Flat Cable Harness for Space Launcher Applications

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INTRODUCTION

This paper presents the results of the ESA supported project "Improved Design of Harness for Launcher" developed jointly by Arianegroup and Axon' Cable. The aim of this project is to find harnessing solutions allowing to decrease drastically the mass, the volume and the cost of Space Launcher electrical harness.

The first part of the project was devoted to the analysis of the specifications, identification of use cases, and overview of available technologies, leading to a trade-off process. The outcome of this process has pointed out clearly, that the use of flat cabling may give a net advantage when compared with traditional round cable solutions.

The second part of the project has been dedicated to the design of two harnessing use cases based on Ariane 6 Launcher design.

- First, an internal launcher harness, roughly 9m long, 64 connecting points, integrated on the intertank of the Upper Liquid Propulsion Module (ULPM).
- Second, a complete external raceway harness, also on the ULPM, 3m long and counting 208 connecting points, and fully integrated in a composite self-carrying and self-protecting composite, called an ElectroStructural Composite (ESC).

The necessary base harnessing solutions have been developed by Axon Cable SAS. A flat 42 mm wide, eight (8) contacts, kapton isolated flat cable and a specific connector, based on Versatys® series, providing 16 contacts. The first harnessing step is thus composed of pairs of flat cables that can also be protected by 360° shielding.

The third and final part of the project has consisted on the manufacturing of the final scale 1:1 mockups of the two most promising use cases. Verification of some of the trade-off features has been performed, including the ease and impact on integration, the manufacturability, the volume and a mass assessment. A specific electrical testing electrical has also been carried out pointing out some perspectives for future development.

PART 1: ANALYSIS OF THE SPECIFICATION, IDENTIFICATION OF USE CASES AND OVERVIEW OF AVAILABLE TECHNOLOGIES: TRADE-OFF

Context

As a preamble to this chapter, it is important to understand that the particularity of electrical harnessing is to be at the interface/contact:

- Of electrical/electronic equipment, allowing their interconnection: we understand the importance/role of electrical connectors.
- Of the mechanical frame of the spacecraft: we understand the importance of mechanical supports and the impact on volume allocation and assembly operations.

That is the reason why, from a project point of view, a lot of actors (12) are involved in its specifications as shown in the figure below:

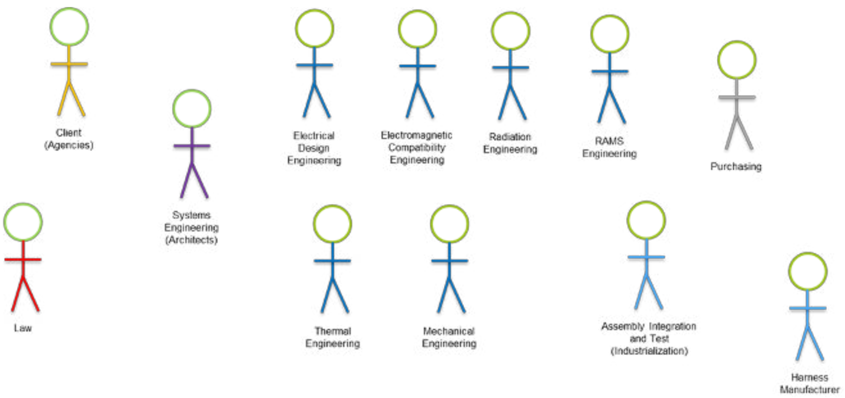

Fig. 1. Actors involved in the specification process of Launcher Harness.

Another important characteristic of spacecraft harness is complexity and its associated robustness/availability:

- The number of electrical interface points for a Launcher can be estimated to several tenths of thousands ($\sim 10^4$). Fail on one single point can lead to loss of the mission. This is the reason why electrical systems are often redundant.
- The number of complexity mechanical interfaces to support harness can be estimated also in the range of ($\sim 10^4$). The impact is related to the on manufacturing and final cost of the installed harness.

We have focused our study in Ariane 6 Uppers stage harnessing and the figure below shows a harness diagram, showing the different zones where harnesses are installed:

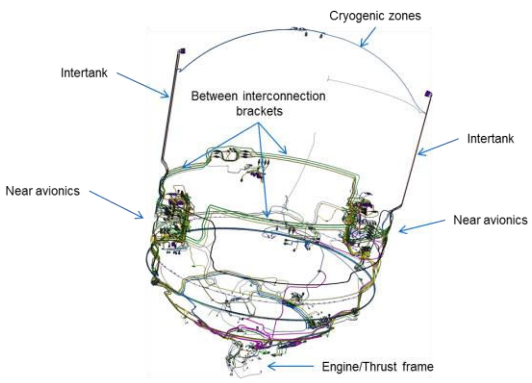

Fig. 2. Upper stage launcher Harness complete diagram and identification of installation zones.

A space launcher/ upper stage cabling represents:

- Around 10 km kilometres of cable arranged in 140 harnesses.

- 400 kg of installed mass which is the 6-7% of the net mass of the launcher/stage (considering supports, protections and mounting plates).
- Around 5% of the total avionics cost.
- A total installed cost ~7% , thus installation representing ~30% of overall own cost of harness (installed).

The table below gives some interesting features:

Table 1. Estimated Harness features on a Launcher Upper Stage (Ariane 6).

Nb. Harness	140
Nb. km cable	10 km
Harness net Mass	200 kg
Installed harness Mass including supports/protection, mounting plates	400 kg
Harness net ROM Cost (% of avionics)	5 %
Installed harness ROM Cost (% of avionics)	7 %
Harness Volume/Installed Harness Volume	0.135 m^3/ 10 m^3

We can state that almost 100% of electrical Harnesses in current European Launchers are based on Round Wire Cable technology (RWC) even if different topological zones can be described where harness present specific particularities and also face specific environments:

- Internal launcher harness:
  - Near equipment on Avionic specific boxes.
  - Between internal disconnection brackets.
  - On cryogenic zones.
- External harness:
  - Intertank (through raceways).
  - Engine and Engine thrust frame.

The table below describes the specificities of each of the presented zones:

Table 2. Main harness characteristics, by zone.

Feature	Internal Harness			External Harness	
	Near Avionics	Between interconnection brackets	Cryogenic zones	Intertank	Engine/Thrust Frame
Length	Small	Long	Medium	Medium-Long	Short-Medium
Topology	Curved/Small radii curvature /Spliced	Curved and Straight/Big radii curvature	Curved and Straight/Big radii curvature	Straight	Curved/Small radii curvature /Spliced
Temperature range of the zone	-50°C/70°C	-150°C/200°C	-253°C/70°C	-150°C/400°C	-150°C/300°C
Protection	No protection	No protection	Protected by jacket (Thermal protection)	Protected by Covers	Protected by jacket (thermal protection)
Shielding	Overshielding /Shielding/No shielding	Shielding	Shielding	Overshielding	Overshielding
Supports	T-raps on plastic glued supports every 5-10	T-raps on dedicated fastened supports (ramps,	T-raps on dedicated fastened supports (ramps, “colonettes”, pipes)	T-raps on dedicated fastened supports (raceway)	T-raps on dedicated fastened supports (ramps, pipes)
Ratio mass harness-support-protection	80%-20%	50%-50%	50%-50%	80% -20%	50%-50%

Specification review

Taking that into account, we have focused in decomposing the problem recalling that the three main components/parts of a, integrated harness are:

1. Cable
2. Connectors
3. Supports

Following these basic components and relevant documentation [1],[2],[3],[4],[5],[6],[7], the complete set of identified requirements (leading to 43) , has been decomposed in the following manner.

