EXECUTIVE SUMMARY REPORT

Medium-to-high gain X-band antenna with customisable pattern and polarization

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1. *INTRODUCTION*

This report summarises the work performed during the ESA project entitled “Medium-to-high gain X-band antenna with customisable pattern and polarization”. The designed antenna configurations are developed by means of Modulated Metasurface (MTS) technology which has emerged in the recent years as a solution to realize high performance low-profile antennas, providing advantages in terms of feeding simplicity, low profile and low weight, reduced complexity and cost of manufacturing.

2. *OBJEVTIVE OF THE ACTIVITY*

The main objective of the activity was to raise the technology of metasurface (MTS) antennas to at least TRL 5-6 (up to E(Q)M level) by designing, manufacturing and testing a Medium-to-high gain X-band antenna. A Qualification campaign to ESA PA standards was not required by the SoW.

Two baseline MTS antenna configurations were requested by the SoW:

a. Pencil Beam Antennas (PBA) for Science and Space Exploration;
b. Data DownLink (DDL) antenna for LEO mission.

Both of them have been led up to Detailed Design Level but only the DDL prototype has been realized and tested.

The antenna requirements either in terms of electrical and thermo-mechanical specifications, assessed during the first Task of the activity, are summarized in the following tables.

<u>PENCIL BEAM ANTENNA (PBA) REQUIREMENTS</u>

Requirement	Value
Frequencies band (MHz)/ channels	Rx: 7145-7235 Tx: 8400-8450
HPWB	Rx: max 6° TX: max 5°
Minimum gain	Rx: > 30 dBi Tx: > 35 dBi
Gain shape	Pencil Beam
Polarisation	CP
Cross polar isolation within coverage	> 20 dB
RF power handling	80 W
Multipaction	6 dB margin at maximum power
Mass	< 2.6 kg

Requirements	Value
Orbit	Journey to mission
Distance	1e9 Km (Saturn distance) 149 e6 Km (Sun distance)
Sine vibration	
Frequency range (Hz)	Level
5-20	19 mm (0 – peak)
20-100	20g (0 – peak)
Random vibration - all axes	
Frequency range (Hz)	Level
20-100	+6 dB/octave
100-500	1.3 g^2/Hz
500-2000	-6 dB/octave
Global	40 g
Duration	2.5 min
Quasi-static	50g
Thermal requirements	
Temperature range	-150°C to 150°C

Table 2.1 Summary of the specifications for the PBA antenna: RF (right) and thermo-mechanical (left) requirements.

DATA DOWNLINK (DDL) ANTENNA REQUIREMENTS

Requirement	Value
Frequencies band / channels	8.025-8.400 GHz. 250 MHz channel
Minimum gain	6.0 dBi at reference satellite quote
Gain profile for 0º < nadir angle < θmax	Isoflux profile considering spatial attenuation
Polarisation	RHCP (goal Double Polarization)
Cross polar isolation within coverage	> 15 dB (>18 dB to operate in double polarization.)
RF power handling	80 W, (100 W goal per channel)
Phase variation vs frequency within channel (nonlinear component)	< 3º peak to peak
Amplitude variation vs frequency within channel	< 1 dB peak to peak (goal 0.5 dB).
Azimuth amplitude ripple	< 1 dB peak to peak
Mass	< 2.6 kg

Requirements	Value
Orbit	Sun synchronous
Altitude	400 – 1000 km
Sine vibration	
Frequency range (Hz)	Level
5-20	19 mm (0 – peak)
20-100	20g (0 – peak)
Random vibration - all axes	
Frequency range (Hz)	Level
20-100	+6 dB/octave
100-500	1.3 g^2/Hz
500-2000	-6 dB/octave
Global	40 g
Duration	2.5 min
Quasi-static	50g
Thermal requirements	
Temperature range	-110ºC to 110ºC

Table 2.2 Summary of the RF requirements for the double polarized PDHT antenna.

3. *ANTENNAS DESIGN RESULTS*

Here we describe the detailed antenna design of the PBA for an asteroid exploration mission and of the DDL antenna for LEO satellite.

