Conformal Antenna Array for Next Generation Launchers

Executive Summary Report

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ABSTRACT

This activity has successfully concluded with a 4x4 S band retrodirective antenna breadboard, designed to be compatible with the Ariane LVs. Four of these retrodirective arrays, when mounted around the circumference of the LV, can provide close to 360° spherical coverage, data throughput of ≈8 Mbps, with ability to track during LV roll and high accelerations. Full compliance was reached for the full 360° spherical coverage of the LV, apart from a partial compliance for axial ratio, only in the region of $80° < |\theta| < 90°$. The final breadboards provided close agreement with the simulated results on an element and array level. The retrodirective steering was validated practically over a steering range of ±75°, showing good steering ability, with a slight ripple on the radiation patterns experienced due to EMC issues. The analogue tracking circuits showed fast measured update rates, of 167 Hz, compared to the 1Hz requirement.

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Abbreviations and Terms

ACM	:	Adaptive Coding & Modulation
AR	:	Axial Ratio
COTS	:	Commercial Off-The-Shelf
DLL	:	Delay Locked Loop
EIRP	:	Equivalent Isotropic Radiated Power
FOV	:	Field of view
IF	:	Intermediate Frequency
LNA	:	Low Noise Amplifier
LO	:	Local Oscillator
LHCP	:	Left Hand Circular Polarisation
LV	:	Launch Vehicle
MODCOD	:	(Modulation and Coding) scheme
PA	:	Power Amplifier
PCB	:	Printed Circuit Board
PLL	:	Phase Locked Loop
PC	:	Phase Conjugating
RF	:	Radio Frequency
RHCP	:	Right Hand Circular Polarisation
Rx	:	Receive
SGH	:	Standard Gain Horn
SPF	:	Single Point Failure
TBC	:	To Be Checked
TBD	:	To Be Defined
Tx	:	Transmit

Change log

ID	Date	Description	Comments
1	15-11-23	Initial version for review	
2			
3			

1 Introduction

The aim of this project was to demonstrate a retrodirective launch vehicle antenna breadboard, which would be suitable for further development for use in Next Generation Launchers. The retrodirective array offers a potentially simpler and faster tracking solution, compared to currently available solutions which use omnidirectional, low gain antennas or complex mechanical/electronic steering arrangements. This is due to the analogue signal processing capability of the retrodirective antenna requiring simpler circuits and the ability of the antenna to point and track to a particular signal, without the need for additional position information from sources such as accelerometers/gyros or GPS/GNSS.

This project has leveraged the skills of three organisations, QUB, Arianegroup and Magister. Arianegroup have provided the essential know-how of the current launch vehicles, with this study primarily aimed at the Ariane class launch vehicles. QUB have provided the retrodirective breadboards which operate in the S-band region. Magister have offered detailed modelling of the telemetry link, to show that the retrodirective antenna can provide higher data rates and more reliable communications during all phases of the launch. The retrodirective circuits are further improved versions, based on what was successfully demonstrated in past ESA TRP activities, such as “Self Focusing Retro-Reflective Antennas for Mobile Terminal Applications, AO/1-6168/09/NL/JD”, “Robust TM System for Future Launchers, AO/1-8045/14/NL/FE” and “Retro-Directive Antenna, ARTES-5.1 - Activity Reference 7C.014”

1.1 State of the art Launch Vehicle Antennas survey

Prior to the design work commencing within the activity a detailed survey was carried out by Arianegroup, to put the project into the perspective of current state of the art. The survey was focused on S-band telemetry antennae on-board civilian and military launchers.

The survey included Medium and heavy launchers. The information presented in this survey was provided by Arianegroup under Export/transfer authorization: licence no. 20 002690 1/1 1.0

Figure 1 depicts the range of launch vehicles that was surveyed, the majority of these using helix, patch or slot antennas, with only one reported to use a phased array.

State-of-the-art on launcher telemetry antennae in S-band

Nota: all of launchers operating today have not been introduced here since no relevant information on their antenna system is available.

Launcher	Delta IV	Atlas V	Falcon 9	Minotaur	Vega	Ariane 5	Ariane 6	M51	Trident II
Antenna technology	Patch	Slot	N/A	-Cavity-backed -Phased array	Quadrifilar helix	Quadrifilar helix	Cavity-backed element	patch	patch

Figure 1. Summary of state of the art telemetry antennae in S-band

2 Conformal Array Antenna Concepts and Requirements

This section details the final chosen system concepts for S-Band and Ka band. Several system concepts were thoroughly evaluated during the project. These were detailed in “D02: Conformal Array Antenna Concepts and Requirements”. Only the selected concepts are presented here.

2.1 S Band Antenna Array System Concept

The selected S Band System concept involves a beam scanning architecture, using four antenna panels, each panel containing sixteen elements (Figure 2). The panels are intended to be mounted equidistant around the circumference of the LV, to obtain full FOV coverage, with some reduction in performance in the longitudinal axis (end fire) direction, which has been allowed for in the link budget. Sector definitions are also shown in Figure 2. There is one sector of 180° defined in pitch/yaw axis and four sectors of 90° defined in roll axis. Each sector in the roll axis is covered by one antenna panel, thereby requiring a total of four antenna panels.