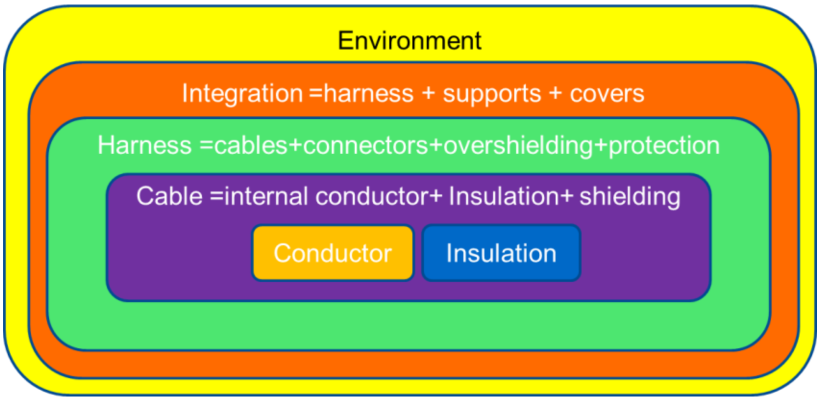

Fig. 3. Classification of requirements.

- Conductor requirements: which concern the conductive material used in cable construction.
- Insulation layer requirements: which concern the isolation layers used in cable construction.
- Cable requirements: which concern the assembly of several conductors (typically 2) plus their insulation layers ,and eventually the shielding to obtain a cable.
- Harness requirements: which concern the assembly of several cables, their associated connectors, and eventually the overshielding and extra mechanical protection sheets.
- Integration requirements: which concern the integration of harness on the spacecraft structure and their associated supports.
- Environment and requirements: which concern the external environment that the installed harness has to withstand and the use requirements.

Technologies Review

In parallel to the specification, a review of available technologies has also been performed. As already stated, Round Wire Cable (RWC) based Harness is the current baseline for most of the harnessing of existing European space Launchers/Spacecraft. In current Launchers it represents almost 100% of the cabling.

Nevertheless, promising technologies based in Flat Conductor Cable/Flat Flexible Cable (FCC/FFC)/ or PCB Flex Cabling are available, some of them being tested by Arianegroup in collaboration with Axon for over a decade.

Interesting literature produced by NASA [8] also pointed out already in 1973 the interest of Flat Conductor Cable over Round Wire Cable.

- Showing a potential weight savings of 80% on supports and at least 40% on the harness.
- Showing space savings between 80-90%.
- Pointing out 80 % cost reduction.

Trade-off Process and Technological Conclusions

A trade-off process has been performed in order to understand the potential benefits of replacing technologies. The most interesting conclusion with regard to the main requirements (cost, mass, volume) are shown in the following table:

Table 3. Trade-off summary.

Target	Round Wire Cable	Flat Conductor Cable- Flex	Flat Conductor Cable- Continuous
Cost target (-50%)	Difficult to challenge ESA/SCC harness providers to tackle the target. Hybrid cables are positioned at least 30% more expensive than traditional cabling, so the target can not be challenged at cable level.	The FCC Flex is a costly solution, due to the manufacturing process and possible automation for the stripping process.	The FCC may attain significant cost reduction, due to the simpler manufacturing process and possible automation for the stripping process. The isolation layer can be reduced in thickness
Mass target (-30%)	The mass target can only be challenged by hybrid cables. For most used gauges the mass gain is estimated to 10 %.	The mass target can be challenged mainly by the optimization of the isolating layers and of the shielding. This can be estimated to 10-20% The use of Aluminum on conductors remains possible, but the impact on crimping or soldering makes it reasonable only for small gauges.	The mass target can be challenged mainly by the optimization of the isolating layers and of the shielding. This can be estimated to 10-20% The use of Aluminum on conductors remains possible, but the impact on crimping or soldering makes it reasonable only for small gauges.
Volume target (-80%)	Volume can not be challenged at cable or harness level. The only way to optimize that would be to arrange the RWC in flat ribbons.	Volume can be challenged by the fact that flat assemblies optimize by 15% the use of space at harness level and by 80% at installation level.	Volume can be challenged by the fact that flat assemblies optimize by 15% the use of space at harness level and by 80% at installation level.

The final outcome of the process showed that the use of Flat Conductor Cable Continuous technology shall bring the highest savings/potential.

With that result in mind, we stated that the two necessary technological bricks to develop on the frame of the project shall be:

- A Flat Cable Conductor.
- An associated Connector.

The two bricks where quickly developed by Axon Cable SAS as shown in the figure below.

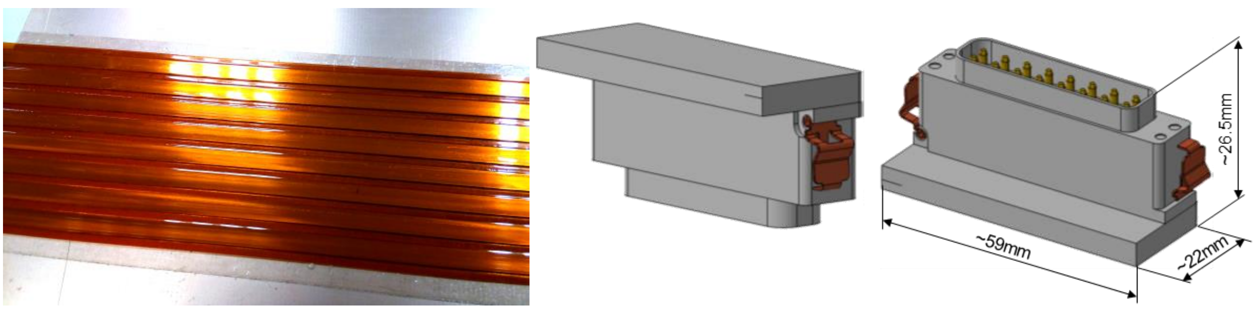

Fig. 4. Flat Conductor Cable composed of 8 conductors with a pitch of 5 mm, AWG 18 (left picture). Versatys prototype capable of interconnecting two flat cable conductors, 16 points, gauge 20 contact (right picture).

PART 2: LAUNCHER HARNESS DESIGN

In this part of the project, three specific harness/zones corresponding to a launcher upper-stage had been chosen as a target study. Internal inter-tank harnessing, external raceway harnessing and avionics bay harnessing as showed on the figure below:

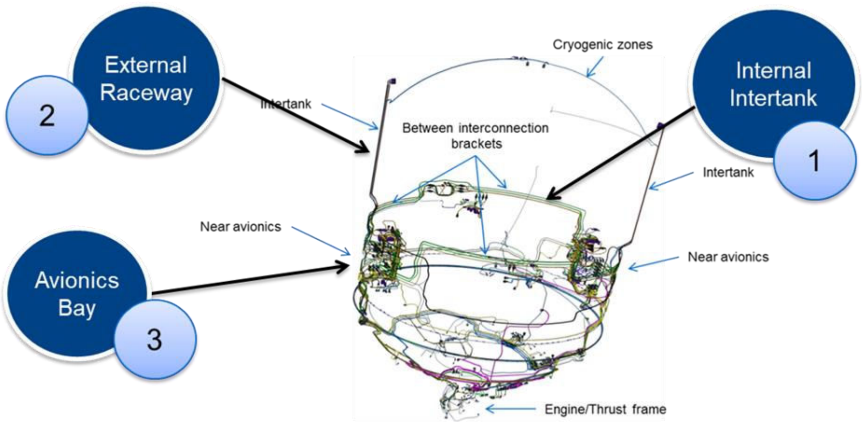

Fig. 5. Three selected study zones on Ariane 6 Upper Stage.