3.1 **PBA *antennas.***

To fulfill the electrical specifications requested by the SoW, the RF design of the PBA antenna is based on two planar MTS antennas operating in the deep space X-band with different gain and size for the Tx (larger) and Rx (smaller) antennas. Both the antennas are designed with the same dielectric substrate (Rogers Corp. TMM6) of thickness h_d = 1.524 mm (Tx antenna) and h_d = 1.905 (Rx antenna). Such material is characterized by a relative dielectric constant ε_r=6.3 and loss tangent $\tan\delta = 0.0023$. The diameters of the two apertures have been sized to be fitted within a 1m-side square area. All the numerical simulations have been obtained by a FMM-MoM solver, a Wave Up proprietary code for the analysis of printed structures.

3.2 *Tx antenna*

In the following we present the design of the Tx antenna, implemented by patches with elliptical shape. The MTS antenna is realized on a circular disk of about 750mm of diameter.

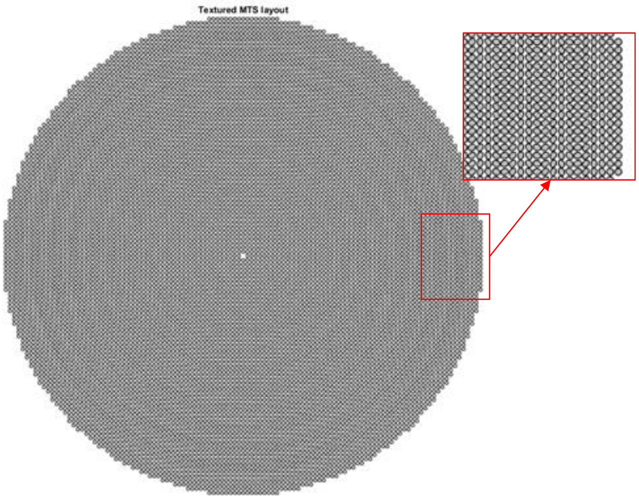

Figure 3.1 Textured layout of the TX antenna. The inset shows a detail of the surface.

Directive patterns along the azimuthal cut φ=0 (spectral line v=0) at frequencies of 8.400 GHz, 8.425GHz, 8.450 GHz are shown in Figure 3.2. The aperture efficiency is around 85%, with a peak directivity of around 35.75dBi, leaving a good margin for uncertainties and RF losses. Peak directivity is reduced of about 0.1 dB at the edges of the operating band. The antenna has been designed to have a RH circular polarization with cross polar level below -25 dB with respect to the maximum of the pattern. However, the antenna can be easily designed in LH polarization, still maintaining the same radiation performances.

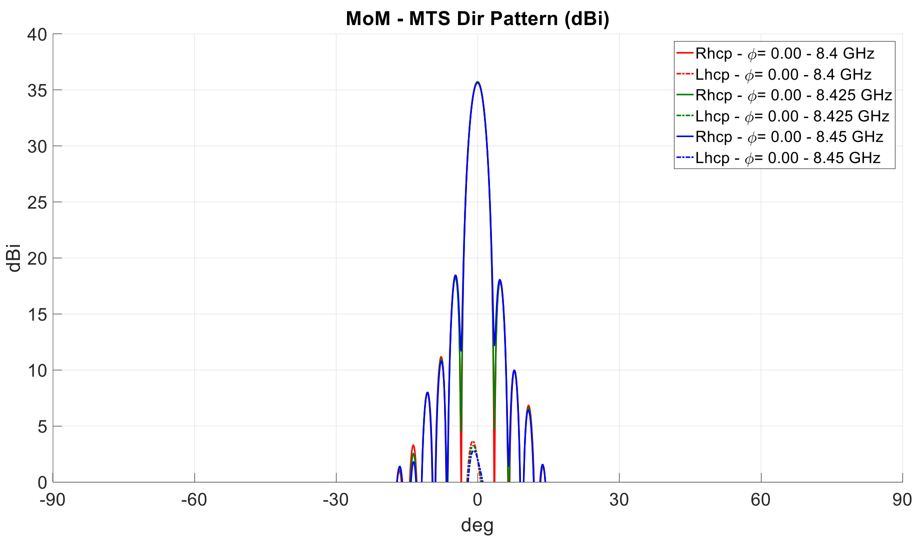

Figure 3.2 Directivity pattern of the Tx MTS antenna at 8.4, 8.425 and 8.450 GHz for the baseline solution. Solid line: co-polar component; dashed line: cross-polar component.