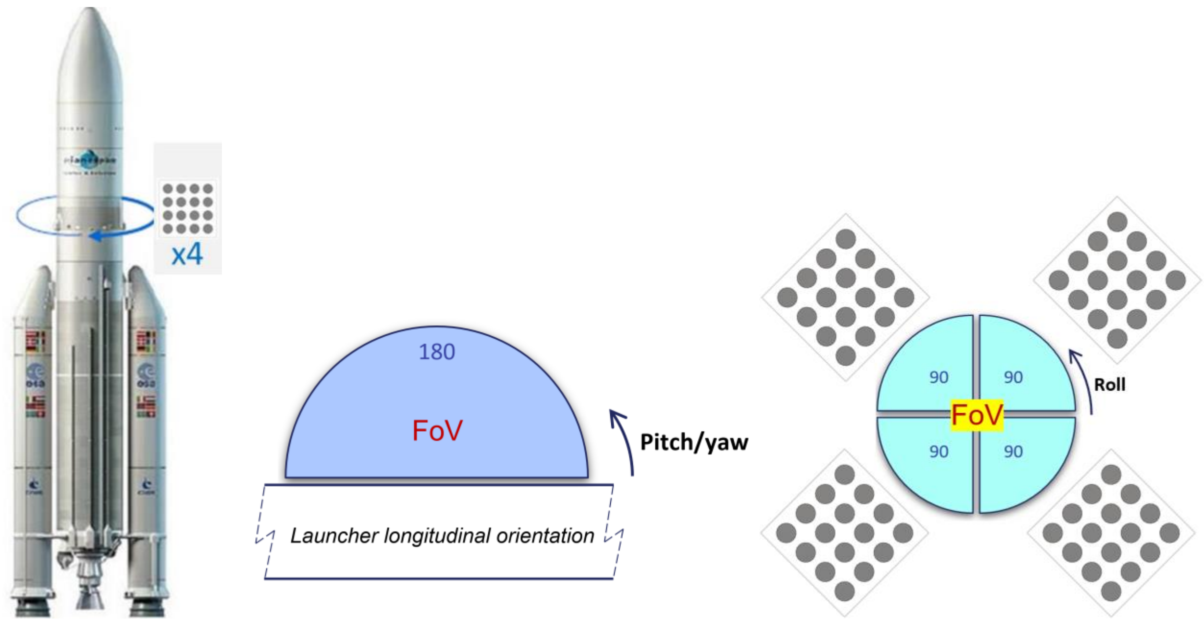


Figure 2. S Band system concept and sector definition

2.2 Ka Band Antenna Array System Concept

The array layout for Ka band concepts, within one antenna panel, is shown in Figure 3. A minimum of 400 broadside elements are required to achieve the required gain, the HPBW will be around 5° in both directions. The sectors for Ka band concepts are also defined in Figure 3. The broadside antenna covers four sectors in roll axis each of 90° and 1 sector in pitch/yaw axis of 180°.

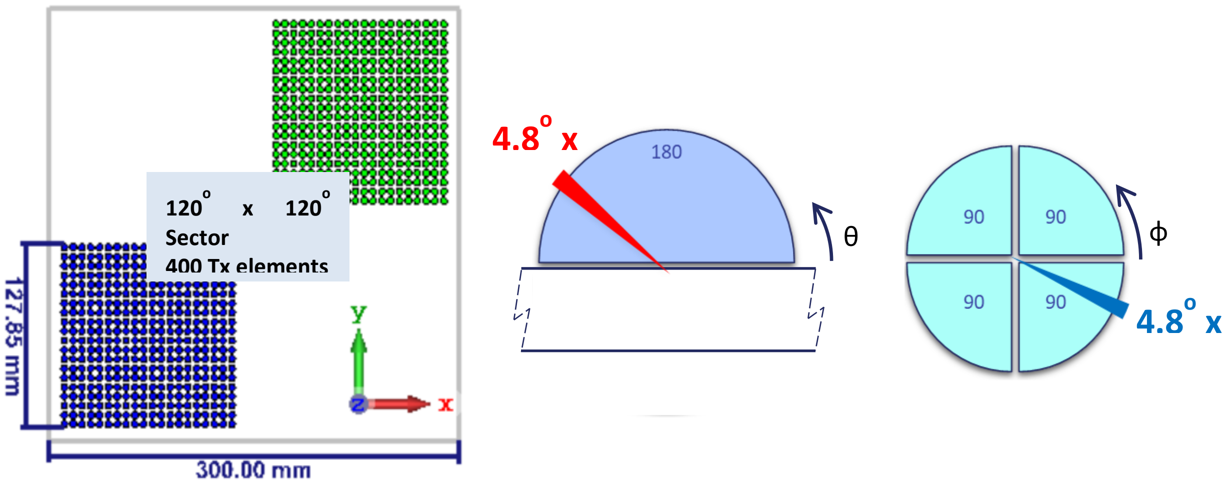
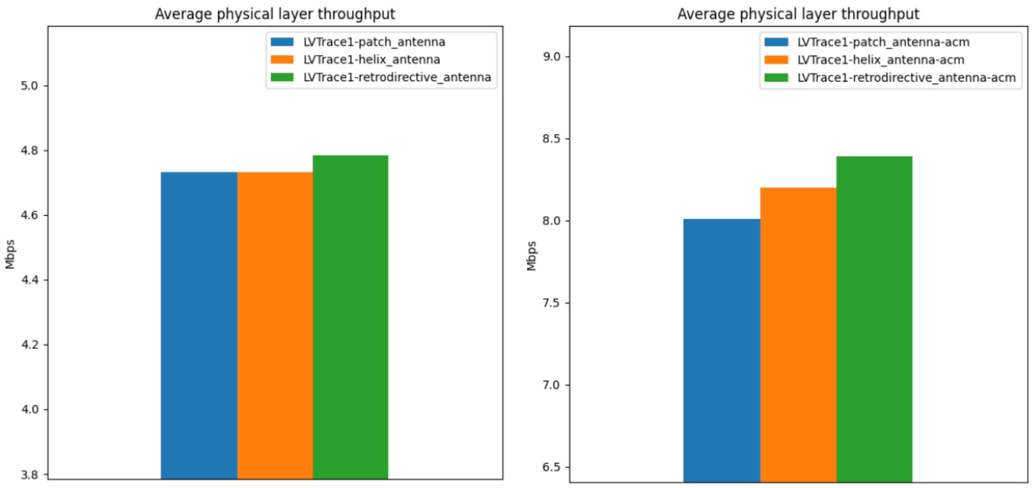


Figure 3. Array layout and sector definition for one antenna panel for Ka band

2.3 Retrodirective gain pattern in NTM-Simulator - Magister

As part of the project contract, the project partner, Magister solutions, were tasked with simulating the developed S band retrodirective LV system , using their NTM simulator that was developed for “AO/1-8045/14/NL/FE, Robust TM System for Future Launchers” and reported in [3].

Two different launch phases were simulated, Dtmin-1 and MT3. These traces were taken from the Vega launch vehicle manual [2]. Three types of antenna were simulated Patch, Helix and Retrodirective. To simulate average throughput, two modulation scenarios were applied, one with no Adaptive coding and Modulation (ACM), the other with ACM. The average throughput result over the Dtmin-1 launch phase are shown in Figure 4. The results obtained were very encouraging, in all cases the retrodirective system showed an increased average physical layer throughput. The most notable of these being an 8.4 Mbps average throughout for Dtmin-1 with ACM (Figure 4(b))



(a) Dtmin-1 launch phase, No ACM (b) Dtmin-1 launch phase, with ACM

Figure 4 Simulated Average Physical layer throughput for Patch, Helix and Retrodirective for Dtmin-1 phase

2.4 System Concepts - Recommendation

It was recommended, at concept selection stage, to select the **retrodirective system** at **S-band.** Within the scope of the project, this solution was considered to be novel and practically realizable.

3 Key findings from critical breadboards

3.1 Critical breadboards definitions

The critical breadboards for the retrodirective system is shown in Figure 5. Two critical bread boards were actually produced in the project, a retrodirective system and a phased array system. Only the retrodirective system will be detailed in this final report.