Flat Harness Architecting Principle and technological implementation

The base for design had to rely on a simple architecting principle allowing for maximum savings as pointed out in the trade-off process. The choice then was based on the need to « To minimize the installation footprint ». This consideration is based on return of experience where classical round wire harness routing and integration accounts for a huge design and integration effort between electrical and mechanical design offices.

The figure below depicts the flat harnessing architecting solution chosen:

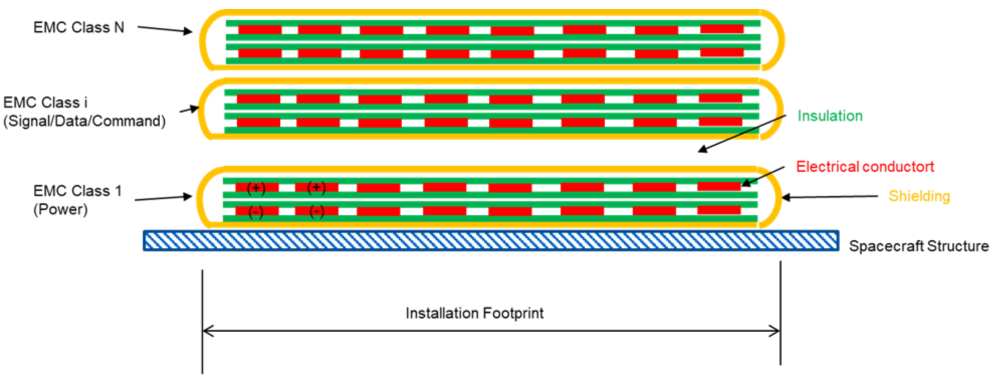

Fig. 6. Flat harness architecture with minimum installation footprint impact.

The installation footprint is approximately the width of the flat cable technology chosen. In our case, the FFC developed is 42 mm (for 8 conductors spaced 5 mm). It we take into account for some available space on each side in order to implement the shielding and additional insulation the total installation footprint is considered to be of 50 mm.

The different cables are then organized according to their functionality. The functions defined are:

- Power Input/Output : all power leads that make part of the power distribution chain. Input leads are those between the power sources (batteries, ground power) and distribution equipment and output leads are those between distribution equipment and consumer equipment.
- Power Command : all command sending electrical power as servo-actuators ,electro-valves, or heaters.
- Control/Status line (binary) : all lines used to provide a simple electrical status that can be interpreted as a Boolean 0 or Sensor/Analogical : all lines connected to sensors that provide a continuous electrical signal.
- Communication Bus : all lines used for bus communication, following a specific protocol (ie. RS-422, 1553, Time-triggered Ethernet).
- Pyro Lines : electro-pyrotechnical lines used for fire operations (engine ignition, stage separations, thermal batteries ignition, satellite dispensing…).

Finally, the classes are "packed" on the flat harness following the segregation principle presented in the table below:

Table 4. Segregation policy for Flat Cable Harness.

EMC Class Number	EMC Class Type	Polluter	Sensible	Shield	Colour	Compatible with
1	Power Input/Output	Yes. Medium	No	No	Green	2,3
2	Power Command/EV	Yes, high	No	Yes	Magenta	1,3
3	Control/Status line (binary)	No	No. Low	No	Orange	1,2
4	Sensor/Analogical	No	Yes.Highly	Yes	Red	None
5	Communication Bus	Yes. Medium	Yes.Highly	Yes	Blue	None
6	Pyro Lines	No	Yes.Highly	Yes	Yellow	None

A "pack" consists on a shielded stacking of single flat flexible cables. A preferred embodiment of the packing is a pair number of FFCs, and affecting the plus (+) and minus (-) to the upper and lower FFCs. A lateral signal assignment can also be used.
The three first classes 1, 2 and 3 being compatible amongst them, they are integrated as the first layers of the FFC close to the spacecraft structure. This choice is made in order to minimize the common mode pollution created by the harness loop defined by the harness and the spacecraft structure, as the power and command classes are a well known contribution to low-medium frequency noise.
The rest of the classes, 4, 5 and 6, are packed separately and staked on the top layers of the harness.

Internal inter-tank harnessing preliminary design

This harness describes a typical routing architecture of an internal cabling inside an inter-tank zone. The baseline routing uses longitudinal stringers as attachment zones and tries to avoid collisions/segregation with the rest of the routing. As a consequence, extra length is needed for the routing and the impact on installation becomes important as a lot of manual operations are needed to install/protect every harness.

The basic idea of redesign on this topology/zone is:

- To minimize the length of cabling by routing as short as possible between
- To Install mechanical support directly on top of the transversal beams that present a flat surface.
    - Thus avoiding multiple supports on longitudinal stringers: harness installed traversing longitudinal stringers need at least one support every two stringers.
    - Without the need of harness protection as tape winding/metallic protection sheets/ or helicoid plastic protection sleeves: in fact, harness installed crossing longitudinal stringers at 90 ° are exposed to cut.
- Override EMC lateral segregation rules using flat cable stacking with shielding and positioning rules.

The final redesigned solution obtained is shown in the figure below:

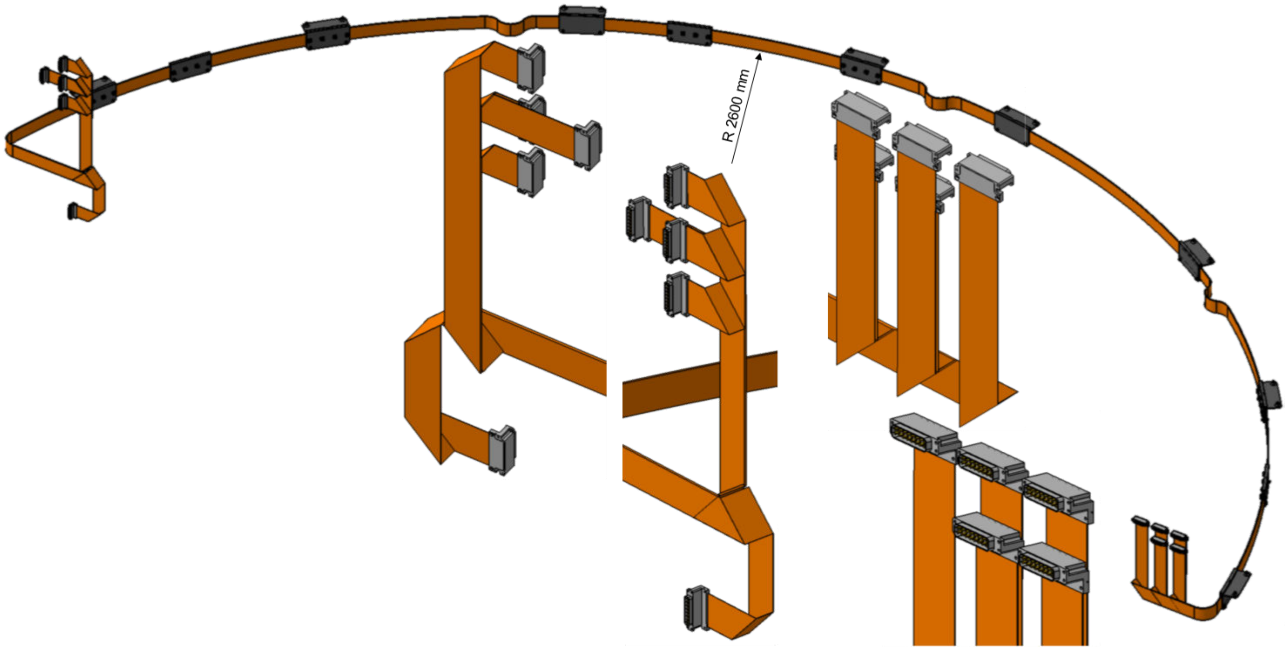

Fig. 7. Overall view of the redesign solution for Internal Intertank harness including supports and connectors.

