Space Harness Design Optimization
Opportunities on ECSS derating rules

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ABSTRACT

The constraints imposed on electrical harness for Space applications are increasing with the growing complexity and power needs of scientific and commercial spacecrafts.

It becomes mandatory to optimize satellites harness and take the full potential of the state-of-the-art harness technologies and components, while guarantying that the design remains safe in a large diversity of environments and operating conditions.

After a quick review of the key issues on harness design, it is shown on the basis of Astrium experience that there is an opportunity to revise ECSS derating rules on cables & connectors in order to cover a widened range of environment conditions and open the door to improvements of the performance and the safety of Space harness.

INTRODUCTION

Onboard spacecrafts, the electrical harness is certainly among the most complex electrical equipments only made of Passive Components. It is also a key element driving the performance of the electrical system, as well as a significant contributor to the mass budget. The best utilisation of passive components in the harness is therefore crucial.

For most of the Space programs, the sizing of the EEE components is ruled by the *ECSS Space product assurance - Derating - EEE components* [1]. As written in the introduction of this document, the aim is to *"specify derating requirements applicable to electronic, electrical and electromechanical components (...) to obtain reliable and high performance equipment without over sizing of the components."*

The problem is that the harness design may cover a huge range of loads and environment conditions according to the mission and the various on-ground and in-flight configurations. The derating rules specified in [1] for the wires and cables are the result of several iterations involving ECSS participants and does not pretend to cover accurately all possible cases, but rather to propose simple rules covering worst case loads in the most common temperature environments.

Based on the experience gained in the past few years on numerous complex and high power satellites and taking benefit of the progress made on the thermal analysis simulations, this paper will explore some opportunities to tailor the ECSS derating rules of harness passive components in order to cover more accurately the different loads and environment conditions. This should allow widening the range of applicability of the ECSS derating rules and reducing the size of the electrical harness, while keeping a full control on the safety margins. The thermal simulations performed in Astrium on some flight harnesses suggest that a mass saving from 5 to more than 20% could be expected, depending on the spacecraft.

FACING COMPLEXITY

If we could compare a satellite to the human body, the electrical harness would represent the blood vessels conveying the power and the nervous network transmitting the commands and sensor information to each organ and muscle. It's therefore not surprising that the harness appears to be very complex, as illustrated in Fig. 1 (Courtesy Astrium). In a large satellite, the harness may require more than 50 000 connections located on about 1000 connectors linked by 20km of wires, and the mass may exceed 100kg.

Fig. 1: 3D View of the harness bundles in a large Satcom

A CROSSROAD OF REQUIREMENTS

As most of the other on-board systems, the harness is submitted to a long list of requirements related to Electrical performance, mass, EMC and ESD protection, thermal and radiation environments, mechanical mounting and a few more requirements that are specific to each mission.

The harness accommodation is also heavily constrained by the structure of the satellite and the location of the different units that are themselves driven by the mission's requirements.

On top of that, the satellite's dimension tends to go in two opposite directions that both become critical for harness design and performance:

- Large, powerful satellites (e.g. Alphasat, Direct TV15) require long wires with large sections, impacting the mass.
- Small satellites (for small launchers) do not provide a lot of space for harness accommodation and inter-panels connections (i.e. harness on hinges, interface connectors). This is also valid for scientific equipments, as shown in Fig. 2 (Courtesy Astrium)

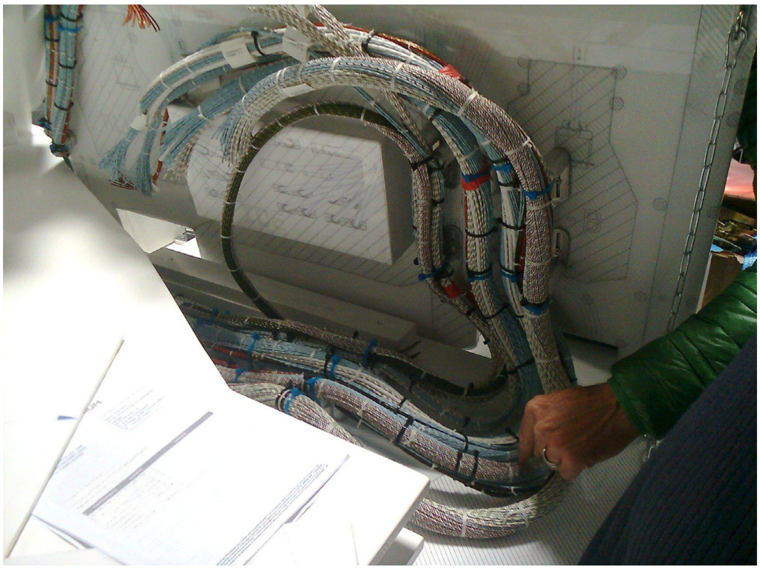


Fig. 2: Detail of the hinge harness mockup on EarthCare Atmospheric Lidar Instrument.