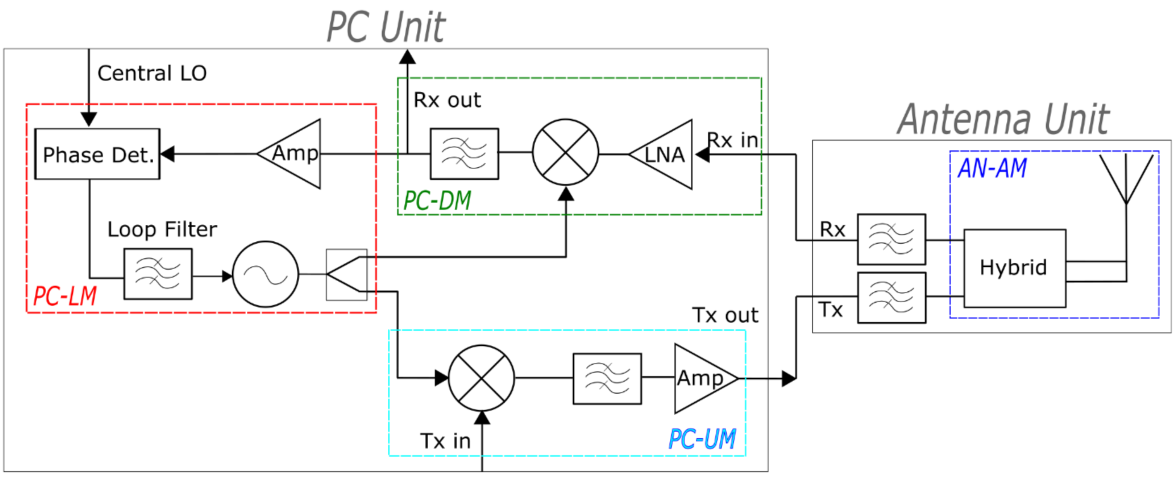


Figure 5. Retrodirective system

3.2 Testing of antenna unit

The antenna module as shown in Figure 6 was fabricated and tested according to the test plan detailed in the D04 document. The outer body of the antenna structure is precision milled out of Aluminium alloy block. The antenna module is then assembled with printed circuit boards and soldered with SMA connectors. The two connectors each produce different circular polarization radiation. One connector is used for transmit operation while the other is used for receive operation.

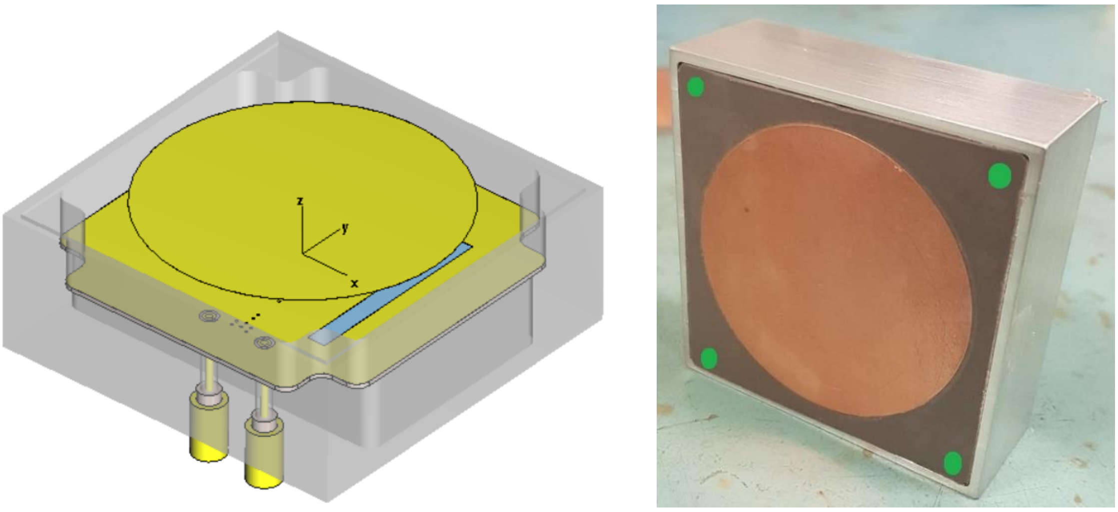


Figure 6 Fabricated antenna unit structure

3.2.1 Frequency of operation Measurement

Figure 7 shows the frequency of operation of the AN-AM module. It can be observed that for both of the ports, the device is 10 dB matched for entire operating band. The device is broadband, this ensures the operation even in extreme environment with thermal and mechanical variation.

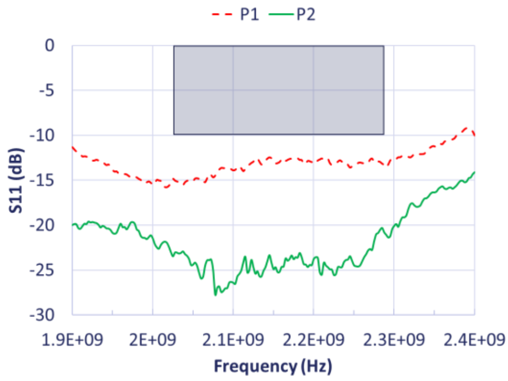
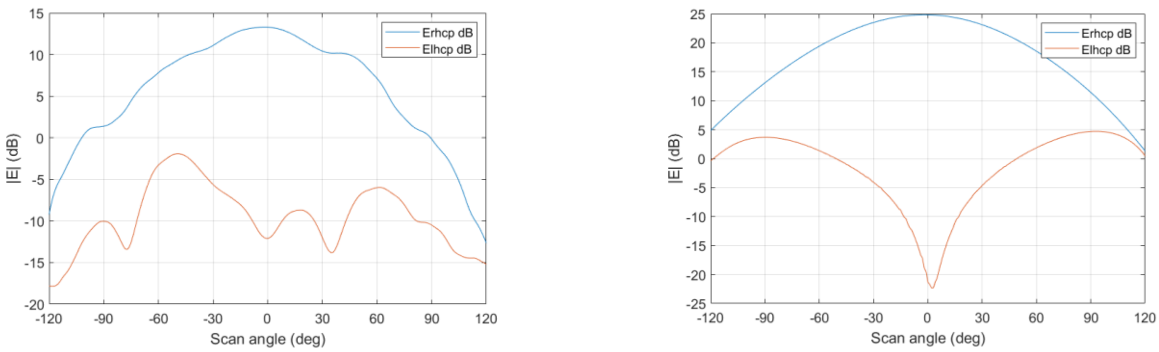