The detail of the staking, being IFI 1 and IFI2 the extremity interfaces (IFI) of the harness:

Table 5. Stacking design for Internal inter-tank harnessing.

IFI1	Stacking	IFI2
	SHIELD	
1 double connector with shielding	50 (2 FFCs AWG18)	1 double connector with shielding
	SHIELD	
	SHIELD	
1 double connector with shielding	30, 10 (2 FFCs AWG22)	1 double connector with shielding
	SHIELD	
	SHIELD	
1 double connector with shielding	10 (2 FFCs AWG22)	1 double connector with shielding
1 double connector (2 FFC)	20 (2 FFCs AWG 22)	1 double connector (2 FFC)
1 simple connector	40 (1 FFCs AWG22)	1 simple connector
	GROUND	

The table defines the cross-section architecture of the Flat Conductot Cable/Flat Flexible Cable :

- Columns IFI1 and IFI2 present the definition of the connector.
- Column stacking present the type of stacking, including the conductor gauge and the presence or not of the shielding.

A risk assessment action had been taken concerning the topology to be respected that implied the folding of the Flat Flexible Cable. The figure below shows the results on a reduced scaled mock-up that allowed to validate the concept:

Fig. 8. Mock-up derisk on internal inter-tank harness.

As a final result of the design process the evaluated features where the following:

- No showstopper concerning folding/topology of the final harness.
- The overall mass savings of the installed product are evaluated to be >30 %.
- The integration time is evaluated to be drastically reduced.

External raceway harnessing preliminary design

In this case we address the design of a very specific harness implementation of launchers which is the external harness used to connect the avionics installed on both sides of propergol tanks (solid or liquid).

The driving idea in this case is to replace all raceway harness including their aerothermal protection by a single element composed of two flat parallel harness, that minimize the aerothermal impact (protuberance) as shown in the figure below. The advantage of FCC on this application is the compacity can achieve with, thus allowing designers to optimize the volume allocation.

The design process is somehow different from the precedent case as there is no routing optimization considered. We suppose that, on the strict perimeter of the raceway, the total length for both RWC and FFC would be slightly the same (even if in reality, the RWC requires overlength for installation purposes, it is not taken into account in our calculations) The lines below summarize the design process followed:

- Affect the signal to an EMC Class Number
- Affect the corresponding gauge to the FFC.
- Estimate the "packing" of FFCs taking into account:
    - the EMC class compatibility table.
    - safety constraints for pyro lines (separated as long as possible from the rest of the lines).
    - The two possible exit points: Launcher Vehicle Adaptor or LH2 tank.

The final redesigned solution obtained is shown in the figure below:

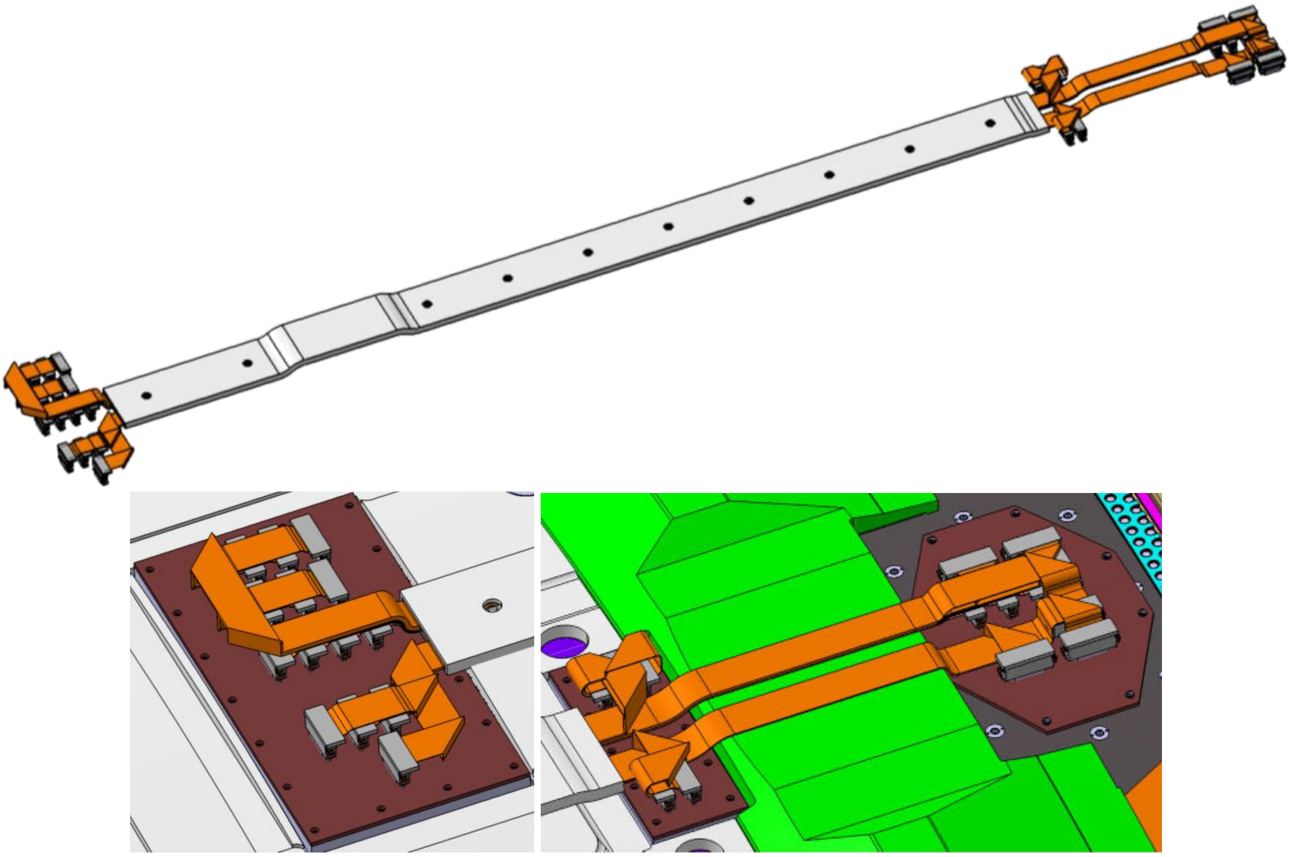

Fig. 9. Overall view of the redesign solution for external raceway including aero-thermal covers (top). Detailed view of the three interfaces (bottom).

