Embedded thermal control of an Active Antenna using 3D printing

Executive Summary Report

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1 Introduction, scope and objectives

Thales Alenia Space owns a very strong experience in the field of active antennas for Space programs, starting from the end of the 20th century with STENTOR AA-Tx and presently with active anti-jammed antennas for SYRACUSE French defense system and IRIDIUM Next constellation with its 81 satellites.

In recent years the commercial satellite market has been evolving rapidly. The experience of Thales Alenia Space of advance active antennas thermal control for Space is key to best prepare the emergence of future high dissipative Active Antennas for VHTS mission, including frequency flexibility, power exchange among the beams and coverage re-configurability.

The use of active antennas with very high dissipated power has been increasing (up to 7kW). However, the current thermal management is efficient for quite low dissipated power (up to 400W). A new thermal control is thus needed for future antennas with very high value of dissipated power. A previous ESA study showed that a Mechanically Pumped Loop (MPL) is very well suited for the thermal control of active antennas.

Moreover, the use of additive manufacturing (AM) technologies has a high added value for performance increase and innovation. Combining these developments in AM with the advances in MPL systems will allow the realization of an embedded thermal control solution for antennas with very high dissipation power.

With this objective, the European Space Agency launched the activity “Embedded thermal control of an active antenna using 3D printing”. The scope of the activity was to develop an advanced active antenna structure, made by additive manufacturing, with embedded thermal control connected to the satellite MPL. Another objective was also to validate a methodology for both the design and models construction that can be applied to any type of active antenna.

The study was organised in 4 main phases : an engineering phase, a database phase, a breadboard manufacturing and controls phase and a breadboard integration and tests phase.

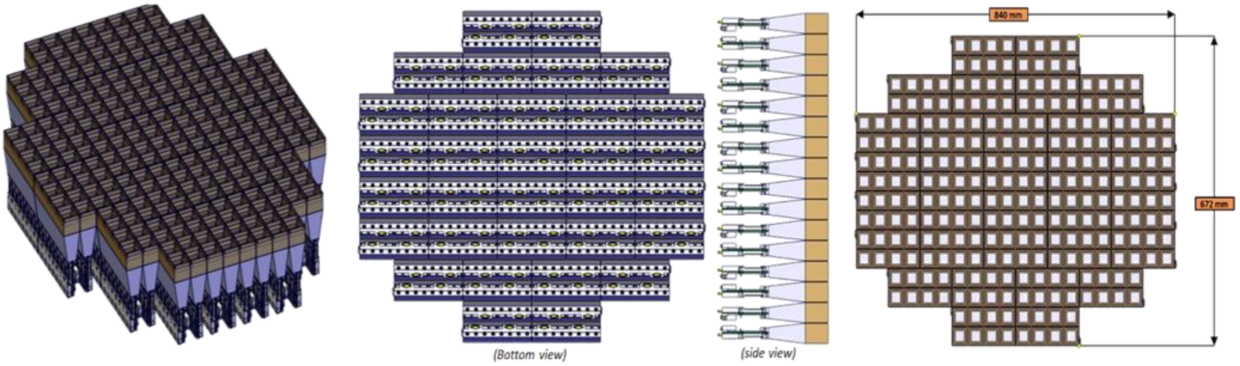
The first engineering phase consisted in the selection of the active antenna use case based on Thales Alenia Space heritage, the definition of the whole concept of the antenna and the breadboard and then, its mechanical and thermal justification.
In parallel, the database phase on samples was performed to get a characterization of the chosen material which is AlSi7Mg0.
Regarding the phase of manufacturing and controls of the breadboard, following the manufacturer recommendations, a Proof of Concept has been first manufactured in order to limit the risks identified during the co-engineering activity. Then, the breadboard to be tested has been manufactured and controlled.
A phase of the project was dedicated to the mechanical and thermal tests on the manufactured breadboard. It also included comparison and correlation with the experimental results and the tests predictions previously done
As the final step of the study, an evaluation of the proposed solution for an advanced active antenna with embedded thermal control using 3D printing was done.