3.3 ***Rx antenna***

The Rx-band antenna has a disk diameter of about 500. The complete antenna configuration realized by means of elliptical patches texture is reported in Figure 3.3.

Figure 3.4 shows the radiation pattern along the azimuthal cut φ=0 (spectral line v=0): peak directivity is around 30.75 dBi, achieving an aperture efficiency of about 83%. At the edges of the operating band [7.145-7.190] GHz, peak directivity is reduced by less than 0.1 dB. The aperture is in LH circular polarization and the cross-polarization levels are below 20 dB with respect to the maximum of the co-polar pattern. As for the Tx case, the antenna can be easily re-designed in RH circular polarization, still maintaining the same radiation performances.

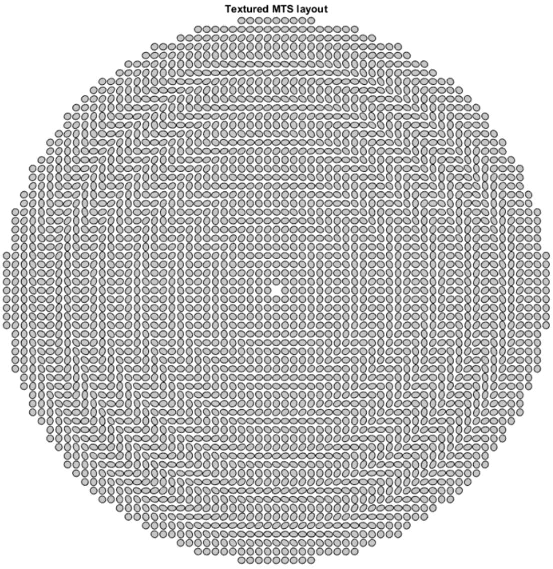

Figure 3.3 Textured layout for the RX antenna

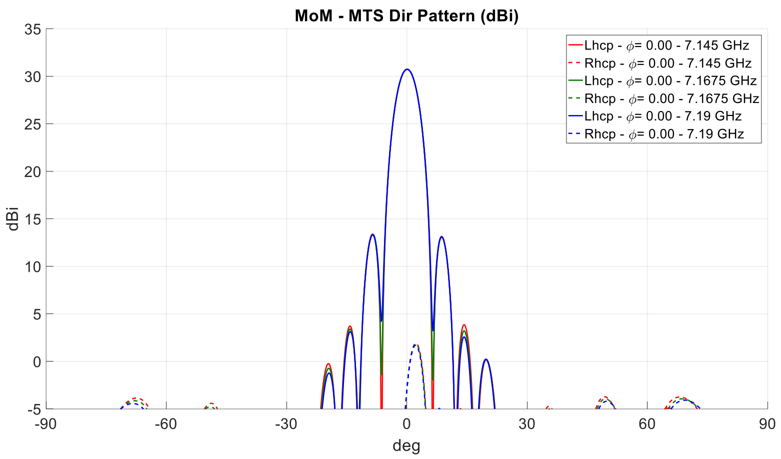

Figure 3.4 Directivity pattern of the Rx MTS antenna at 7.145, 7.1675 and 7.190 GHz along the azimuthal cut at φ=0 (spectral line v=0) for the baseline solution.

3.4 **DDL *antenna***

Considering the good radiation performance obtained in the early phases of the activity, the design effort has been redirected to fulfil the requirements for a DDL antenna able to operate in double polarization over the goal bandwidth of 250 MHz.

