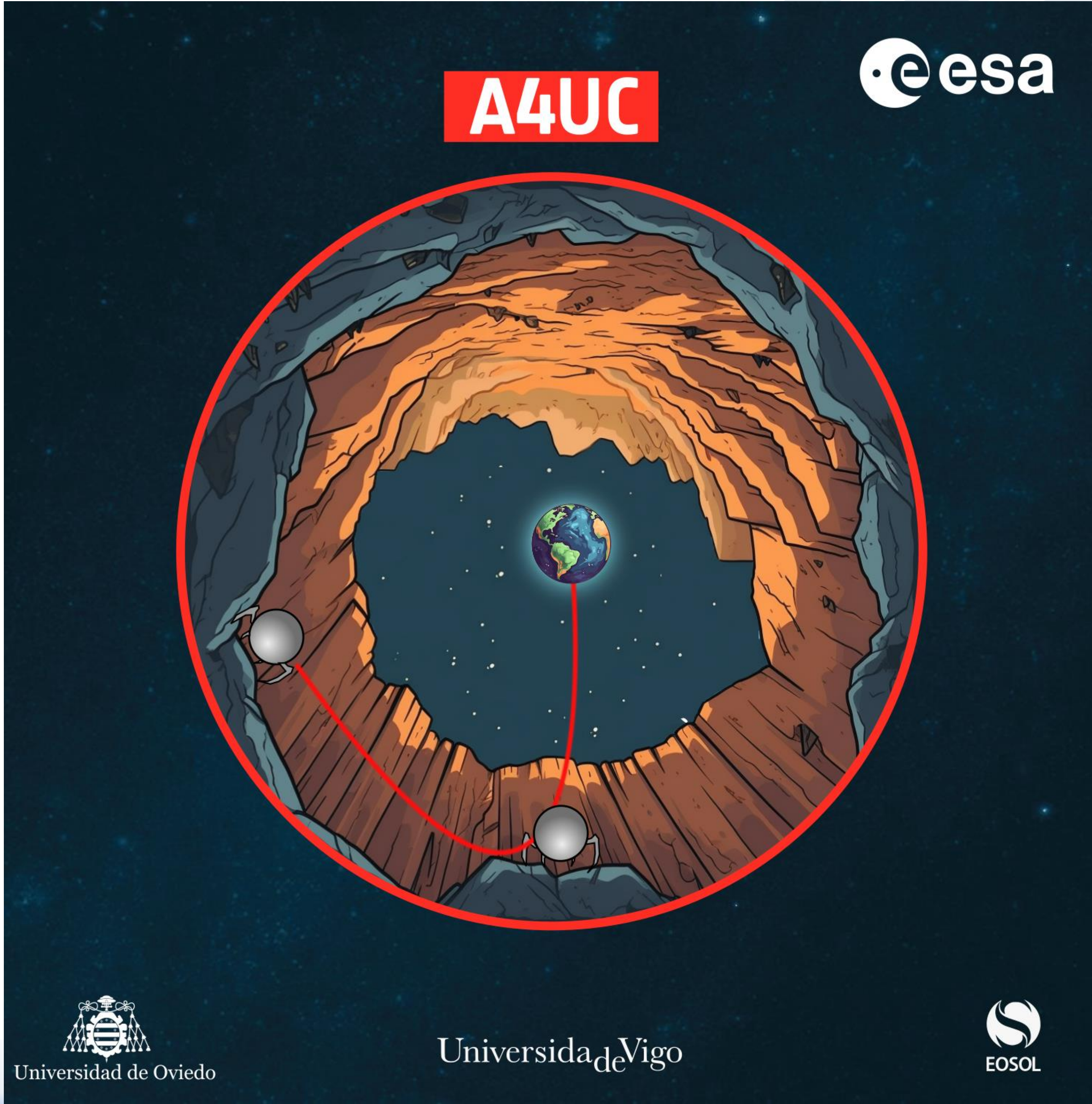
Antennas for Underground Communications

Final Presentation

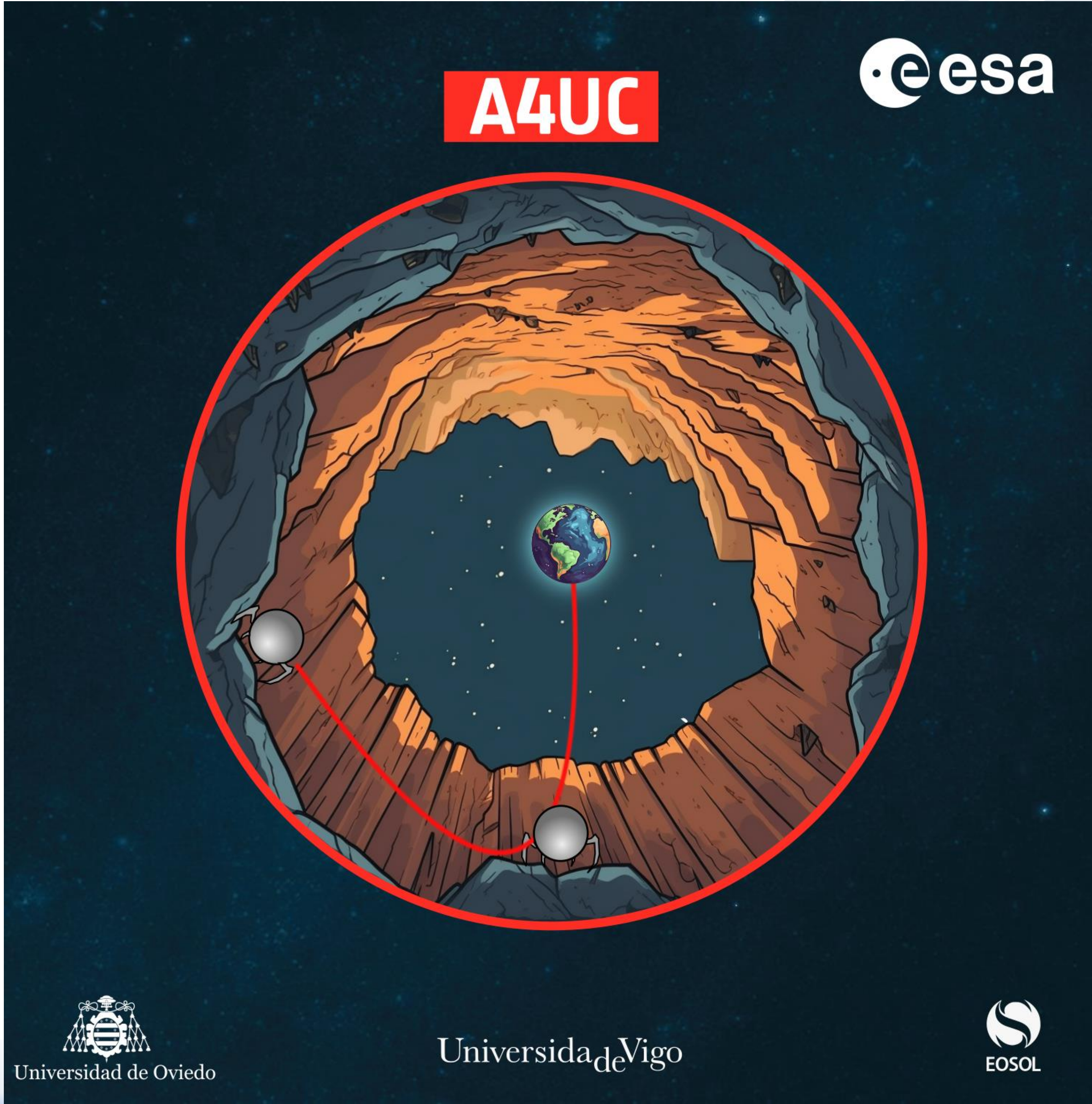
4th July 2024



AGENDA

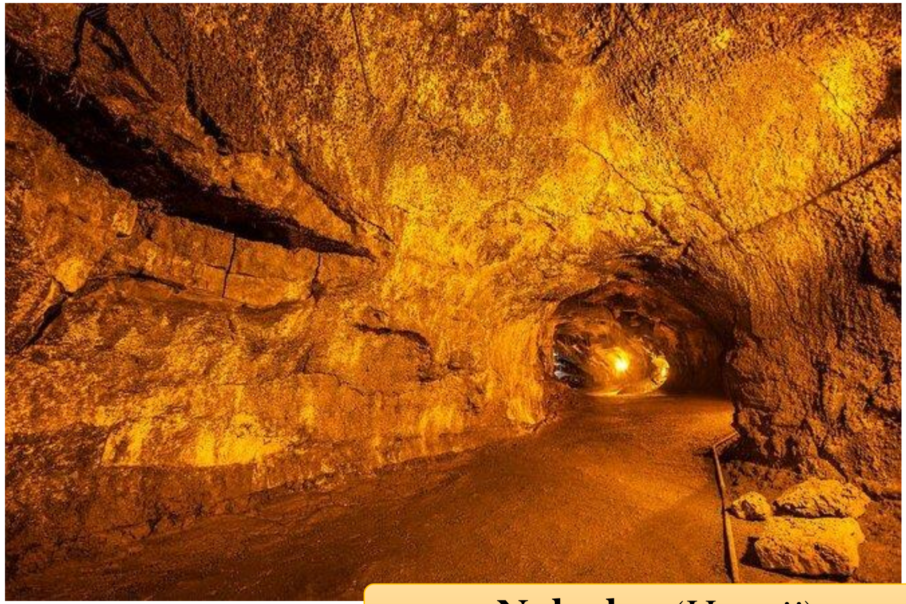
Antennas for Underground Communications

Introduction

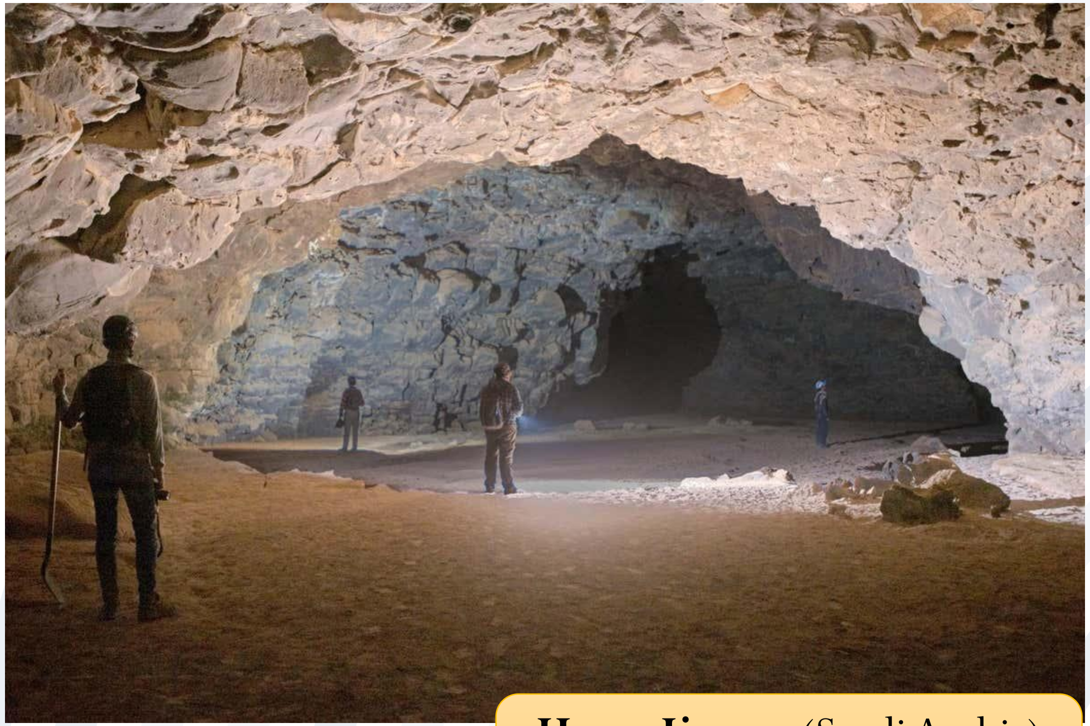


What are Lava Caves?

La Corona Volcano
(Lanzarote, Spain)



Nahuku (Hawaii)

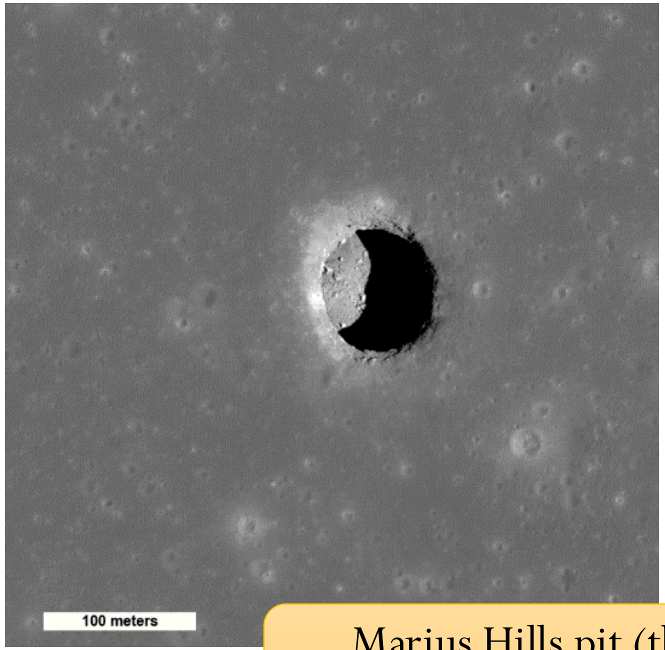


Umm Jirsan (Saudi Arabia)
Evidence of an ancient shelter

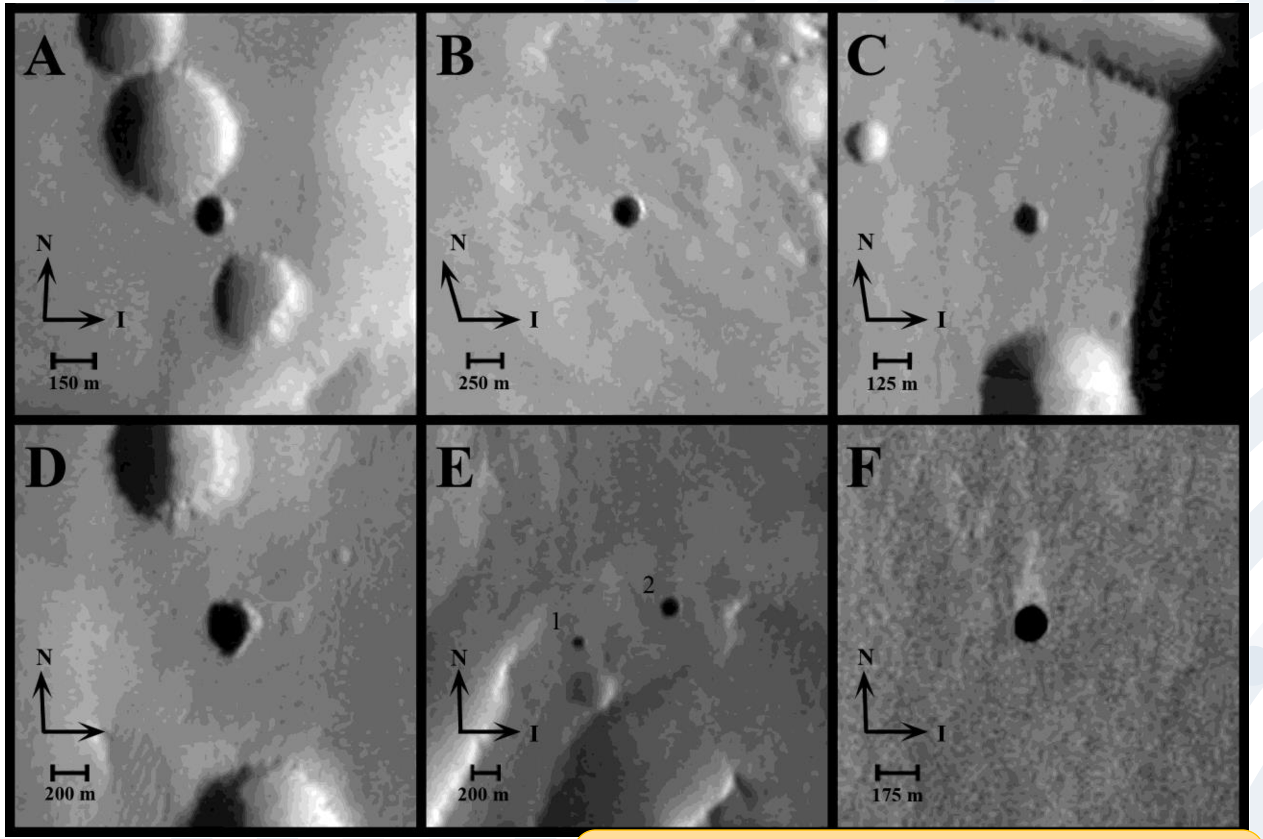
What are Lava Caves?
And skylights?

Jameo de la Puerta Falsa
(La Corona Volcano)

Skylight on the Moon and Mars



Marius Hills pit (the Moon)
[NASA/Goddard/Arizona State University]



Seven Possible Cave Skylights (Mars)
[NASA/JPL-Caltech/ASU/USGS]

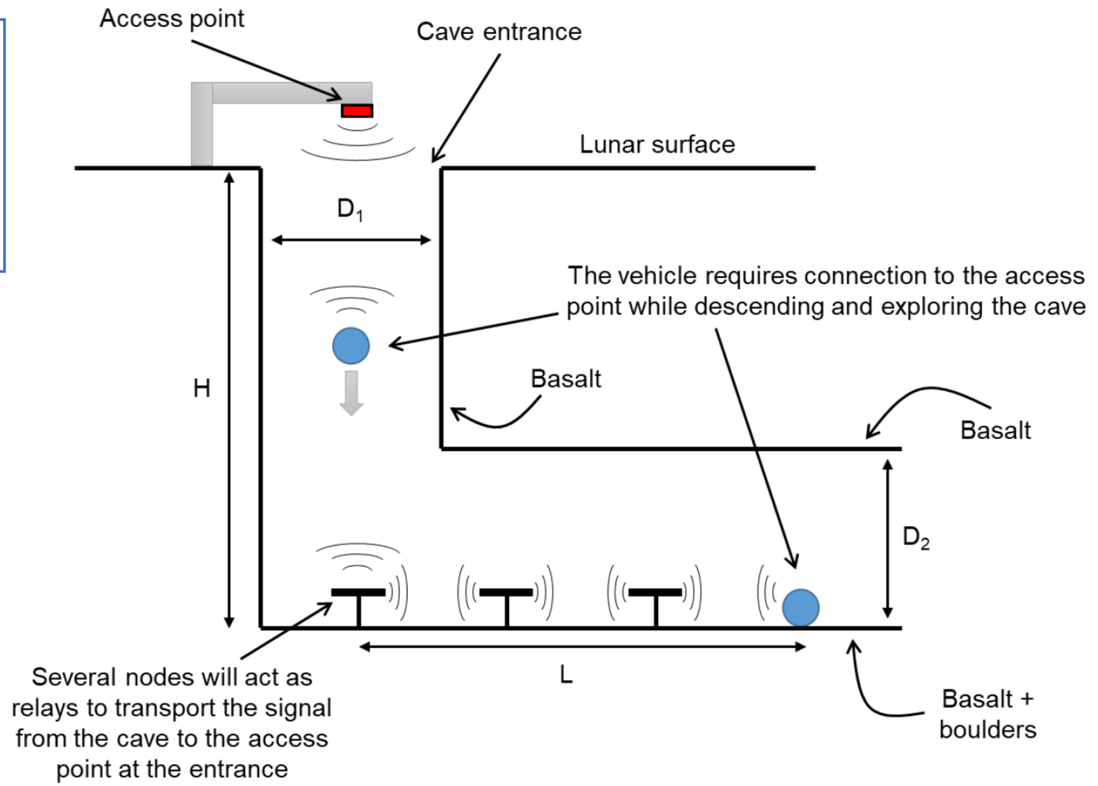
The Marius pit is about 34 meters (about 111 feet) deep and 65 by 90 meters (approximately 213 by 295 feet) wide.

La Corona Tube (Lanzarote)

Los Naturalistas cave (Lanzarote)

Objectives of the project

The objective of this activity is to provide of **model of the propagation of signals within natural caves** and to **design an antenna** that can **support and maximize data transmission** to the entrance of the cave



REQ-050 – Power consumption
< 2 W for the entire communications system (TBC)

REQ-060 – Mass
< 180 g for the entire communications system (TBC)

REQ-070 – Size
< 20 cm diameter/diagonal (TBC)

REQ-080 – Operational temperature
-20º to 60ºC (TBC)

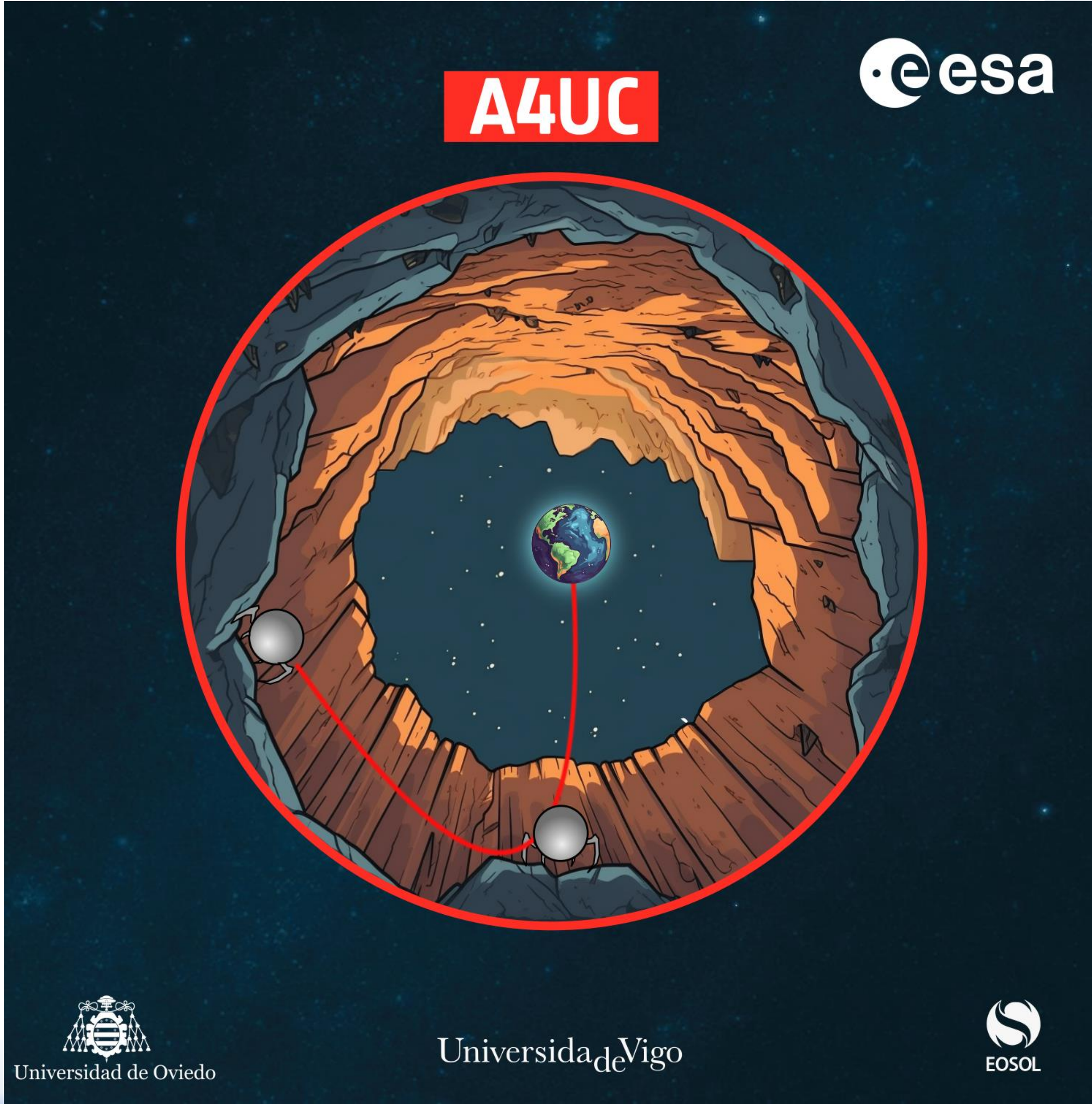
REQ-090 – Data rate
> 25 Mbit/s (TBC)

REQ-130 – Distance to be covered from the base of the pit (L in Fig. A1.1)
> 200 m (TBC). The target is to maximize this distance with the minimum number of nodes. The maximum achievable distance depending on the obstacles shall be defined within the activity.

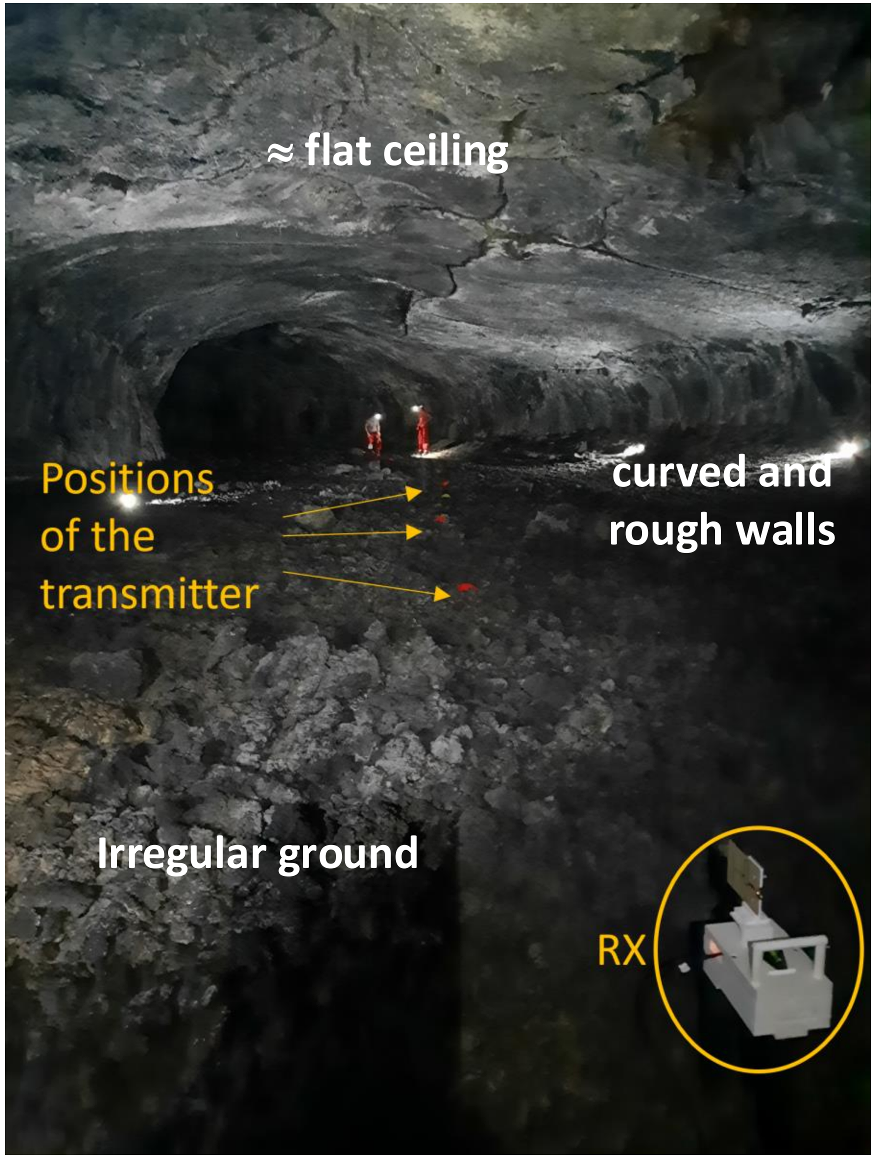
REQ-140 – Number of nodes
3 (TBC).

Antennas for Underground Communications

Propagation models

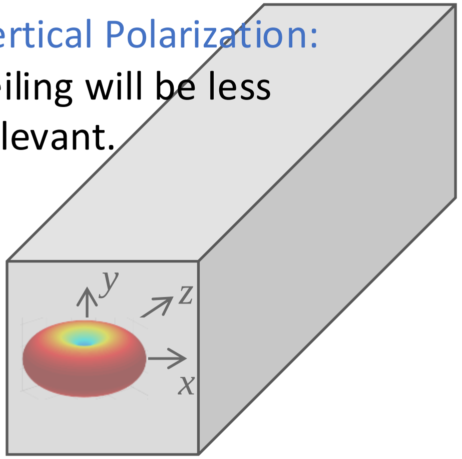


Propagation into caves

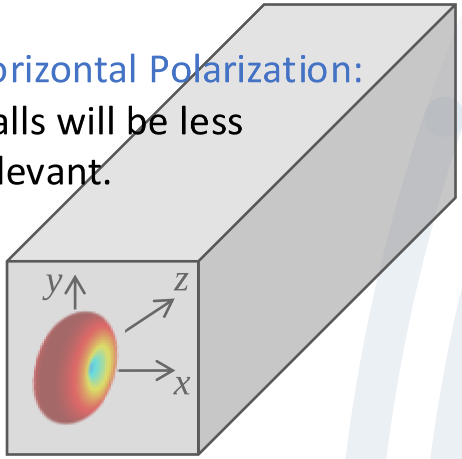


Propagation model

Vertical Polarization: ceiling will be less relevant.



Horizontal Polarization: walls will be less relevant.



- Propagation model based on image theory.
- Images relative to ground, floor, and both walls.
- Line of Sight.
- Reflection coeficientes:

$$\rho_{\perp} = \frac{\eta_2 cos\theta_i - \eta_0 \cos\theta_t}{\eta_2 cos\theta_i + \eta_0 \cos\theta_t} \qquad \rho_{\parallel} = \frac{\eta_2 cos\theta_t - \eta_0 \cos\theta_i}{\eta_2 cos\theta_t + \eta_0 \cos\theta_i}$$

$$\eta_0 = 377\ \Omega$$

$$\varepsilon_{r2} = 9$$

$$\sigma_2 = 0.05\ S/m \qquad \eta_2 = \sqrt{\frac{\mu_0}{\varepsilon_{r2}\varepsilon_0 - j\,\omega/\sigma_2}}\ (\Omega)$$

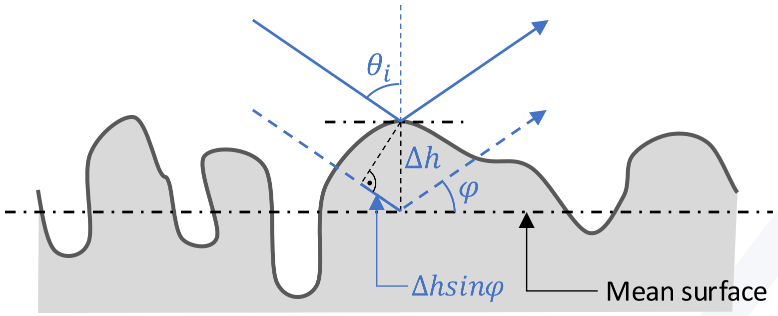
$$sin\theta_i = \sqrt{\varepsilon_{r2}}sin\theta_t$$

- Antennas are simulated as $\lambda/2$ dipoles, with a radiation ppattern similar to the ones used in measurements.