Figure 7 Antenna reflection coefficient

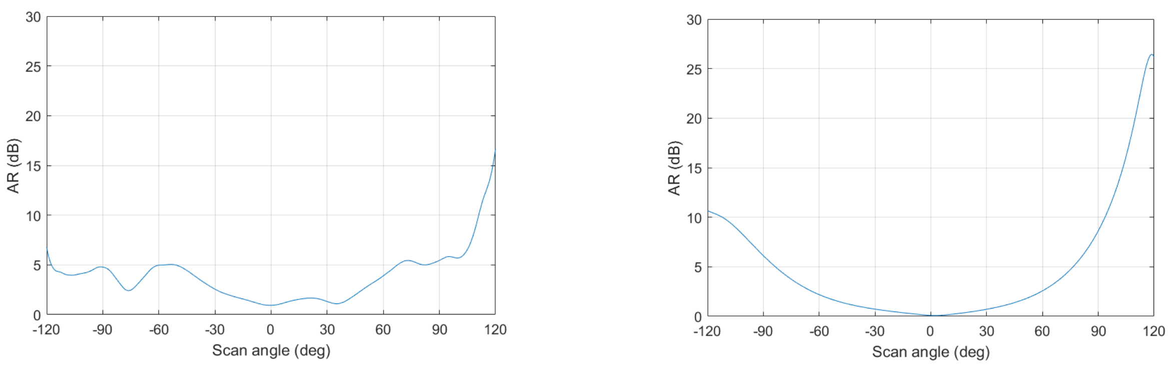
3.2.2 Radiation characteristics

The radiation patterns for the antenna cavity are shown in Figure 8 at 2200 MHz where the measured (a) and simulated (b) results are compared. Excellent agreement in beam shape was observed. Axial ratio, Figure 9, also provides good agreement showing a slight increase around the 0° scan angle for the measured case, which is not unexpected, considering manufacturing tolerances.



(a) **(b)**

Figure 8 (a) Measured and (b) simulated radiation patterns at 2200 MHz



(a) **(b)**

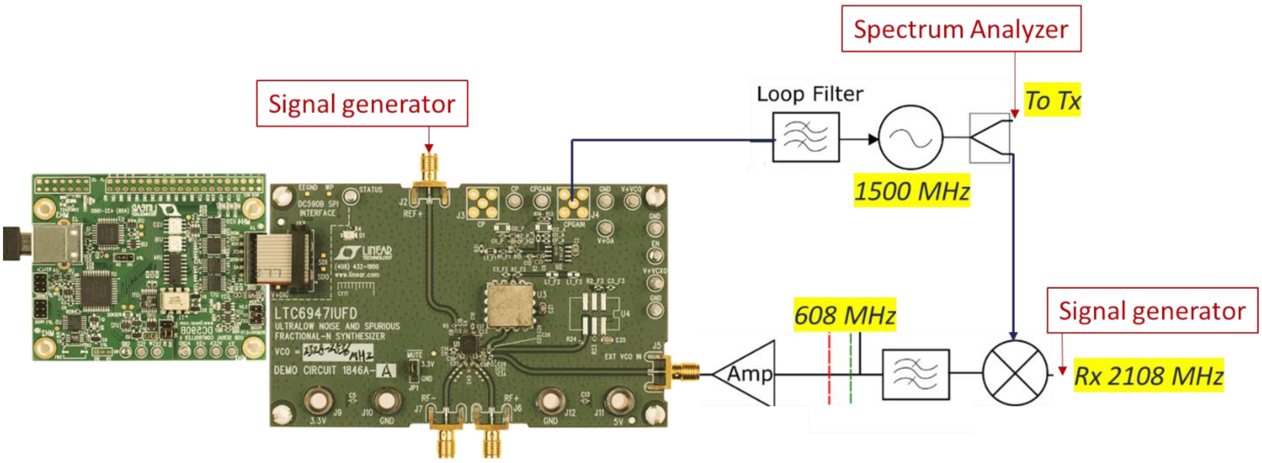
Figure 9 (a) Measured and (b) simulated axial ratio at 2200 MHz

3.3 Phase Conjugating Loop Tracking Measurement

The purpose of the loop tracking measurement was to determine how long it took the PLL to settle from the unlocked to locked condition. This time delay from unlocked to locked can be considered as a worst case time period when calculating update rate. The update rate can then be calculated from:

$$Update\ Rate\ (Hz) = \frac{1}{Loop\ Seetling\ Time}$$

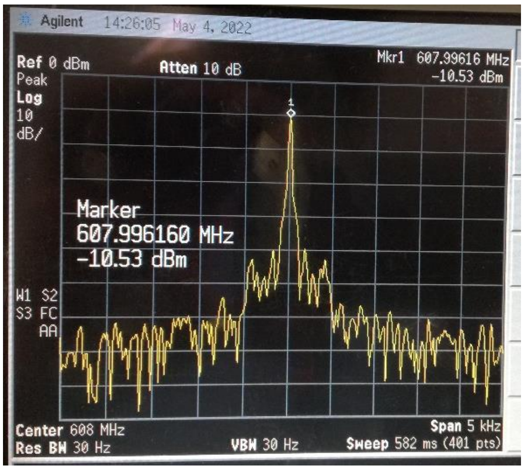
The measurement setup for PC-LM module is detailed in Figure 10

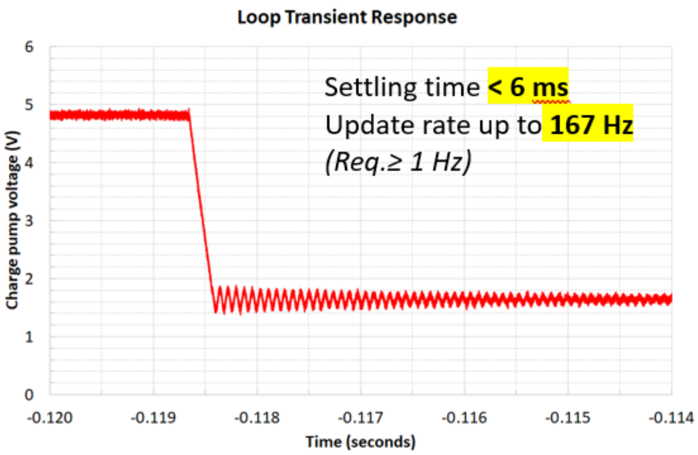


(a) PC loop testing Measurement setup block diagram

Figure 10. Setup for measuring PC-LM

The results of the PC loop measurements are shown in Figure 11. It can be observed that a stable spectrum output is being produced, Figure 11(a) indicating a stable loop lock. The transient response, which was obtained between the output of the loop filter and the input to the VCO shows the VCO control voltage moving from an unlocked to locked state. The time period of the duration of the steep downward slope obtained, produces the settling time of the loop. The numerical results of the loop settling time are plotted in Figure 11(b), which shows a settling time of <6ms, which yields a worst case update rate of 167 Hz. These results were also presented in [4].





(a) Output spectrum from PLL **(b) transient response of the loop**

Figure 11 PC loop testing measured Results

4 Final breadboard testing – Key Findings

This section details the final measurements to a 4x4 S band retrodirective array, mounted on a ground plane structure which is representative of the Ariane 5 launch Vehicle. The measurement results are used to revise the compliance matrix, which appears in Section 7.1.