2 Selection of the active antenna application case

The proposed mission for this study is the future very high throughput Geostationary broadband Multimedia Missions including frequency flexibility, power exchange among the beams and coverage re-configurability.
Digital payload including Digital Transparent Processor (DTP) are well known for providing frequency flexibility and efficient processing of the frequency resource by optimal allocation of channels to users.

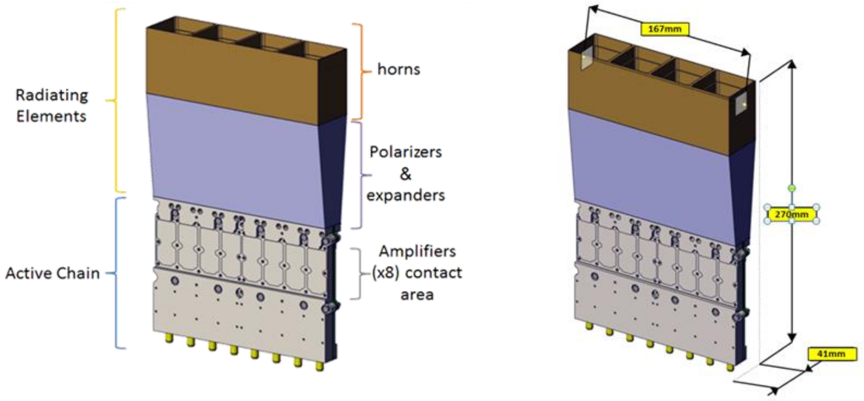
In the framework of the project, the selected active antenna is a Ka Band direct transmit phased array antenna. Direct Radiating Array (DRA) presents several advantages (numerous agile beams, full-power exchange, very low RF degradation…).

As the best compromise between good RF performances and industrial feasibility, the studied antenna is a phased array composed of 256 square horns with the dimensions 840mmx672mm and a square lattice of 42mm as illustrated in the figure below.



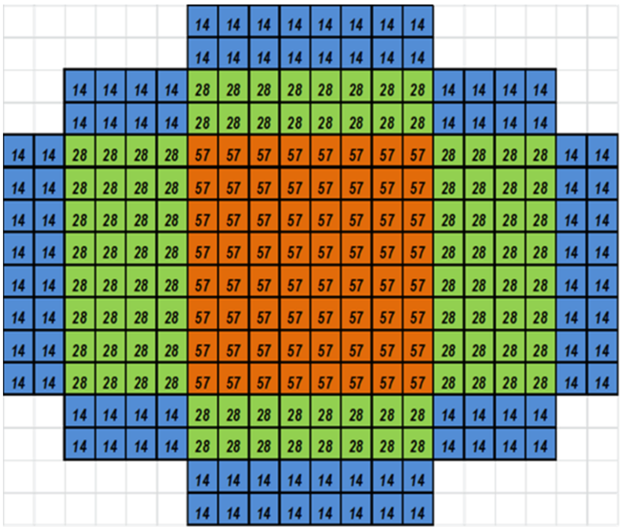
Transmit phased array antenna dimensions (256 RE)

More precisely, it is composed of 64 identical radiative element Quad FERM (each one including 4 bipolar RF chains).



Quad FERM design adapted to the proposed DRA

To achieve a good isolation for frequency reuse, an amplitude taper (0,3,6 dB) was considered. It leads to a non-uniform antenna dissipated power distribution as illustrated below.