Propagation into caves

Propagation model

- Diffuse reflection due to irregularities:



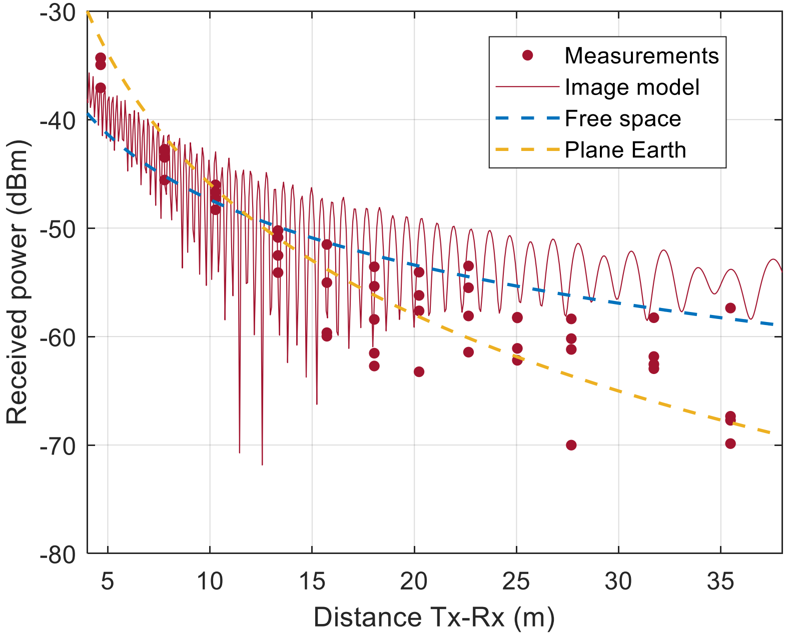
$$g = \frac{4\pi\Delta h sin\varphi}{\lambda}$$

$$\rho_f = \exp(-{}^1/_2\, g^2) I_0({}^1/_2\, g^2)$$

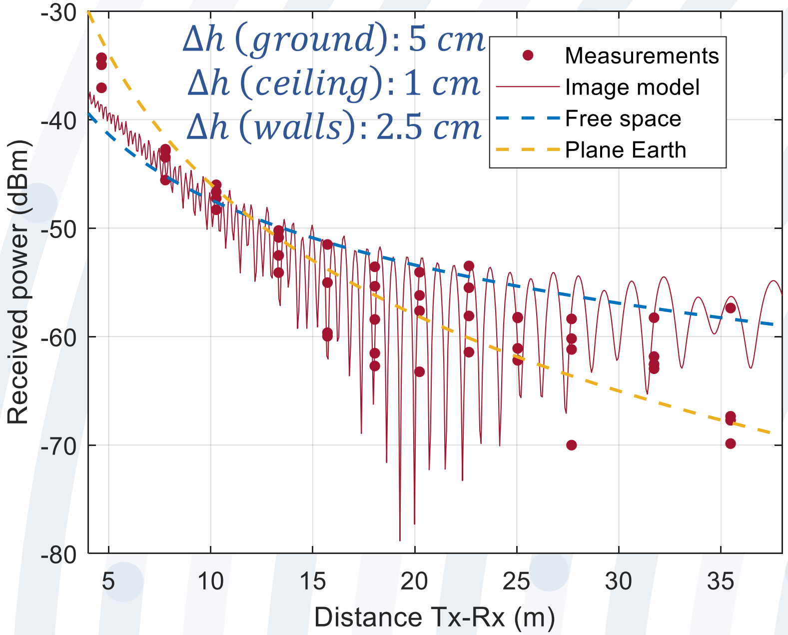
$$\rho_{eff_{\perp,\parallel}} = \rho_f \cdot \rho_{\perp,\parallel}$$

Measurements in Naturalistas Cave

Specular reflection



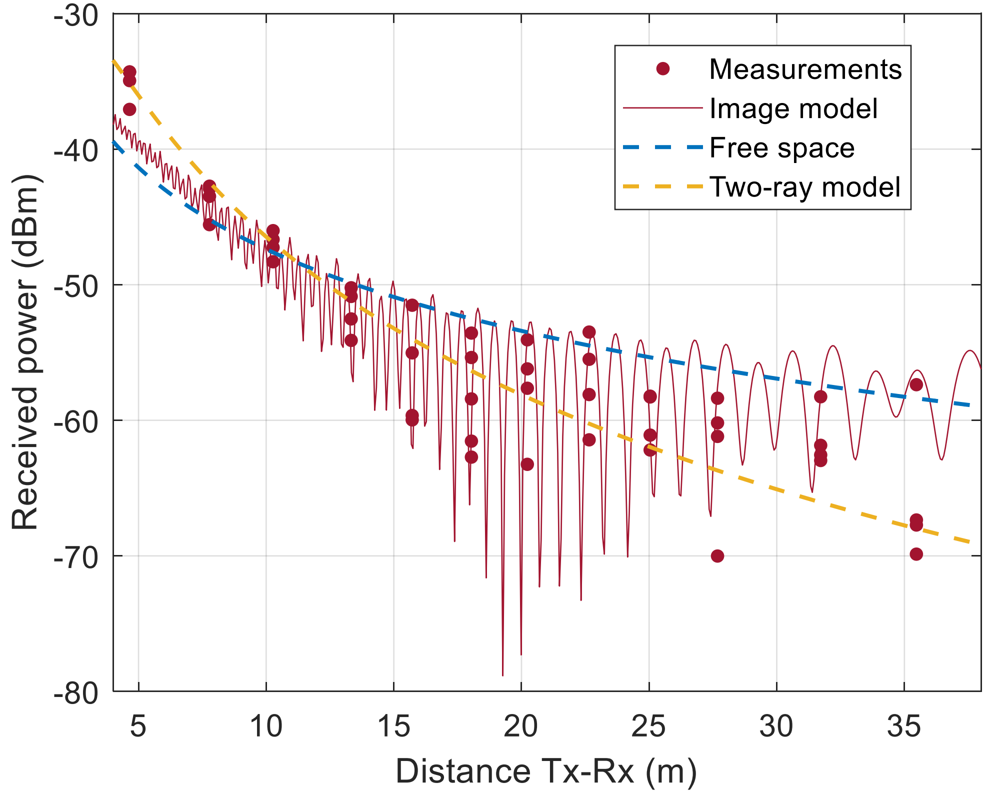
Diffuse reflection



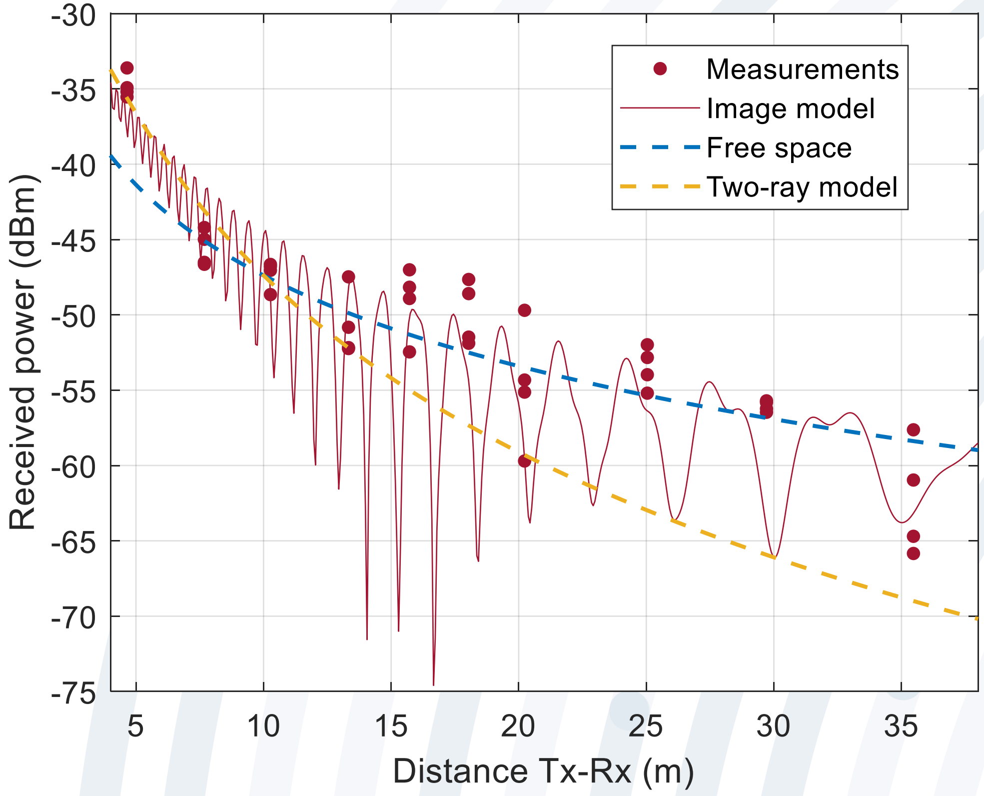
Propagation into caves

Measurements in Naturalistas Cave

2.4 GHz, Vertical polarization ($h_t = h_r = 37\ cm$)



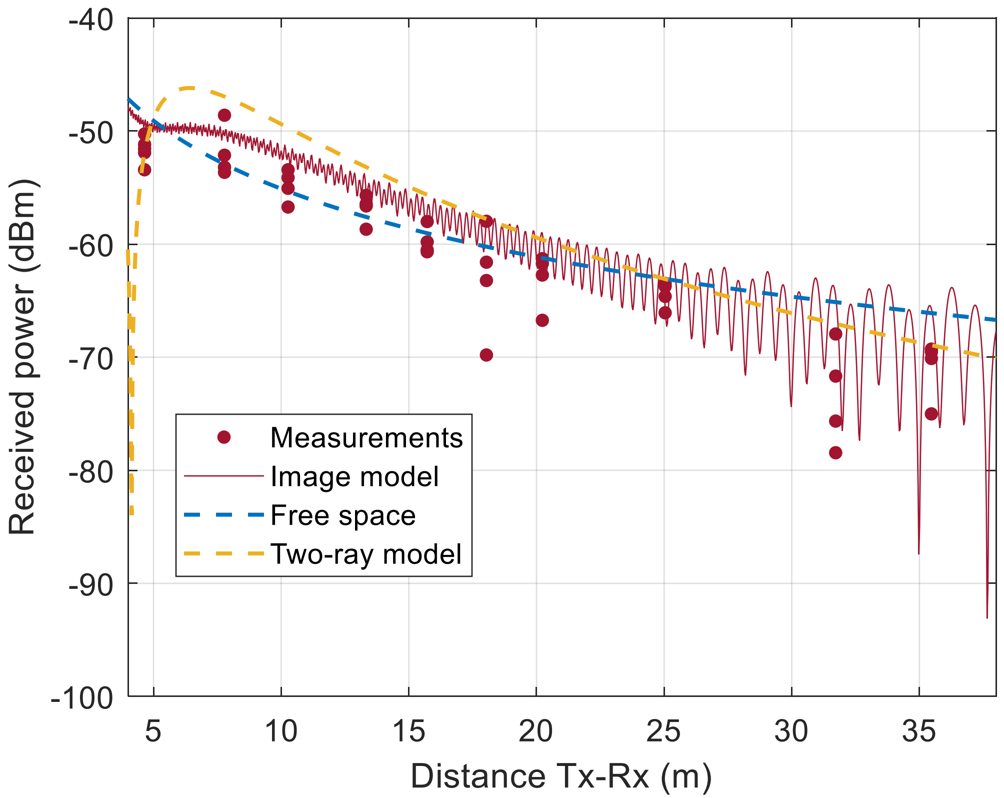
2.4 GHz, Horizontal polarization ($h_t = h_r = 33\ cm$)



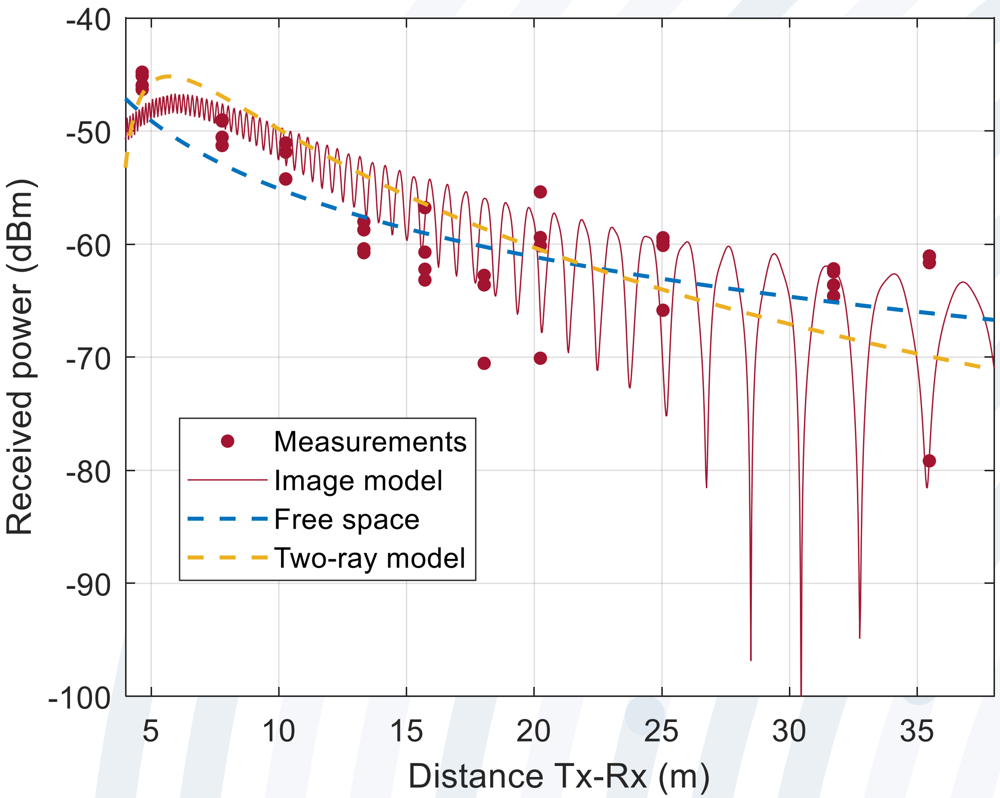
Propagation into caves

Measurements in Naturalistas Cave

5 GHz, Vertical polarization ($h_t = h_r = 35\ cm$)



2.4 GHz, Horizontal polarization ($h_t = h_r = 33\ cm$)



Propagation into caves

Simulations for a big cave:

$200m\ (width) \times 50m\ (height)$

- The effect of walls and ceiling is minimized.
- The received power tends to the value given by the two-ray model ($\rho = -1$) /Plane Earth, ***regardless of the ground roughness:***

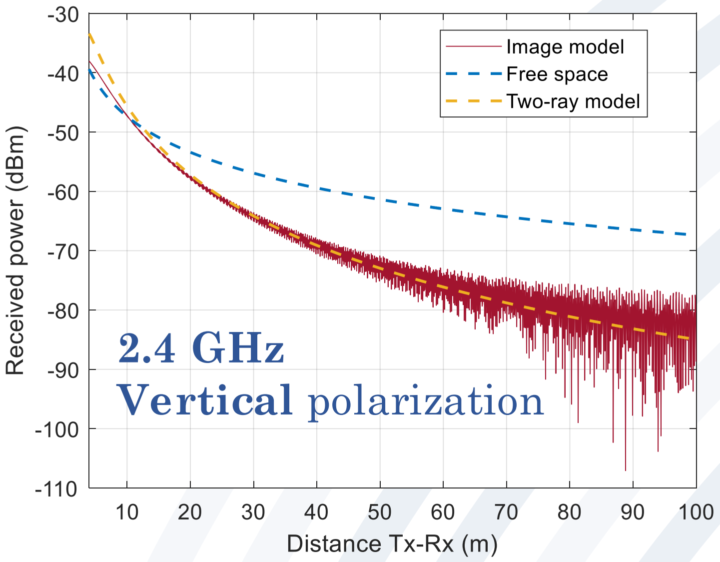
$$h_t, h_r \ll d \quad \Rightarrow \quad \theta_i \approx 90°, \varphi \approx 0°$$

$$g \approx 0$$

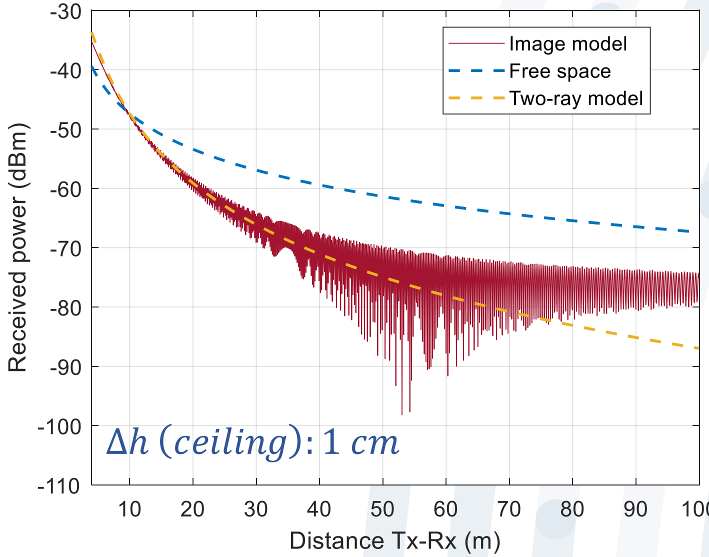
$$\rho_f \approx 1$$

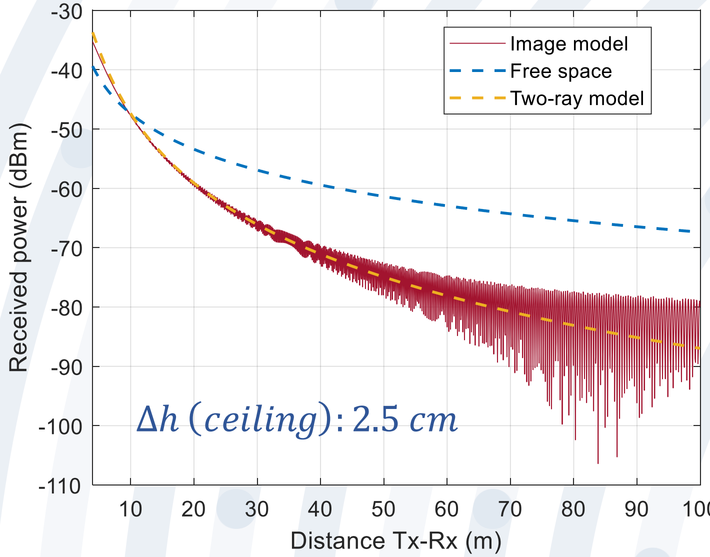
$$\rho_{eff_{\perp,\parallel}} \approx \rho_{\perp,\parallel}$$

Ground reflection coefficient ≈ -1 for both polarizations.

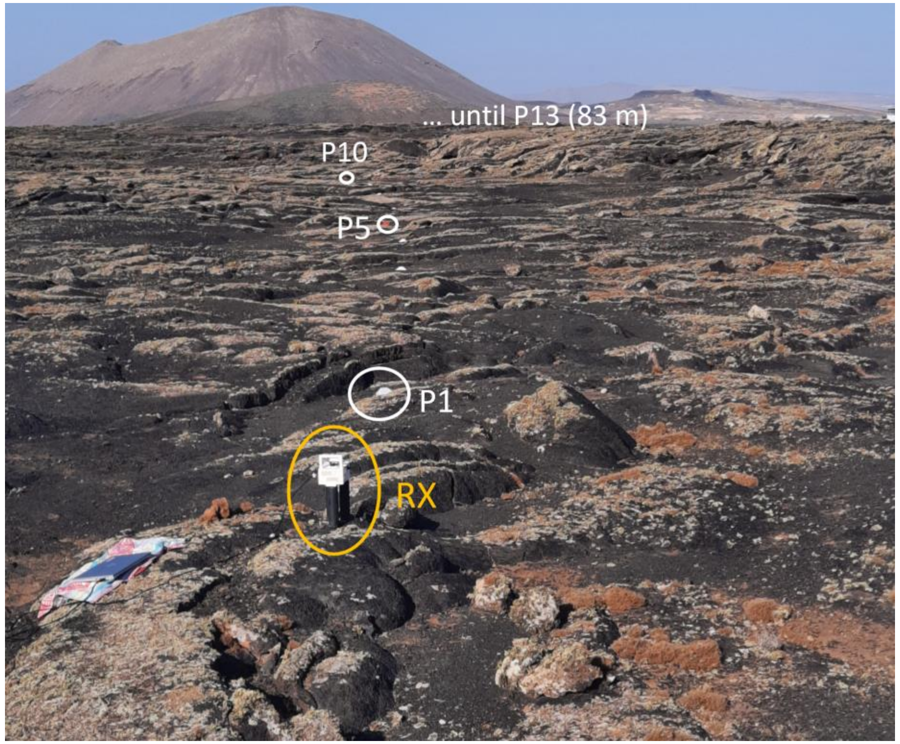


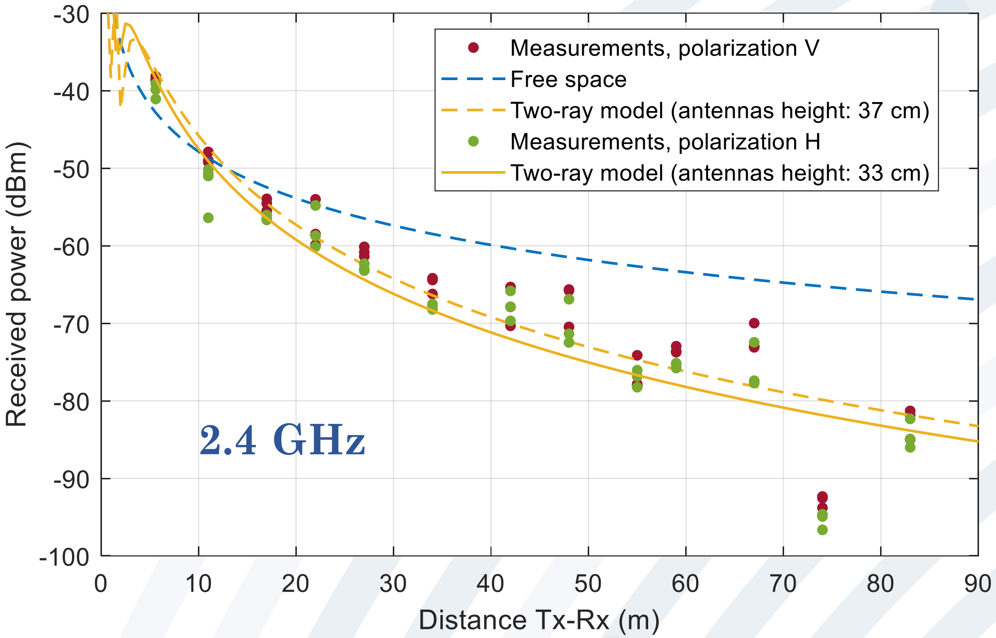
2.4 GHz, Horizontal polarization

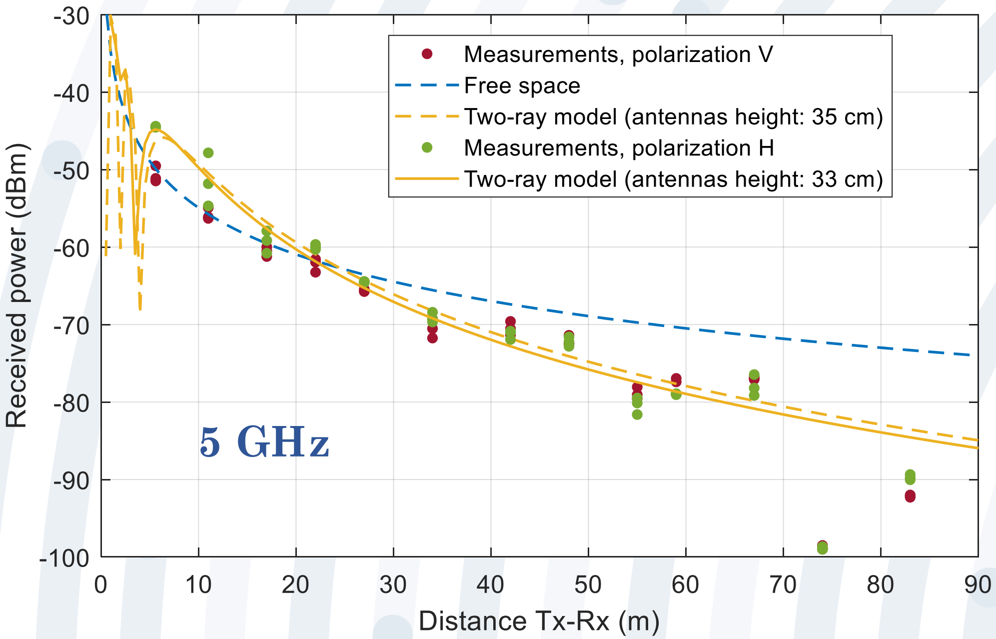




Propagation in open area

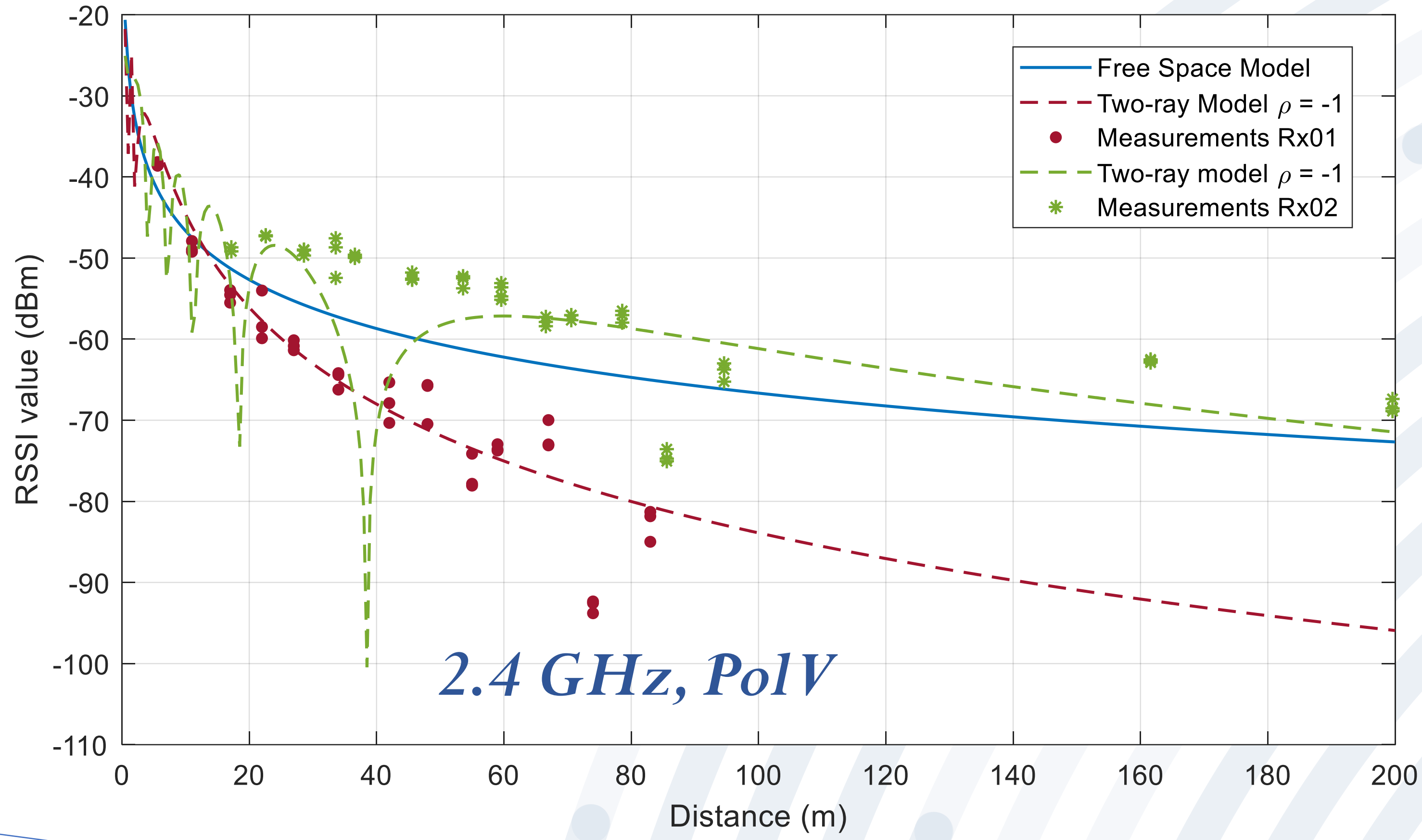


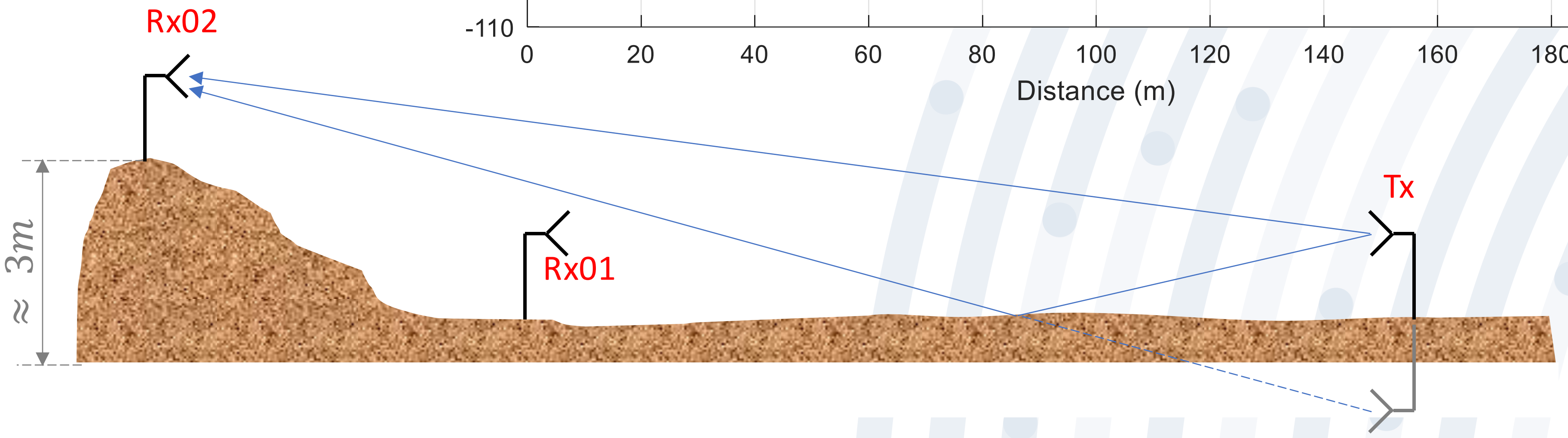




- Measurements are similar for both frequencies and both polarizations.
- Small differences due to the slight differences in antenas heights.
- Agreement with Plane Earth model, which only depends on antennas height.