The detail of the staking, being IFI 1 and IFI2 the extremity interfaces (IFI) of the harness:

Table 6. Stacking design for the external raceway harnessing.

IFI1	Stacking LEFT SIDE	IFI2
	HOT THERMAL PROTECTION	
	COMPOSITE (glass fiber)	
	SHIELD	
	80 (1 FCC AWG22)	
1 Versatys (Exit IFS)	90 (1 FFC AWG22)	1 Versatys (Exit Tank)
	SHIELD	
	SHIELD	
1 Versatys (Exit IFS)	80 (2 FFCs AWG22)	1 Versatys (Exit Tank)
	SHIELD	
	SHIELD	
1 Versatys (Exit IFS)	80 (2 FFCs AWG22)	1 Versatys (Exit Tank)
	SHIELD	
	SHIELD	
1 Versatys (Exit IFS)	120 (2 FFCs AWG22)	1 Versatys (Exit LVA)
	SHIELD	
	SHIELD	
	100 (1 FFC AWG22)	
1 Versatys (Exit IFS)	120 (1 FFC AWG22)	1 Versatys (Exit LVA)
	SHIELD	
	SHIELD	
1 Versatys (Exit IFS)	110 (2 FFCs AWG22)	1 Versatys (Exit LVA)
	SHIELD	
	SHIELD	
1 Versatys (Exit IFS)	100 (2 FFCs AWG22)	1 Versatys (Exit LVA)
	SHIELD	
1 Versatys (Exit IFS)	20 (2 FFCs AWG18)	1 Versatys (Exit LVA)
1 Versatys (Exit IFS)	10 (2 FFCs AWG18)	1 Versatys (Exit LVA)
1 Versatys (Exit IFS) Half equipped	10 (1 FFCs AWG18)	1 Versatys (Exit LVA) Half equipped
	COLD THERMAL PROTECTION	
	GROUND	

IFI1	Stacking RIGHT SIDE	IFI2
	HOT THERMAL PROTECTION	
	COMPOSITE (glass fiber)	
	SHIELD	
1 Versatys (Exit IFS) half equipped	70 (1 FFCs AWG18)	1 Versatys (Exit Tank) half equipped
	SHIELD	
	SHIELD	
1 Versatys (Exit IFS)	70 (2 FFCs AWG18)	1 Versatys (Exit Tank)
	SHIELD	
	SHIELD	
1 Versatys (Exit IFS)	60, 50 (2 FFCs AWG18)	1 Versatys (Exit LVA)
	SHIELD	
	SHIELD	
1 Versatys (Exit IFS)	40,30 (2 FFCs AWG18)	1 Versatys (Exit LVA)
	SHIELD	
	COMPOSITE (glass fiber)	
	COLD THERMAL PROTECTION	
	GROUND	

In this case, it is interesting to note that the designed stacking presents two parallels routes. This choice has been based in safety considerations, leaving all pyrotechnical signals in one segregated route. The left hand side route presents a stacking of 19 Flat Flexible cables and the right hand route a stacking of 7 Flat Flexible cables.

As an additional feature, the whole stacking is integrated in a single part, following a composite integration process as shown in the figure below:

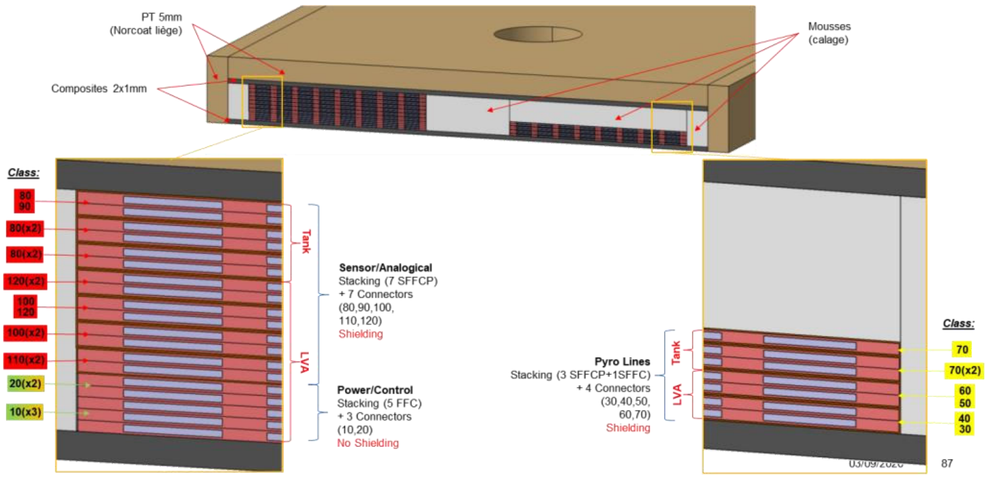

Fig. 10. Composite sandwich including thermal protection and mechanical fixation supports

In brown, we can see the external thermal protection, made of Norcoat® cork. In dark grey we notice the composite skins (around 1 mm thick). The light grey represent non occupied zones that are filled with a core material (i.e. a foam).

The feasibility process was also tested promptly by manufacturing small derisking specimens in order to validate the concept as shown in the figure below:

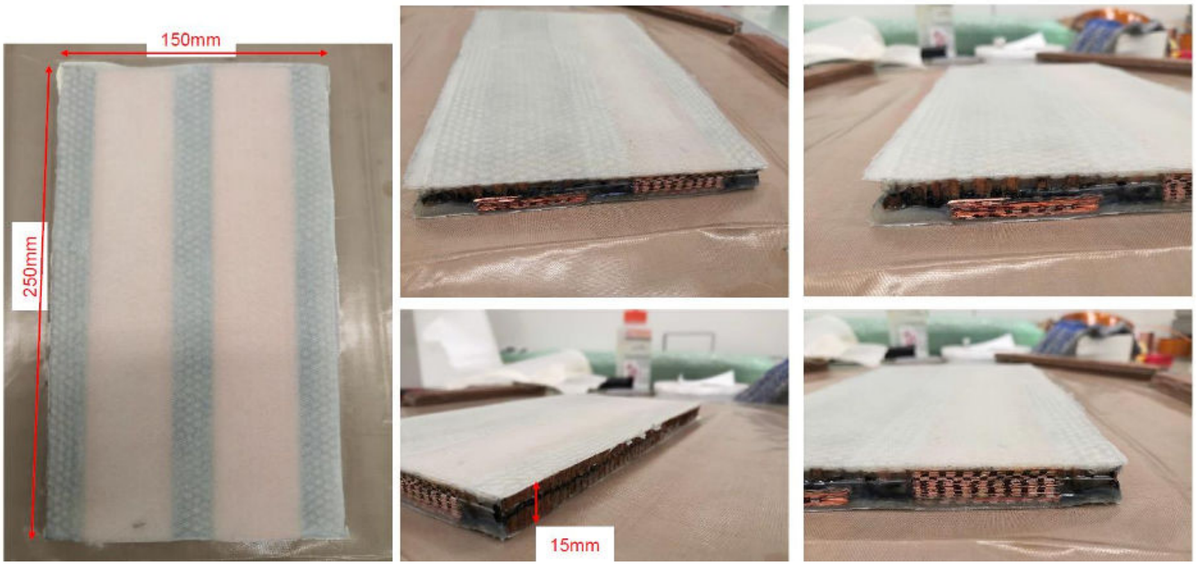

Fig. 11. Composite derisk mockup for external raceway harness.