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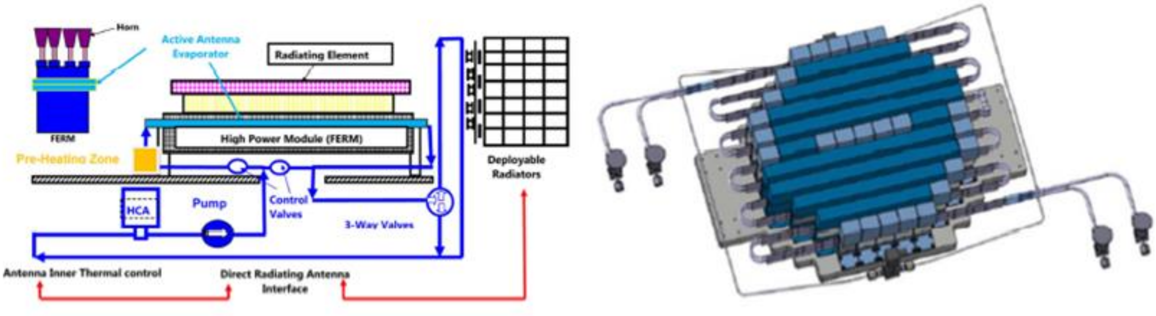
Antenna dissipated power budget distribution

The total antenna dissipated power in operational mode is : 7.7 kW

The thermal control solution selected for this Ka Band TX radiating panel is based on a Two Phase Mechanically Pumped Loop (2Ø-MPL) because it is the most effective thermal control technologies: Very high heat transfer coefficients achievable, Very high power transport capability on long distance, Isothermal capability.



Antenna Thermal control solution for high dissipative phased array antenna (2Ø-MPL)

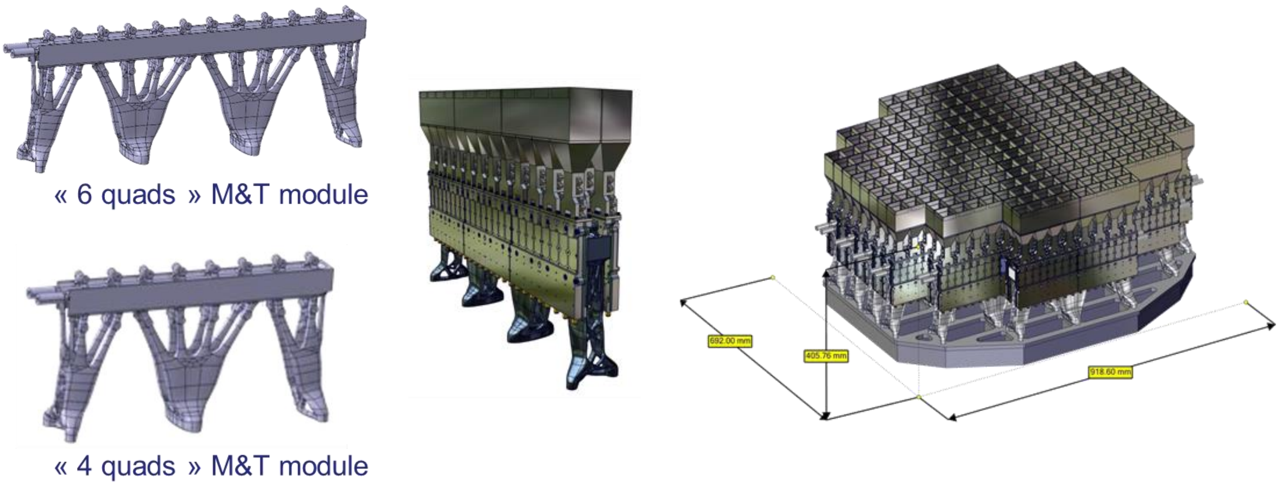
For this study, the developed advanced active antenna had to meet several constraints and requirements. They are of 4 types : design drivers, mechanical requirements, thermal and RF requirements and cost and planning drivers.

3 Description of the proposed technical solution

One of the most challenging aspects of this study was to manage the architecture of the antenna. The concept of the structure with embedded thermal control had to be compatible with the big dimensions of the phased array antenna and low accessibility between the quad FERM. Consequently, despite the use of AM, it was impossible to define a single bloc structure solution.