Propagation in open area

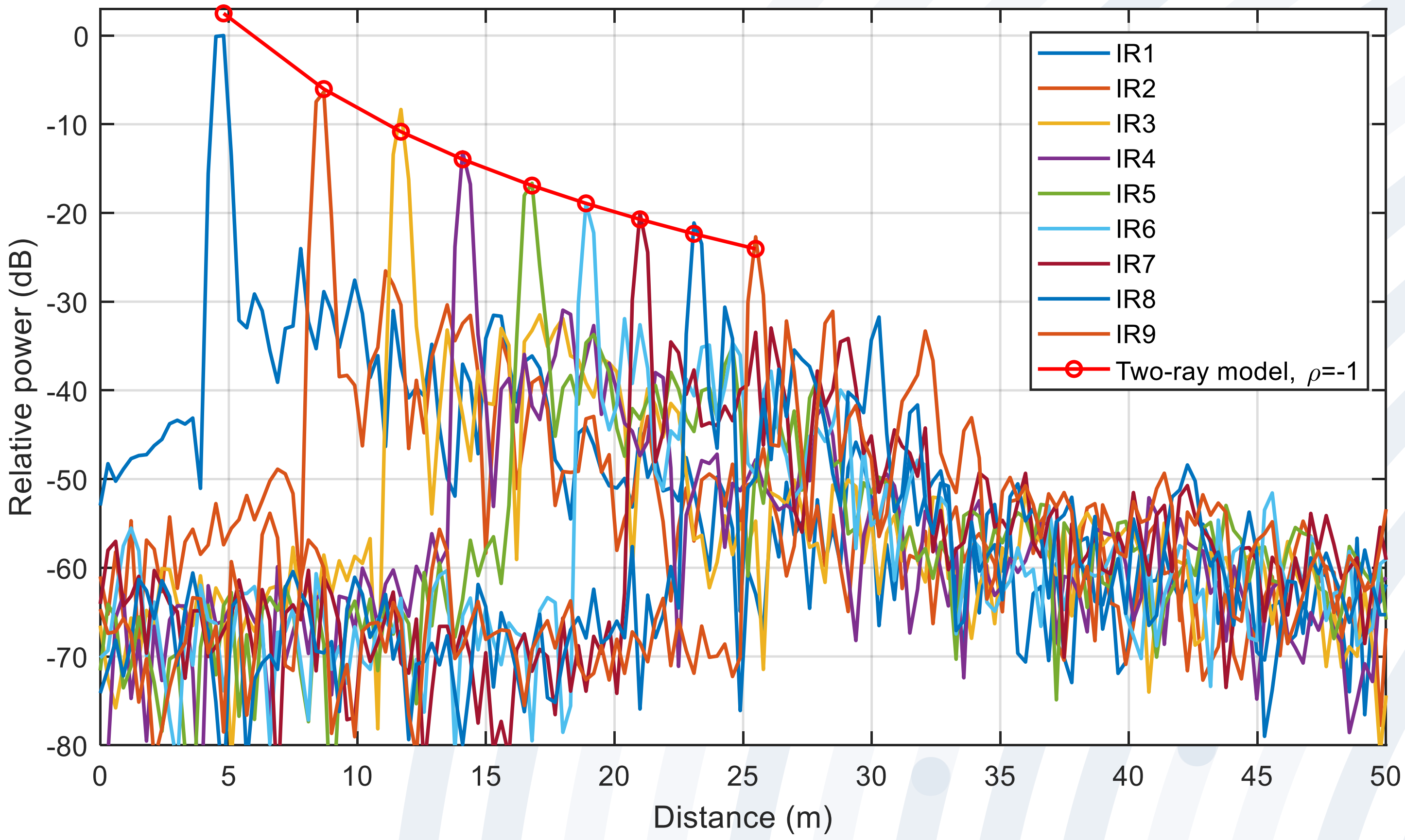




Propagation into caves

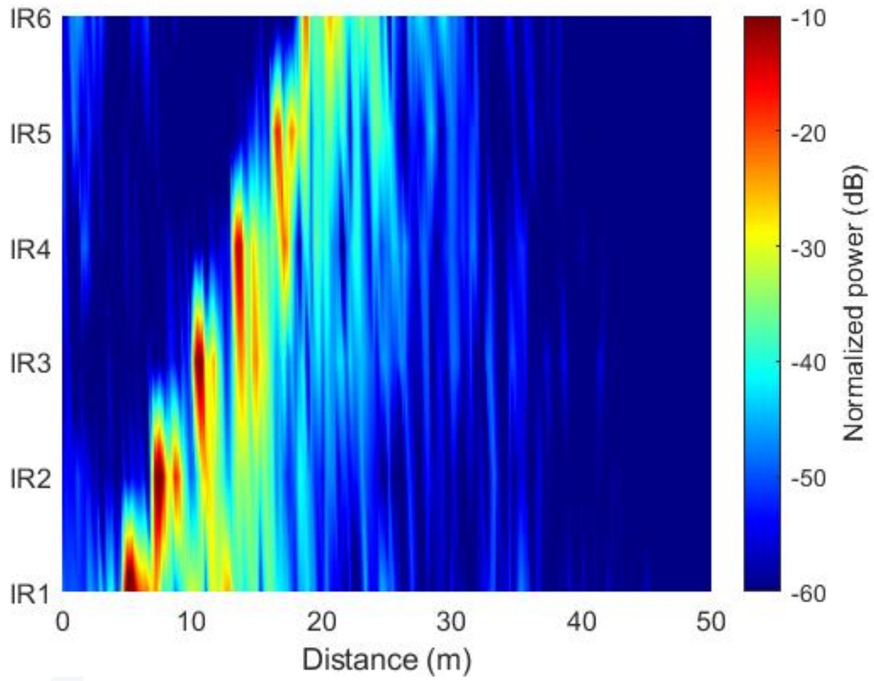
Measurements in Naturalistas Cave

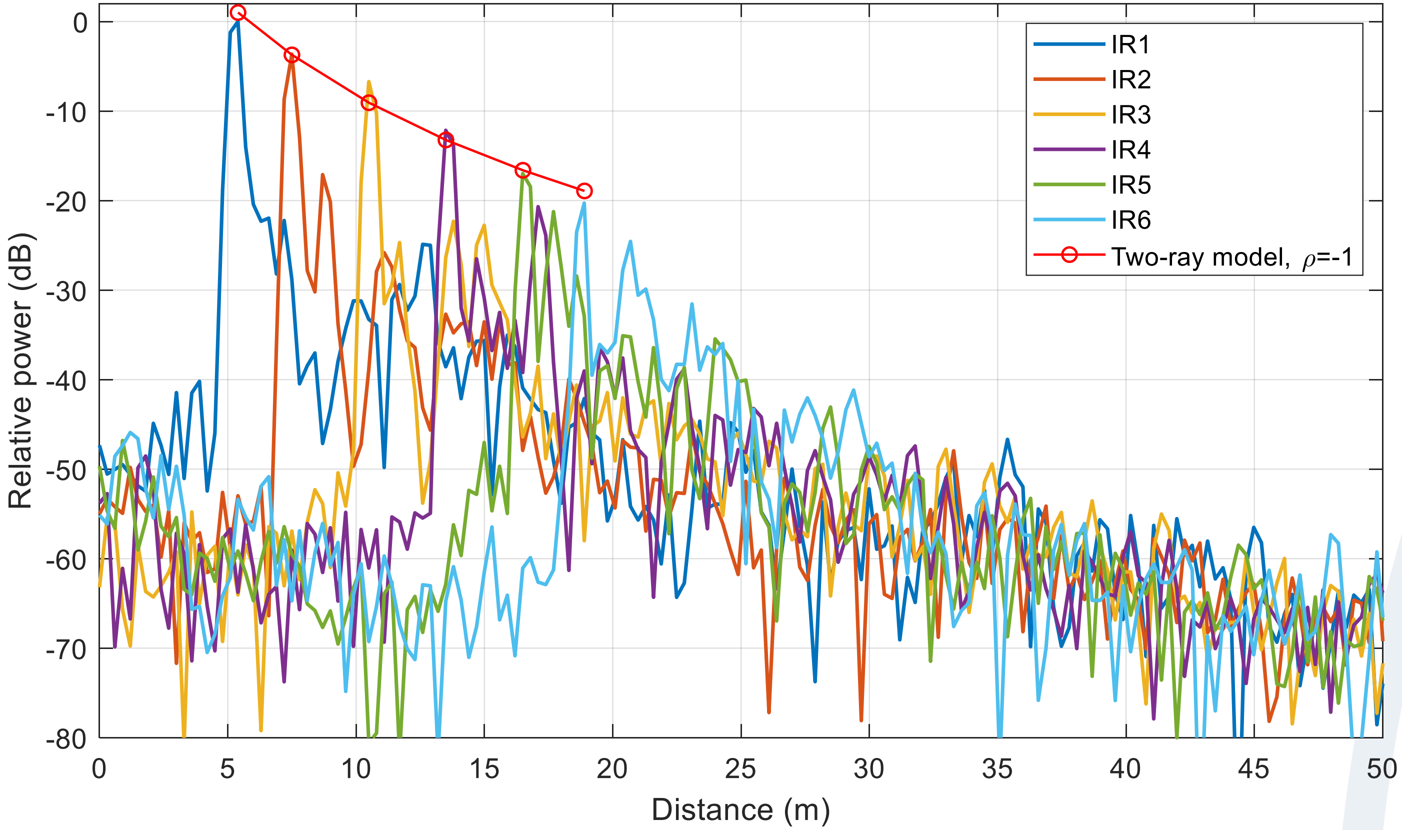
- The measure of impulse responses under LoS conditions also shows that the amplitude of the dominant path (direct path + ground reflected path) fits the two-ray model.

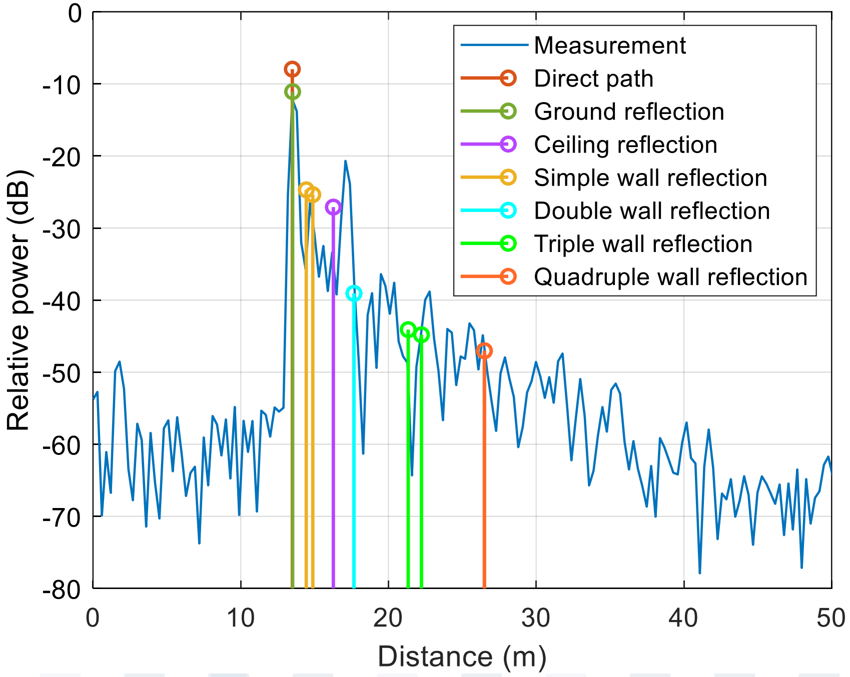


Propagation into caves

Measurements in La Corona

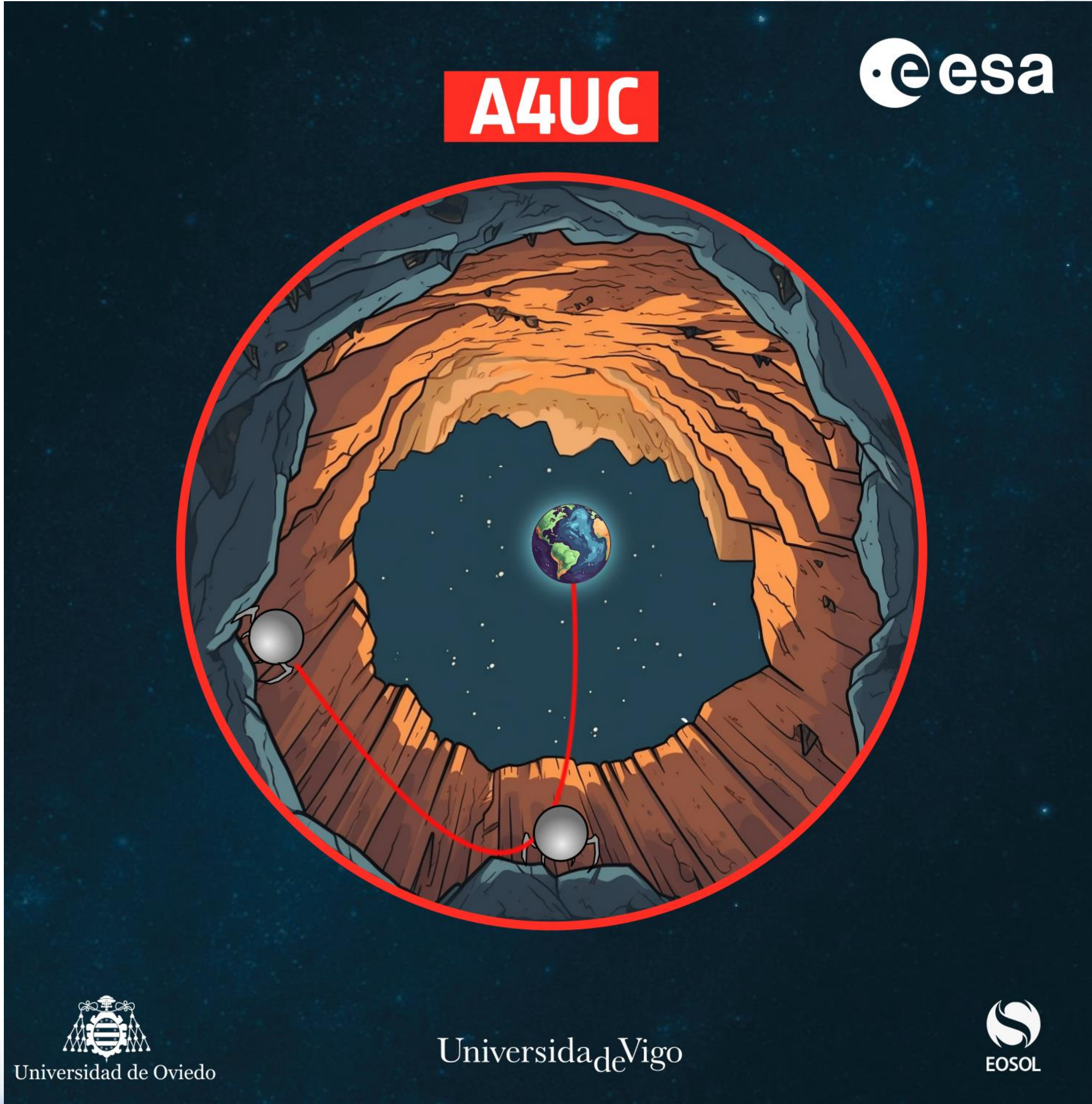






Antennas for Underground Communications

Link budget and requirements consolidation



MANETs for exploration

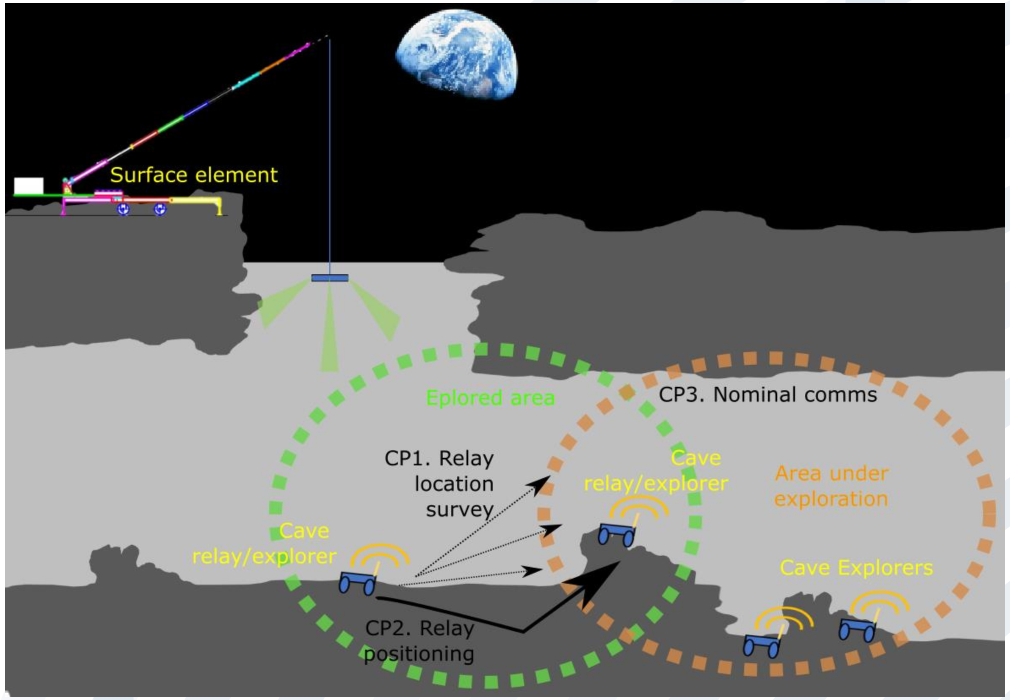
Deployment of a Network with no planning in advance.

System Requirements:

Resilience: Resilience is the ability to provide and maintain an acceptable level of service in the face of faults and challenges to normal operation. Hence, the **network must provide and maintain essential services under adverse conditions** as well.

Mobility: Mobile nodes facilitate the deployment and redeployment of the network, making it possible to tailor the network topology to the incident zone conditions. Moreover, the positions of **the nodes can be modified to improve network performance**.

Monitoring Link: The CSS shall have an algorithm capable to monitor the link quality.



Frequency:

920 MHz	Low TRL for high data rate (802.11ah)
2.4 GHz	**Project baseline**
5.0 GHz	Less efficient. No special reason to use it

Transmitted / received power

SoW REQ-050 : average power consumption 2W (TBC).

Tx: Baseline 802.11n MCS 7, 40 MHz, 150 Mbps → One antenna : **17 dBm (SISO)**
→ Two antennas : **16 dBm (MIMO)**

Rx: Baseline 802.11n MCS 7, 40 MHz, 150 Mbps → **-71dBm**

Wi-Fi 4 (802.11n)	Max. data rate (Mbps)	Power Consump	Tx power	Sensitivity	Module Example
1x1 20 MHz	72.2	Max 0.4 A (1.3 W)	16±2 dBm	-73±2 dBm	M2-MAYA-W1
1x1 40 MHz	150			-71±2 dBm	
2x2 20 MHz	144.4	510mA 606mA (2W) Rx: 0.7 W	16±2 dBm 20±2 dBm	-73±2 dBm	Laird 60-2230C Doodle Labs NM-DB-2
2x2 40 MHz	300			-76±2 dBm	

Link Budget

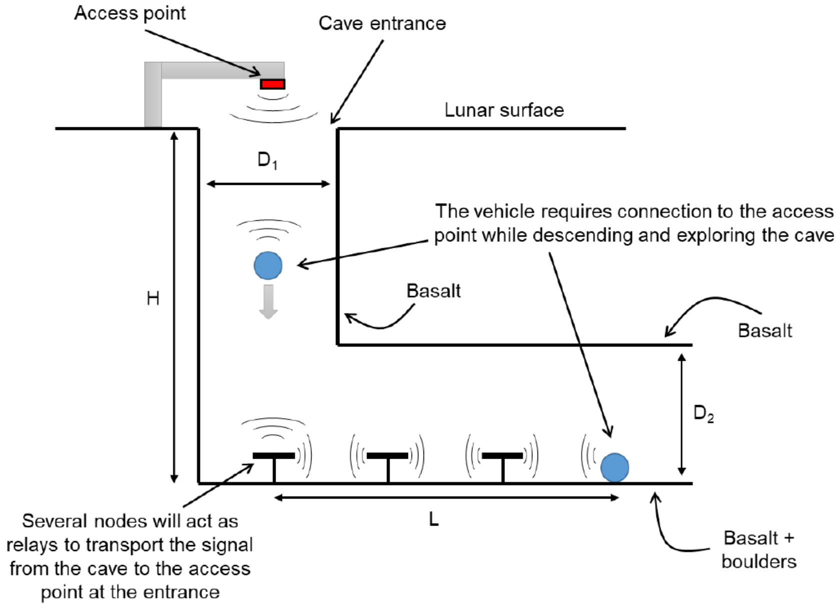
REQ-090 – Data rate
> 25 Mbit/s (TBC)

REQ-130 – Distance to be covered from the base of the pit (L in Fig. A1.1)
> 200 m (TBC). The target is to maximize this distance with the minimum number of nodes. The maximum achievable distance depending on the obstacles shall be defined within the activity.

REQ-140 – Number of nodes
3 (TBC).

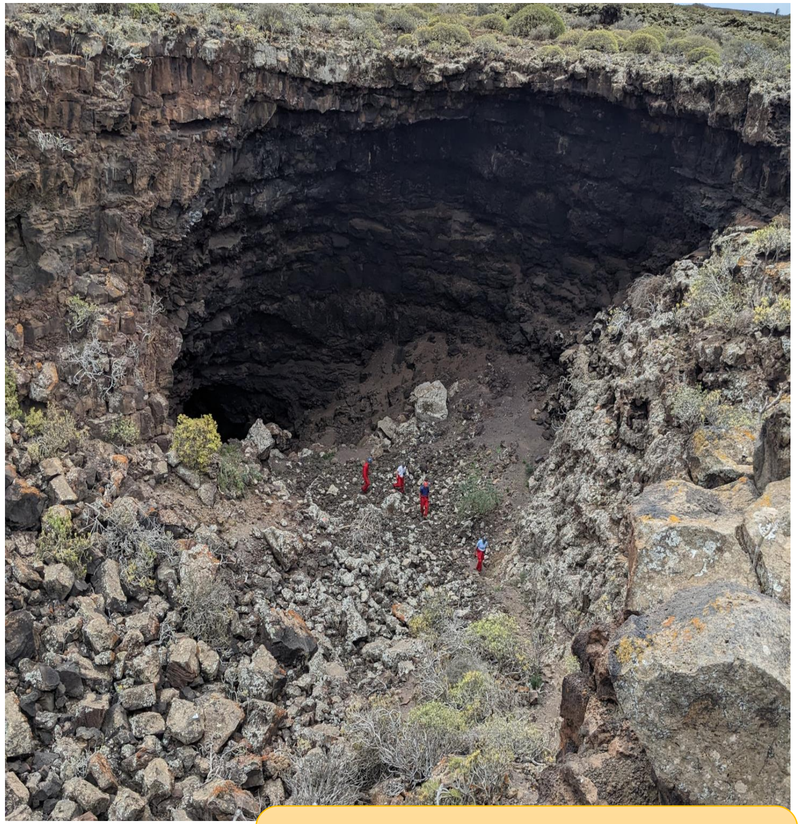
$$\frac{1}{DR_{total}} = \sum_i \frac{1}{DR_i}$$ (Best case)

Example:
DR_1=DR_2 = 150 Mbps
DR_3= 60 Mbps
Margin 20%: DRtotal > 25Mbps

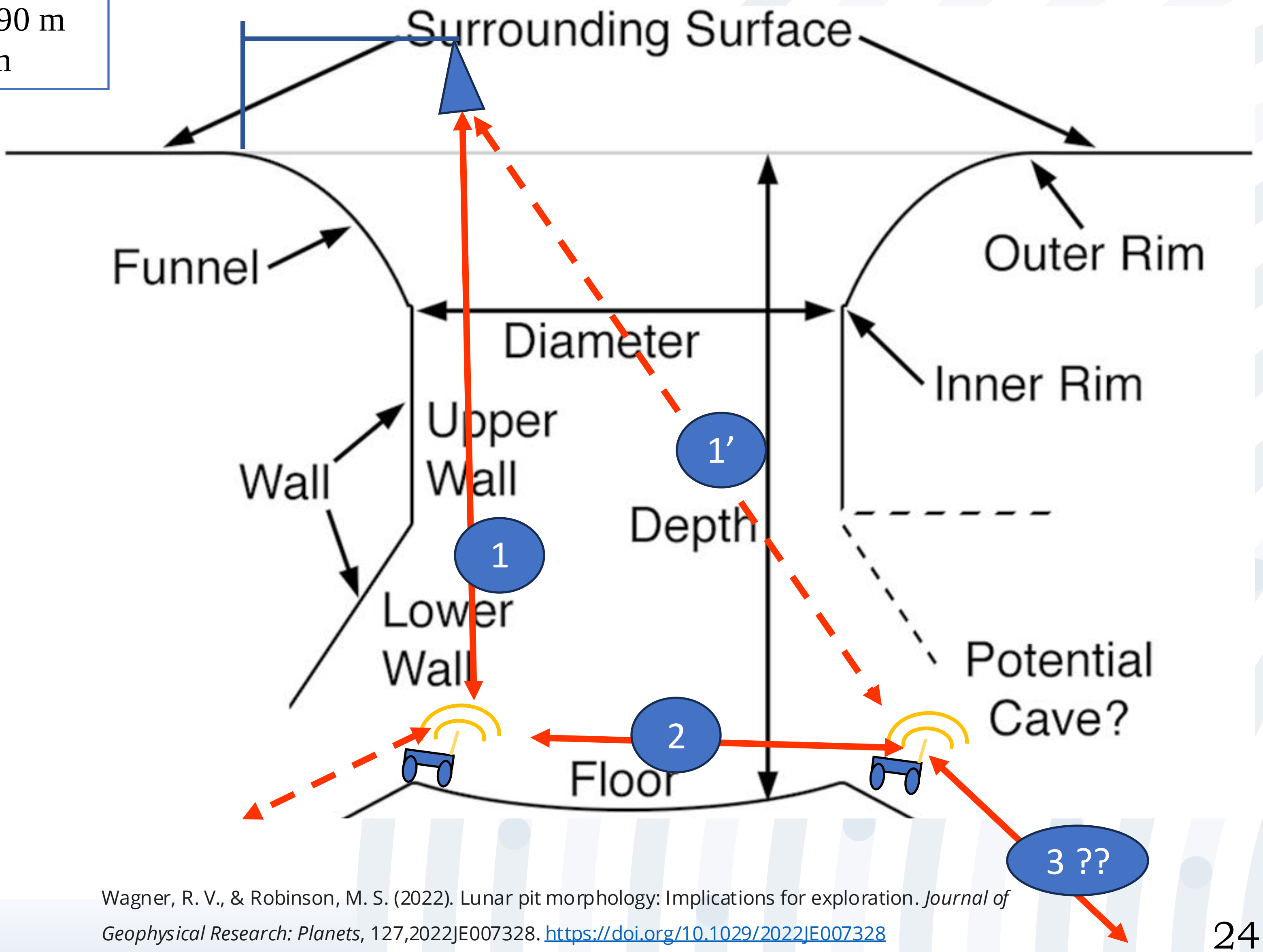


Communications Network inside a Lunar Cave

Diameter ~ 90 m
Depth ~ 60m

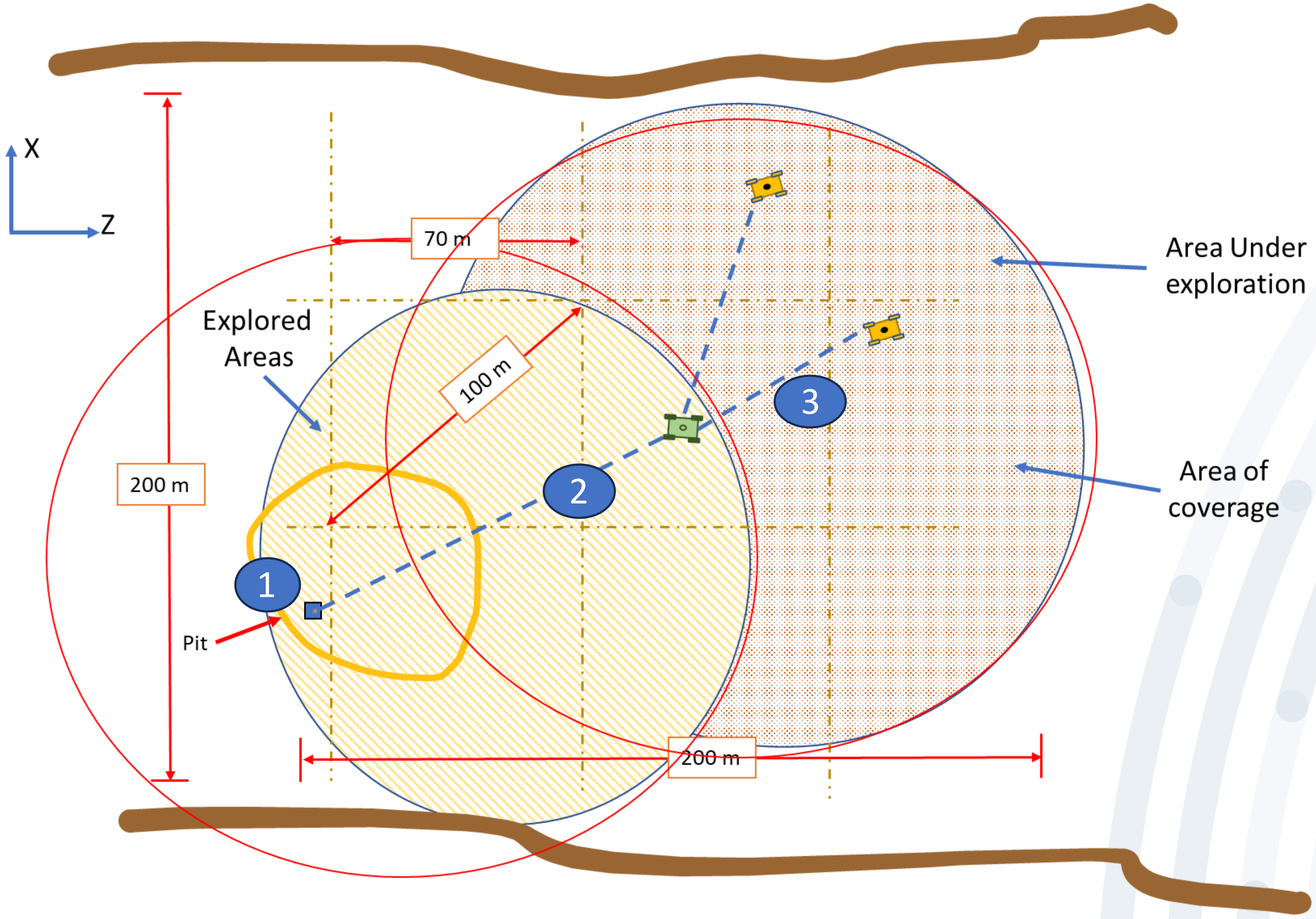


Jameo de la Gente
(La Corona Volcano)



Wagner, R. V., & Robinson, M. S. (2022). Lunar pit morphology: Implications for exploration. *Journal of Geophysical Research: Planets*, 127,2022JE007328. https://doi.org/10.1029/2022JE007328

Communications Network (top view)



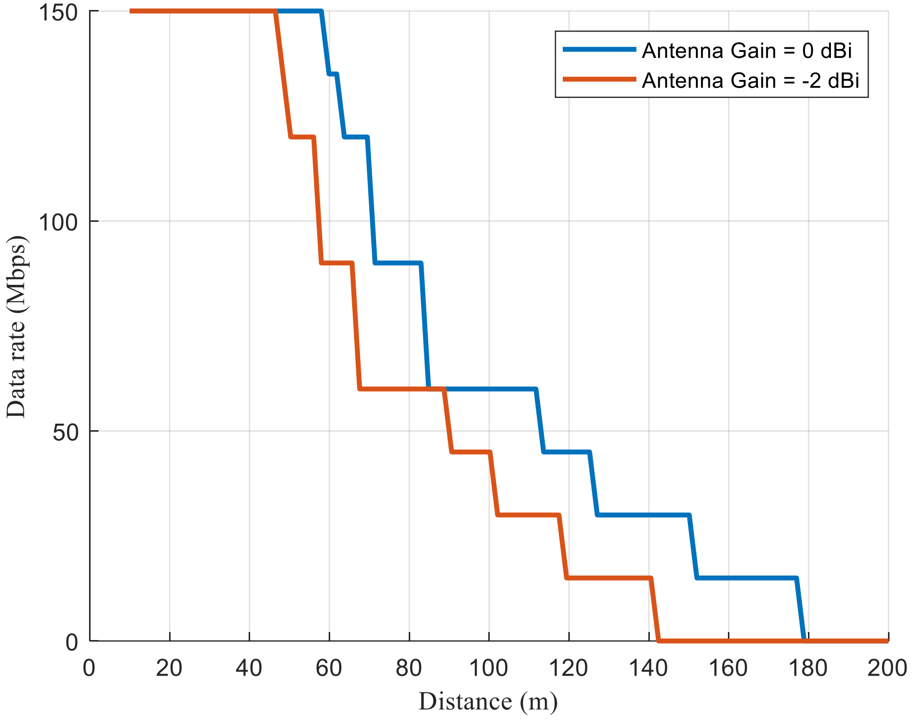
Tx Power	16 dBm
Polarization or depointing Losses	11dB
Sensibility	-71 dBm
Link Margin	6 (TBC)
ANTENNA GAIN	**> 0dBi**

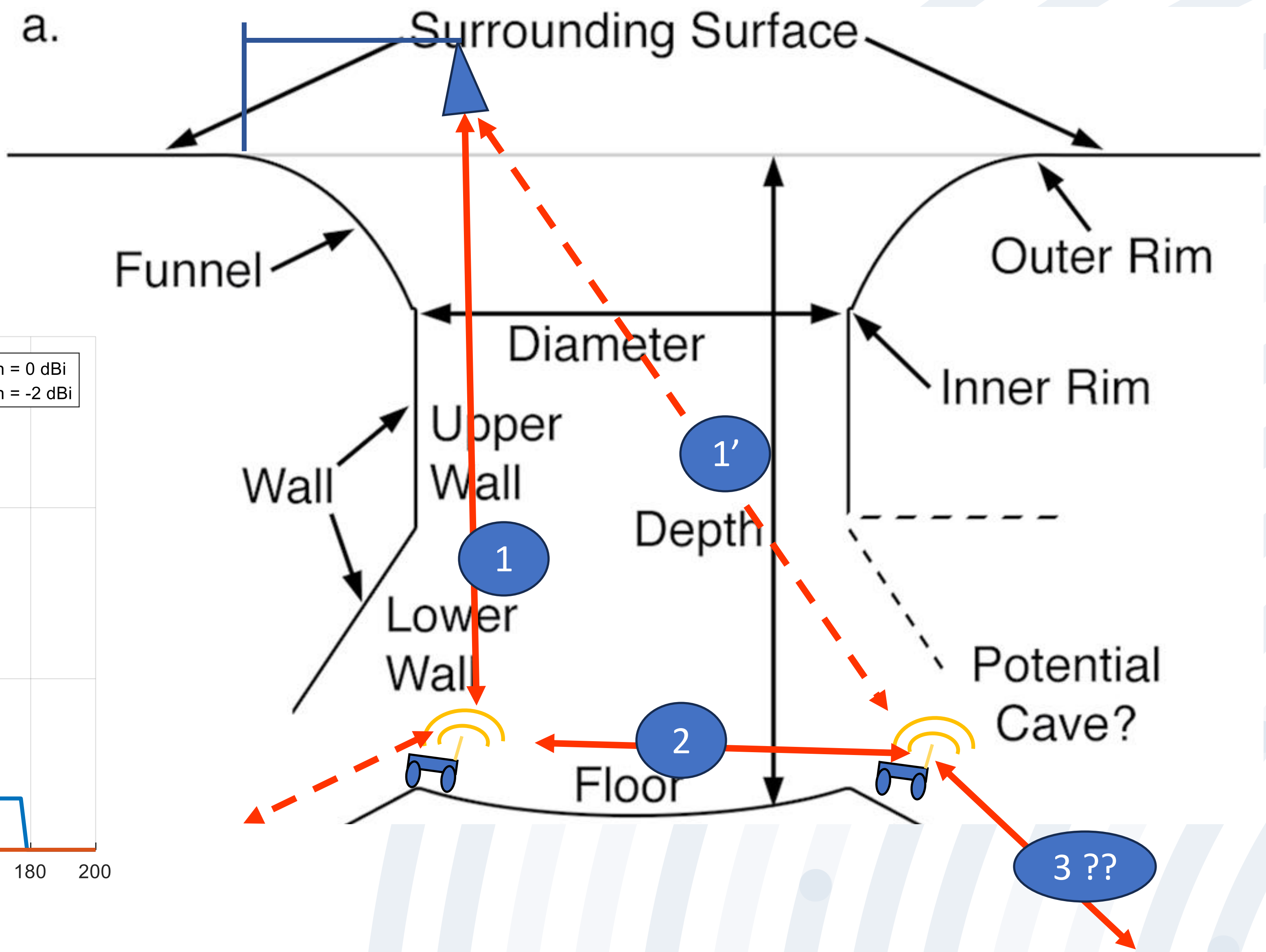
Difficulty: the longer the link, most likely to find an obstacle