3.4.1 RF design

The final design configuration is resented in Figure 3.5. The proposed solutions make use of an equivalent planar anisotropic surface impedance, realized by means of metallic grooves with different depth. The antenna is fed by a low profile feeding system realized by a coaxial waveguide (WG) and a small sub-reflector. In this configuration a corrugated sub-reflector is attached directly to the inner conductor of the coaxial waveguide. By changing the width and depth of the three grooves in the sub-reflector, the amplitude and phase of the TM and TE components of the source field, almost independently, can be manipulated. The structure is excited by an impressed TE_{11} mode, supported by the coaxial WG. A small ring of dielectric material (Eccostock, er=2.53) is placed at the end of the WG in order to improve the mechanical stability. Thanks to the azimuthal symmetry of the geometry, the simulations and optimization processes have been performed by using MoM-BoR code, proprietary Wave Up simulation tool, allowing to minimize the computational effort.

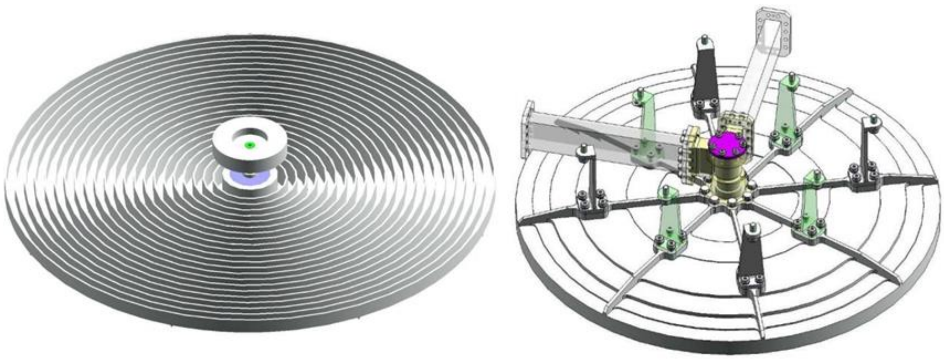

Figure 3.5 Final PDHT antenna configuration.

3.4.1.1 Simulation Results

In this section we report the results for the antenna arrangement previously presented. In Figure 3.6 the directivity radiation pattern in the bandwidth of 250MHz centred at 8.2 GHz with step of 25 MHz, has been shown. The co-polar behaviour respects the lower mask except for a very small angular range around 63° but the level of directivity are considered acceptable. The cross polar levels are below -20 dB in the entire angular range of interest for all the simulated frequencies, widely below the requested value of 18 dB (Figure 3.6 right).

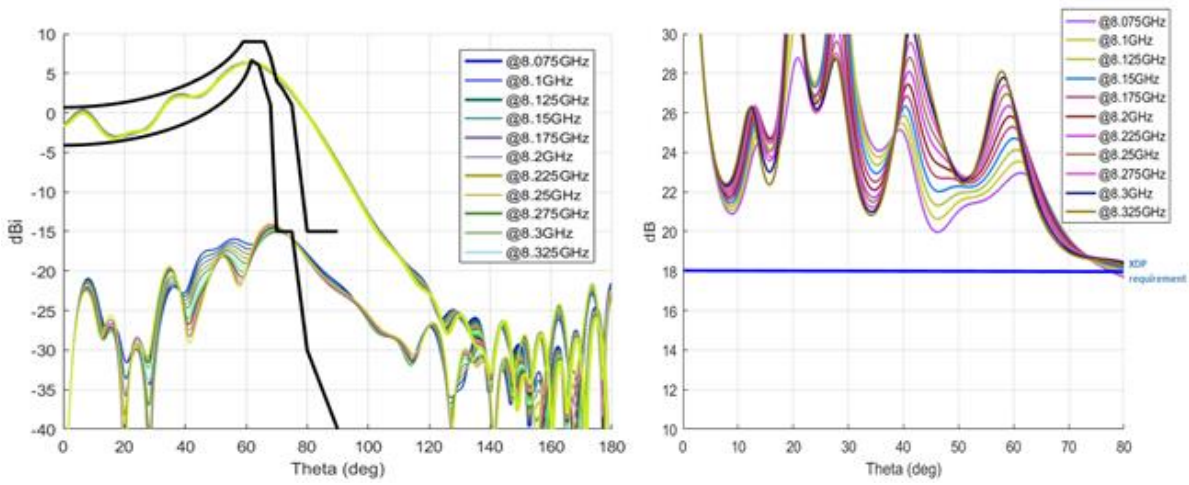

Figure 3.6 Directivity radiation pattern of the optimized grooved-type PDHT antenna (left), XPD variation vs the observation angle theta for various frequencies (right).