That is why the selected technical solution is an assembly of several aluminum “modules” on a baseplate, directly fixed on the satellite. A module, made by AM in aluminum alloy AlSi7Mg06, is composed of the mechanical structure, the thermal control and all the necessary fixations for the baseplate and the quad FERM. All the modules form a channel network that can be connected to the satellite MPL.

There are two sizes of modules in additive manufacturing : a “4 quads module” and a “6 quads module”. This proposed concept is a robust design solution that could be adjusted to any variations of antenna architecture and allows a simplified antenna assembly procedure.


« 6 quads » M&T module

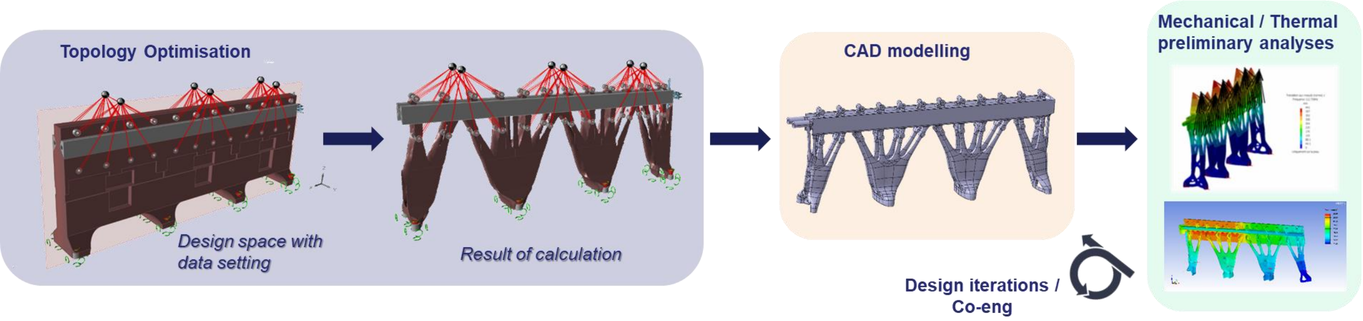
« 4 quads » M&T module

Sub-Assembly modules description

The dimensions and consequently the number of modules have been defined in order to be compatible with the dimensions of qualified machines of additive manufacturing.

Within the project, the best breadboard to manufacture in order to meet the representativeness of the active antenna and the budget was a “6 quads module”.

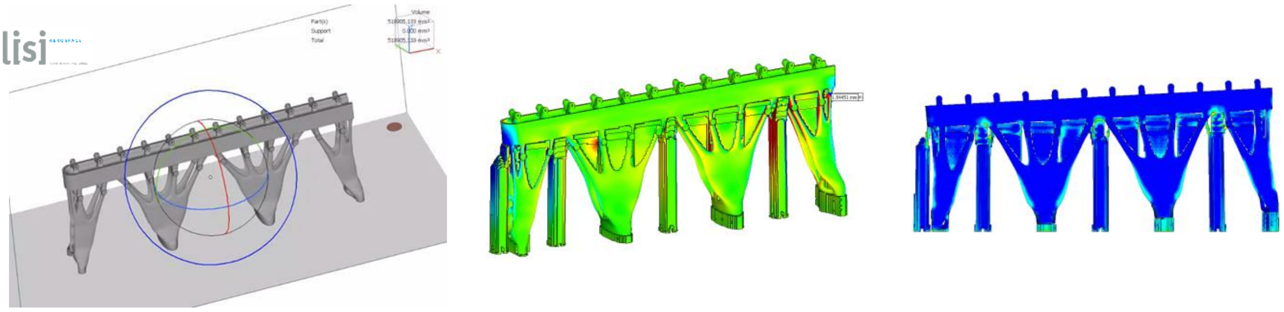
The design of the solution results from topology optimization calculations. Indeed, in accordance with the requirements, it was interesting to get the best stiffness / mass ratio.
The objective was to define a mechanical structure satisfying the specifications, including the thermal control which links the quads FERM to the mounting interfaces. A surface reconstruction of the most conclusive topology optimization result has been made and a validation of the design has been performed by mechanical and thermal preliminary analyses to check among others the frequency, the mechanical stresses under QS loads, the thermal gradient…
At this step, the design was compliant with all the requirements.