Link Budget Update

1 Out of the scope of the project

2

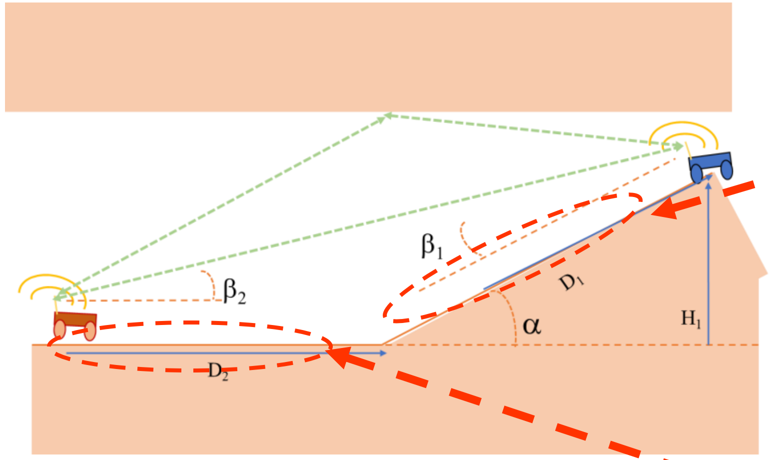


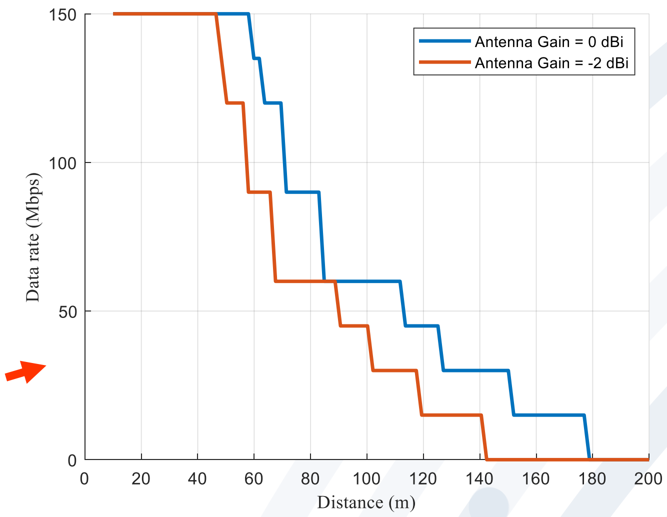


Wagner, R. V., & Robinson, M. S. (2022). Lunar pit morphology: Implications for exploration. *Journal of Geophysical Research: Planets*, 127,2022JE007328. https://doi.org/10.1029/2022JE007328

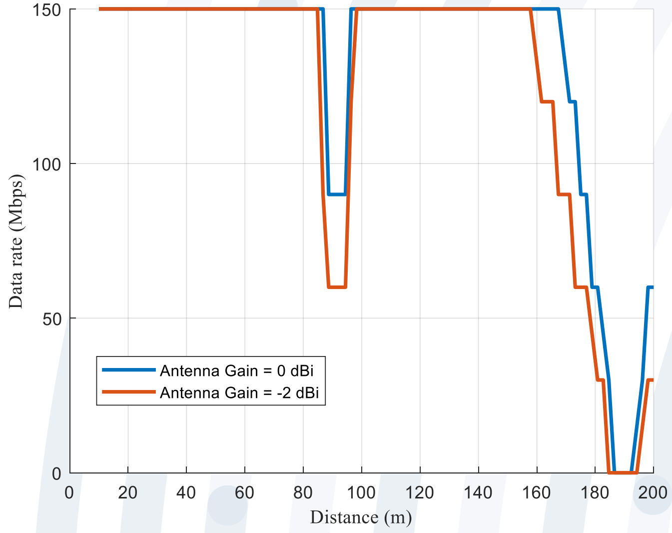
Link Budget Update

3 Under study



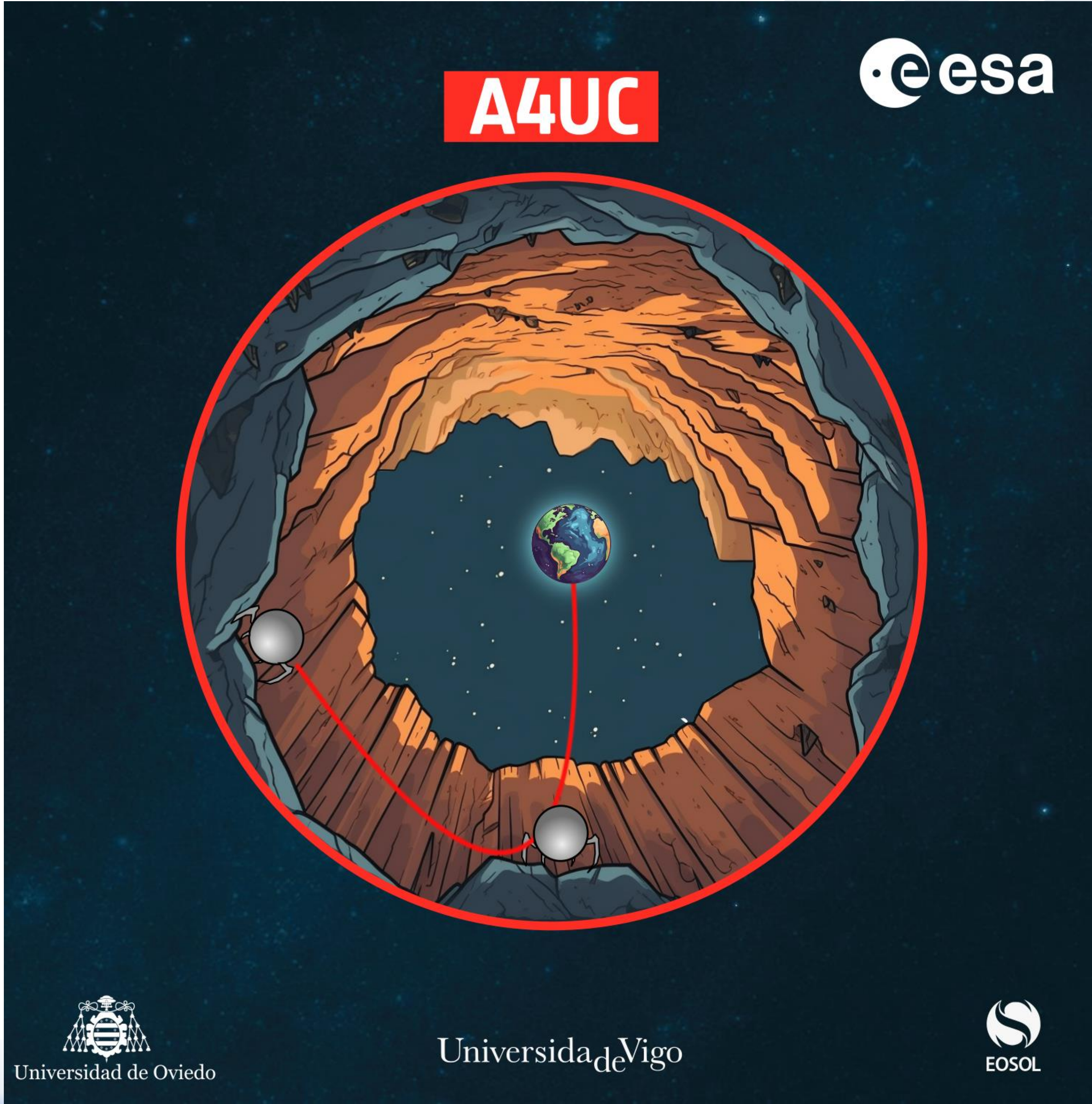


H_1= 30m



Antennas for Underground Communications

Antenna developments



ANTENNA DESIGN

Pagoda antenna (A4UC1000-E02)

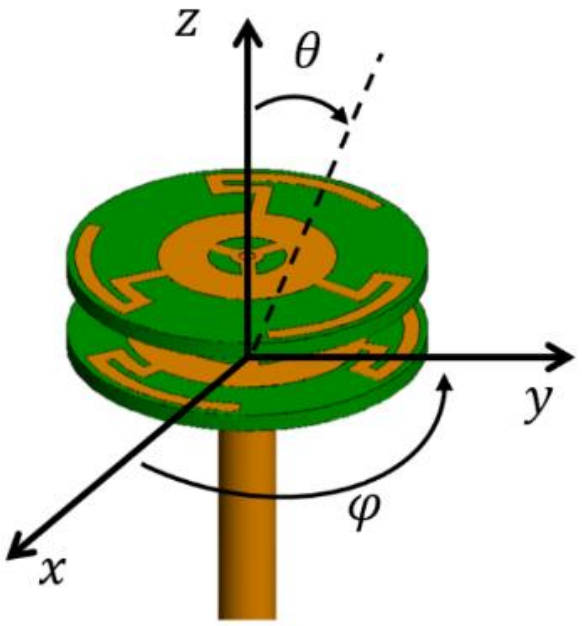


Table 3. Product tree of the pagoda antenna

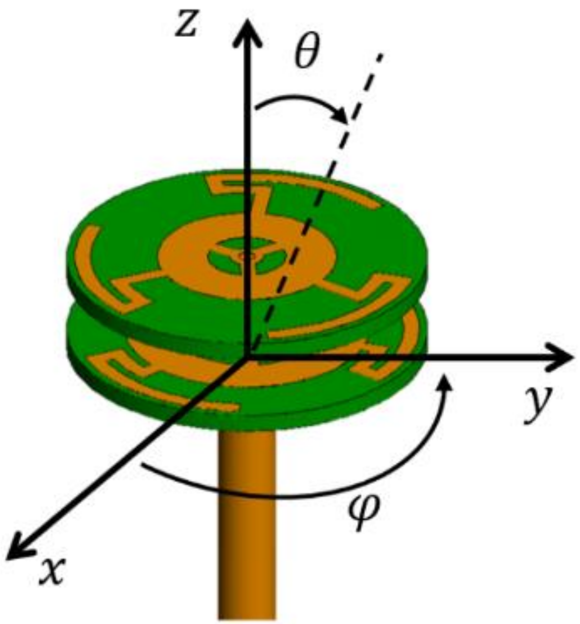
Class	Part Num.	E	M	Name	Description	Material
Sub-system	**A4UC1100**	**4**	**2**	**RF-ANT**	**RF Antenna**	
Equipment	A4UC1110	4	1	RF-ANT-PCB	RF Antenna PCB	RT/duroid 5880
Comp.	A4UC1111	4	1	RF-ANT-PCB_TOP	RF Antenna PCB top disc	RT/duroid 5880
Comp.	A4UC1112	4	1	RF-ANT-PCB_BOT	RF Antenna PCB bottom disc	RT/duroid 5880
Equipment	A4UC1120	4	1	RF-ANT-COAX	RF Antenna coaxial cable	Teflon/Copper
Equipment	A4UC1130	4	2	RF-ANT-SUP	RF Antenna support base	Al6082 Aluminium
Equipment	A4UC1140	4	1	RF-ANT-TUBE	RF Antenna support tubes	PEEK
Comp.	A4UC1140_P01	4	1	RF-ANT-TUBE_P01	RF Antenna top support tube	PEEK
Comp.	A4UC1140_P02	4	1	RF-ANT-TUBE_P02	RF Antenna middle support tube	PEEK
Equipment	A4UC1150	4	1	RF-ANT-RADO	RF Antenna radome	PEEK

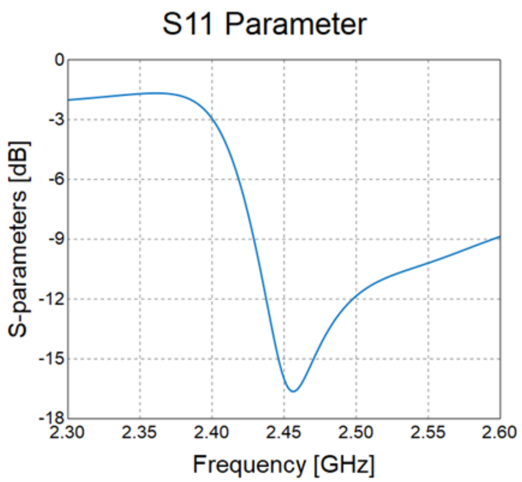
Table 4. A4UC1100-E02 mechanical properties

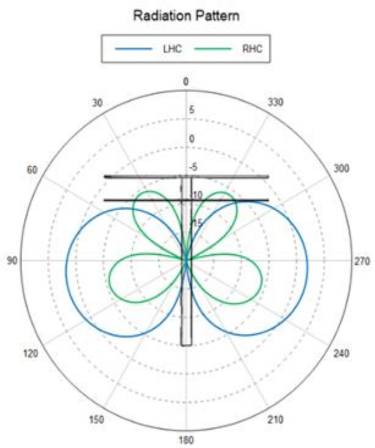
Parameter	Value
Width (Ø)	60 mm
Height (H)	60 mm
Disc separation	8 mm
Inner wire diameter	0.91 mm
Dielectric diameter	3.58 mm
Dielectric material	Teflon
Substrate material	Duroid 5880
Substrate dielectric constant	2.2

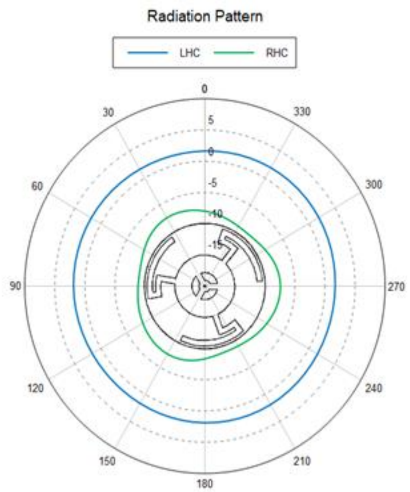
ANTENNA DESIGN

Pagoda antenna (A4UC1000-E02)



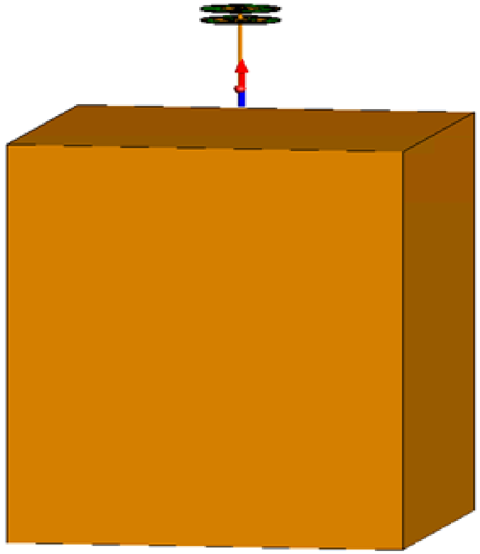




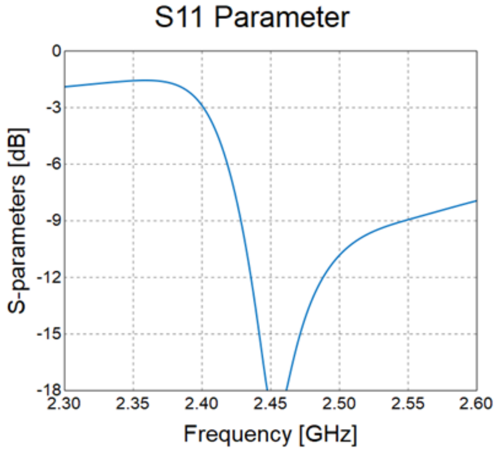


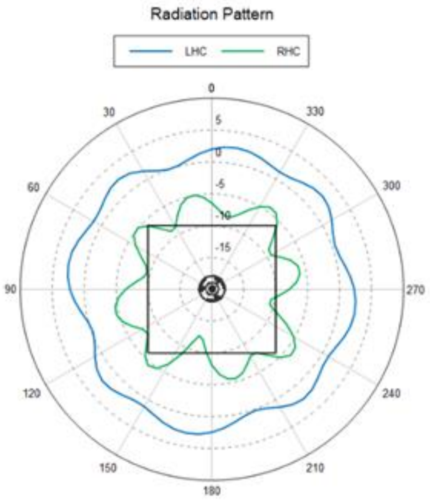
ANTENNA DESIGN

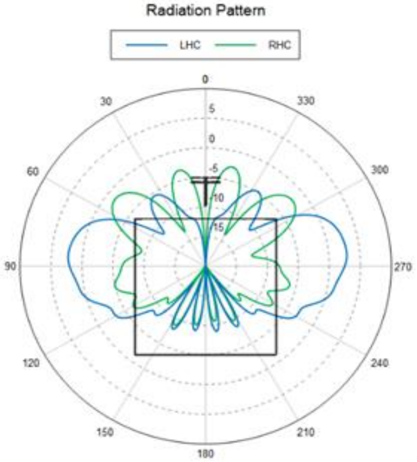
Rover Environment Simulations



Parameter	Nominal	Rover Configuration
Horizontal Peak Gain	2.1 dBi	2.9 dBi
Horizontal Min. Gain	2.1 dBi	-0.2 dBi
Vertical 3dB Beamwidth	±28 deg	±23 deg

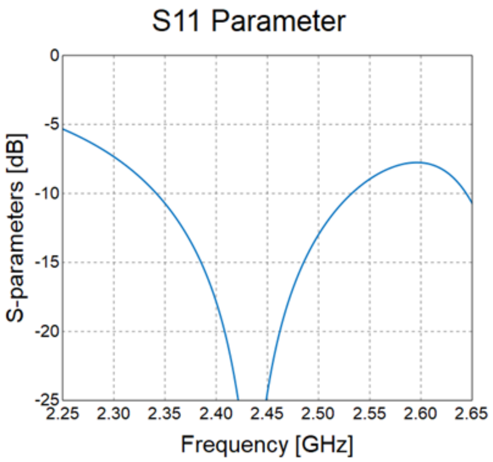


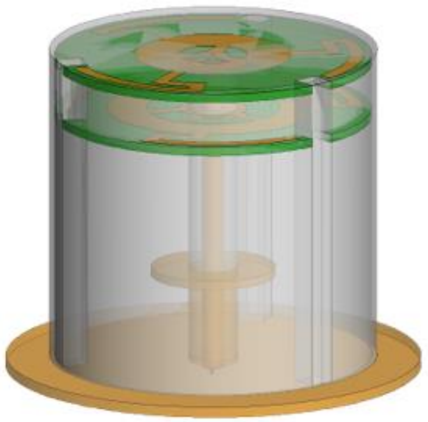


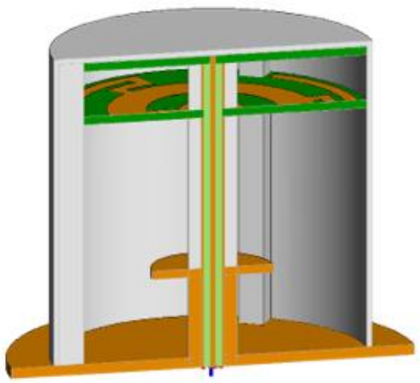


ANTENNA DESIGN

Pagoda antenna with radome and support (A4UC1000-E04)

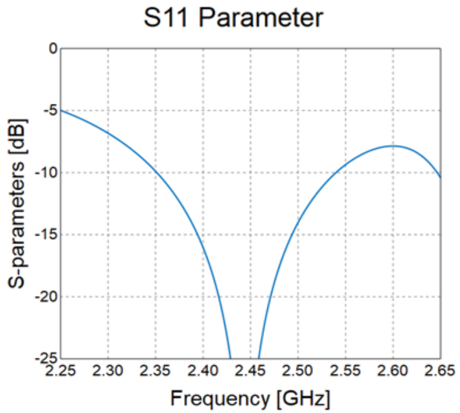


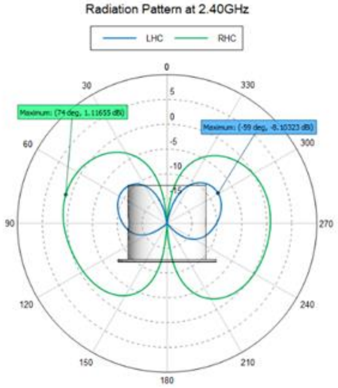


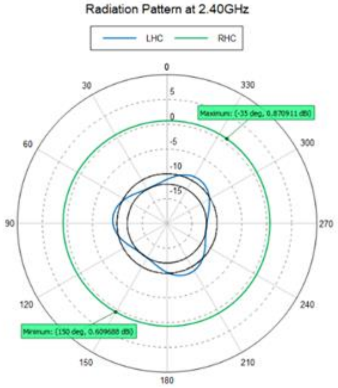


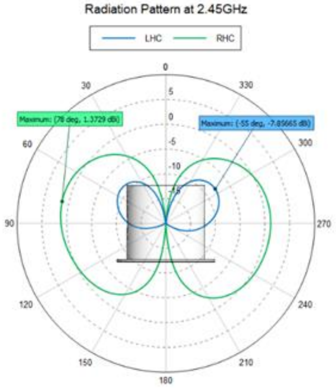
ANTENNA DESIGN

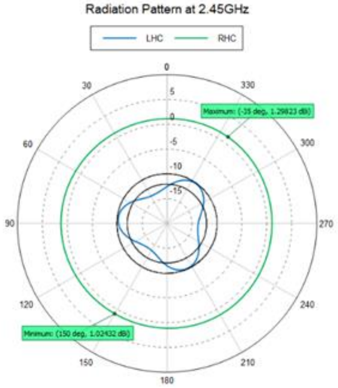
PEEK Tolerance

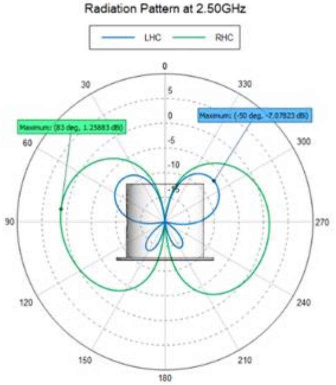












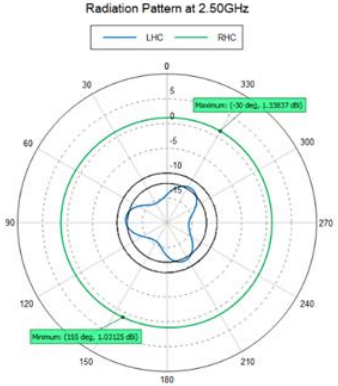


Table 6. Comparison of A4UC1100-E04 RF performance at 2.45 GHz

Parameter	Nominal	-0.2 Diel. Constant	+0.2 Diel. Constant
Horizontal Peak Gain	1.29 dBi	1.30 dBi	1.29 dBi
Horizontal Min. Gain	1.02 dBi	1.02 dBi	1.00 dBi
Vertical 0dBi Beamwidth	±35 deg	±35 deg	±35 deg

ANTENNA DESIGN

Mechanical model

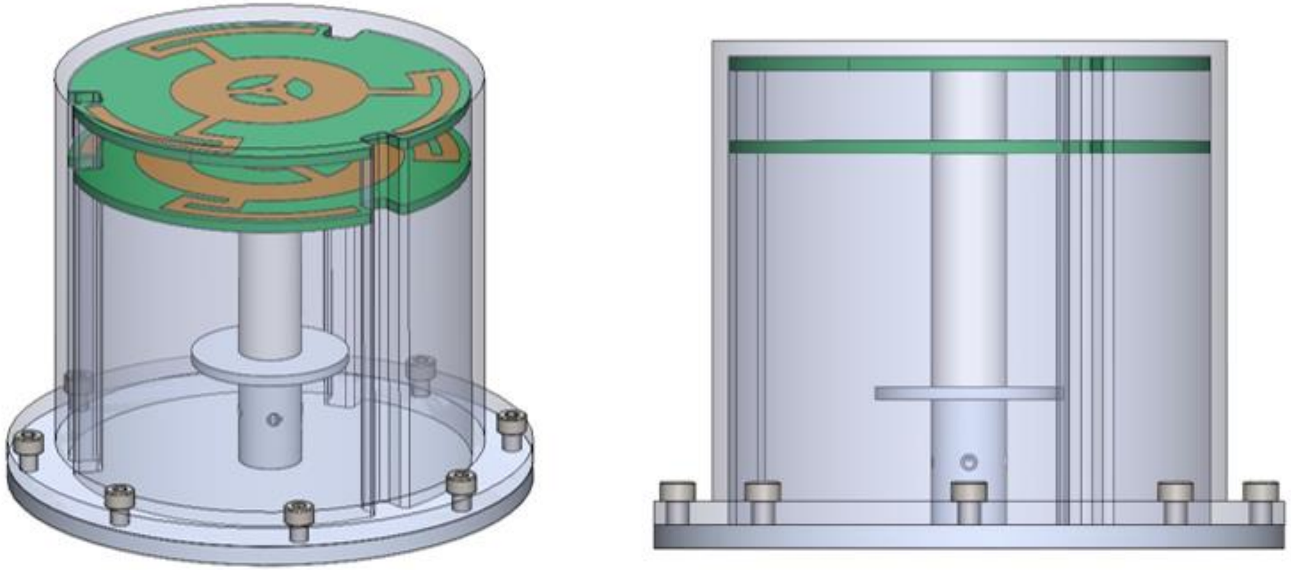


Figure 14. A4UC1100-E04M02 RF mechanical model

Table 7. A4UC1100-E04M02 mechanical properties

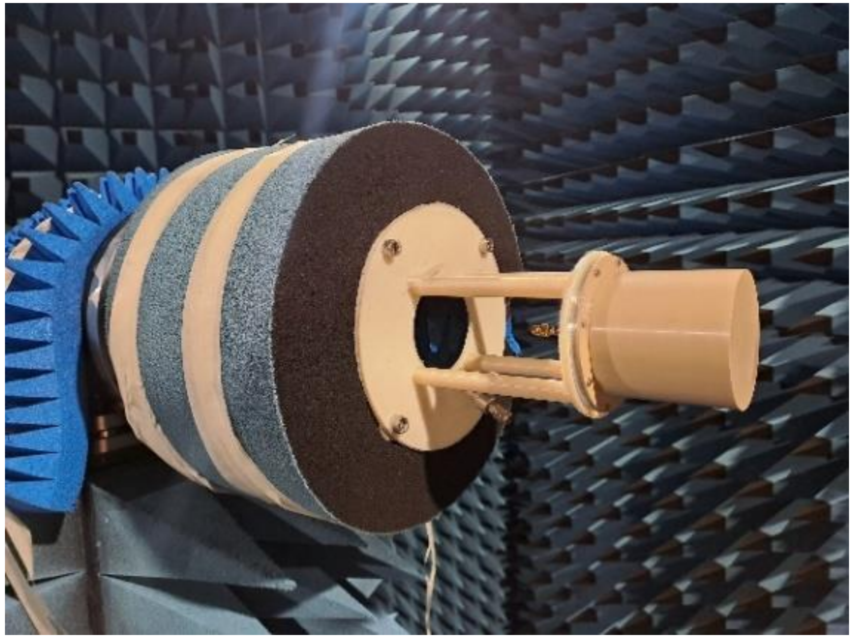
Parameter	Value
Width (Ø)	65 mm
Height (H)	65 mm
Disc separation	9 mm
Inner wire diameter	0.91 mm
Dielectric diameter	3.58 mm
Dielectric material	Teflon
Substrate height	1.575 mm (62 mils)
Substrate material	Duroid 5880
Substrate dielectric constant	2.2
Radome thickness	1 mm
Radome material	PEEK
Radome dielectric constant	3.3
Antenna weight	< 120 g

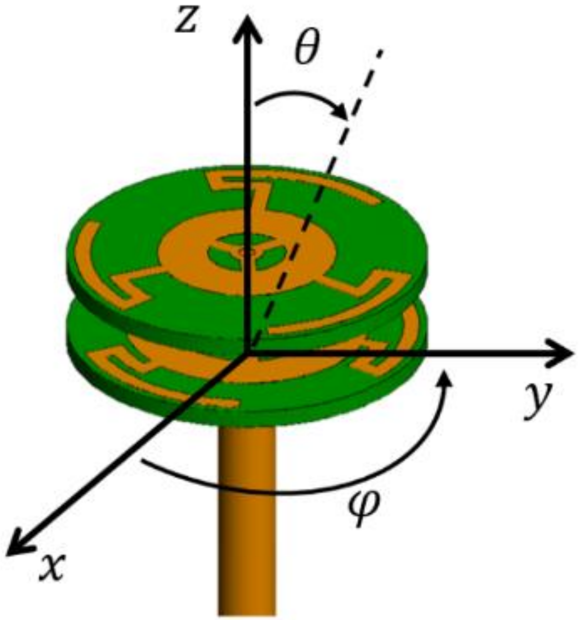
ANTENNA DESIGN. Compliance Matrix

Req. ID	Requirement	Unit	Requested	Offered	SoC
ANT-FUN-010	Frequency Band	GHz	2.40 – 2.50	2.35 – 2.50	C
ANT-FUN-020	Polarization	-	Circular	Circular	C
ANT-FUN-030	Horizontal Gain	dBi	> 0	> 1	C
ANT-FUN-040	Vertical Gain	dBi	> 0 in ±30 deg	> 0 in ±35 deg	C
ANT-NFun-010	Mass	g	< 180	< 120	C
ANT-NFun-020	Diameter	cm	< 20	< 7	C
ANT-NFun-030	Operating Temperature	ºC	-20 to +60	YES	C

QM MEASUREMENTS IN ANECOICH CHAMBER

ANT-FUN-020	The antenna shall be circularly polarized.
ANT-FUN-030	The antenna shall have a realized gain greater than 0 dBi in the whole horizontal plane.
ANT-FUN-040	The antenna shall have a realized gain greater than 0 dBi in the vertical plane, between 60º and 120º.