Figure 3.7 shows the gain and phase variation against the frequency characteristic, respectively. Both the requirements are meet for the entire angular range of interest.

Finally, the behaviour of the return loss at the input port of the antenna is reported in Figure 3.8. The reflection coefficient results better than -20 dB, compliant with the requirement.

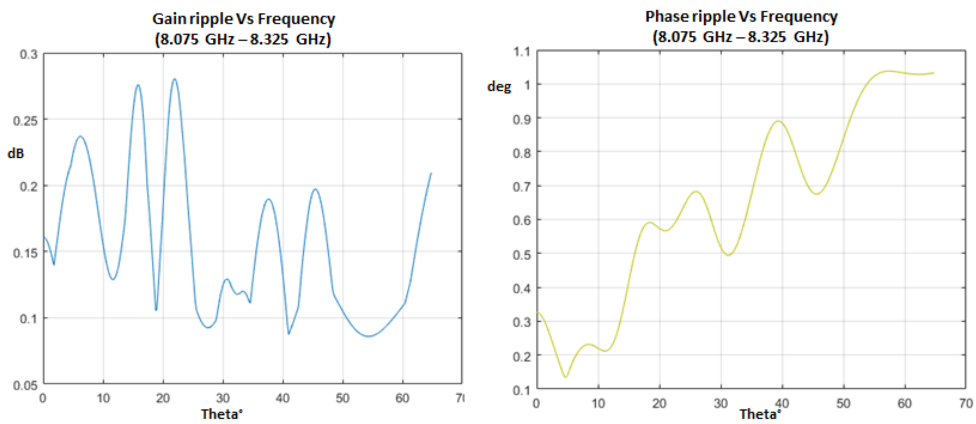

Figure 3.7 Gain ripple Vs Frequency Characteristics (Left), Phase ripple Vs Frequency Characteristics (Right) in the frequency range between 8.075 GHz to 8.325 GHz.

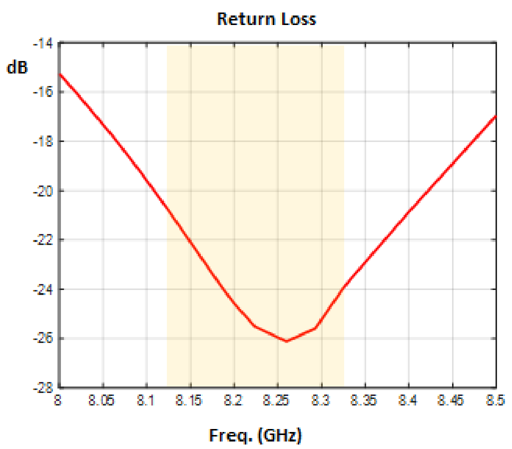

Figure 3.8 Reflection coefficient at the input port of the groove-type PDHT antenna.

4. ***REALIZATION AND MEASUREMENTS***

The optimized design of the DDL antenna presented in the previous section has been fabricated and tested. Some pictures of the prototype fixed on the testing support are reported in Figure 4.1. The RF, vibration and thermal tests are performed by the TAS-I Antenna AIT center in Rome. The all tests are fully passed and the DDL antenna design are confirmed by the test.

Figure 4.1 Pictures of the DDL antenna prototype.

In Figure 4.2 the comparison between the measured and simulated S parameters at the two input ports of the antenna are shown. The return loss is in good agreement with the simulated one, while a frequency shift of about 70 MHz is present in the port coupling.

In Figure 4.3 the measurements at some frequency samples of the gain radiation pattern for different azimuthal cuts are reported. The results are in good agreement with the simulated one (black lines in the graphs of the figure) especially for the co-polar of the radiated field; the cross-polar components present some discrepancies but the levels remain below the specifications except for some angular range for certain frequencies.