Design process of antenna modules

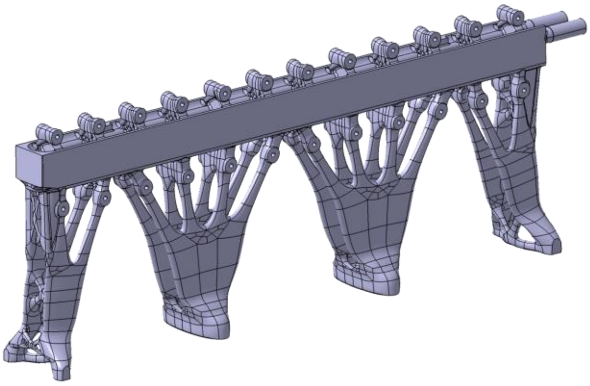
In parallel, through a co-engineering phase, the manufacturer LAAM has validated the feasibility of the design and mitigated the risks regarding the manufacturing.
Some recommendations have been expressed on the design to ease the manufacturing, to reduce the quantity of supporting structure and to suppress or limit the defects.

LAAM had identified a few risks of manufacturing. It concerns a risk of deformation confirmed by a simulation analysis and a potential difficulty for the cleaning of the internal surfaces of the thermal control and the machining of the functional areas.



Co-engineering phase : Results of simulation analysis

The breadboard design has been then modified in accordance with the manufacturer LAAM and the mechanical analyst recommendations. The impacts of the new design solution are the following : minor modifications of the Quad FERM design without impact on RF performances and mass, slight mass saving of the whole antenna mass, a potentially more expensive manufacturing and a shorter manufacturing and assembly, integration and test lead time.



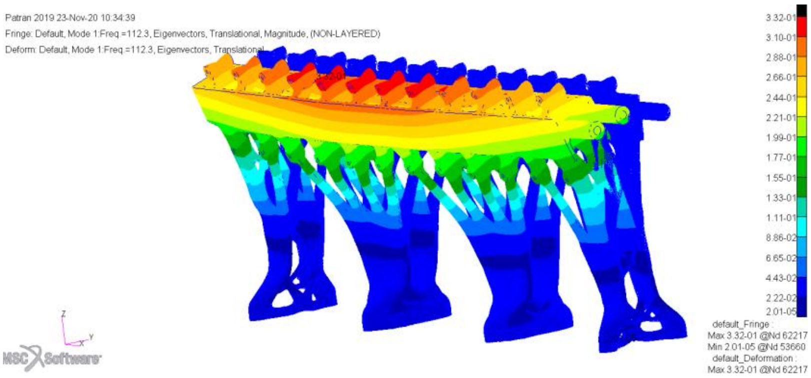
Final design of the breadboard

4 Mechanical and Thermal justification

Before manufacturing, the breadboard has been validated by mechanical and thermal analyses.

From a mechanical point of view, 3 types of analyses have been performed to check the compliance in regards to the specifications: modal, quasi-static and thermo-elastic analyses. The results of the calculations showed that the design is compliant with all the requirements :

- Frequency higher than required (>60 Hz)
- Positive safety margins regarding the mechanical stresses for all the applied loads
- Positive safety margins regarding the link sizing for all interfaces