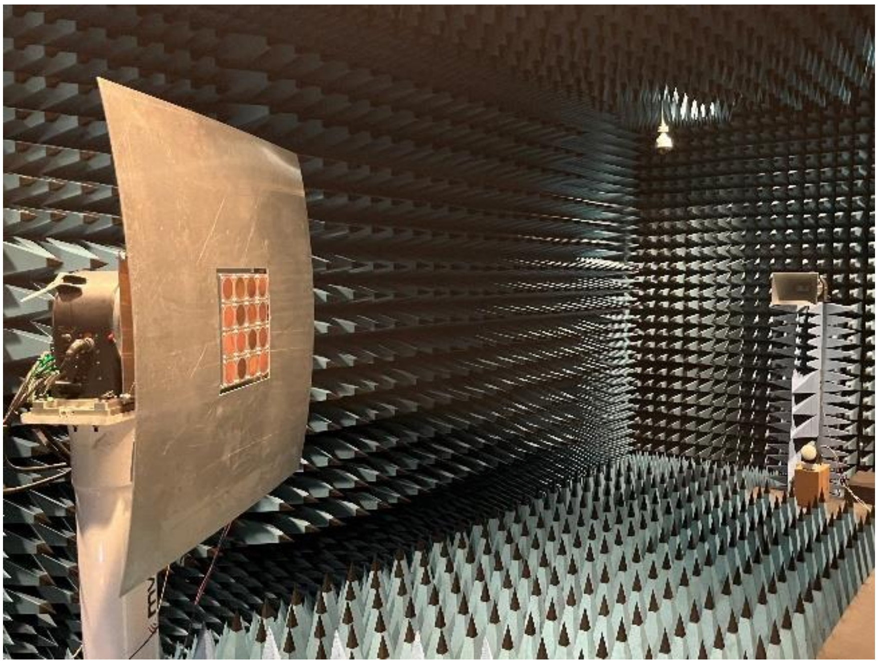


Figure 12 Final breadboard at QUB inside Anechoic Chamber

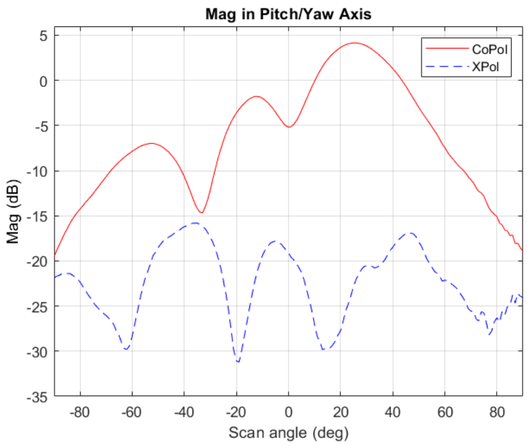
4.1 Bistatic radiation patterns:

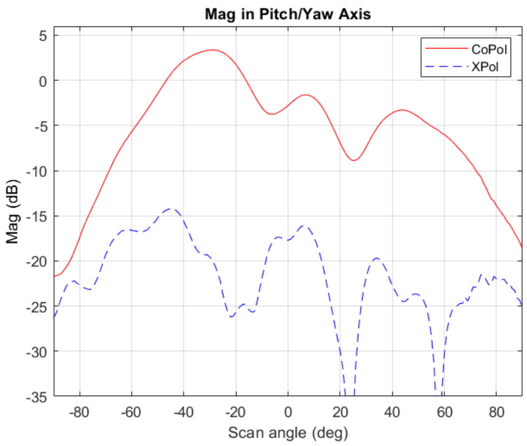
The aim of this measurement was to calculate bistatic patterns from the measured active element patterns, this was a compromise due to the fact that actual bistatic patterns were not measured due to the complexity of the practical configuration required. This bistatic active element patterns method has been shown to be accurate and should provide good agreement if actual bistatic results could be obtained [5].

The magnitude and phase information as obtained from the previous two steps can be combined to generate bistatic patterns, as shown in equation below:

$$F(\theta) = \sum_{i=1}^{4} |f_i(\theta)| * e^{angle(f_i(\varphi))}, \qquad \varphi = \pm 70, \pm 60, \pm 45, \pm 30, \pm 15$$

Array patterns for scan angle φ of ±30° are shown in Figure 13. The plots show cross polarization isolation of better than 25 dB and acceptable sidelobe levels.





(a) **(b)**

Figure 13 Reconstructed measured pattern for (a) φ =+30 degrees (b) φ =--30 degrees.

The co-polar radiation patterns for different scan angles are overlayed in Figure 14 for better comparison. The scan loss of the array, for -70 < θ < +70, is (7 dB, 5dBi to -2dBi magnitude) within expected range from simulation (7 dB 16dBi to 9dBi gain).

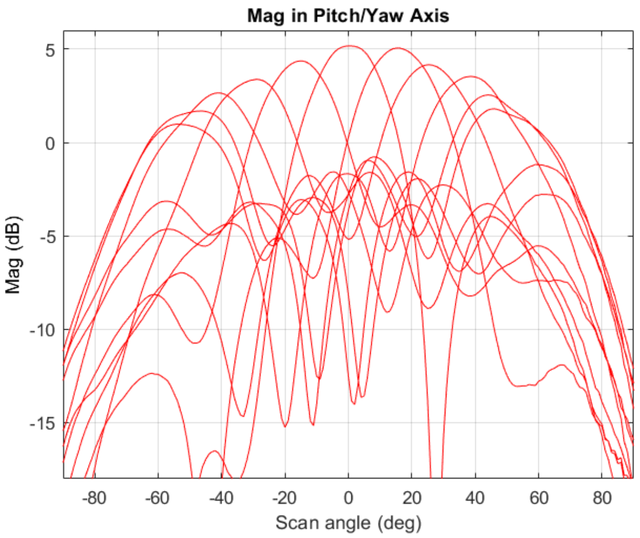
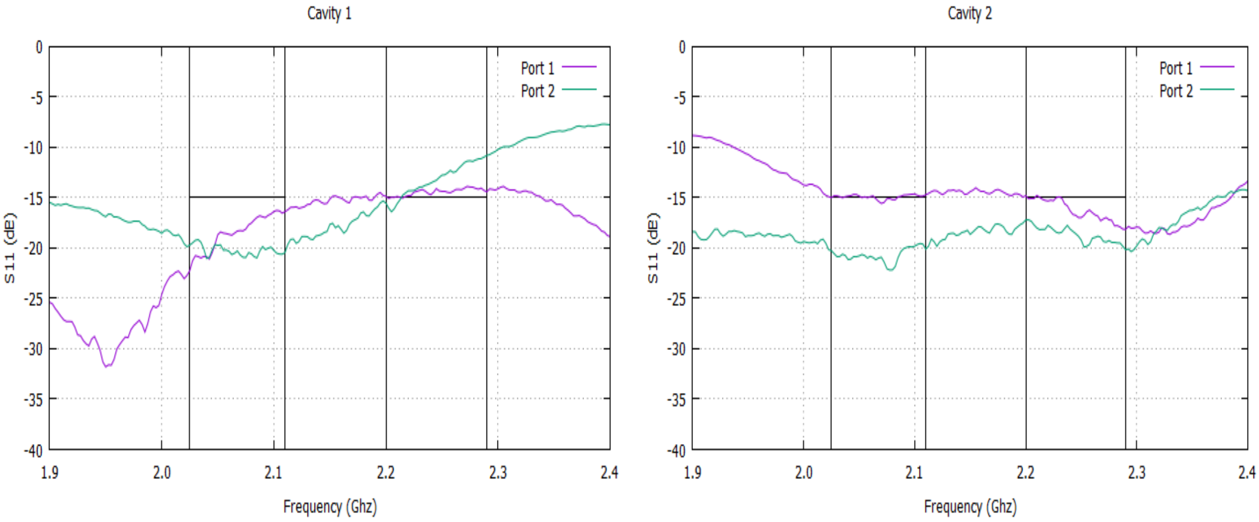