As a final result of the design process the evaluated features where the following:

- No showstopper concerning the composite integration process.
- The total mass savings considering the cabling are evaluated >75 %.
- The overall volume allocation savings are evaluated > 80 %, thus allowing to reduce substantially aero-thermal constraints.

Avionics bay preliminary harnessing

The idea on this use-case is to replace avionics bay harness in order to minimize the volume allocation required for cabling in small spaces. The figure below shows the specific harness (power) to be redesigned:

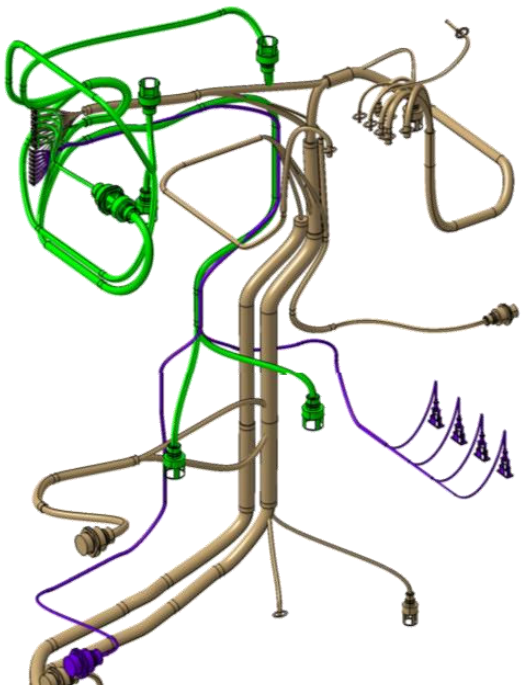

Fig. 12. Avionics Bay power harness.

The hints for design in this case are the following:

- Routing from connector to ground plane is to be made as directly as possible in order to reduce used volume and reduce overall length. Again, we recall here that the principal effect on reducing volume used by harness is to impact the sizing of equipment cabinets. Furthermore, for satellite applications, the potential on this kind of routing would be to embed directly the FFCs on the composite panels holding the equipment.
- EMC segregation is provided by separation shielding and not buy distancing rules.

The specific difficulty when arriving to already existing equipment on their mounting plates is multifold:

- The connectors choice can not be changed. In our case, the existing connectors are not adapted to FFC, so an extra interface would be necessary (FFC to round, for instance), and so de-optimizing the design.
- The connector orientation on the equipment can not be changed, thus forcing the routing solutions and de-optimizing thus the design.

The detail of the staking, much simpler in this case, is shown here below:

Table 7. Stacking design for the avionics bay harnessing.

IFI1	Stacking	IFI2
	SHIELD	
1 connector with shielding	10 (1 FFCs AWG20)	1 connector with shielding
	SHIELD	
1 connector without shielding	20 (1 FFCs AWG22)	1 connector without shielding
	GROUND	

The overall mass assessment assume that the routing is optimized only 10% in length.

The design process is summarized as follows:

- Estimate total mass of existing RWC.
- Calculate final FFC total and lineic mass.

The supports calculation is not performed in this case, as the baseline for installation of the FFC is not still clearly defined. We assume that the delta between both solutions would not be a key driver for this application.

As a final result of the design process the evaluated features where the following

- The reuse of connectors at Equipment level seems a showstopper for this application.
- The estimated potential gain is ~25 % in mass only on the cabling.

Design phase conclusion

An iterative design methodology has been put in place and applied to three different launcher harness mockups. Reduced scaled models have been developed in order to validate progressively the adopted solutions.

The potential of the use of FFC cabling is clearly demonstrated when looking at estimated mass and volume impacts.

- Mass savings >30 % on internal harnessing.
- Mass savings >75 % on external raceways.
- Volume savings that can be over 80% and of course, when embedding into composite pannels, the impact is even higher.

The manufacturing of the two most promising implementations is launched.

PART 3: MOCKUP MANUFACTURING AND TEST

This part consisted mainly on the manufacturing of the two most promising analysed use cases: the Internal Intertank harness and the External Raceway harness.

Mockup manufacturing

The complete manufacturing and integration of the Flat Conductor Cable can be decomposed in the following sequences:

- Manufacturing of the flat individual cables or cable pairs
- Manufacturing of connectors
- Mating of connectors with the flat cables
- Assembly of the flat cables to create the harness
- Integration of the harness on pre-installed supports.

The manufacturing of the flat flexible cable is performed by Axon in a roll to roll process. The basic brick is the single layer composed of 8 copper conductors in a pitch of 5.08mm. It is possible to assemble 2 or more FFCs such to create a shielded FFC pair as shown here below:

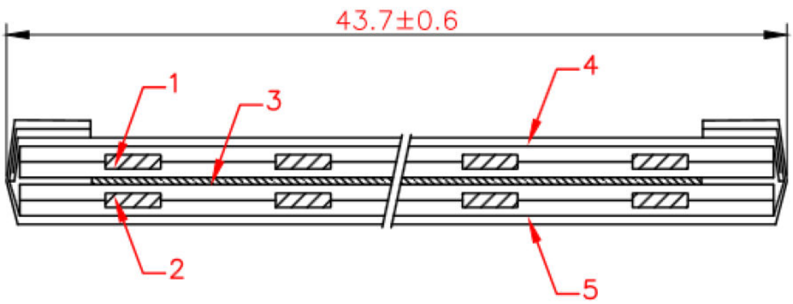

Fig. 13. Definition of a shielded AWG22 FFC pair.

The tape assuring the shielding is folded around the edges to provide 360° cover and better handling.

The connector base used is the well know and flight proven Versatys® of Axon. The adaptation of the Versatys base to mate two FFC cables has been performed by Axon in the frame of the project. It can be equipped with 16 xAWG12 contacts that allow their use in power application or 16xAWG16 for signal applications. The connector backshell has been also designed to be used with a shielded "stack" of 2 FFCs (as shown in the following picture). The connection is consequently fully shielded thanks to the connector backshell. The angled shape of the backshell in this image is for a specific integration requirement, but straight backshells are equally possible. Axon's DClick fast-locking system is also used for rapid and tool-less integration.

Fig. 14. Mating of the FCC with the connectors.

As the final length of the different flat cables corresponding to the harness has to be precisely determined, a 3D representation of the mockup interfaces is prepared. Every individual flat cable is then prepositioned and cut to its final length as well as correctly positioned in the order of stacking.

The final harness is checked in a specific tooling as shown in the figure below, where the representation of the harness is printed on a plan and the position of the connectors precisely determined with the help of mounting plates (made of Teflon, in white on the picture) fitted with guides for insert :

Fig. 15. Final Harness checking.

Fig. 16. Harness integration test (above) and final result on a 9 m long internal inter-tank mockup (below).

The integration effort is minimized as the positioning and fixation of the flat harness is guided by the curvature of the harness that orients the positioning on the connectors. There is indeed a ‘sense’ for integration while that is not the case for round wire cabling where the indentation of connectors can be a problem.

In order to manufacture the external raceway, additional steps were necessary:

- Cutting of individual composite constituents (prepreg, honeycomb, Norcoat®, glue film).
- Assembly of constituents on the curing mold, including the flat conductor cable.
- Environment preparation and curing.
- De-molding and control.