A summary of the RF measurement results of the DDL antenna prototype are reported in Table 4.1, split up between the RHCP and LHCP port.

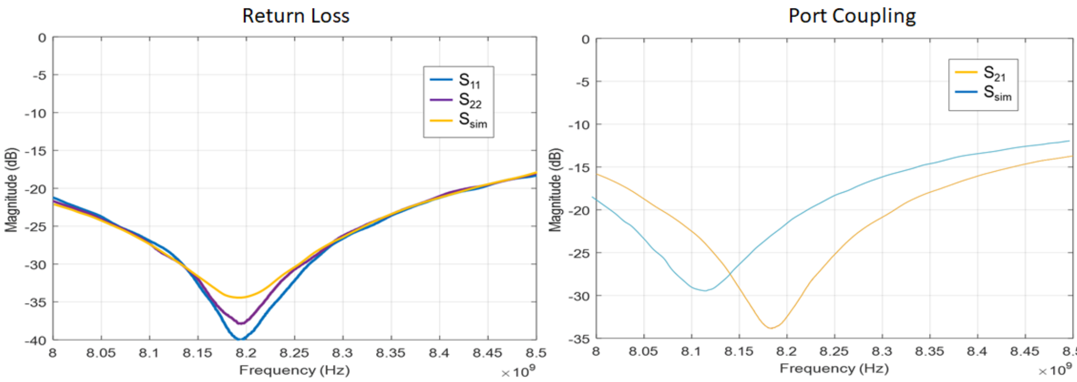

Figure 4.2 Comparison between the measured and simulated scattering parameters at the input ports: return loss (left), port coupling (right).