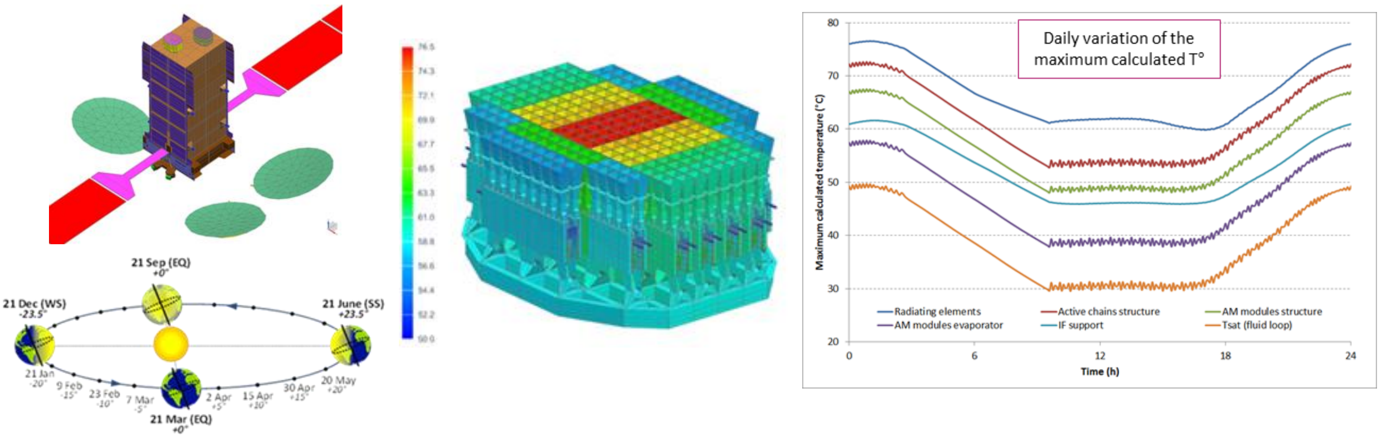


Shape of the Y axis 1st principal mode

For the thermal aspects, in order to validate the performances of the implemented thermal management solution which is a 2Ø-MPL, a thermal analysis of Ka Band DRA Antenna has been carried out, in geostationary orbit, considering 2 operating modes : nominal operating mode (7.7 kW) and overdrive operating mode (8.6 kW).

Both in worst hot case and in cold case, for all RF scenarii, the results demonstrated the efficiency and robustness of the selected technical thermal control solution, which has the capability to manage a huge power budget and allows to answer RF performances specifications:

- The Q-FERM are thermally controlled on their optimum and reduced operating [25°C, 85°C] and non-operating temperature ranges.
- A Quasi-isothermal requirement (DT < 15°Cpp) among all amplifying chains (Quad-FERM interfaces) is guaranteed within the operating range.
- All temperatures of the DRA antenna parts remain inside their Material and Process (M&P) qualification limits temperatures.



DRA Antenna thermal analysis – Worst Hot Case

5 Samples characterization

The phases of design and justification were followed by the characterization of the material AlSi7Mg0.6 through samples printed in the X-Line 2000R machine.

A test plan was defined and aimed at addressing 4 different aspects on the material:

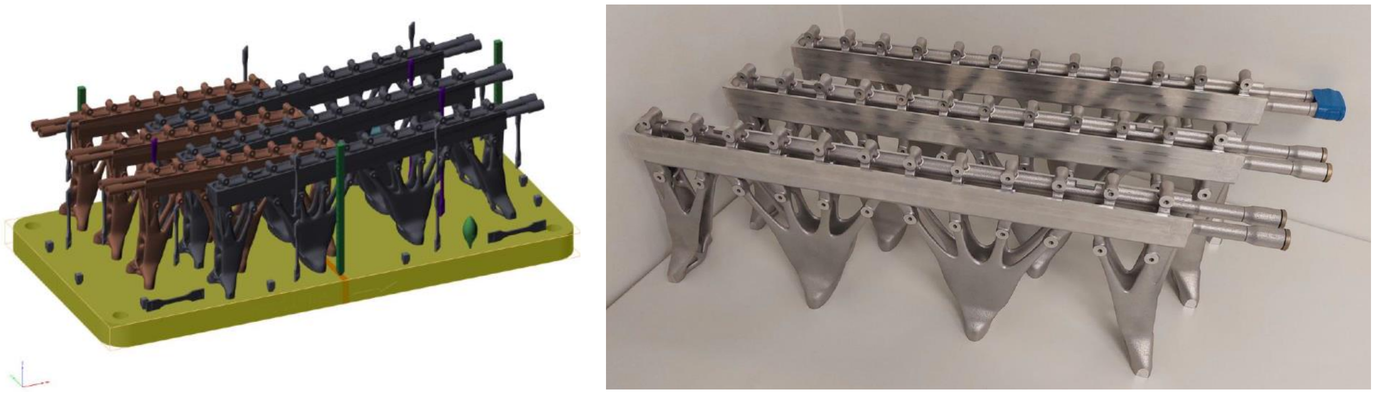
- Mechanical characterization (static and fatigue tests)
- Material health assessment through metallography and CT scan
- Corrosion sensitivity
- Residual stress