The cutting of the different components is assured by traditional cutting machinery:

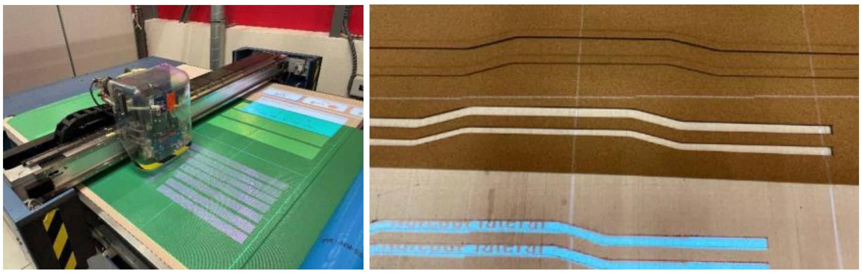

Fig. 17. Cutting of the different components: composite prepreg (left), Norcoat ® and glue film (right).

The assembly of all the component on the curing mold is performed step by step.

The first GFRP skin is laid up over a layer of T89 tissue positioned over the Teflon and the air is chased with a roll. The target thickness is ~1 mm.

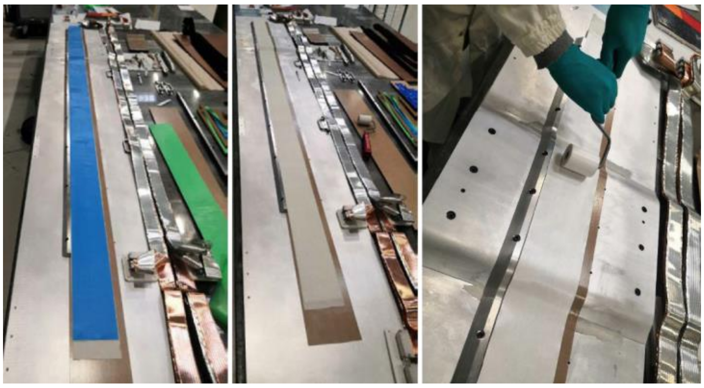

Fig. 18. Lay up of the first composite layers (in groups of 7) and application of the roll.

Fig. 19. Lay up of the a glue film (left), and the Flexible Conductor Cable underneath.

The target of this glue film is to assure the adhesion between the underlying composite, the shielding of the harness, and the Nomex® honeycomb.

Next steps are the layup of the remaining honeycomb and composite skin the positioning of the Norcoat ® thermal protection, and the placement of the curing environment:

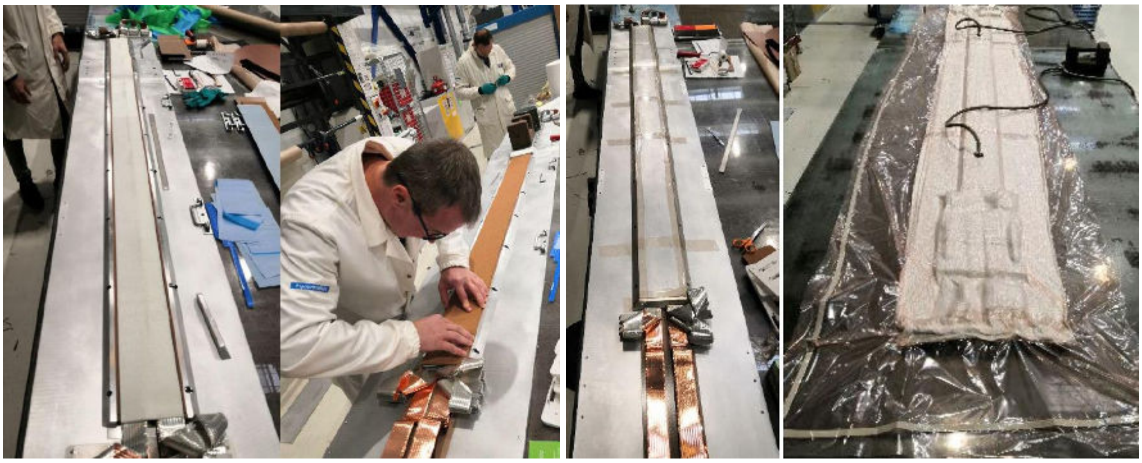

Fig. 20. Upper composite skin (left). Layup of the top thermal protection cover layer (left-middle). Mold closure (right-middle) and curing environment (right).

After de-molding, the complete harness is ready as a single electro-mechanical part, called an Electro-Structural Composite.

Fig. 21.The final mock-up as a single electro-mechanical part (Electro-Structural Composite).

Electrical Testing

A certain number of electrical continuity, isolation and impedance testing have been performed on the Internal Inter-tank harness with the following summarized results.

- Electrical Resistance between connector pin and flat flexible cable.

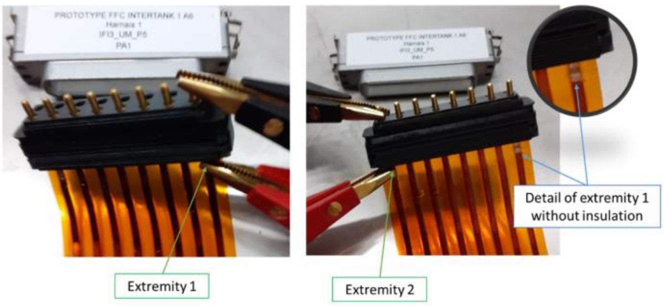

Fig. 22. Example of electrical resistance testing between contact and FFC.

The contact resistance between the connector pin and the conductor seems in the range of ~1 mOhm which is a typical value.

- Electrical Resistance between connector backshell and shielding.

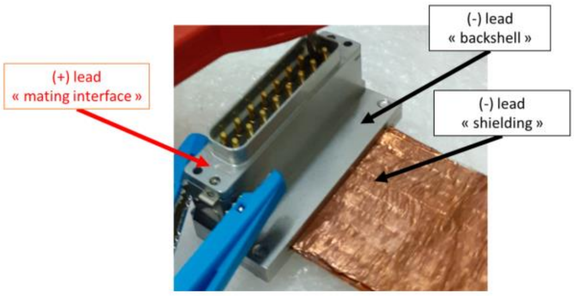

Fig. 23. Example of electrical resistance testing between contact and connector backshell.

There are some bonding values out of the specification. The variability may point out dispersion on the mounting procedure/solution of bonding contact between the shielding and the backshell.

- Insulation resistance test @1 kV between conductor and ground reference and between adjacent conductors.

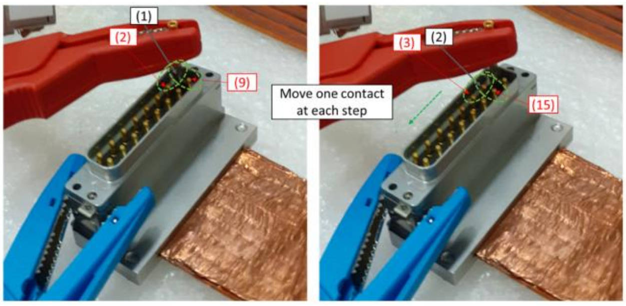

Fig. 24. Example of insulation resistance test.

The test is compliant, and all lines present an insulation resistance in common (pin to shield) and differential (pin to pin) mode well beyond the >1 MΩ target.

- Insulation voltage withstanding between internal conductor and shielding and between adjacent conductors.