Figure 14 Reconstructed measured bistatic patterns.

4.2 Scattering parameters of antenna cavities:

Scattering parameters of individual antenna elements are shown in Figure 15. Only Cavities 1&2 are shown in this report for brevity. It was observed that there is variation in return loss among the cavities, this is due to manufacturing and assembly tolerances of low TRL in-house produced prototype, since a considerable part of the assembly and soldering was done by hand. This can be minimized by employing better controlled manufacturing for the higher TRL product. Despite this, the variations were not significant and typically a return loss of < -10dB could be maintained on both ports over the required frequency range.



(a) Cavity 1 **(b) Cavity 2**

Figure 15 Scattering parameters of individual antenna elements.

4.3 Retrodirective measurements (monostatic)

4.3.1 Anechoic chamber configuration for monostatic measurement:

The test configuration for monostatic measurements is shown in Figure 16. The antenna array is mounted along with ground plane which is representative of the actual launch vehicle diameter. Figure 17 shows the connection diagram for the measurements.

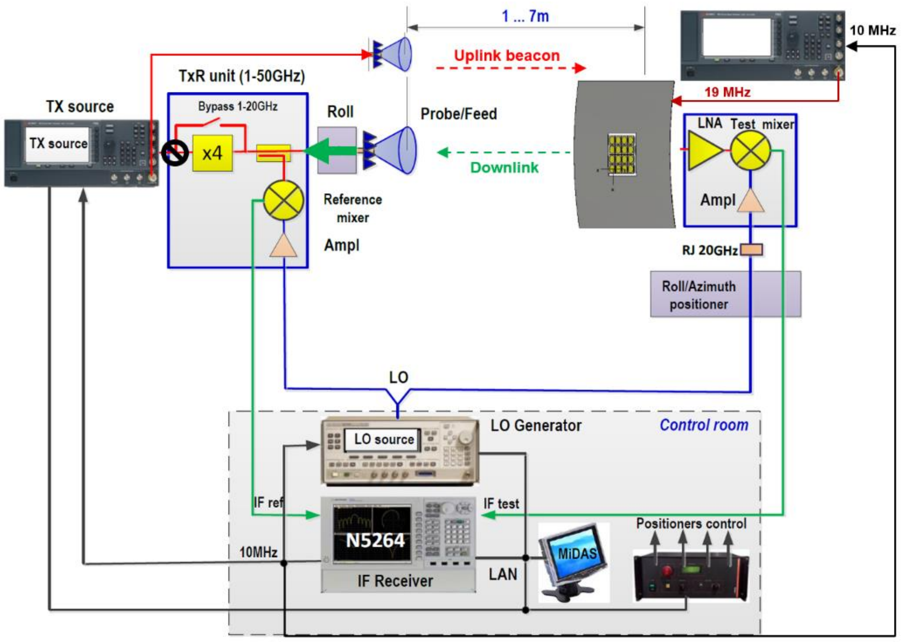


Figure 16. Anechoic chamber test configuration for monostatic measurements

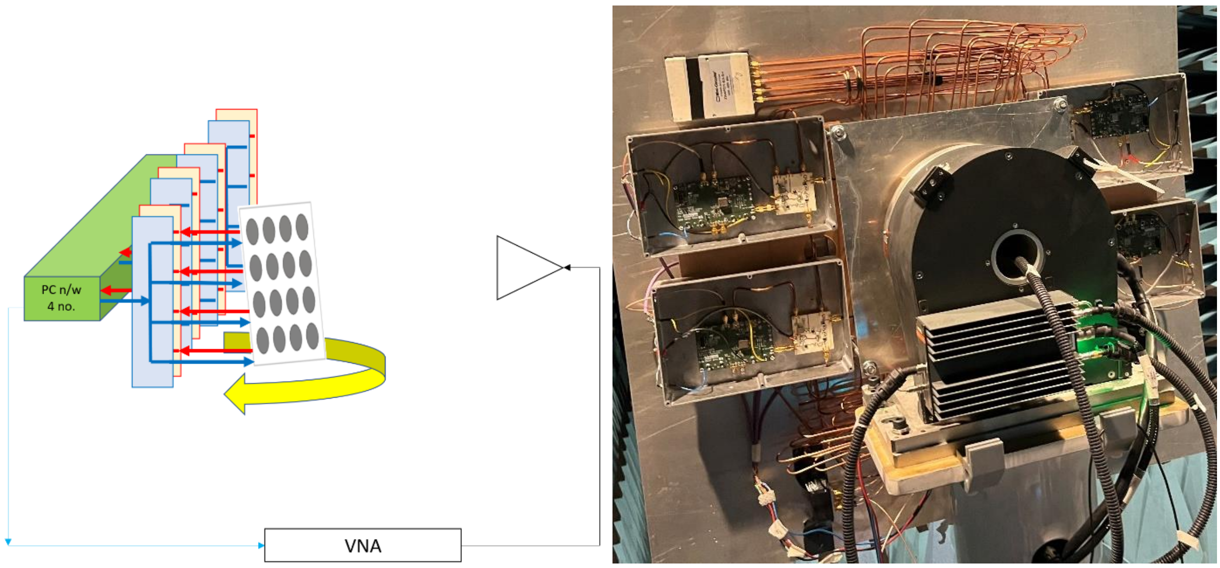
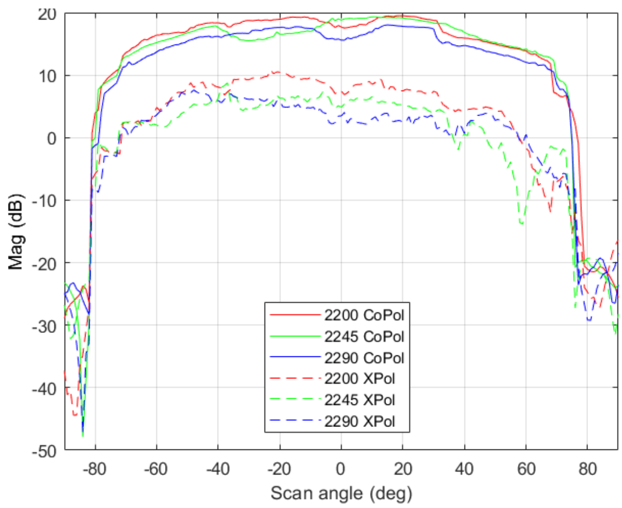