The samples were printed in different jobs with a frozen set of parameters on the machine which has 2 lasers are for melting the powder. Consequently, samples were produced on the whole building plate including the overlap area of both lasers.

The material characterization performed in the frame of this project covers the tests required by the Additive Manufacturing Verification Phase from ECSS-Q-ST-70-80 C.
Activities on corrosion sensitivity should be pushed further to answer the specific technical needs of thermo-fluidic applications.

6 Proof of Concept and Breadboard manufacturing and validation

In the frame of this project, 5 jobs were printed. The first two jobs were dedicated to samples and their characterization. Then, a Proof of Concept was printed in a third job to demonstrate the printing feasibility of the design and mitigate the risks of manufacturing. It allowed to highlight significant deformations of the part due to its geometry. For the next step (4th job), a de-risking approach was adopted: 3 breadboards (3 specimens of 6 quad modules) were printed in order to test different machining strategies to reduce geometrical deviations on the interfaces. This production showed improvements on the geometrical deviations of the part but it was decided to print a breadboard specimen one more time to implement the lessons learnt (5th job).



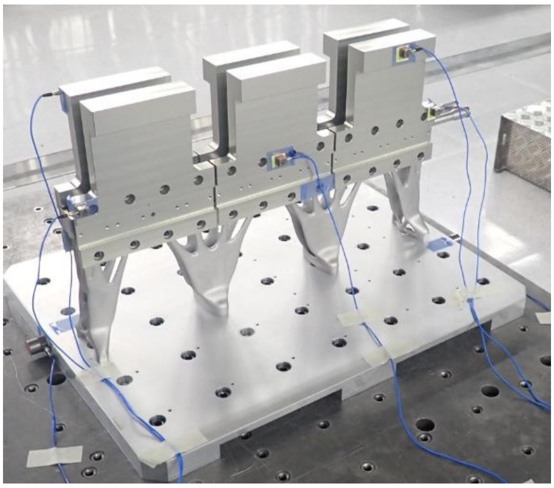
Implementation of the 4th job and breadboards after machining step

Some minor non-compliances have been identified on the last manufactured breadboard but all were acceptable. Indeed, despite the simulation analysis and the optimization of the supporting structure, deformations still remained, that led to shape defects and also to machining non-conformities.
To address this issue, an in-depth but time-consuming study is required in case of future production.

7 Mechanical and thermal tests on breadboard

Once the manufactured breadboard validated, mechanical and thermal tests have been performed. The dummies, 6 in number, used to represent the quad FERM were the same for all the tests.

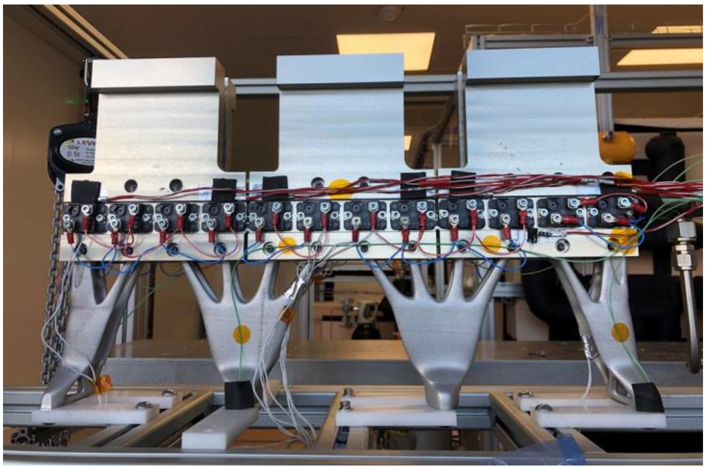
The objective of the mechanical test which was a low level sine test, was to perform a modal characterization of the antenna support along the 3 axes, with Thales Alenia Space Toulouse test means facilities.