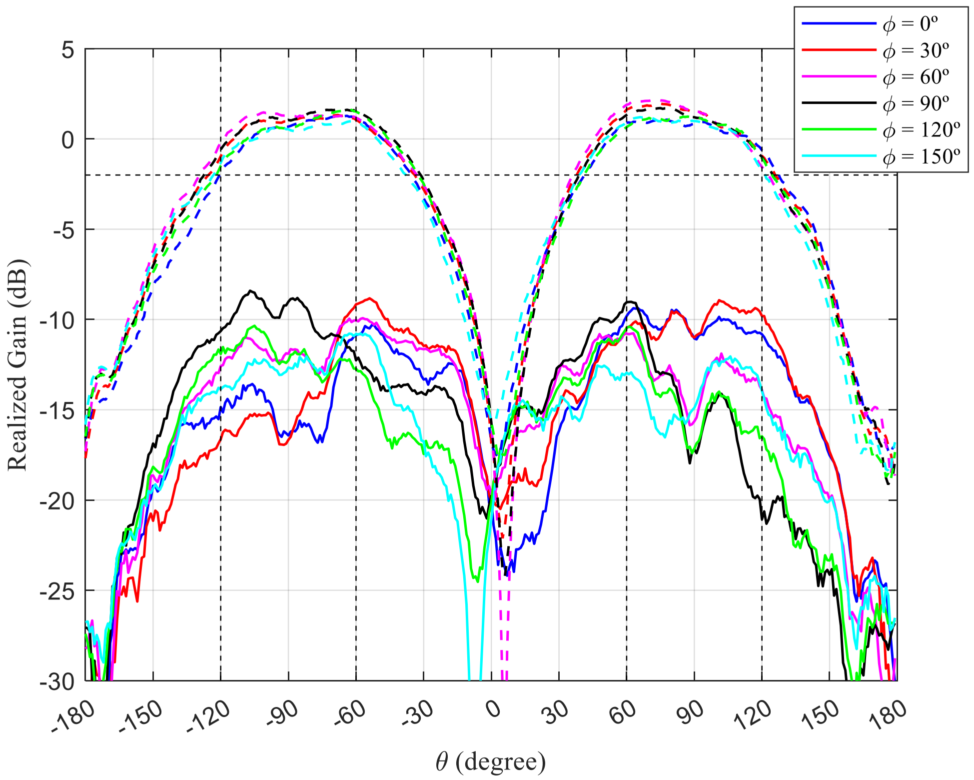




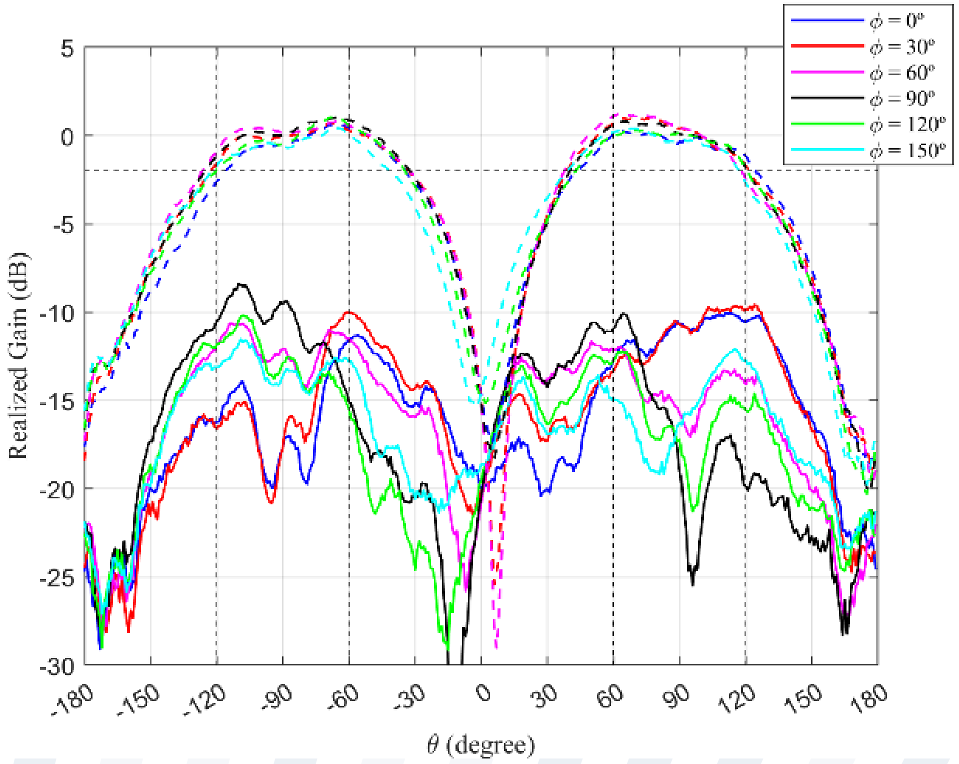
Set 1: Roll angle (ϕ) fixed

Set 2: Azimuth angle (θ) fixed

QM1-Antenna Gain Set 1

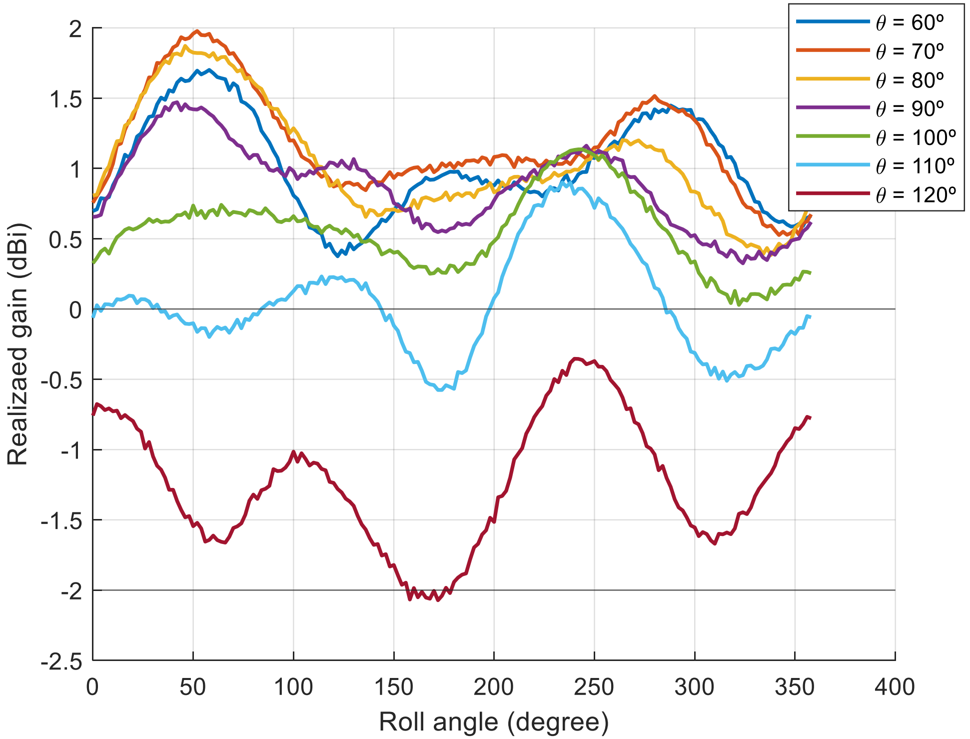


2.4 GHz

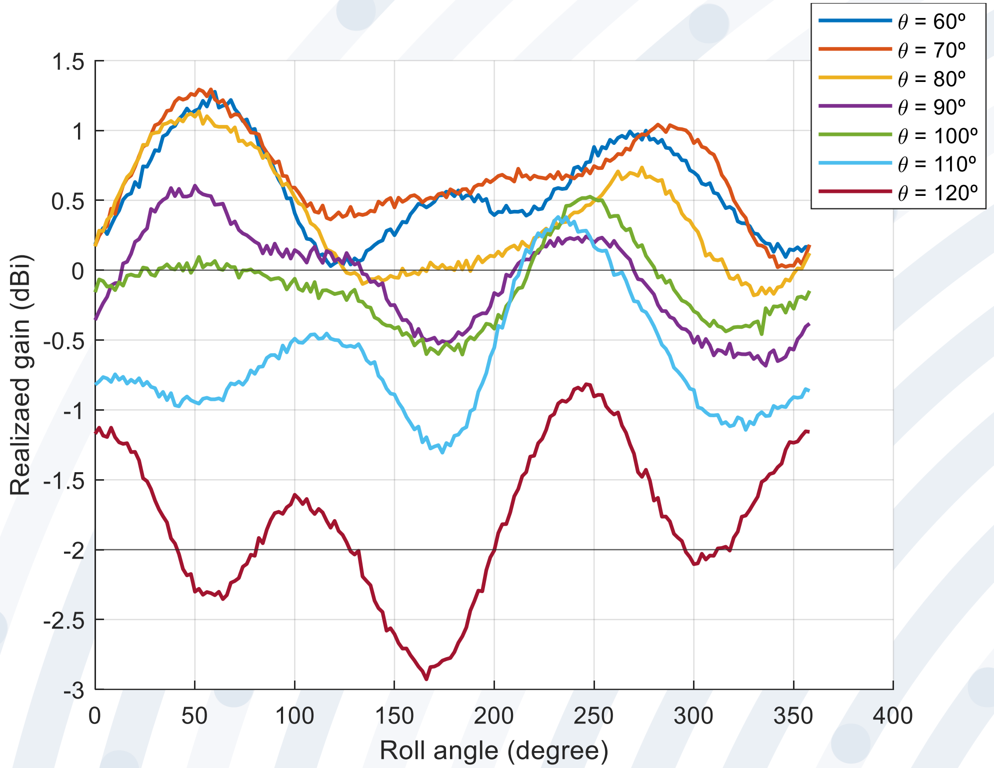


2.5 GHz

QM1-Antenna Gain Set 2

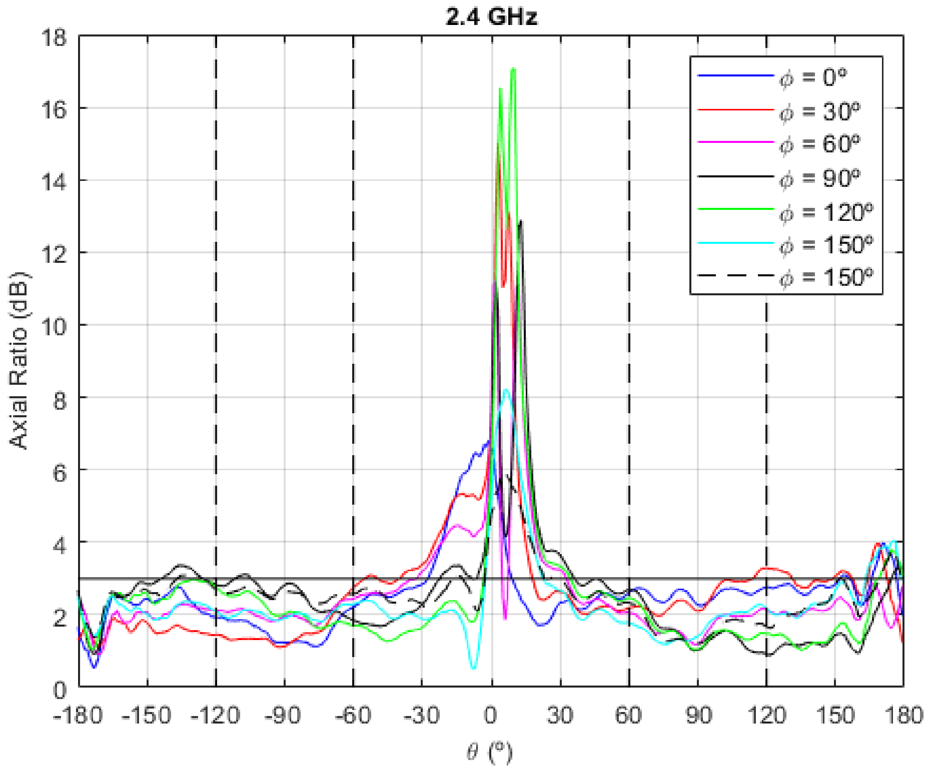


2.4 GHz

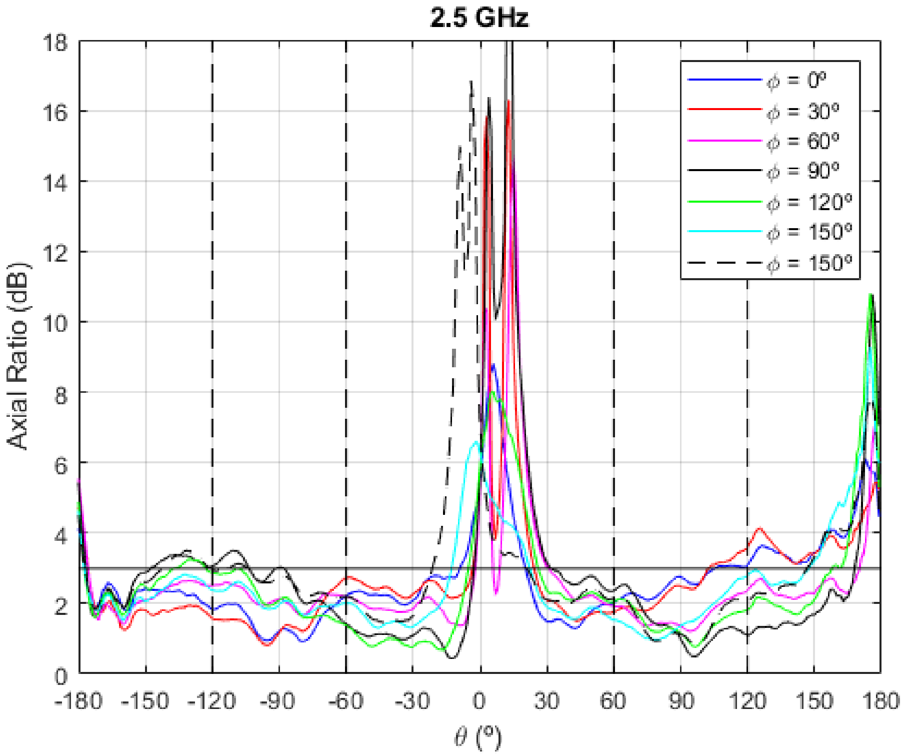


2.5 GHz

QM1- Axial Ratio (Set 1)

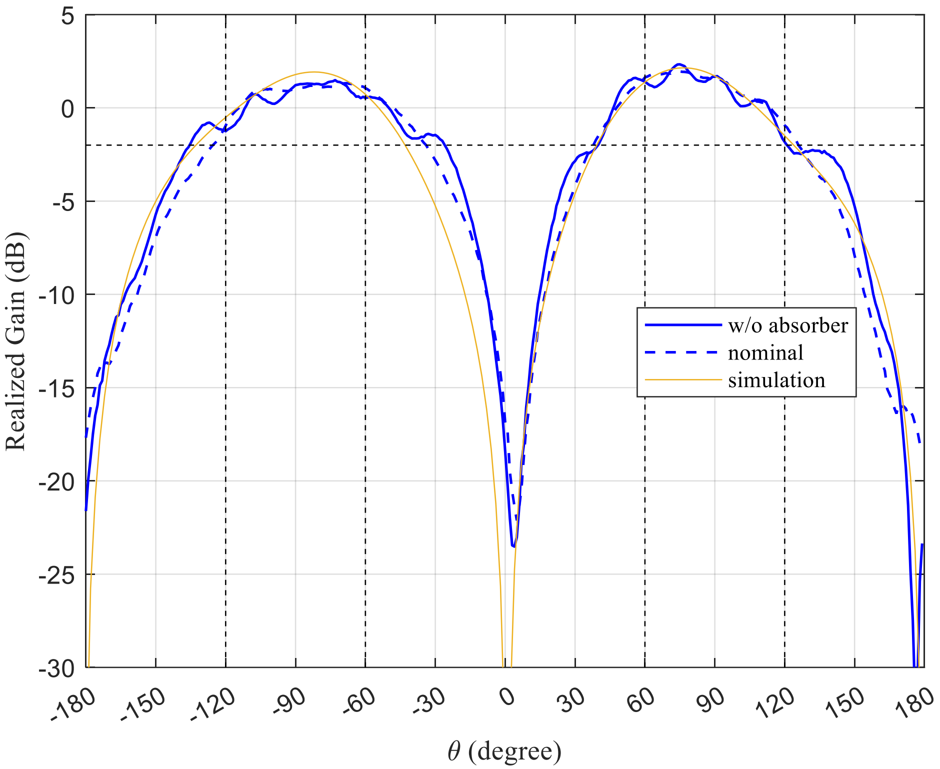


2.4 GHz

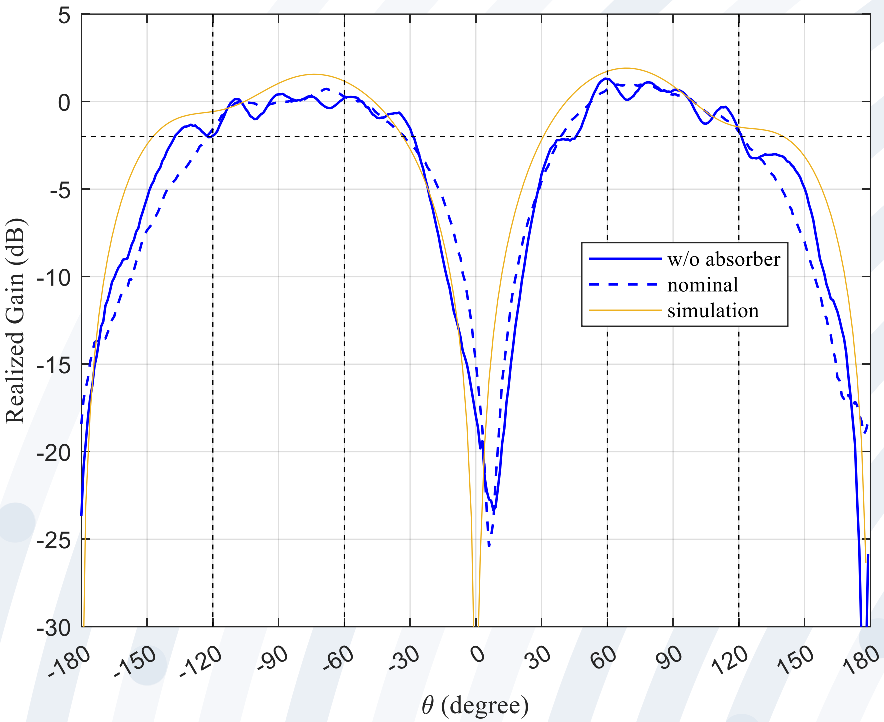


2.5 GHz

QM1- Simulation vs Measurements



2.4 GHz



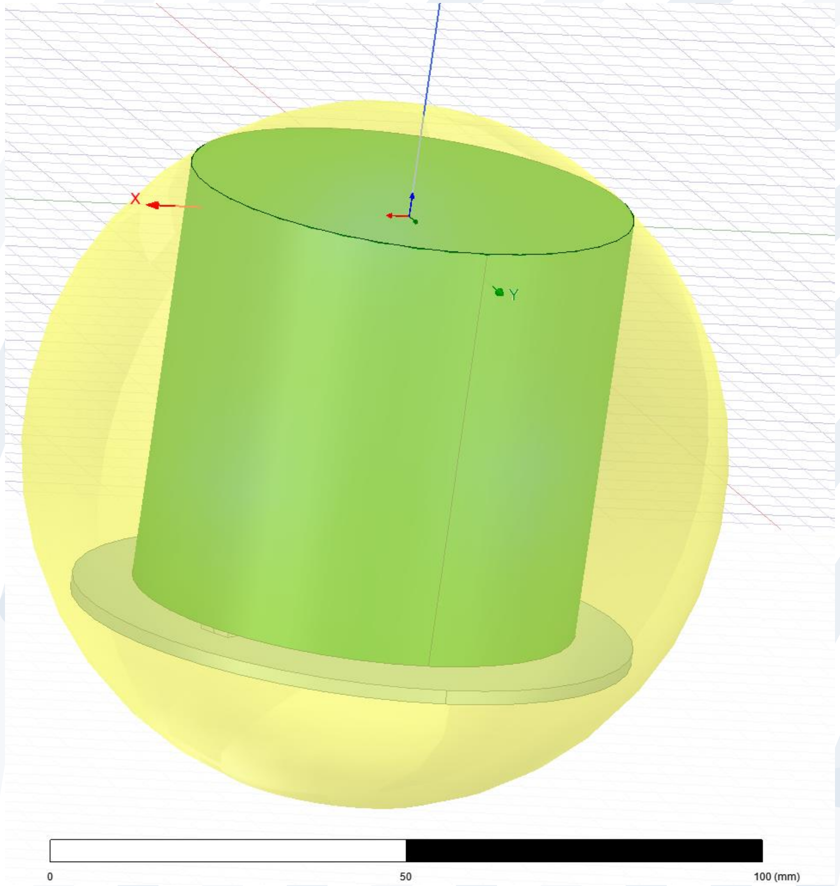
2.5 GHz

QM Mass and Volume

ID	Statement	SoW [AD01] ID
ANT-NFun-010	The mass of the antenna shall be below 120g (TBC)	REQ-060
ANT-NFun-020	The diameter of a sphere involving the antenna set shall be below 20 cm (TBC)	REQ-070

Mass = 105g

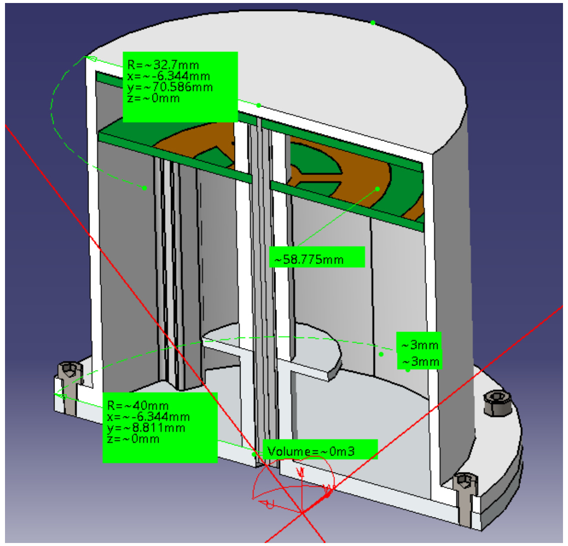
Diameter of the sphere: 100mm

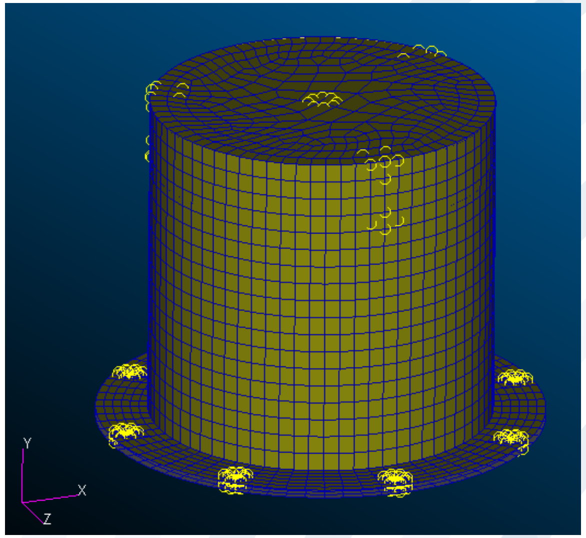


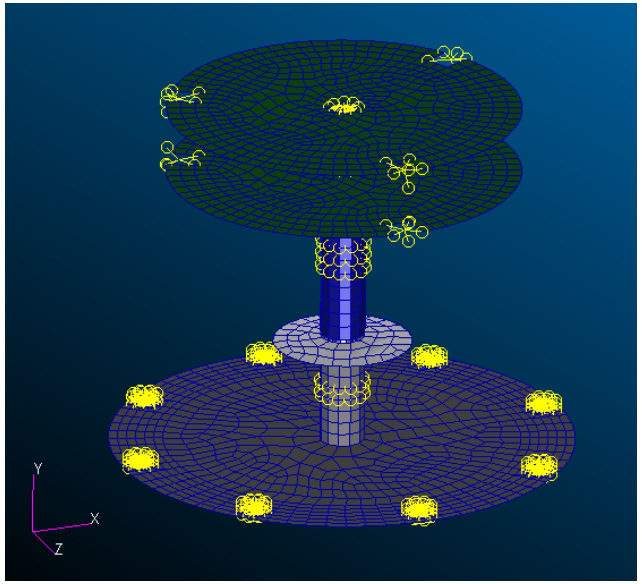
Antenna structural analysis

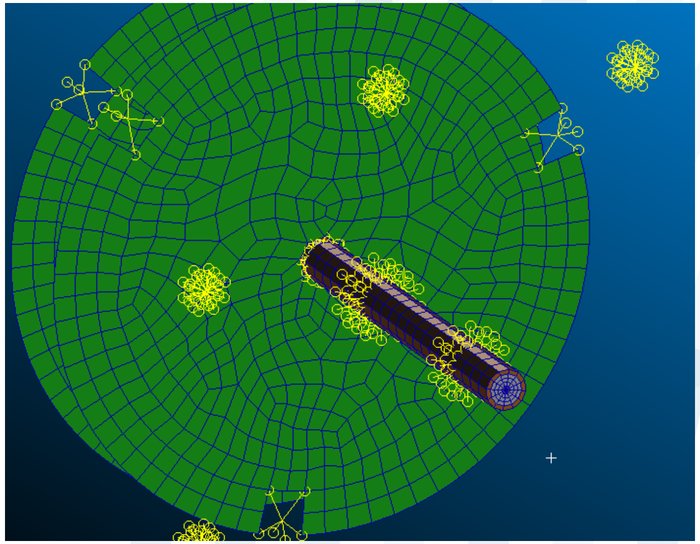
Model overview

- Structural concept
- Model philosophy
- Joints





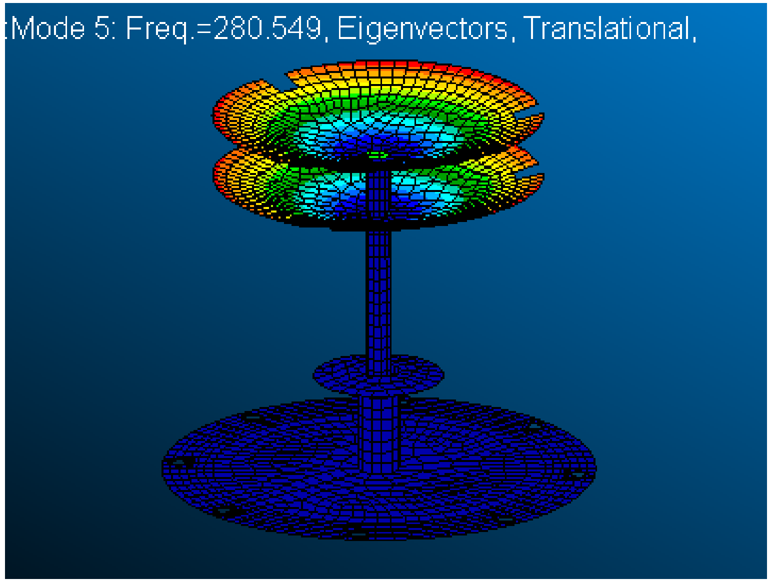


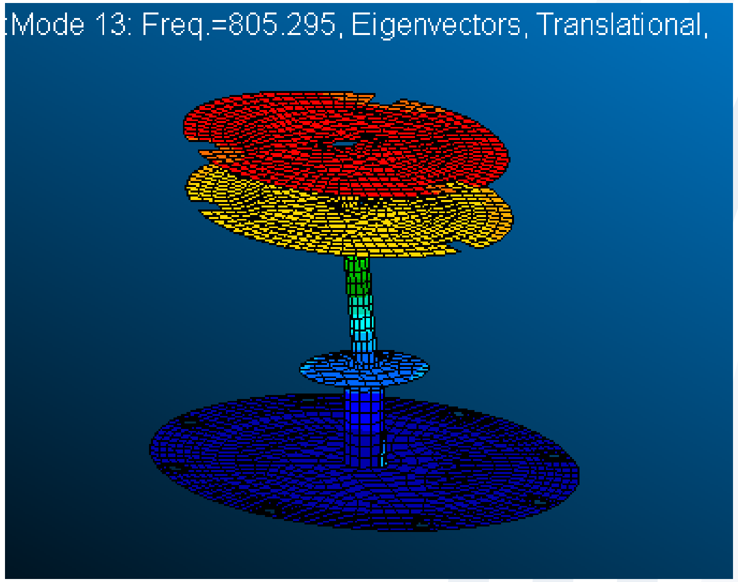


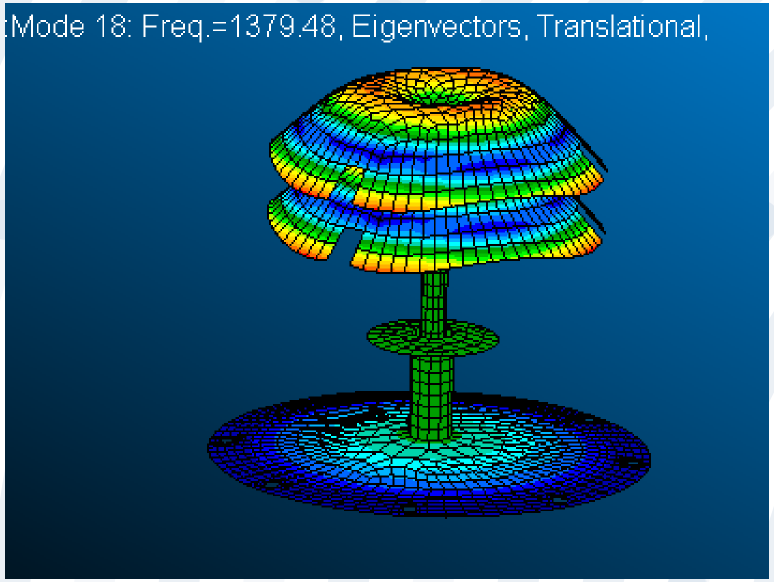
Antenna structural analysis

Normal modes analysis

- First OOP global mode 280 Hz (21% MEMF)
- First IP twin global modes 805 Hz (29% MEMF)
- Relevant OOP mode at 1380 Hz (284% MEMF)



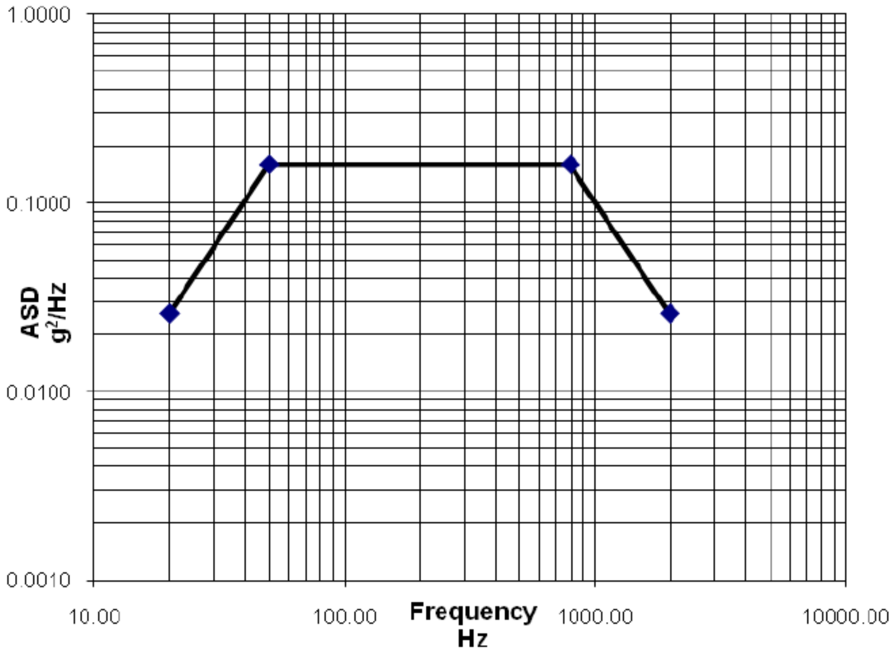




Antenna structural analysis

Random vibration analysis

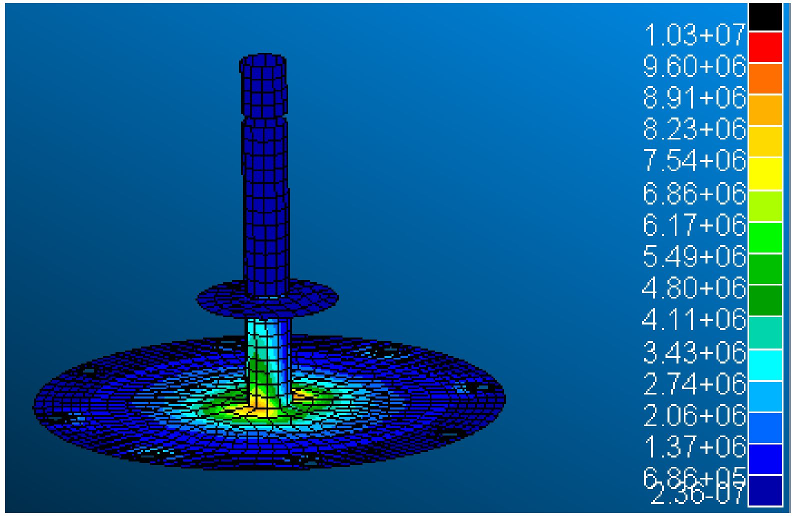
- NASA GEVs levels in all axes (14.1 gRMS)

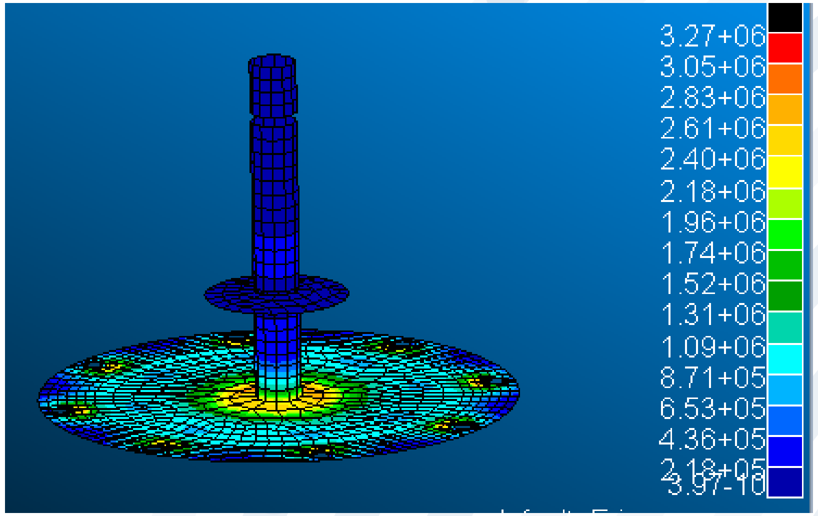


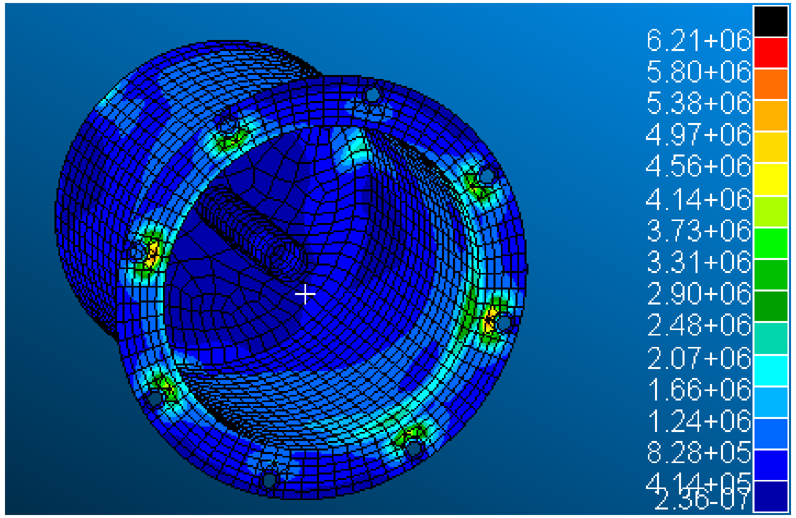
Frequency (Hz)	Acceleration Spectral Density Levels
20	.026 g^2/Hz
20-50	+6 dB/octave
50-800	.16 g^2/Hz
800-2000	-6 dB/octave
2000	.026 g^2/Hz
Overall	14.1 grms