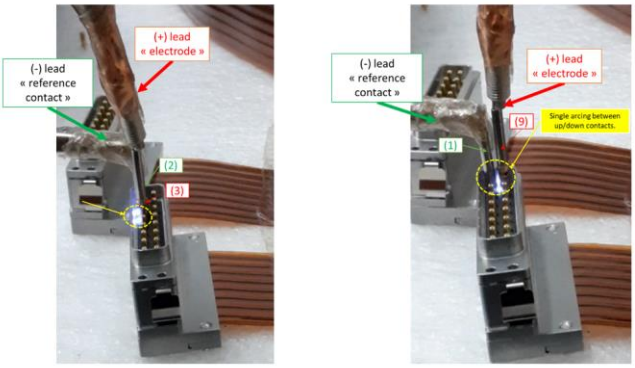

Fig. 25. Example of insulation voltage test.

The test is globally compliant and shown an overall breakout voltage in common mode .~3 kV and in differential mode ~5 kV. Nevertheless there is one non compliancy (loss of isolation) and one case in which the discharge is partially created inside the connector, pointing out also a loss of insulation inside the connector.

- Electrical per unit length resistance of the shielding.

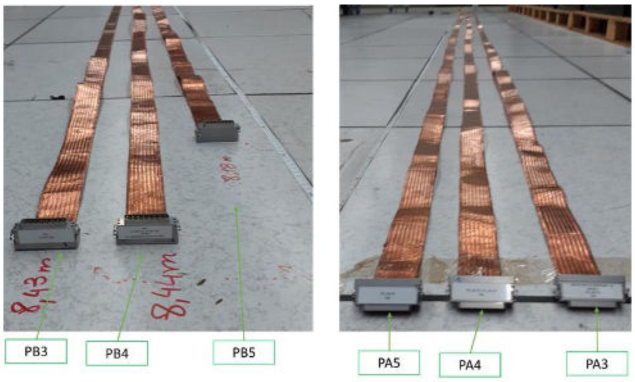

Fig. 26. Setup for per unit length resistance of the shielding.

The resistance per unit length of the shield is in the range 5-6 mOhm/m. This value might be used during design phases, as EMC coupling analysis as presented in [9].

- Open or Short circuit impedance, capacitance or inductance between: Two adjacent pairs, not shielded bundle, two superposed pairs, no shielding, two adjacent pairs, shielded bundle, two superposed pairs, shielding.

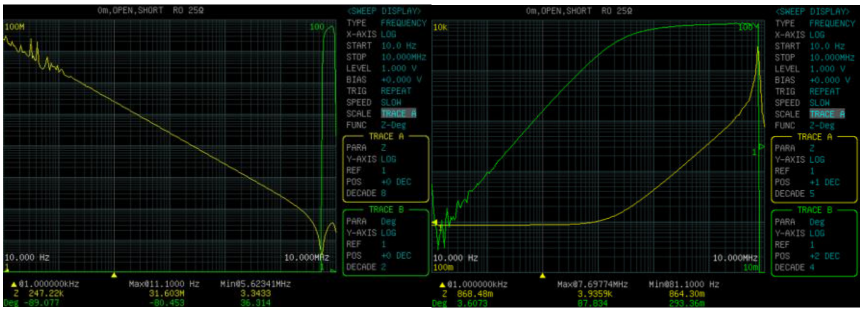

Fig. 27. Example of Open (left) and Short (right) impedance on two adjacent pairs, not shielded.

The inductance/ capacitance of the different possible transmission schemes has been characterized and may be used for simulation purposes.

CONCLUSIONS AND PERSPECTIVES

The project developed under ESA Contract No. 4000130437/20/NL/FE has proven the potential of Flat Flexible Cable technologies to be used in different Space/Launcher applications.

This project has brought several key enabling technologies that were not existing so forth at a European level:

- A standardized flat cable definition 42 mm wide, polyimide isolated, with 8 copper plain conductors with gauges extending from AWG18 to 22.
- A dedicated connector, rectangular, 16 contacts gauge AWG16, capable of interconnecting one or two superposed flat cables and with a backshell fixture allowing to assure the electrical continuity of the connector with the shielding (based on Axon Versatys ®).
- The possibility of shielding one or two superposed flat cables with a continuous copper sheet placed on both sides.
- A proof of concept on a realistic internal inter-tank Launcher cabling, allowing to demonstrate the possibilities of the harnessing based on flat cabling (rooting including bending).
- A proof of concept on a realistic external Launcher raceway, including composite multi-functional integration of mechanical and thermal protection.

The main improvements brought by the use of the flat cabling technology are depicted herein:

- Design: The design of flat cabling structures, considering allocation of signals is simple and straightforward. It is easy to understand where a specific electrical signal has been mapped in terms of position in the harness. The stacking also allows to include late connection needs. No specific design issue has been encountered during the design activities of both mockups. Furthermore, from our perspective, the flat cabling design process can help reduce time delivery of harness as the allocation of signals to the harnessing is more straightforward A design possibility to speed up the development time can be to pre-allocate a certain number of flat cables to the main communication paths, and then affect progressively the necessary signals to the different connectors/contacts. In case of late design needs, it is easy to add a flat cable to the stacking as is does not modify the need of new supporting brackets. This way of working might need to adapt the engineering approach at Launcher system level with an impact on the current way of specifying through internal design rules which should be adapted to this technology. There is a priori no limitation of the technology in terms of on time delivery.
- Manufacturing: The manufacturing of the harness can be almost fully automated which allows to guarantee quality and cut costs. The manufacturing of the composite over-molding is based on well know processes and allows to incorporate extra functions to the harness (i.e. mechanical and thermal protection).
- Integration: The integration effort is mainly reduced by the fact that the harnessing footprint is minimized at launcher level, requiring a reduced set of brackets.
- Test and troubleshooting: As already stated on the previous point 'Design', the fact of knowing the exact position of allocated signals, shall allow to ease system tests where the identification of specific signals is always cumbersome and time-consuming. The same reasoning is applied for troubleshooting and system level: the concerned link can quickly be determined and the study of the anomaly root cause eased.
- Volume allocation: The volume allocated to harnessing is drastically reduced. The rough estimates of the project point out to >70% savings. This level could be increased on specific applications where the harness may be completely over molded on sandwich panels (i.e., in upper parts charge adaptors, satellite dispenser or directly on payload satellites).
- Mass allocation: The overall mass estimated of the project point out potential mass reductions in the frame of 30-70 %. This is mainly due to the rationalization of mechanical supports/protections devoted to integration.

The perspectives that we observe for the technology proposed are the following:

- For the harnessing technology:
  - Enhance the electrical continuity between the backshell and the shielding, maybe providing a gasket of the exit zone of the backshell or another blocking mechanism allowing to assure a contact pressure between the shielding and the backshell.
  - Characterize the final transfer impedance of the shielding on dedicated samples (~20 cm-to 1 m long).
  - Assess, with a vaster sampling, the isolation provided by the clipping mechanism that interconnects the contacts to the flat cable.
  - Increase the quality of the external shielding, particularly on the junctions zones between the upper and the lower sides.
  - Provide an external protective sheet, easy to deploy, to protect the cabling on specific zones where thermal or mechanical friction could arm the cabling.
- For the composite process:
  - Demonstrate the capabilities of complete integration on sandwich structural panels used on spacecraft construction.
  - Develop and validate the associated mechanical and electrical justification scheme.

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