Equipped breadboard with dummies and accelerometers on vibration tool

The tests were successful : no damaging occurred during the mechanical tests and the modes of the breadboard were similar to the predicted ones, once the correlation was done. Moreover, the reliability of mechanical simulations and the good manufacturing execution have been demonstrated.

Regarding the thermal tests, the main objectives were to demonstrate that the temperature gradient between all FERM does not exceed the specified maximum value of 15°Cpp in all operating conditions and also the ability of predicting the temperature cartography. The test specimen was installed on the two-phase loop, located in Thales Alenia Space Cannes test facilities, with the aim of characterizing the performances of different MPL components.



Equipped breadboard with dummies, heaters and thermal sensors for thermal test

The test plan was built so as to cover the physical range of relevant thermal and fluid parameters associated to realistic fluidic layouts ie the mass flow rate, the inlet subcooling and the power dissipation.

The lessons learnt from the thermal test campaign are the following :
The largest temperature gradient is always lower than the specified value. Considering that the smallest gradient is obtained for lowest mass flow rates, subcooling and thermal dissipation, the design shall favor fluidic layouts with branches in parallel. The numerical simulation demonstrated the ability to predict the temperature field with a characteristic discrepancy of about 1°C.
Moreover, the tests highlighted the necessity to consolidate the cleaning process following the identification of particle release issue.

8 Conclusions

Here below the compliance matrix of the advance active antenna structure with embedded thermal control using 3D-printing developed within the GSTP:

Ref	Specification		Status	
(1)	Compatible dimensions and architecture of the antenna		C	
(2)	AM feasibility and integration		C	
(3)	Embedded thermal control (connected to MPL)		C	
(4)	Alignment requirement		C	
(5)	Structure mass budget	< 35%	C	33 % → Slight mass saving
(6)	No quad FERM design modifications		C	
(7)	First frequency	> 60 Hz	C	F1 > 100 Hz
(8)	Positive safety margins for applied loads		C	
(9)	Power dissipation budget		C	
(10)	M&P temperature limits		C	
(11)	Maximum qualification temperature range		C	
(12)	Thermal gradient	< 15°C pp	C	
(13)	Competitive cost		PC	To be defined at the satellite level
(14)	Shorter manufacturing and AIT lead time		C	

Compliance matrix

This GSTP demonstrates great positive results. The developed solution design combined with the chosen material aluminium AlSi7Mg0.6 meets the main requirements of an active antenna that proves its feasibility. The reliability of simulations is proved. The TRL 5 has been reached for this study.

The optimized structure is robust and secure from a mechanical point of view. It is also a flexible design solution that can be easily adapted to various dimensions and architecture of antennas. Regarding the proposed thermal control, it has the capability to manage a huge power budget while fulfilling the requirements in terms of high level of integration, extended temperature range and antenna quasi-isothermal behavior whatever the antenna fluidic arrangement. Moreover, this project has demonstrated the feasibility of manufacturing such a design of an active antenna structure with embedded thermal control. However, 2 main difficulties have been encountered and remain despite preventive actions : global deformation of the raw part and cleanliness of the embedded thermal control. Additional in-depth studies are required in case of further development.

This advanced antenna structure and thermal control using 3D-printing is a smart solution for the future high capacity transmit phased array antennas using the satellite two phase MPL where there is a strong drive towards lowering the cost of satellite capacity in orbit, leading to the emergence of the flexibility and high throughput systems featuring large numbers of beams.