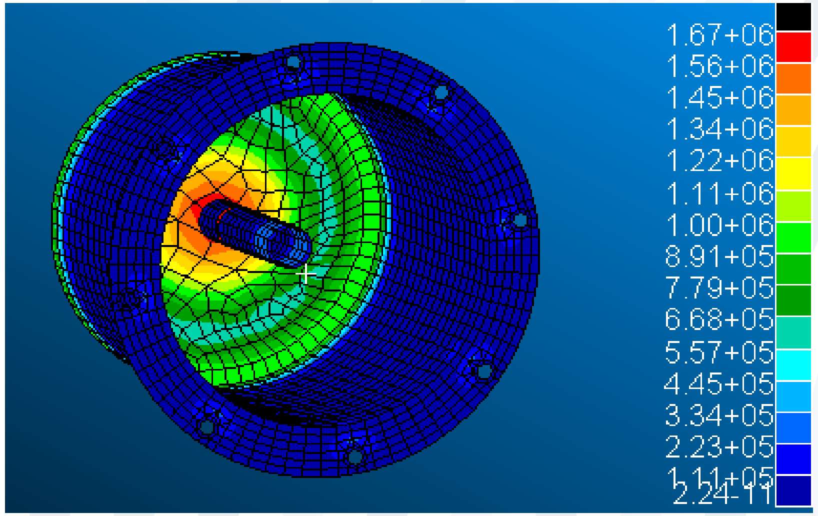
Antenna structural analysis

Random vibration analysis



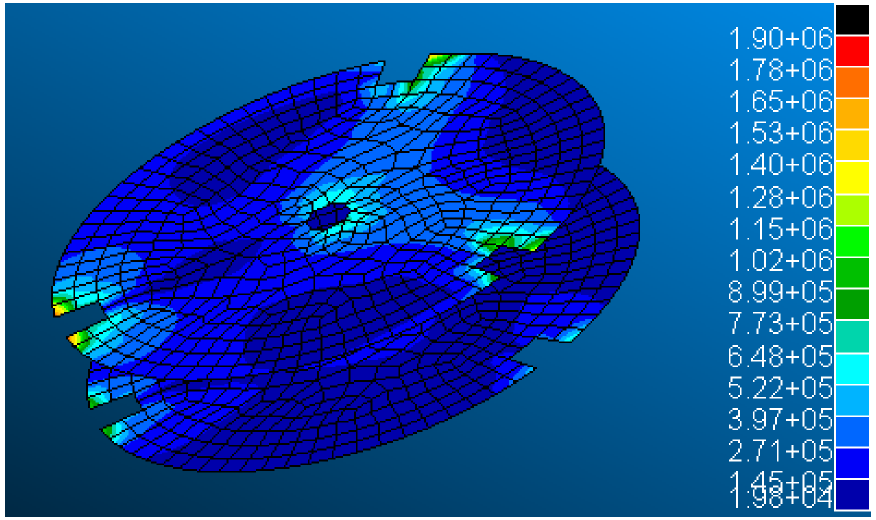


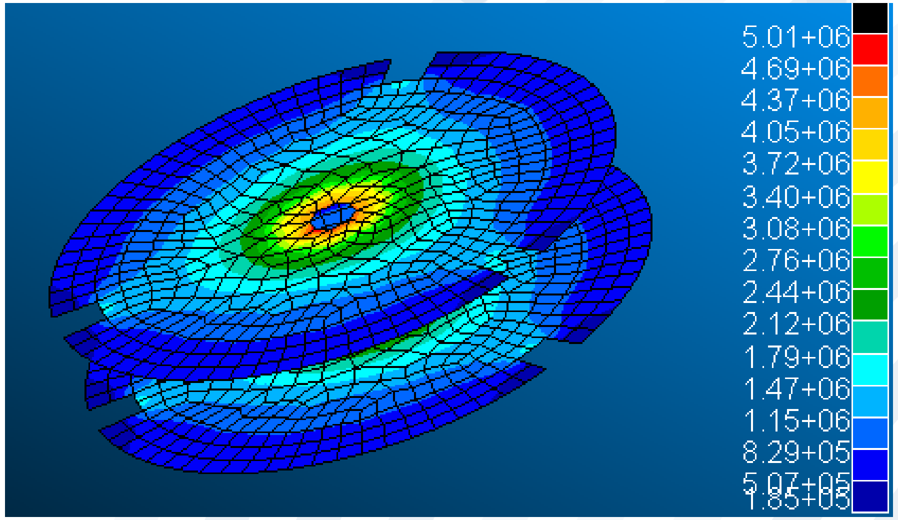


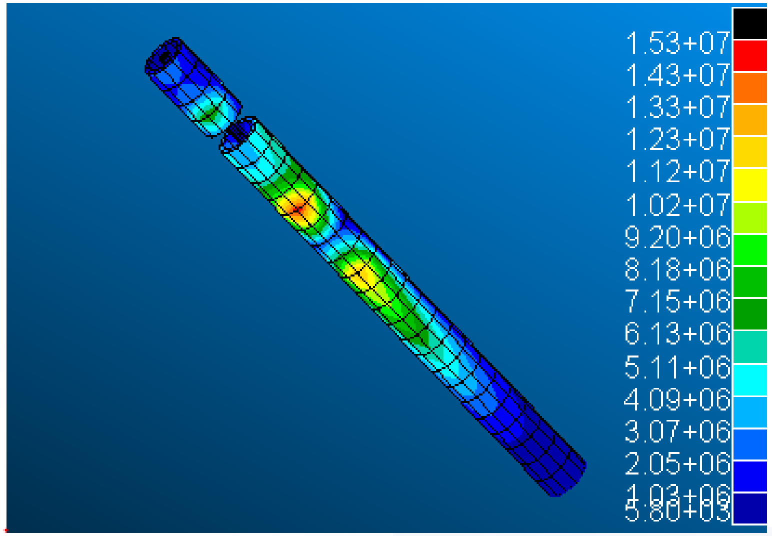


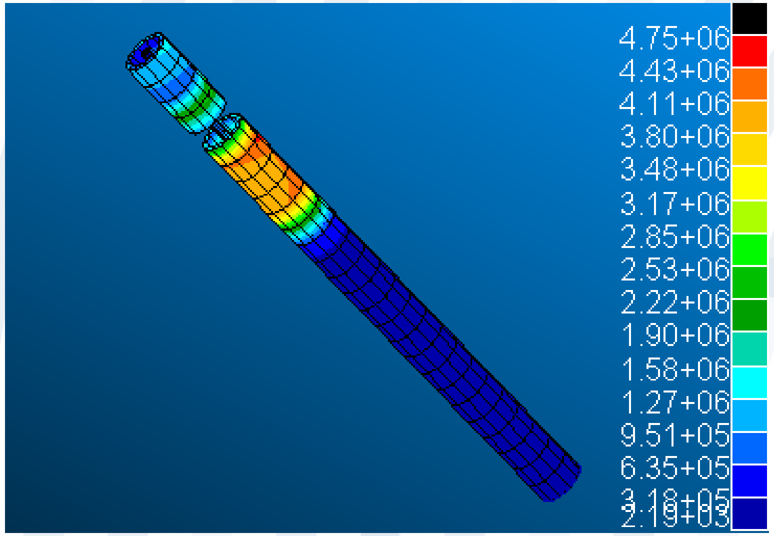
Antenna structural analysis

Random vibration analysis



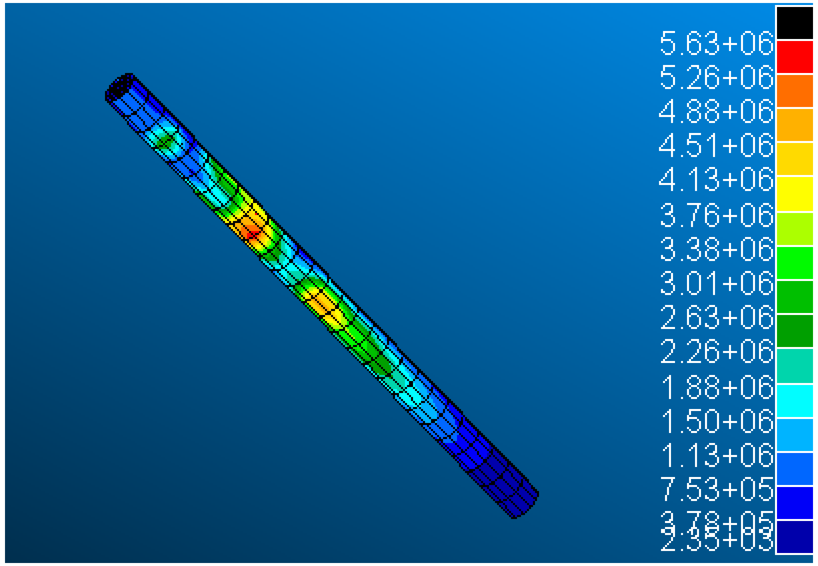


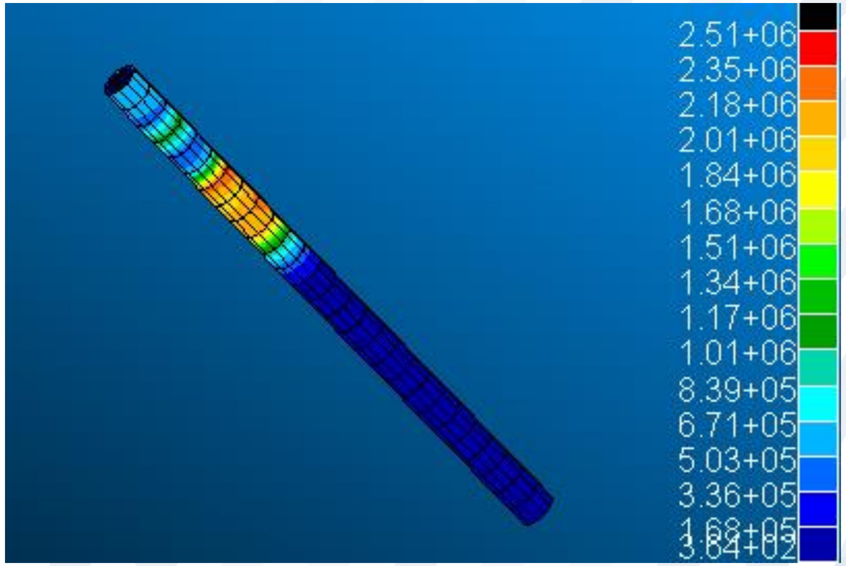




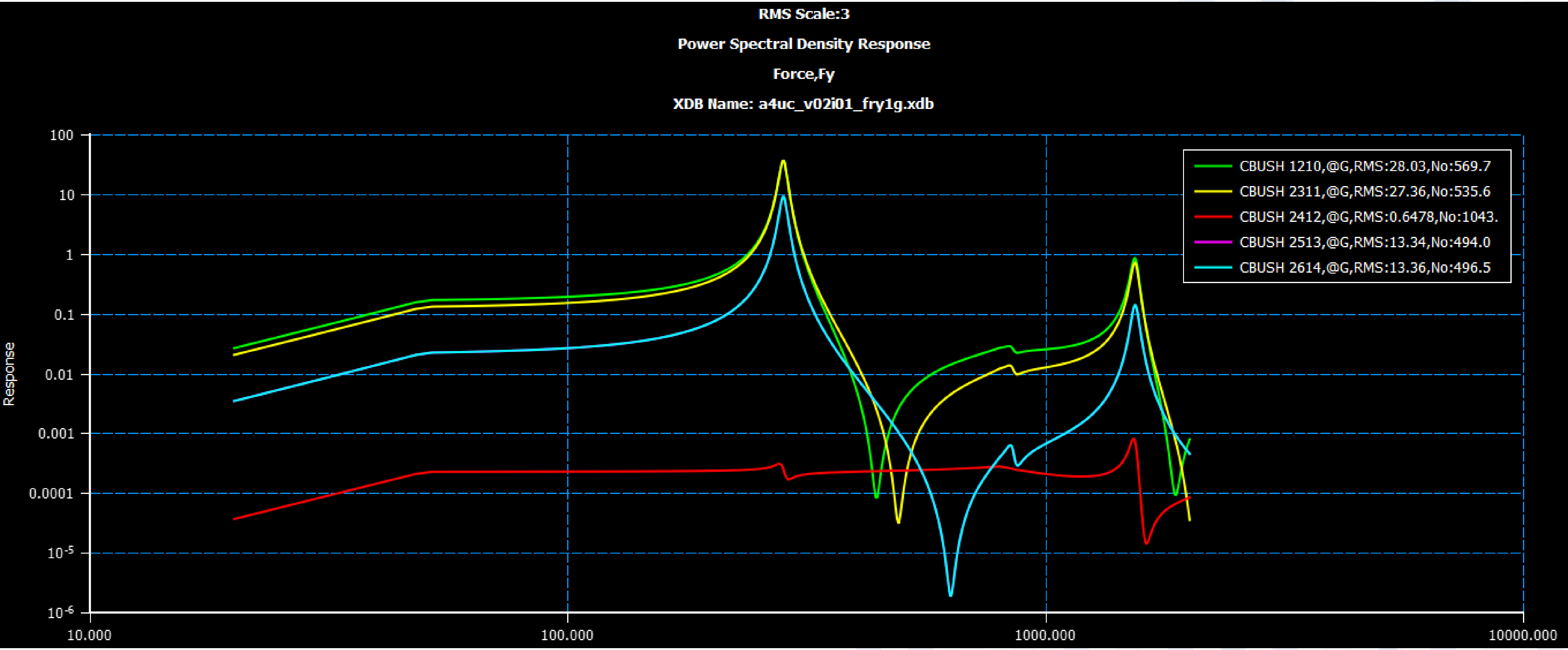
Antenna structural analysis

Random vibration analysis





Antenna structural analysis



Antenna structural analysis

sfy	sfu	km	L [m]	t weld [m]
1.6	2.0	1.2	0.016	0.0005

Random vibration analysis

- Margins of Safety

Material	Al6082	Teflon	Duroid	PEEK	Copper
Yield Str [Pa]	2.50E+08	1.50E+07	2.70E+07	5.00E+07	2.20E+08
Ult. Str [Pa]	2.90E+08	1.50E+07	2.70E+07	5.00E+07	2.76E+08
Rnd Horz stress [Pa]	1.03E+07	5.60E+06	1.90E+06	6.20E+06	1.53E+07
Rnd Vert. Stress [Pa]	3.30E+06	2.50E+06	5.01E+06	1.70E+06	4.75E+06
MoS,y	11.64	0.40	1.81	3.20	6.49
MoS,u	10.73	0.12	1.25	2.36	6.52

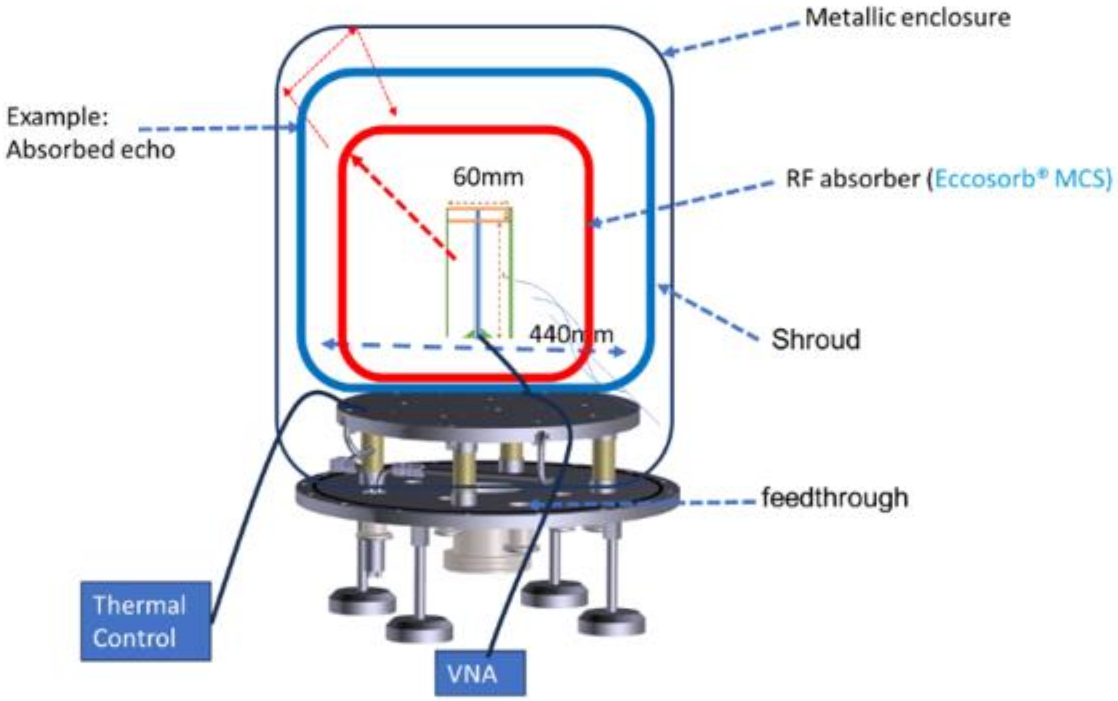
Antenna structural analysis

sfy	sfu	km	L [m]	t weld [m]
1.6	2.0	1.2	0.016	0.0005

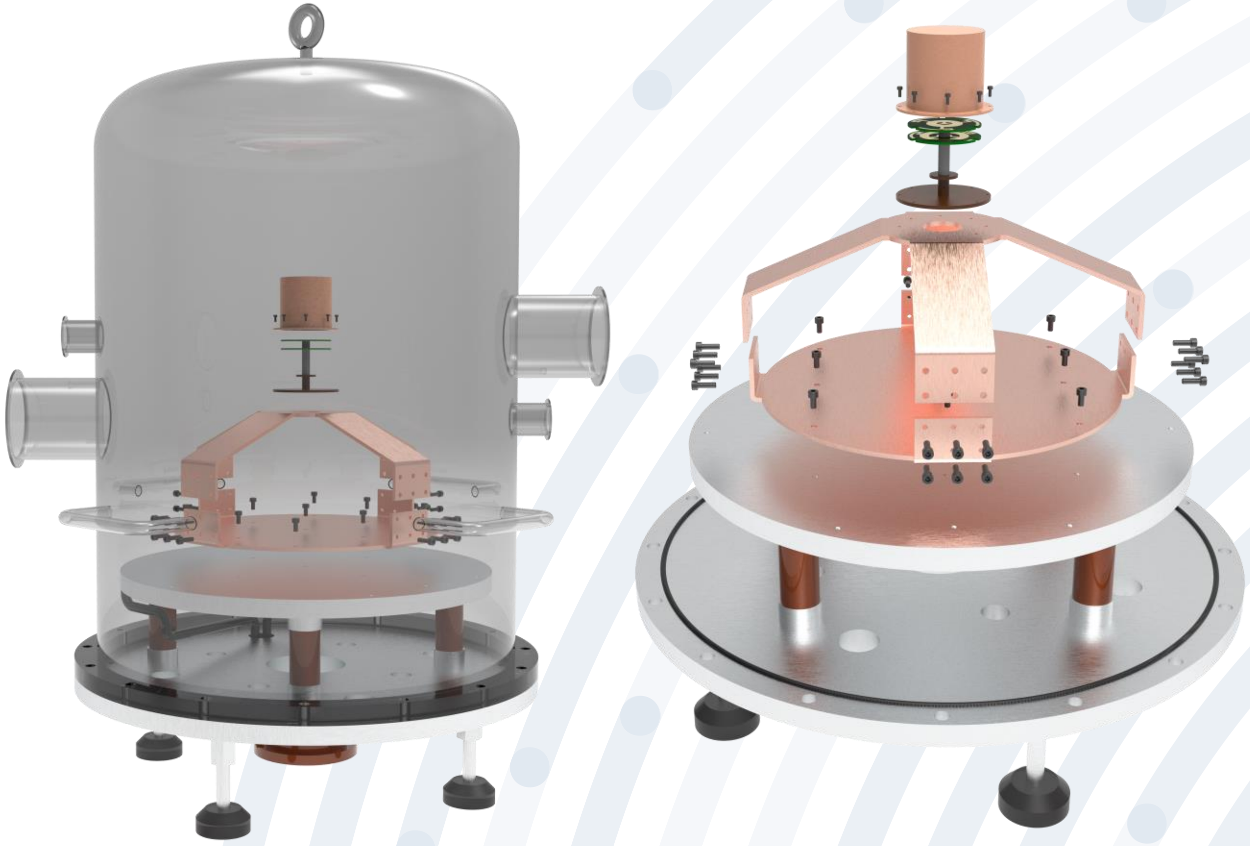
Random vibration analysis: MoS

Union	Glue 12	Weld 25	Weld26	Glue 23
Area [m2]	1.66E-05	7.23E-06	7.23E-06	3.62E-05
Material	A138	Cu	Cu	A138
strength [Pa]	6.00E+06	2.20E+08	2.20E+08	6.00E+06
Load Horiz [N]	1	9.4	3.9	13.8
Load Vert [N]	28.3	13.3	13.4	28.3
epsjoint	0.75	0.1	0.1	0.7
Max strss (L/A) [Pa]	1.71E+06	1.84E+06	1.85E+06	7.82E+05
MoS joint	0.10	3.98	3.94	1.24

Test Set-Up

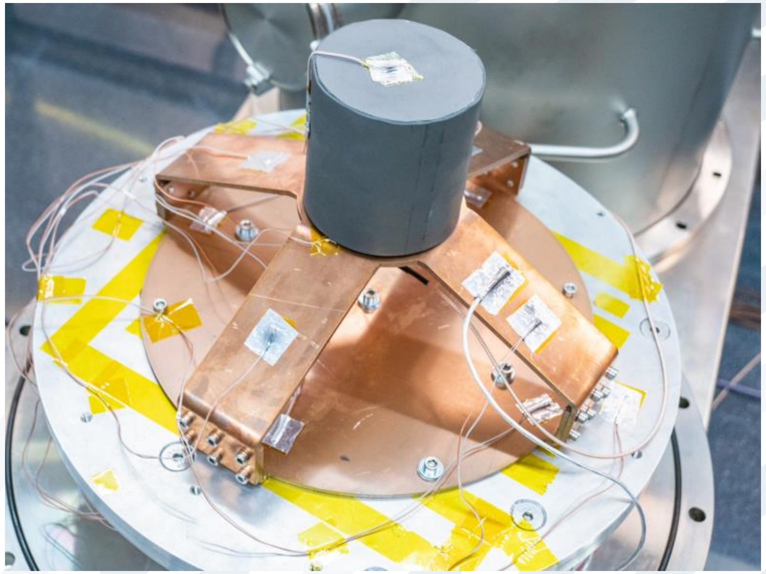


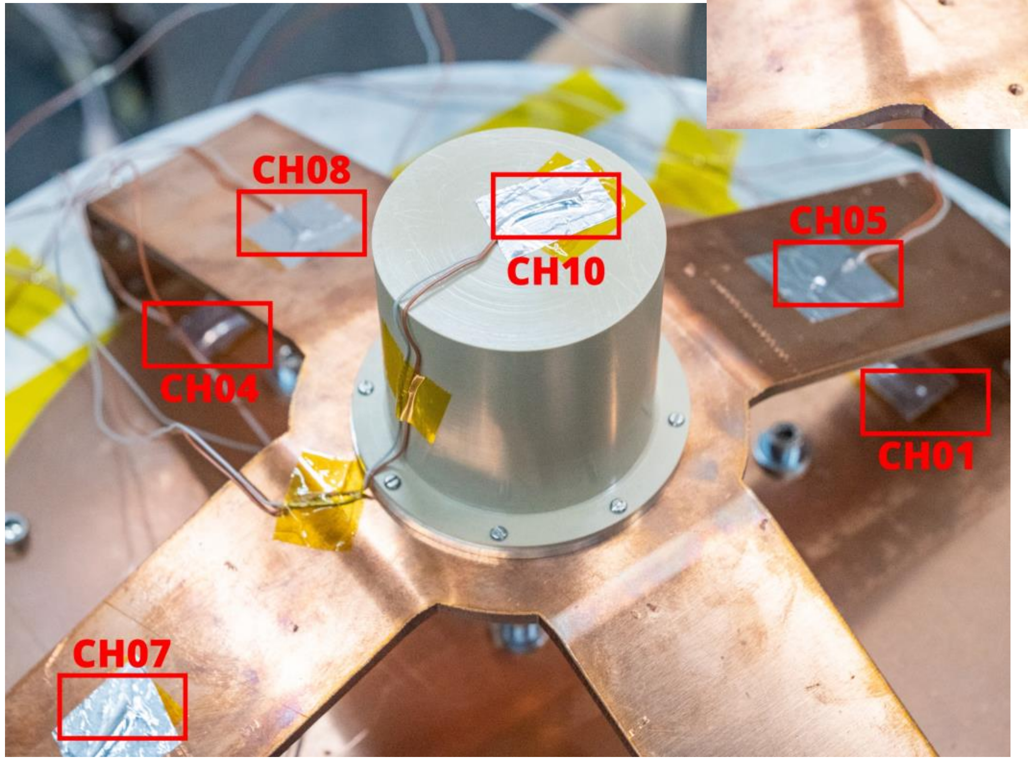
Test Set-up diagram

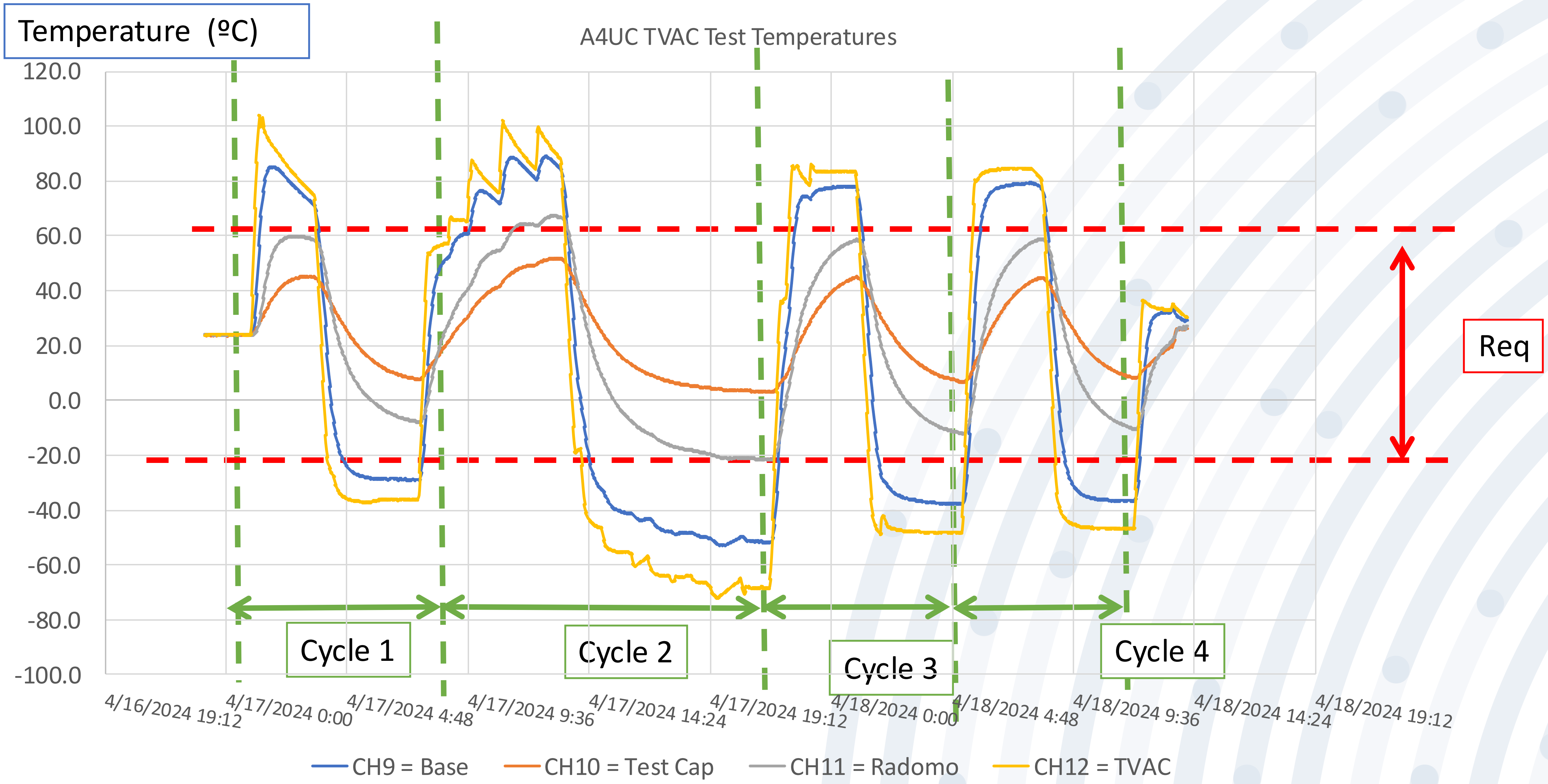


Test set-up 3d model

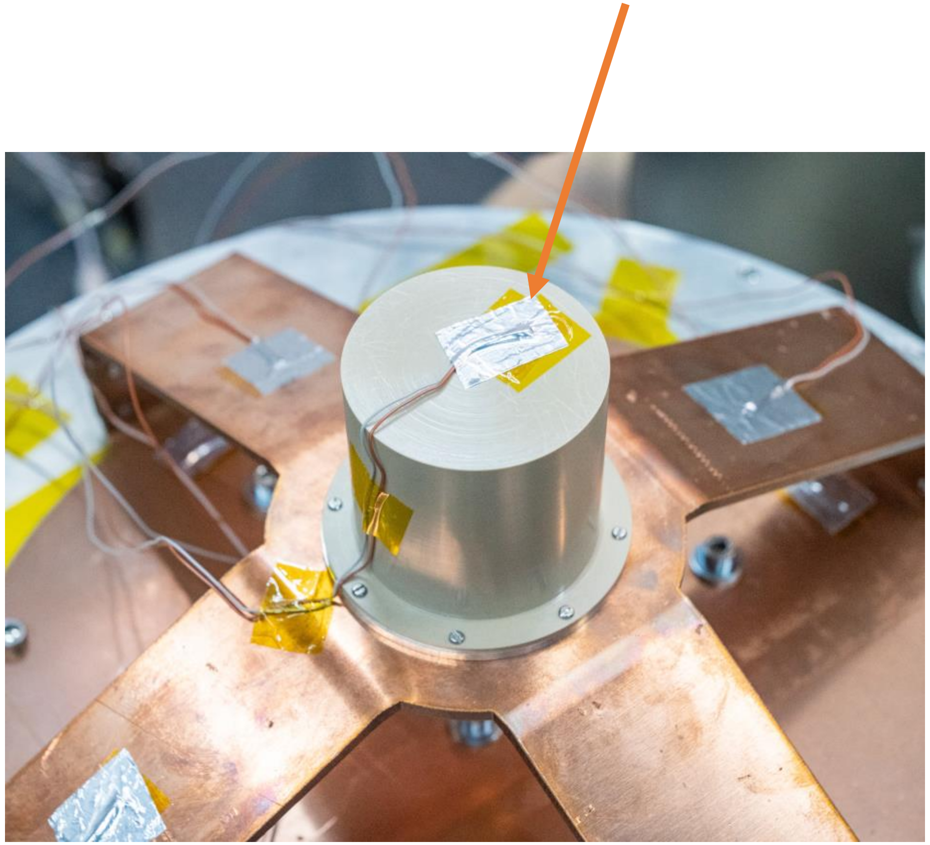
TVAC Set-up

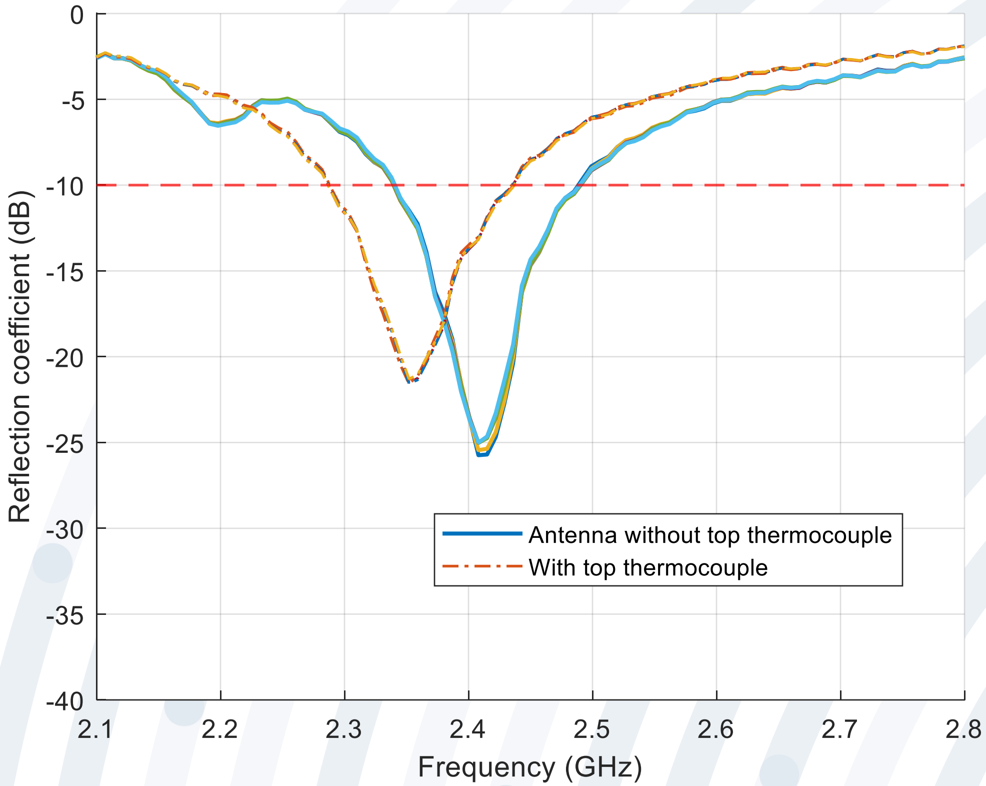




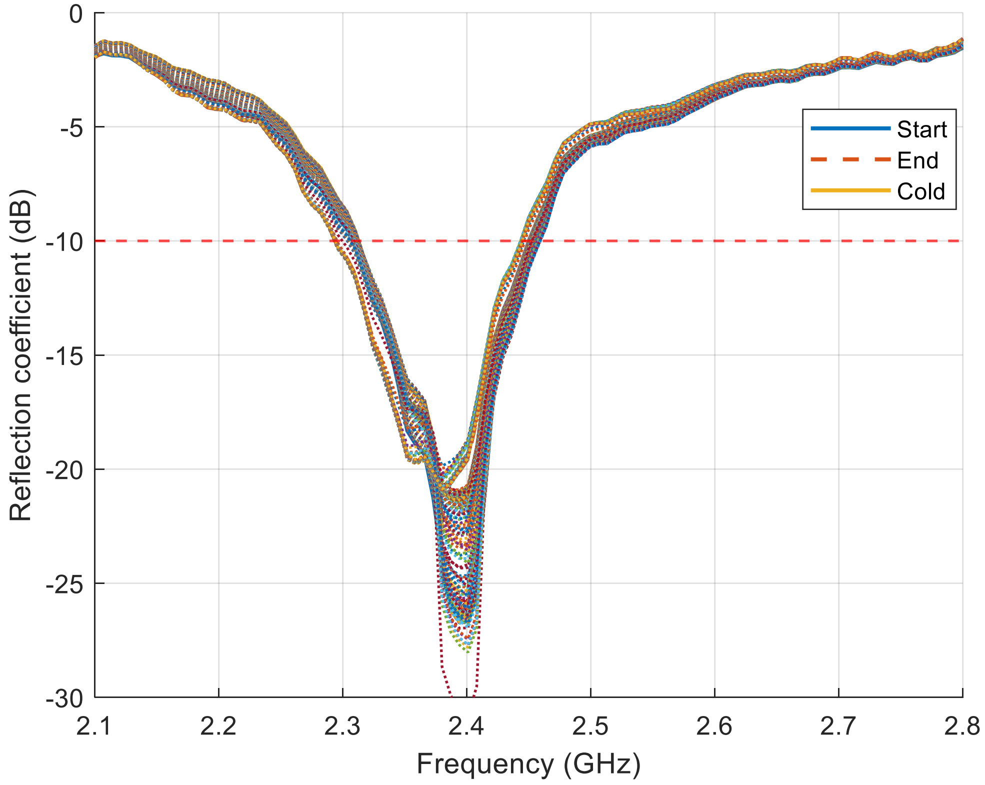

Temperature (ºC)
A4UC TVAC Test Temperatures
120.0
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
-80.0
-100.0
4/16/2024 19:12
4/17/2024 0:00
4/17/2024 4:48
4/17/2024 9:36
4/17/2024 14:24
4/17/2024 19:12
4/18/2024 0:00
4/18/2024 4:48
4/18/2024 9:36
4/18/2024 14:24
4/18/2024 19:12
Cycle 1
Cycle 2
Cycle 3
Cycle 4
Req
CH9 = Base
CH10 = Test Cap
CH11 = Radomo
CH12 = TVAC