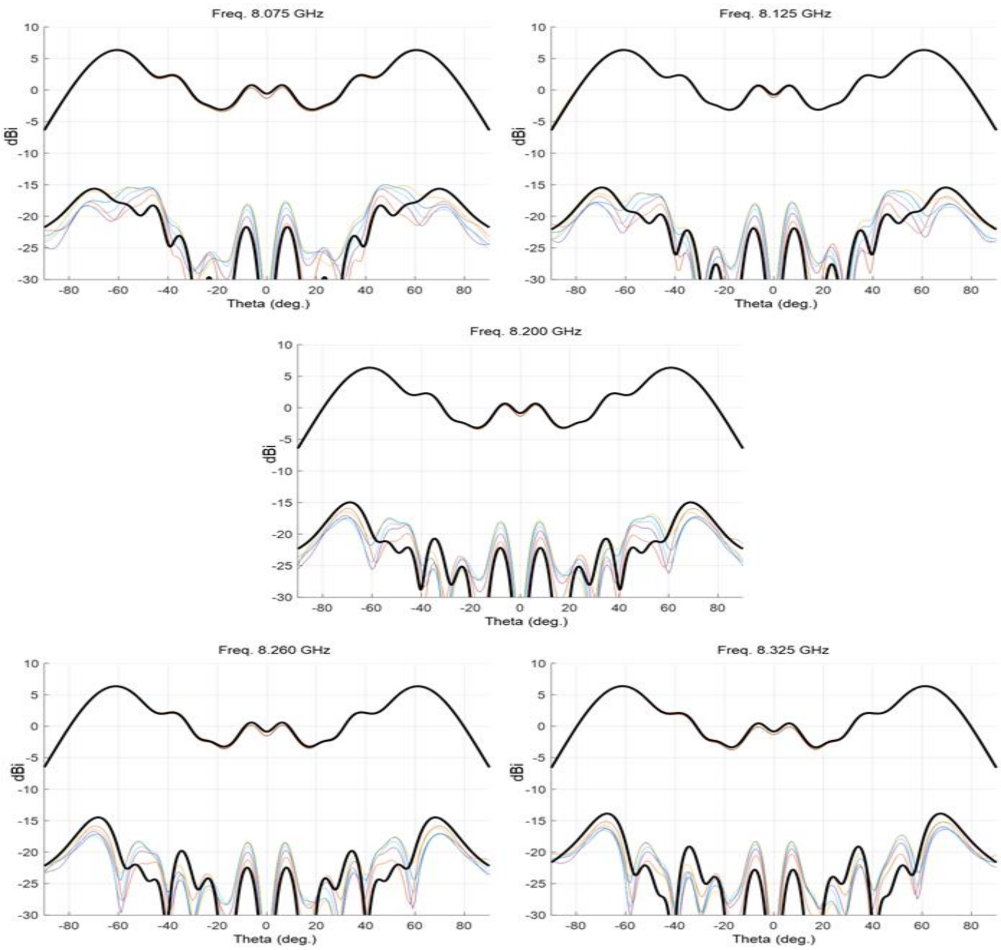

Figure 4.3 Measured gain radiation pattern for various azimuthal cuts for the co and cross polarization at a five frequencies inside the . The black lines are relevant to the predicted radiation pattern.

Table 4.1 Summary of the RF test results

XPD	
X Band Tx - RHCP Port	
Frequency [GHz]	[dB]
8.075	17.9
8.095	18.3
8.188	18.4
8.2	18.0
8.224	16.4
8.26	16.6
8.293	17.1
8.325	18.0
Worst case [dBi]	16.4
Requirement [dB]	18.0
Margin [dB]	-1.6

AMPLITUDE RIPPLE IN BAND	
X Band Tx - RHCP Port	
BAND	AMP. RIPPLE
[GHz]	[dB]
8.075 ÷ 8.325	0.6
Requirement [dB]	0.5
Margin [dB]	-0.1

PHASE RIPPLE IN BAND	
X Band Tx - RHCP Port	
BAND	PHASE RIPPLE
[GHz]	[Degs]
8.075 ÷ 8.325	1.9
Requirement [Degs]	2.5
Margin [Degs]	0.6

XPD	
X Band Tx - LHCP Port	
Frequency [GHz]	[dB]
8.075	18.3
8.095	19.4
8.188	19
8.2	18.1
8.224	15.4
8.26	15.3
8.293	17
8.325	18.9
Worst case [dBi]	15.3
Requirement [dB]	18.0
Margin [dB]	-2.7

AMPLITUDE RIPPLE IN BAND	
X Band Tx - LHCP Port	
BAND	AMP. RIPPLE
[GHz]	[dB]
8.075 ÷ 8.325	0.6
Requirement [dB]	0.5
Margin [dB]	-0.1

PHASE RIPPLE IN BAND	
X Band Tx - LHCP Port	
BAND	PHASE RIPPLE
[GHz]	[Degs]
8.075 ÷ 8.325	2.4
Requirement [Degs]	2.5
Margin [Degs]	0.1

5. *CONCLUSIONS*

As requested by the SOW of the project, two antennas are been designed:

- a PBA for space exploration mission by means of two separate MTS antennas for Tx and Rx band;
- a DDL antenna for LEO mission by means of variable depth metallic grooves;

A DDL antenna prototype has been realized and RF, Vibration and Thermal tests are performed. The excellent performances of the DDL antenna are confirmed by the tests.

In conclusion, the good measurement agreement with the design predictions has been demonstrated during the test campaign. Some discrepancies are due to impossibility at moment to optimize the complete antenna assembly (composed by corrugated assembly and the OMT component). In any case the study shows the intrinsic potentiality to obtain a unequalled model of a DDL antenna able to operate in both polarization (RHCP and LHCP) with evident advantages for total frequency band enlargement.

The proposed design for the DDL antenna entails an improvement of the RF performance wrt the existent solutions in terms of isoflux radiation mask compliance, XPD and ripple figure. Some small further improvements should be introduced for the XPDs.

Some aspects remain open for future investigation/optimization:

- Optimization of the performance on enlargement full bandwidth (8.025-8.400 GHz);
- Operative channel bands (2 per polarizations) and consequently optimization in band of the gain ripple and phase ripple;

Overall optimization of the complete performance including corrugated antenna and OMJ

The following future developments are individuated:

- fully qualification up to EQM/PFM; this involves Quality Assurance control and more stringent qualification levels;

use additive manufacturing technologies to reduce weight, cost and time of procurement; this involves qualification of the materials, technologies and processes;