Figure 17 Retrodirective measurement (monostatic), 16 elements excited with 4 phase conjugating networks.

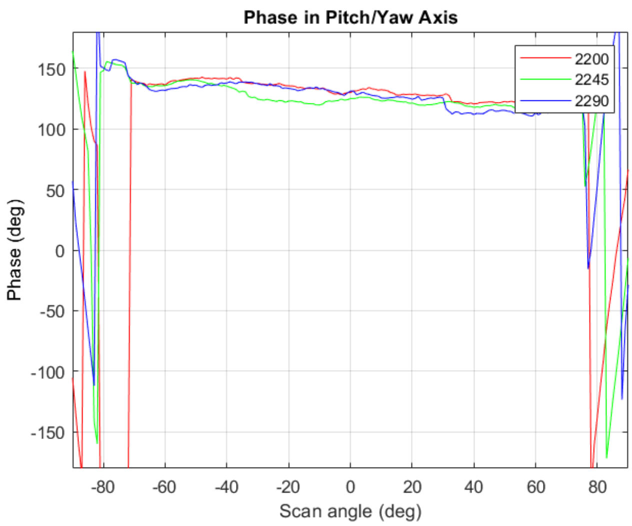
4.3.2 Measured Monostatic results

The antenna along with the ground plane is mounted in the chamber as shown in Figure 12. The uplink-transmit beacon (2108 MHz) and the receiving-downlink antenna (2245 MHz) are mounted on the fixed positioner on the far-side of the chamber. The antenna under test is mounted on the movable positioner and scanned through ±90° in azimuth.

The magnitude (gain) and phase plots of the monostatic radiation patterns are illustrated in Figure 18. The measured patters show stable behaviour for the complete transmit band. The antenna remains in lock for up to ±75°. This is because of the limited power used for beacon and the receiver in the test setup does not use an LNA. The gain meets the requirements of the compliance matrix in Section 5.1. The measured axial ratio, Figure 19, is also within the required mask.



(a) Magnitude



(b) Phase

Figure 18 Monostatic gain measurements

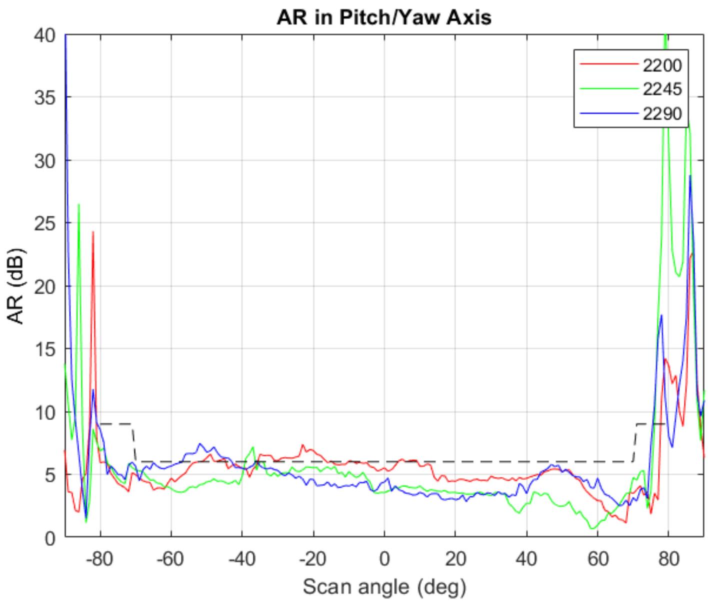
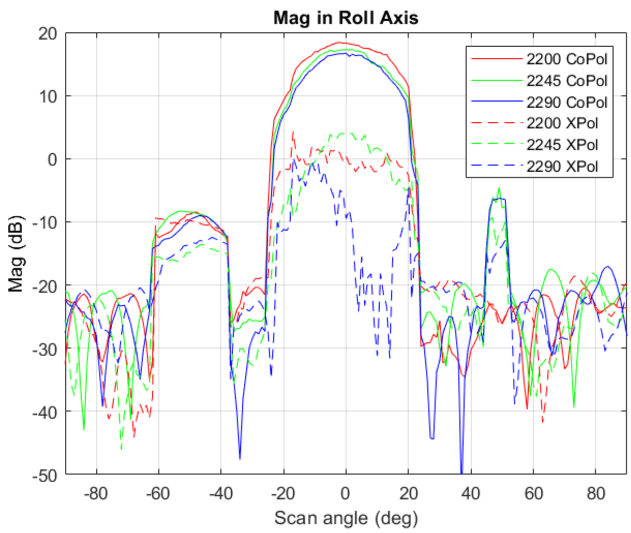
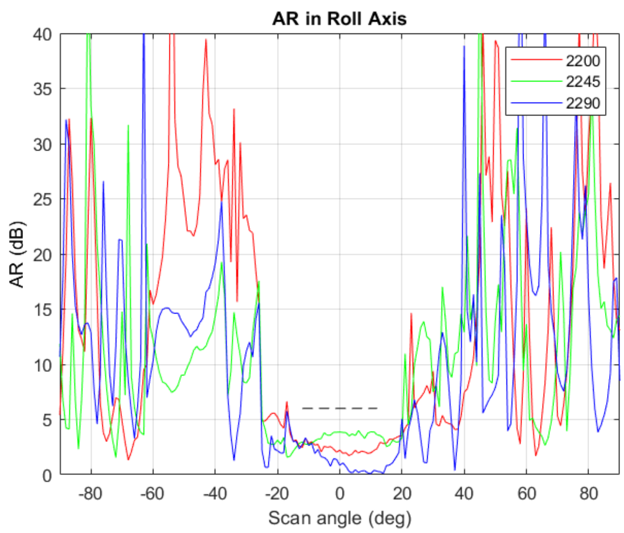


Figure 19 Axial ratio plots for the transmit band.