Antenna with termocouples

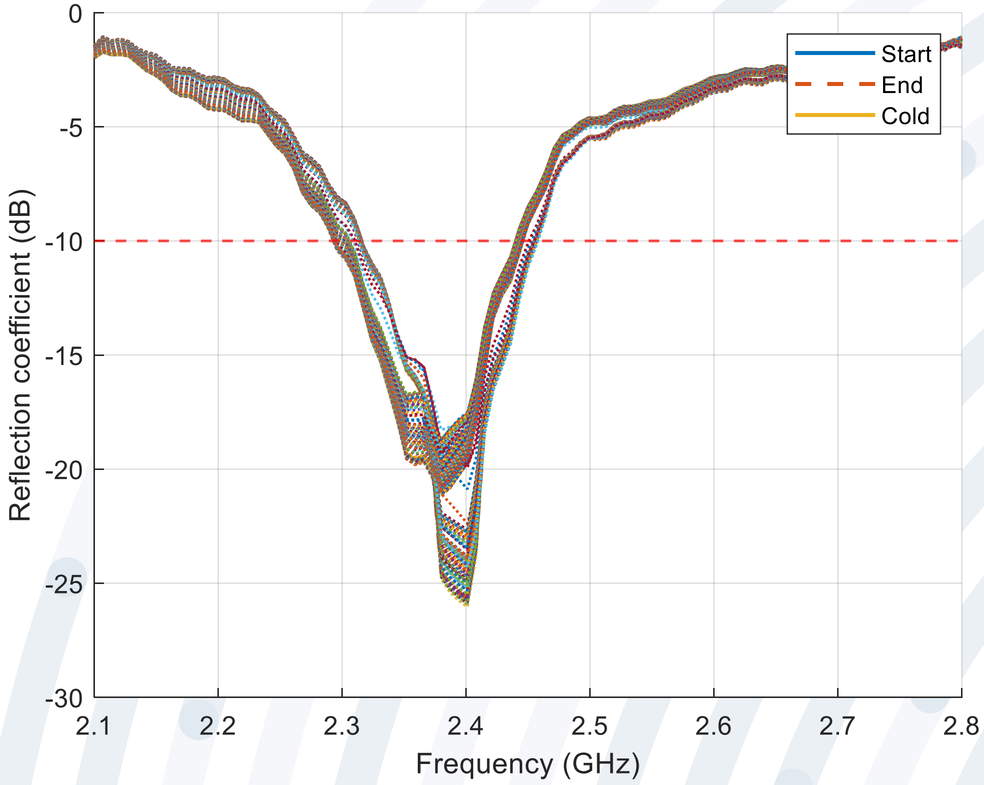




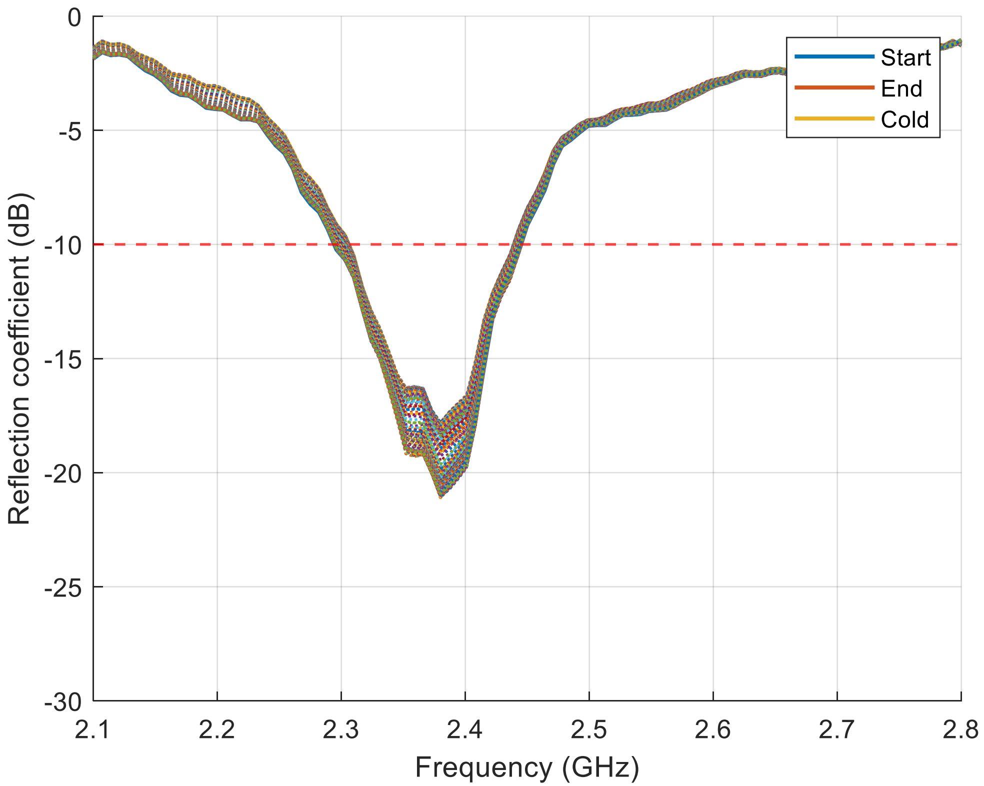
Cycle 1



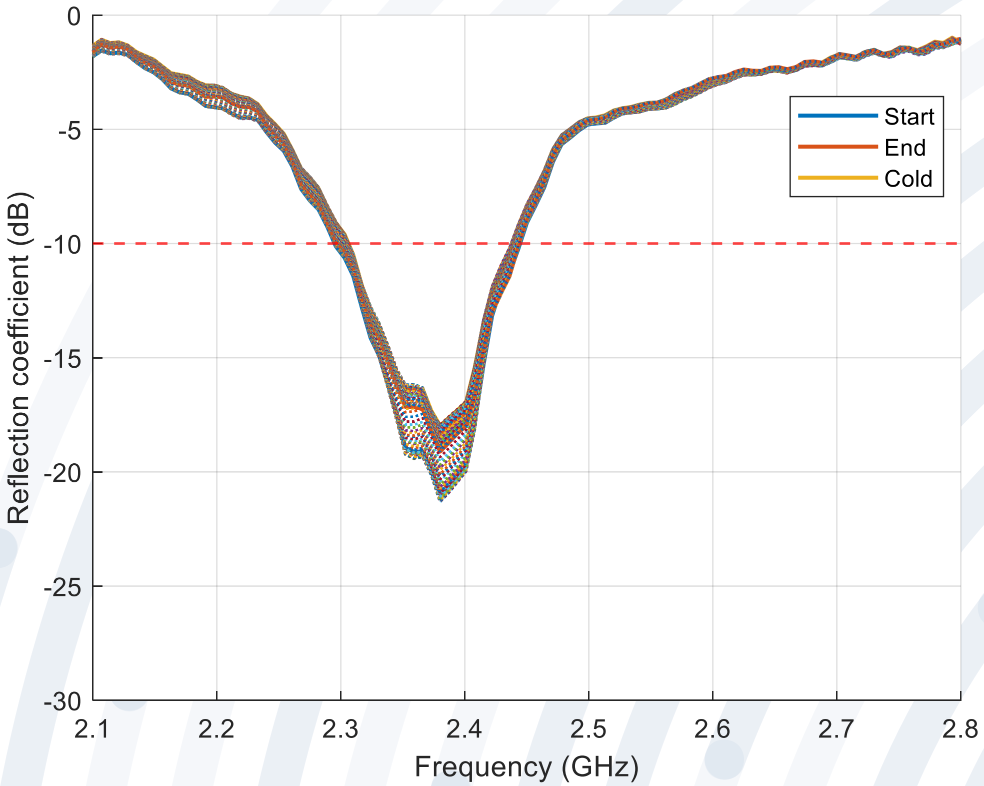
Cycle 2



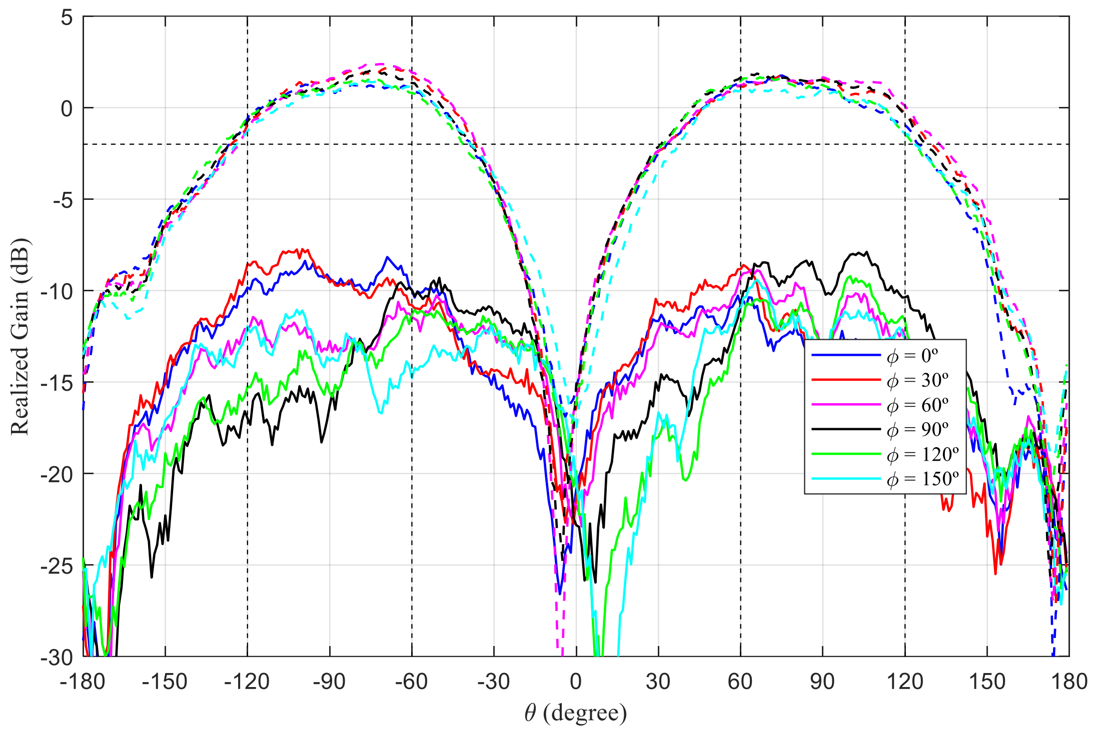
Cycle 3



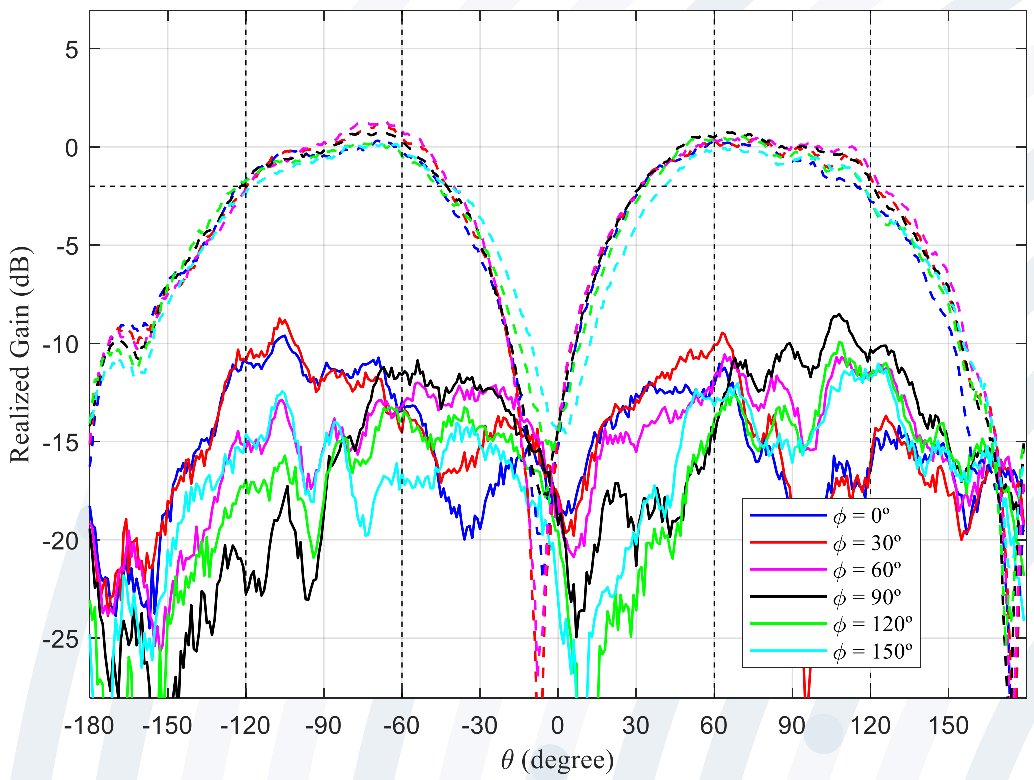
Cycle 4



QM1-Antenna Gain Set 1 (post –TVAC)

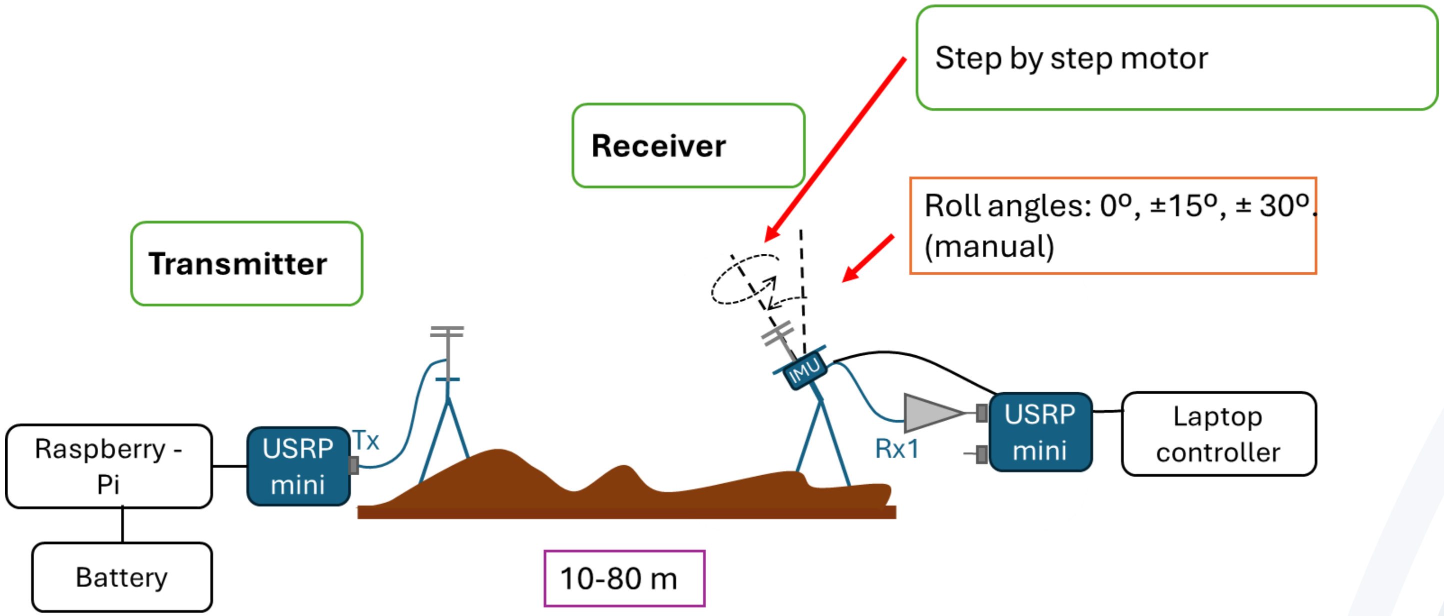


2.4 GHz

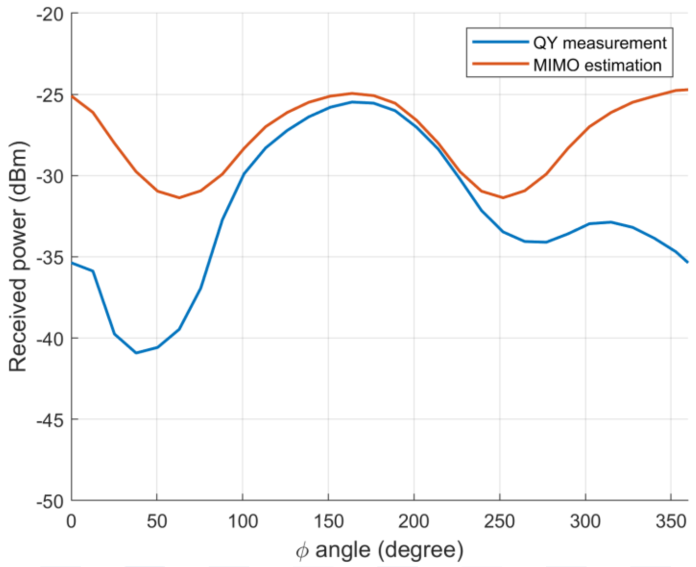


2.5 GHz

Preliminary considerations.

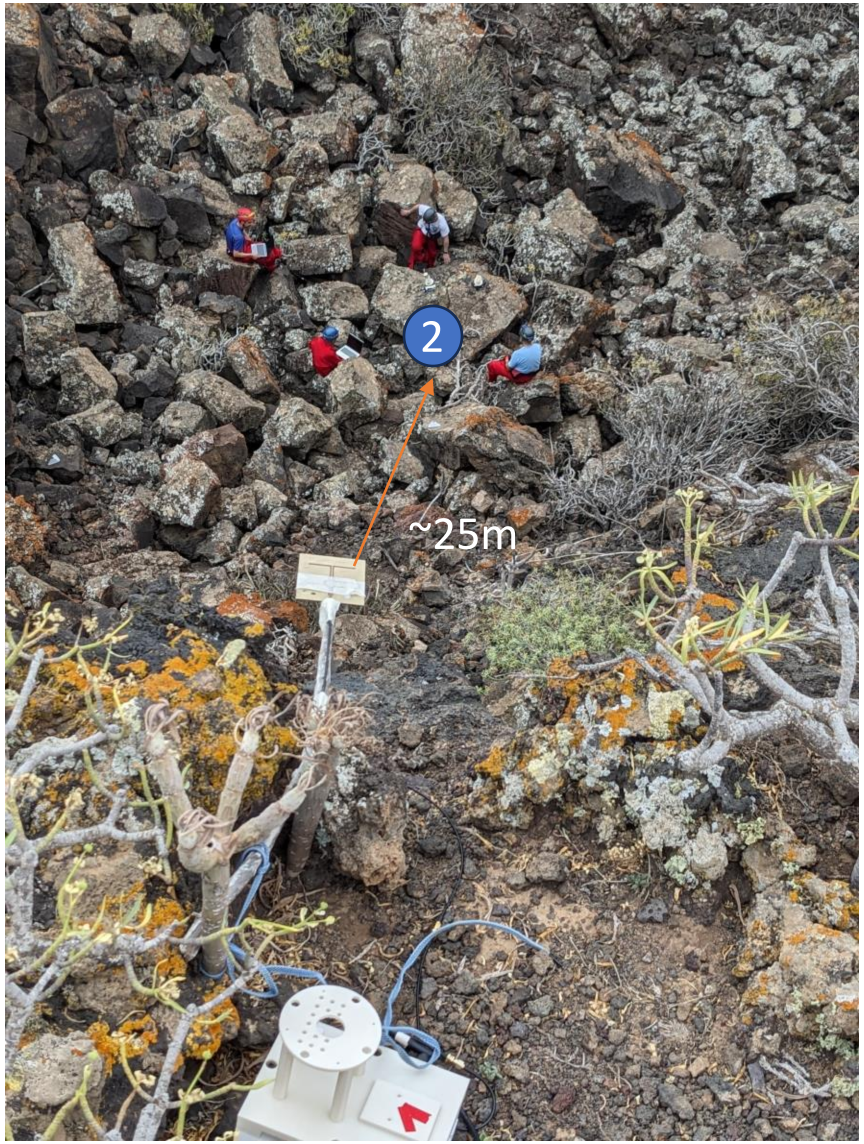


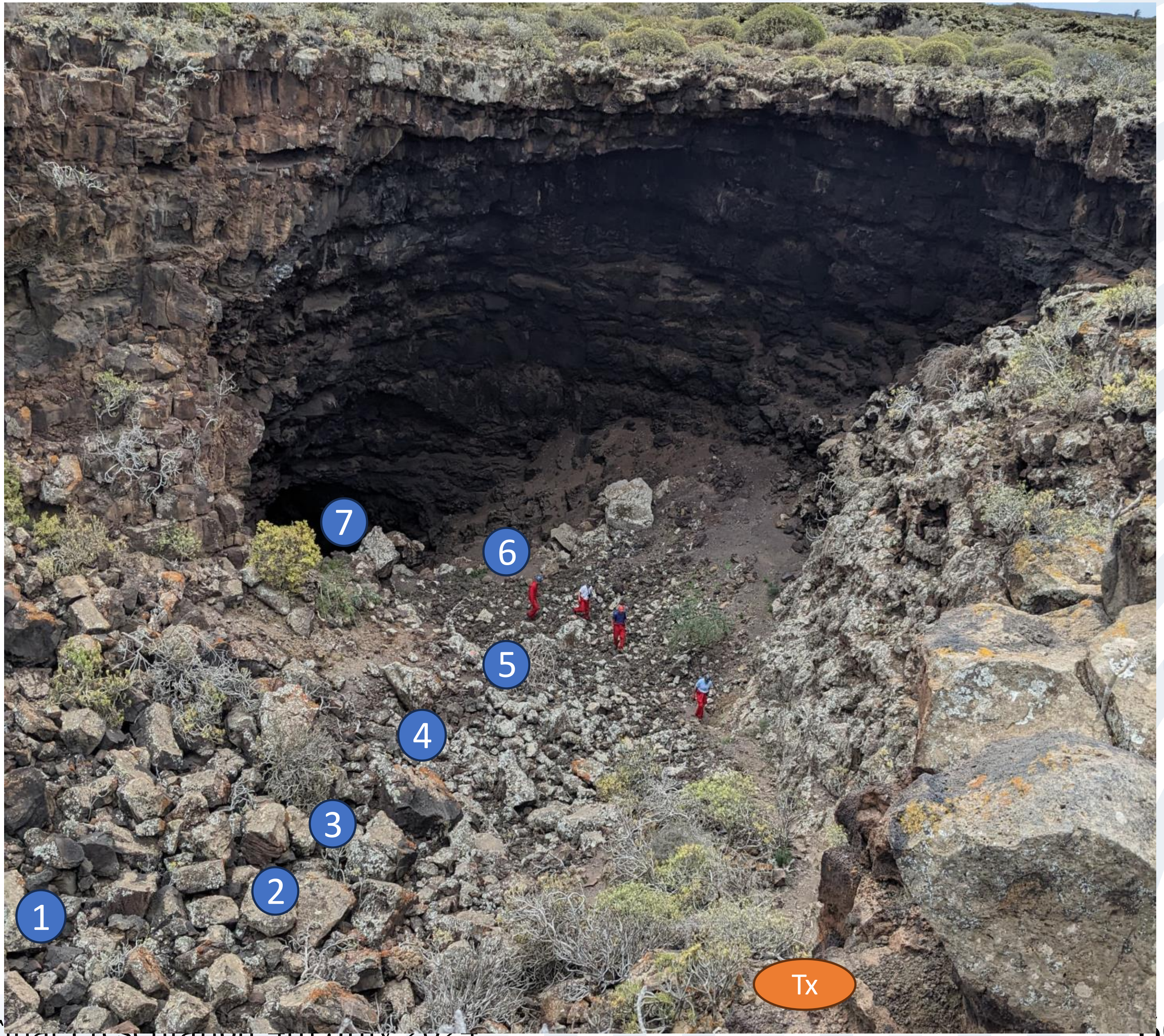
Wi-Fi 4 (802.11n)	Max. data rate (Mbps)	Power Consump	Tx power	Sensitivity	Module Example
1x1 20 MHz	72.2	Max 0.4 A (1.3 W)	16±2 dBm	-73±2 dBm	M2-MAYA-W1
1x1 40 MHz	150			-71±2 dBm	
2x2 20 MHz	144.4	510mA 606mA (2W) Rx: 0.7 W	16±2 dBm 20±2 dBm	-73±2 dBm	Laird 60-2230C Doodle Labs NM-DB-2
2x2 40 MHz	300			-76±2 dBm	