The antenna was also measured in the roll axis when the antenna array in roll axis is configured in such a way as to transmit fixed beam. Excellent sidelobe level performance and cross polarization ratio can be observed from Figure 20(a). The AR is also within the required mask.



(a) Radiation pattern



(b) Axial Ratio

Figure 20 Radiation pattern and AR in roll axis

5 Development Plan

5.1 Updated Compliance Matrix

Table 1 S-band system compliance

Req. ID	Parameter	Consolidated Values		Comments
R01	Tx Frequency (MHz)	2200-2290	Compliant	
R02	Rx Frequency (MHz)	2025-2110	Compliant	
R03	Min. Antenna Gain |θ| < 70°	> 10 dBi	Compliant	
	Min. Antenna Gain 70° < |θ| < 80°	> 7 dBi	Compliant	From reconstructed bistatic measurement
	Min. Antenna Gain 80° < |θ| < 90°	> -1 dBi	Compliant	From reconstructed bistatic measurement
R04	FoV Coverage	Mode 1: 99,5% of the upper half sphere Mode 2: ≈100% in the roll axis and ≈100% at +/- 90° in the pitch/yaw axis	Compliant	
R05	Polarisation	LHCP	Compliant	
R06	Axial Ratio for |θ| < 70°	< 6 dB	Compliant	
	Axial Ratio for 70° < |θ| < 80°	< 9 dB	Compliant	
	Axial Ratio for 80° < |θ| < 90°	< 11 dB	Partial Compliant	Slight deviation from the requirements for limited frequency band
R07	Pointing Update Rate	> 1 Hz	Compliant	

Table 2 Mechanical compliance

Req. ID	Parameter	Consolidated Values		Comments
R15	Diameter	5,4m (Ariane)	Compliant	
R16	Mass	3 kg (TBC) including connector but excluding mounting screws, bolts and any thermal protection	Compliant	
R17	Accommodation	Length of one antenna panel: 300mm (TBC)	Compliant	
		Width of one antenna panel: 300mm (TBC)	Compliant	
		Height (above surface) of one antenna panel: 18mm (TBC) excluding any thermal protection	Compliant	
		Depth (below surface) of one antenna panel: 20mm (TBC)	Compliant	

Table 3 Thermal compliance

Req. ID	Parameter	Consolidated Values		Comments
R18	Minimum Temperature	ARIANE Compatible -55°C (TBC)	Partial Compliant	
	Maximum Temperature	+100 ºC (TBC) under thermal protection	Partial Compliant	
R19	Thermal protection	NORCOAT or equivalent material, thickness (TBD)	Partial Compliant	

5.1.1 Flight Model development and schedule

Schedule	Model	Description
To + 9 mo	Mechanical model +Breadboard + EM (Engineering model)	• Thermal protection design and analysis • RF design. • Array control logic design, implementation of handover between sectors (software). • Performance testing • Environmental testing • COTS
To + 15 mo	TQM (technological qualification model)	• mix of module level and unit level qualification • Component with suitable temperature ranges, Hi-Rel components
To + 20 mo	QM (Qualified model)	• complete product qualification • more stressed testing
To + 28 mo	FM (Flight model)	• manufacturing of first batch of 4 antennas • acceptance level testing

5.1.2 Final FM antenna development and cost

Table 4 BOM

		Qty	Cost per unit £	Total Cost £
Electronics components	Hi-Rel (where available)	1	20,318	20,318
Materials	PCB	4	500	2000
	6082 T6 Aluminium	4	300	1200
	Screws/connectors/cables	128	10	1280
	Radome	4	500	2000
Machining/fabrication	PCB	1	4000	4000
	Metal milling	64	260	16,640
Assembly cabling integration	Soldering	1	200	200
	Cabling	1	200	200
Functional and environmental test campaign for flight models (A rough estimation of the costs from Arianegroup is 300k€)		1	261,000	261,000
Total				£308,838

6 Conclusion

This activity has successfully concluded with a practical demonstration of a 4x4 S band retrodirective antenna, which has been designed to be compatible with the Ariane class launch vehicles. Four of these retrodirective arrays, when mounted around the circumference of the LV, are capable of providing close to 360° spherical coverage, with increased gain and ability to track during LV roll and high accelerations. Further analysis, carried out by Magister Solutions, has proven that data throughput of close to 10 Mbps is possible. The process to reach the final solution has involved *significant* concept designs, tradeoffs and down selection. At the beginning of the study, two frequency ranges (S and Ka band) were considered and two concepts were generated for each, which were taken to the level of detail of full EM models (effectively detailed designs). Although the Ka band concepts showed good functional potential, the designs were not progressed due to complexity of manufacture, with an S-band concept being realized to breadboard. Considerable effort was made ensuring compliance of the retrodirective antenna when steering around the full 360° spherical coverage of the LV. Most of the effort was focused on the coverage of $70° < |\theta| < 90°$. Full compliance was reached within this challenging coverage region with antenna gain, with a partial compliance for axial ratio, but only in the region of $80° < |\theta| < 90°$. The final breadboards provided close agreement with the simulated results on an element and array level. The retrodirective steering was validated practically over a steering range of ±75°, showing good steering ability, some EMC issues were experienced which caused a slight ripple on the radiation patterns, therefore more attention to EMC design should be considered at higher TRLs. Additional features were also shown regarding the ability of the analogue tracking circuits to offer fast update rates, with a worst case measured update rate of 167 Hz being produced, considerably higher than the 1Hz requirement.

7 Reference Documents

1. Ariane 5 User's Manual, Issue 5, Revision 1, July 2011 https://www.arianespace.com/wp-content/uploads/2015/09/Ariane5_users_manual_Issue5_July2011.pdf
2. Vega Users Manual, Issue 4, Arianespace, April 2014, Sec 2-17 "https://www.arianespace.com/wpcontent/uploads/2015/09/Vega-Users-Manual_Issue-04_April-2014.pdf" accessed on 12-5-2020
3. J. Puttonen et al., "Robust telemetry system for future launchers," 2016 International Workshop on Tracking, Telemetry and Command Systems for Space Applications (TTC), 2016, pp. 1-8.
4. U. Naeem and N. Buchanan, "Conformal Retrodirective TM System for Future Generation Launch Vehicles," 2023 IEEE Wireless and Microwave Technology Conference (WAMICON), Melbourne, FL, USA, 2023, pp. 89-92, doi: 10.1109/WAMICON57636.2023.10124919.
5. N. B. Buchanan and V. F. Fusco, "A Simple Measurement Technique for Accurate Bistatic Retrodirective Radiation Pattern Calculation Based on the Active Element Pattern Method," in IEEE Transactions on Antennas and Propagation, vol. 66, no. 1, pp. 472-475, Jan. 2018, doi: 10.1109/TAP.2017.2776611.