Measurements in Jameo de la Gente

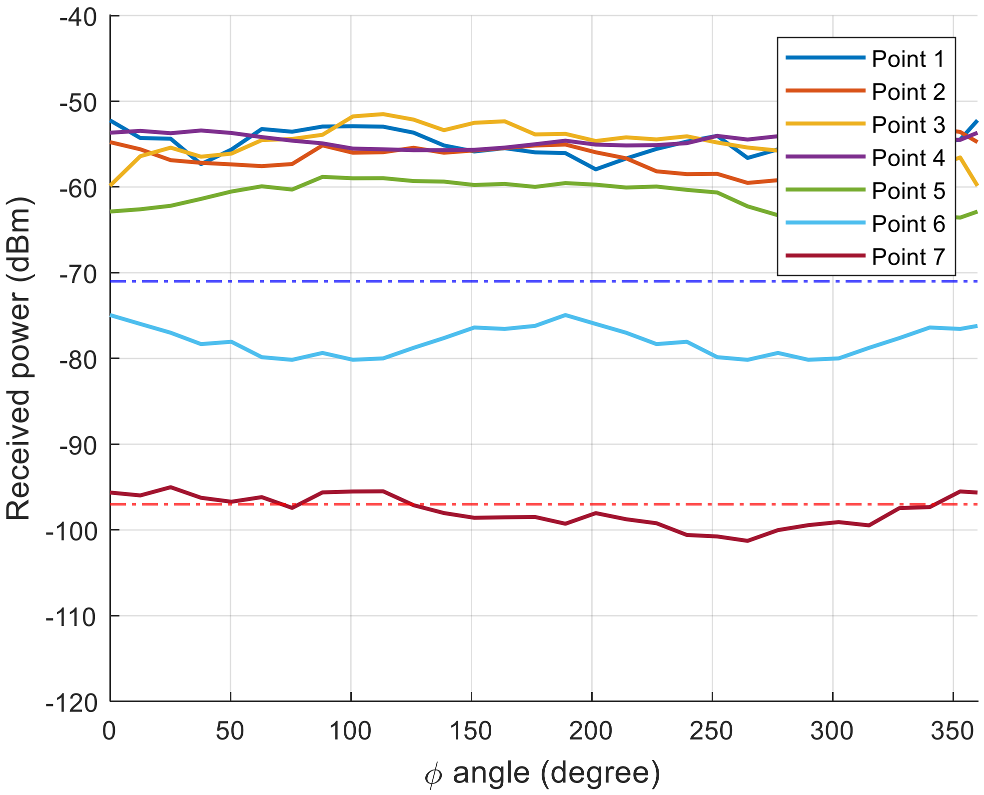
Measurements in Jameo de la Gente



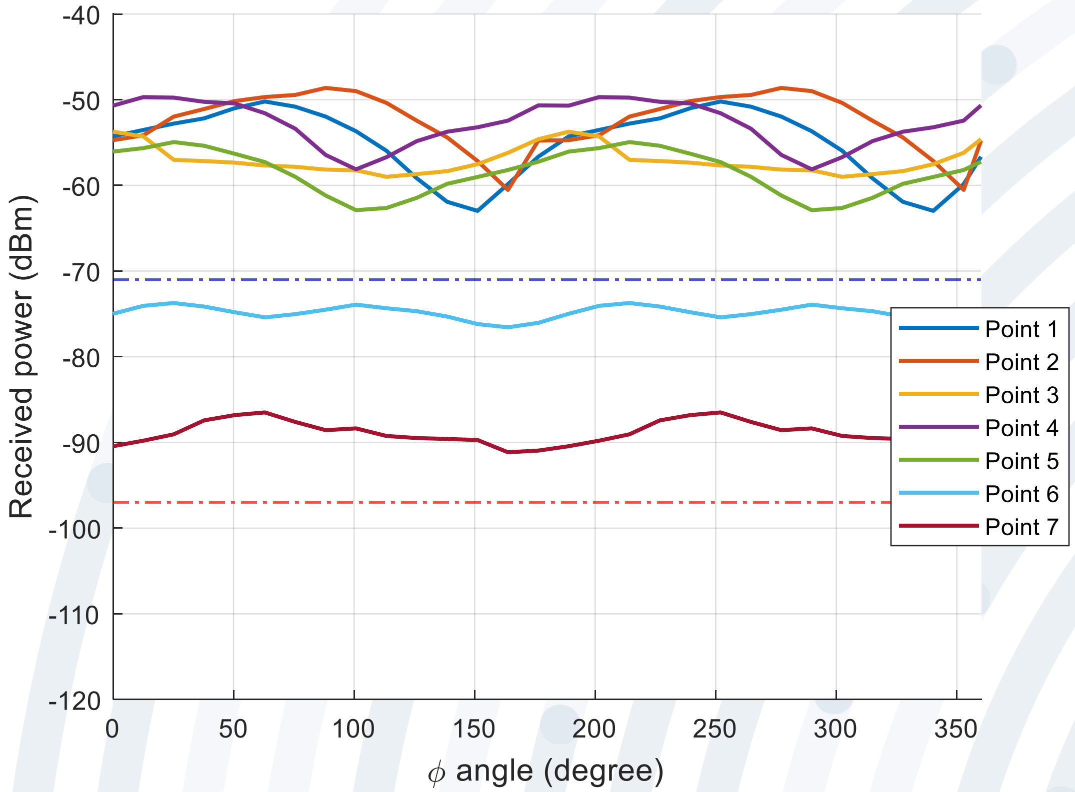


Measurements in Jameo de la Gente

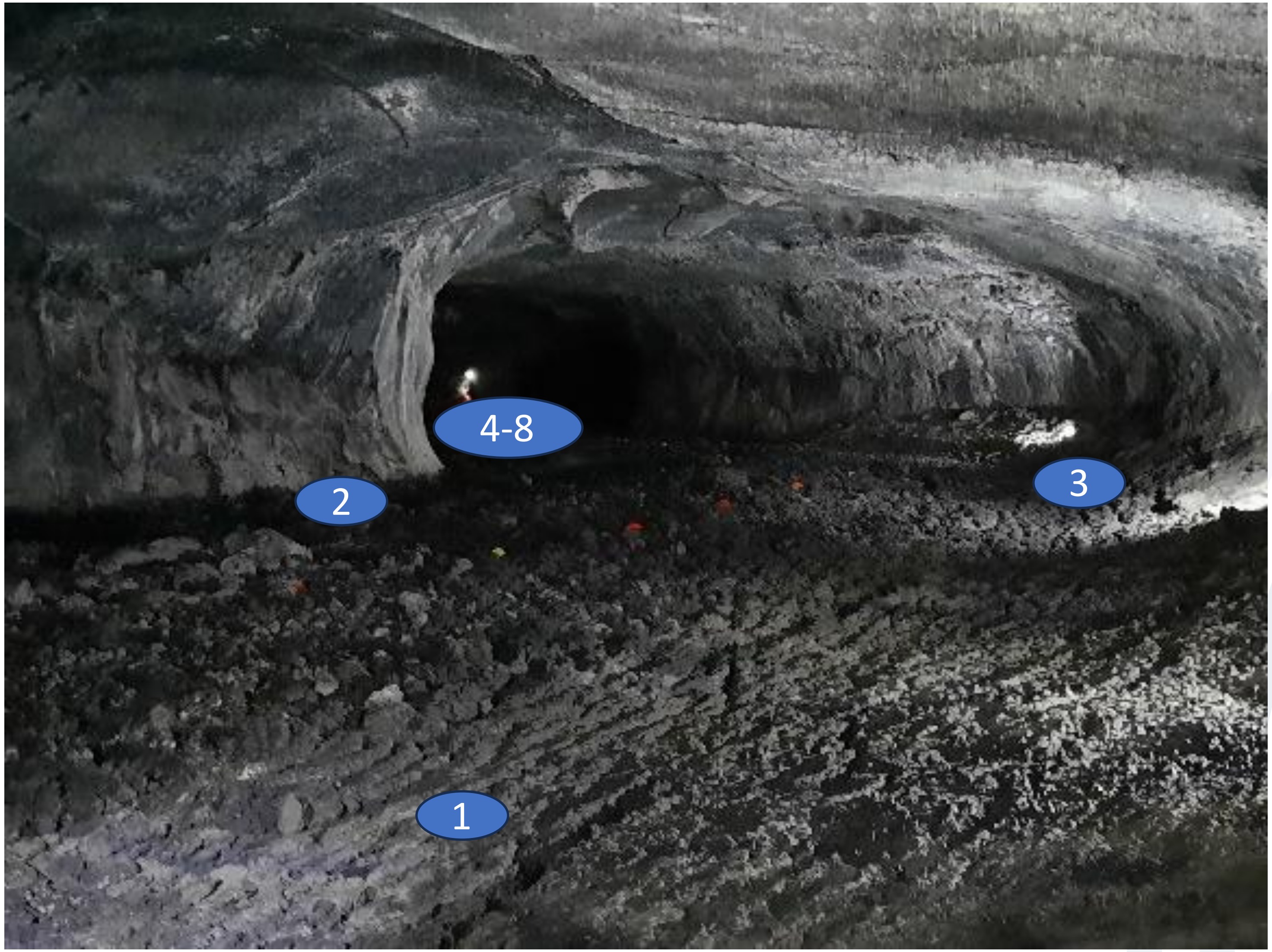
Pagoda



QY - MIMO



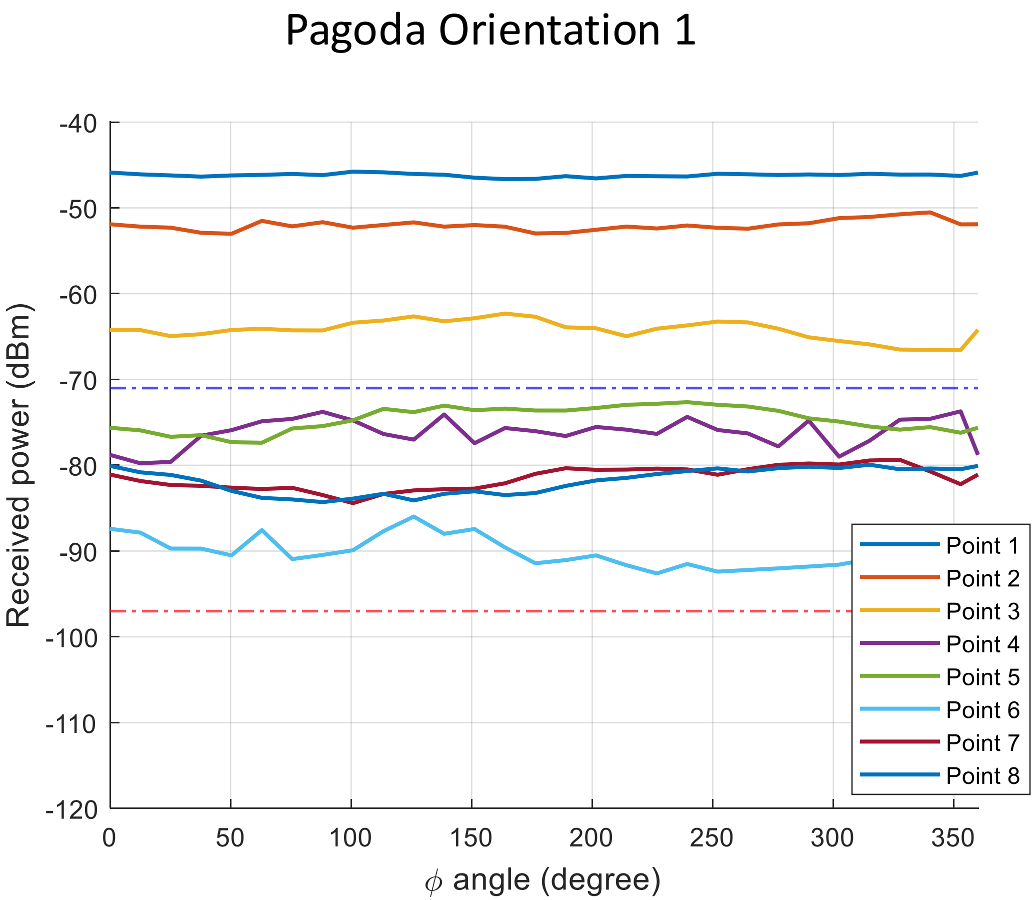
Scenarios in Lanzarote. Naturalistas Cave 1

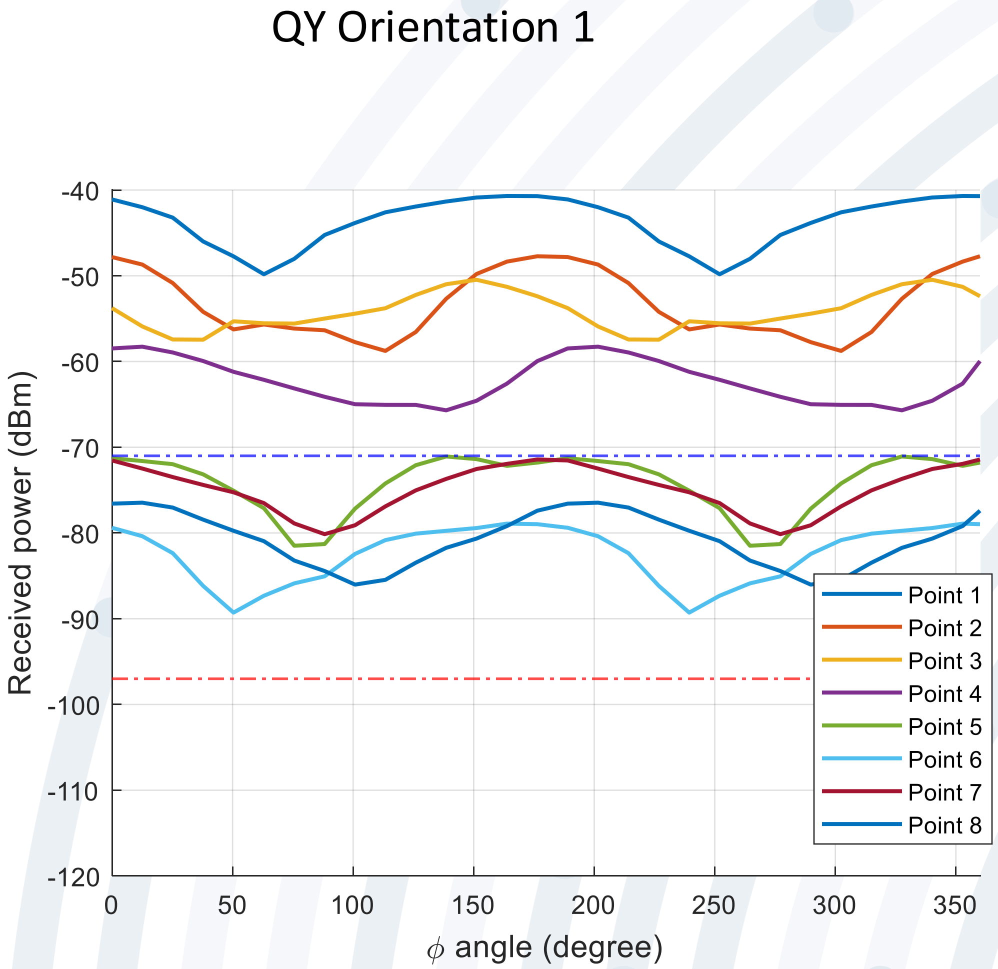


Selected points:

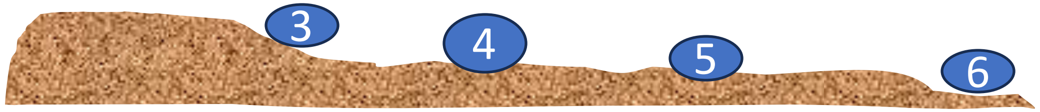
1. Center. 10.4m to Tx. LoS
2. Close to a wall. 15m to Tx. LoS
3. Close to a wall. 26m to Tx. LoS
4. Close to a wall. 31m to Tx. NLoS
5. Middle. 53m to Tx. NLoS
6. Middle. 65m to Tx. NLoS
7. On a boulder. 65m to Tx. NLoS
8. Behind a boulder. 65m to Tx. NLoS

Scenarios in Lanzarote. Naturalistas Cave 1





Scenarios in Lanzarote. Naturalistas Cave 2

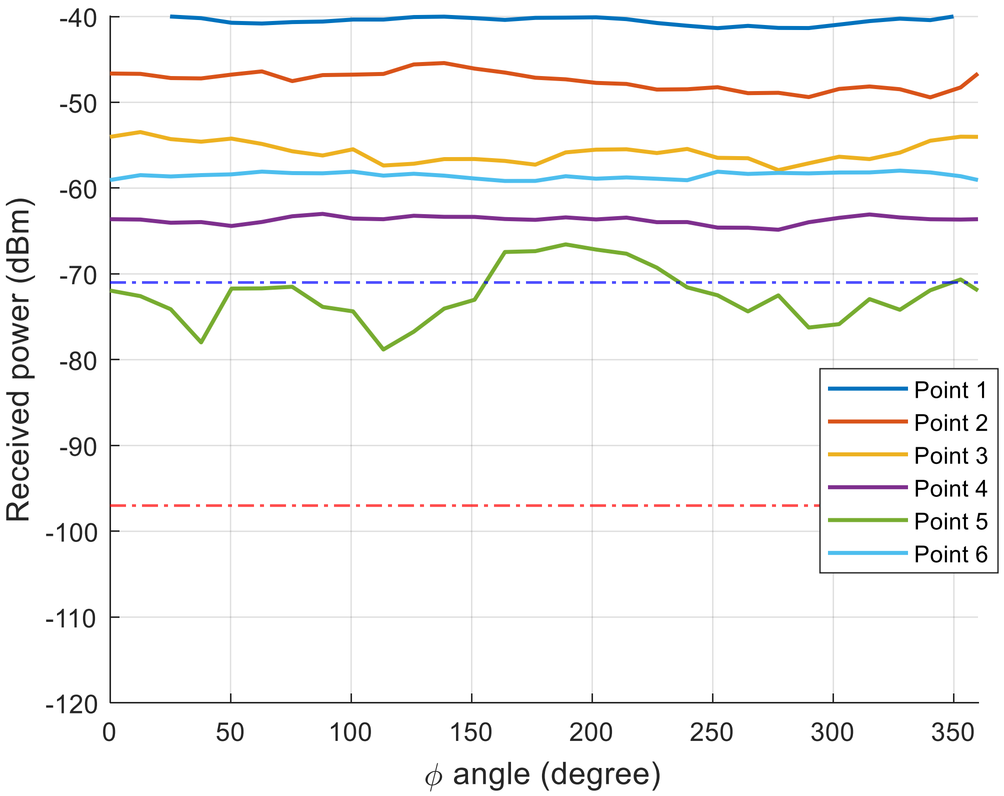


Selected points:

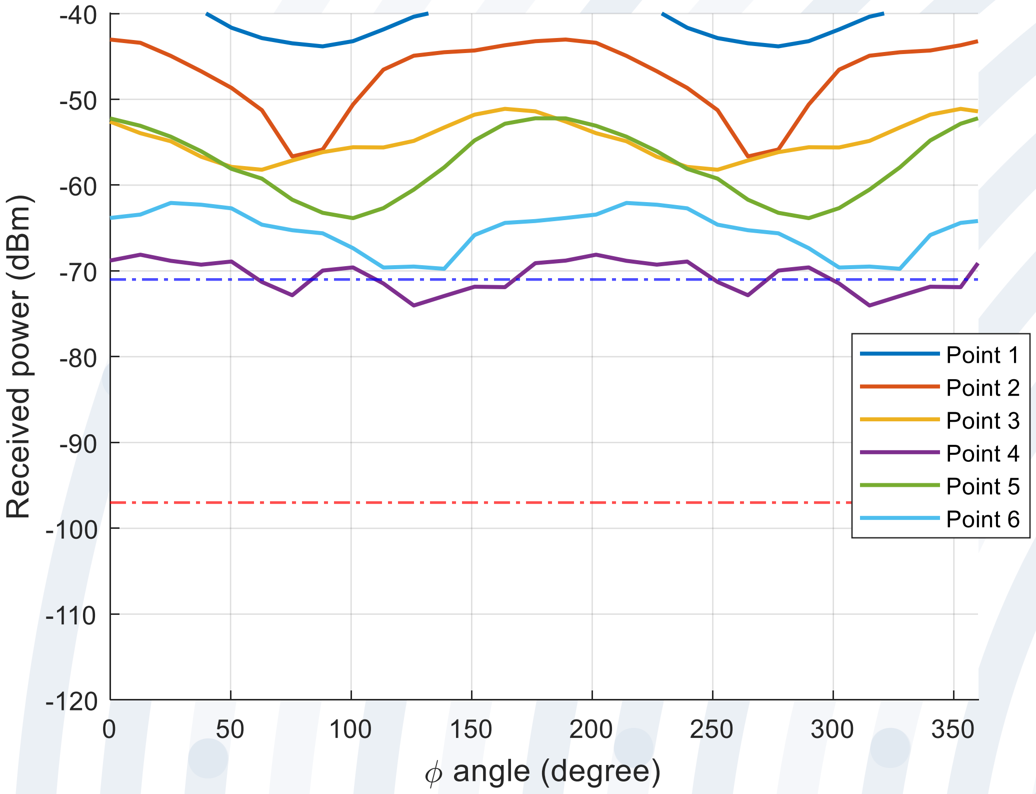
1. Center. 6.5m to Tx. LoS
2. Close to a column. 11m to Tx. LoS
3. Slope. 21m to Tx. NLoS
4. Close to a wall. 22m to Tx. NLoS
5. Middle. 30m to Tx. NLoS
6. Middle. 45m to Tx. LoS

Scenarios in Lanzarote. Naturalistas Cave 2

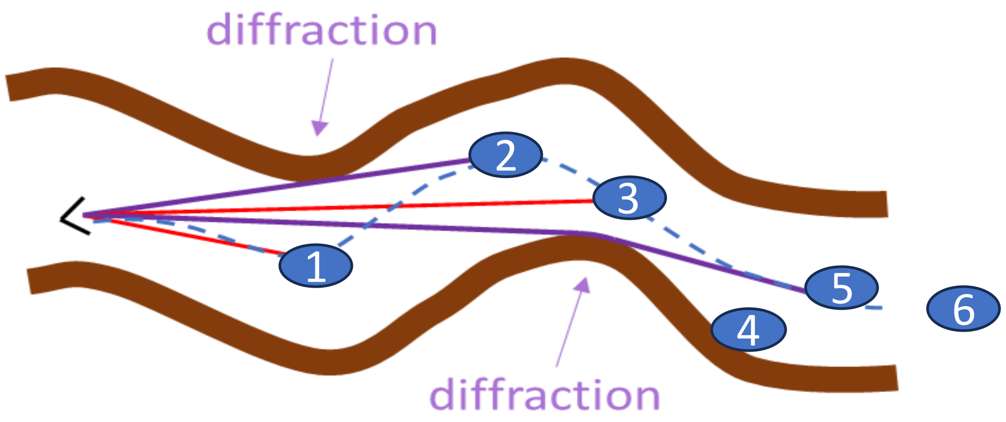
Pagoda



QY - MIMO



Scenarios in Lanzarote. La Corona Tube

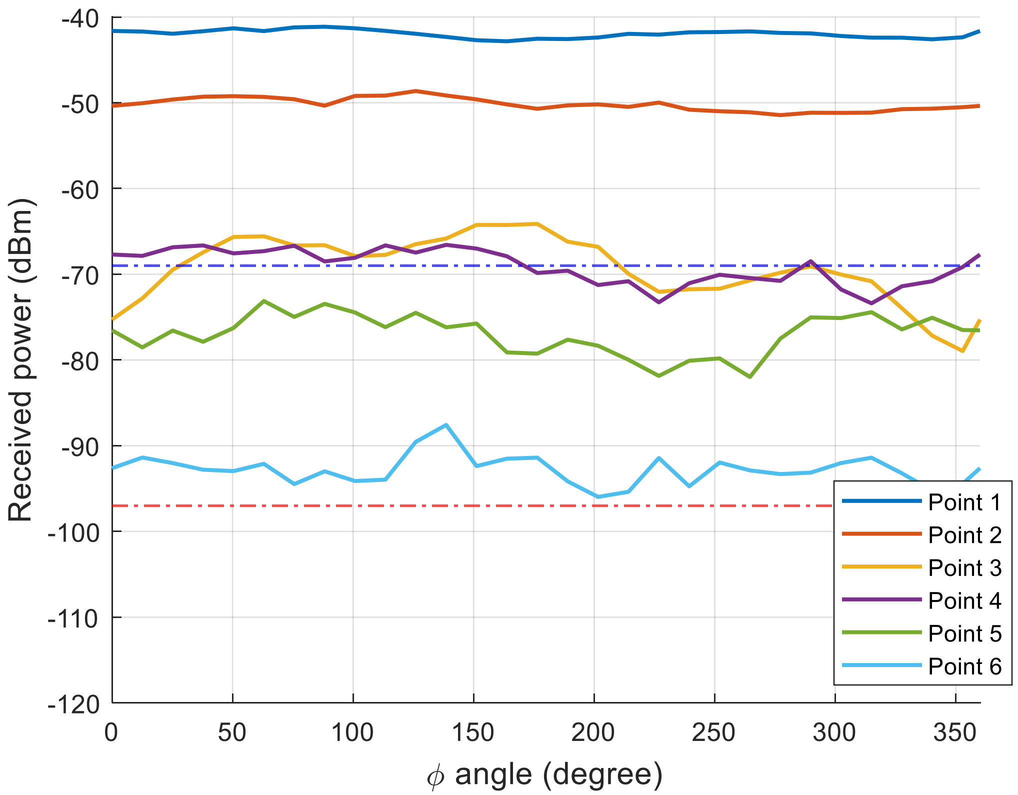


Selected points:

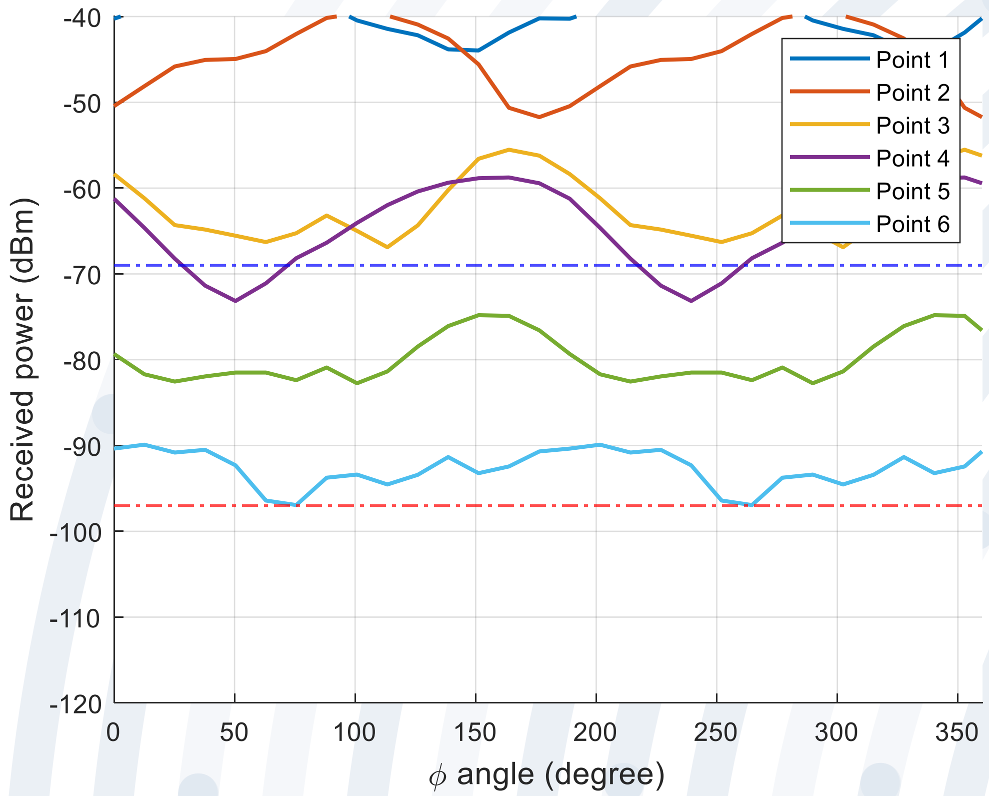
1. Center. 8.5m to Tx. LoS
2. Close to wall. 20m to Tx. LoS
3. Close to wall. 21m to Tx. NLoS
4. Middle. 26m to Tx. NLoS
5. Middle. 40m to Tx. NLoS
6. Middle. 49m to Tx. NLoS

Scenarios in Lanzarote. La Corona Tube

Pagoda



QY - MIMO

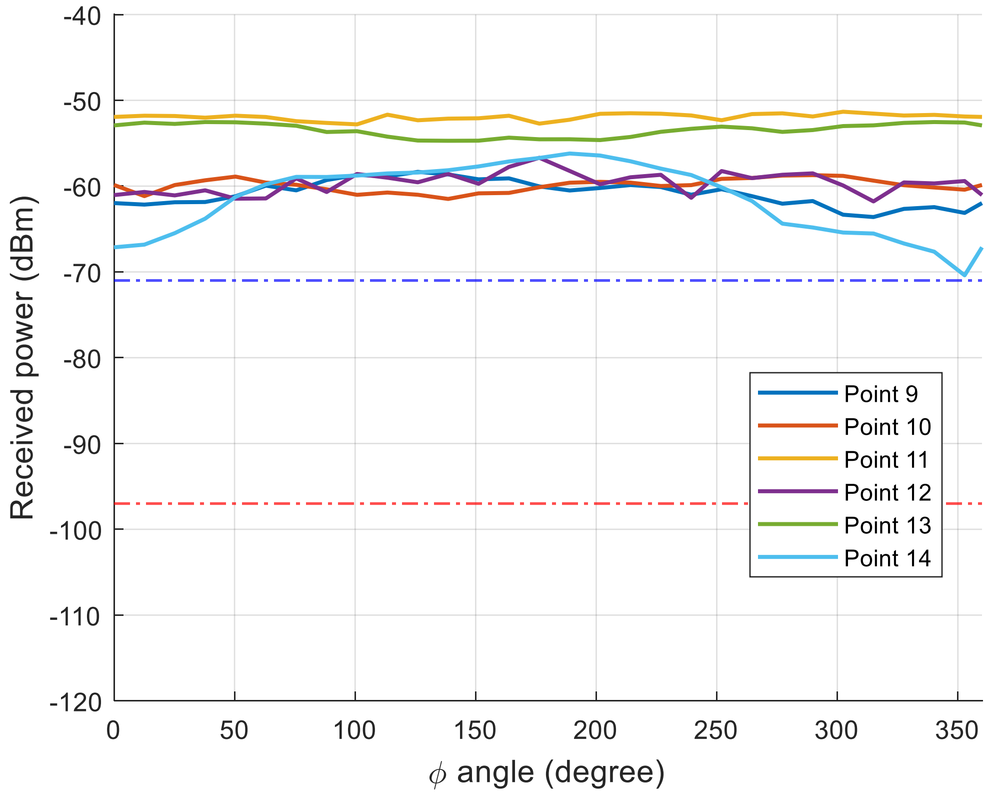


Scenarios in Lanzarote. Naturalistas Cave 1. Boulders

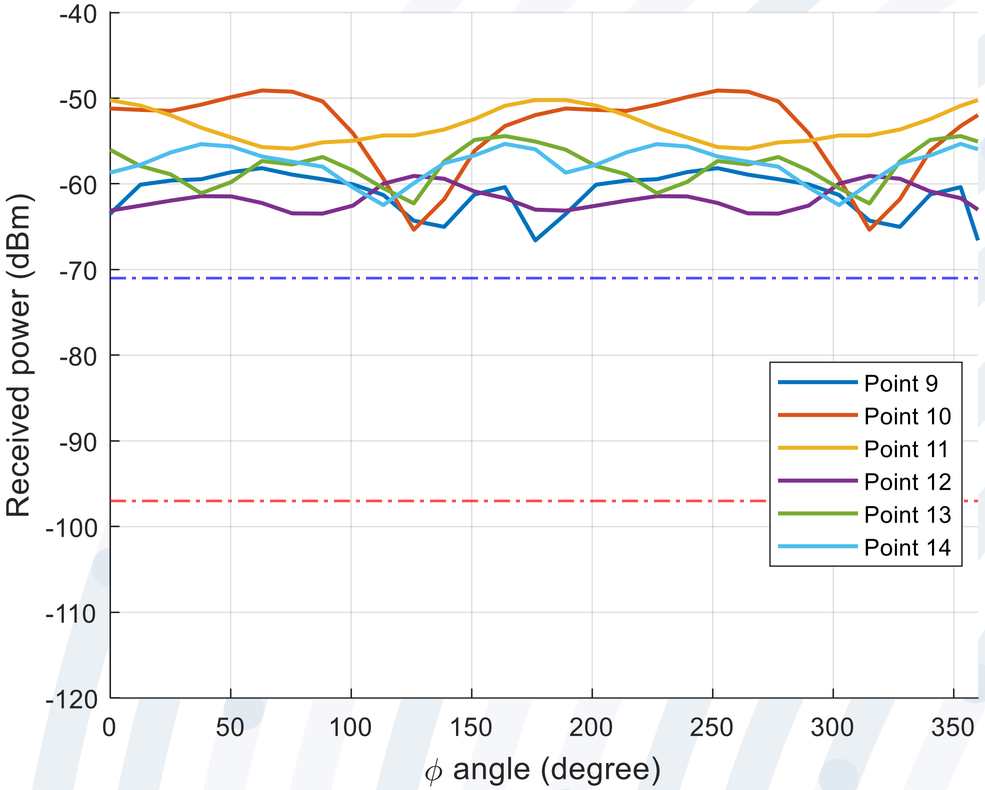
9. Behind a boulder. 15m NLoS
10. On a boulder . 13m NLoS
11. Right side. 13m to Tx. NLoS
12. Behind. 20m to Tx. NLoS
13. On a boulder. 12m to Tx. NLoS
14. Left. 13m to Tx. NLoS

Los Naturalistas Cave 1. Boulders

Pagoda



QY – MIMO – orientation 1



Achivements

- Two propagation models have been developed and experimentally validated in lava caves. One model is a simple model based on images and the other one is based on Physical Optics, more complex, in terms of computation.
- Based on these models, the link budget and the requirements of a medium-data rate communications subsystems have been consolidated.
- An antenna with TRL 5, has been designed and manufactured. The antenna shows an omnidirectional radiation pattern suitable for lunar cave exploration. The reflection coefficient of the antenna has been measured in different thermal-vacuum cycles.
- The behavior of the antenna has been validated in Earth analogues caves.

and…

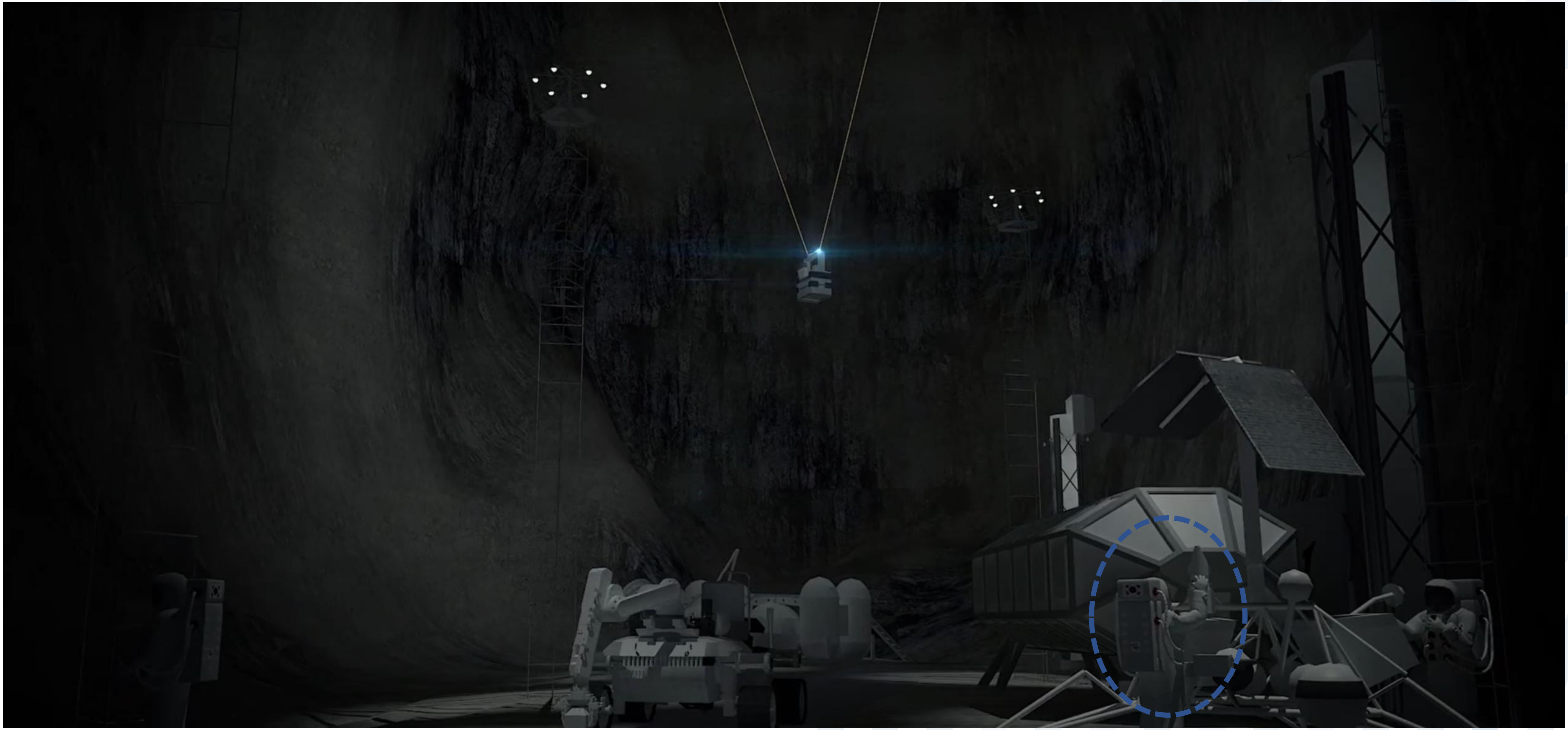
- At least five contributions to international conferences
- Several appearances in the local press

Acknowledgments

- ESA Team
- Casa de los Volcanes
- Medioambiente Cabildo de Lanzarote
- Gustavo de Vulkan Vertical
- Federación Gallega de Espeleología

Back-up slides

Imagine a Lunar base under the surface…



Imagine a Lunar base under the surface…