The evolution of scientific and commercial space missions results in a constant increase of the power and complexity of the satellites. Both of them directly impact the harness design and performance: the power usually drives the wire size while the complexity is related to the number of wires and connectors.

Beside the technical requirements, industrial and quality aspects have also got to be taken into account: the harness must be "On Quality, On Time, On Cost":

- Despite -or due to- its complexity, the harness must comply with a strict zero default requirement and must be 100% safe.
- The harness schedule is always on the critical path of the project. This is because the harness is the last design to be frozen (all of the electrical interfaces and the spacecraft accommodation shall be frozen before) and one of the first equipment to be installed on the satellite (no electrical testing is possible on the spacecraft without the harness).
- Last but not least, the costs shall be minimized for the harness engineering and manufacturing.

To comply with this abundance of requirements and deliver the best performance, the harness design needs to be highly optimized.

HOW TO OPTIMIZE THE HARNESS

The first way to optimize the harness is obviously to minimize the requirements: in the past years a very significant saving has been achieved by a critical review and simplification of the harness specifications focusing on the justification of each requirement. Work is still to be done in this field but it will not be addressed here as it's out of the scope of the present paper.

Another way to save mass is to minimize the length of the wires and cables. This is already considered as "normal work" during the accommodation of the satellite and the routing of the harness. There is usually no major opportunity to find some major savings in that field except if the harness constraints are taken into account very early in the program, during Phases A&B.

However new saving opportunities can be found taking into account the specificities of each type of harness. The harness mainly provides two functions: **transmit information** (e.g.: databus, telemetries, bi-level commands) and **convey power** (e.g.: primary & secondary power supply lines). Sometimes, the same wires can provide both, as for pulsed commands on pyrotechnics, relays or RF switches for example.

Except the data busses, the harness used for data transmission is usually made of numerous cables of small core sections, often shielded. This is well illustrated on Fig. 3. The best way to reduce this harness (in terms of mass and complexity) would be to decrease the number of wires. A good example is the on-going evolution from analogue to digital data transfers that shall more and more rely on data busses instead of point-to-point links. However, this approach requires significant efforts as it implies deep changes in the electrical architecture, the interface of electronics and it needs the qualification of new active components.

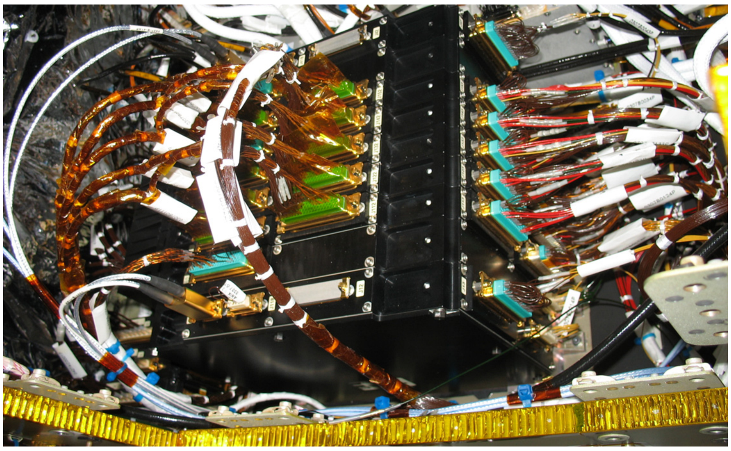


Fig. 3: TM & TC wires on a Satcom Payload Interface Unit

On the other hand, the power distribution harness represents fewer wires but uses larger sections. The reduction of this harness may be obtained by developing and qualifying new components, but this requires significant amounts of money and time. Another way is to optimize the utilization of existing components (wires, cables and connectors). This means using the right component for the right need and avoiding over design. It requires a good characterisation of the component's loads and environment but also clear rules and guidelines to perform the sizing. This approach could be based on engineering work, simulation tools and validation tests. It does not require any change on the existing passive components that are used for harness manufacturing.

Some thermal simulations of real harness bundles have been performed on telecom spacecrafts and have already allowed reducing over-design and harness mass by several kilograms, still keeping significant margin versus the harness acceptance limits. These simulations have been validated by some vacuum tests. No global trend analysis was conducted yet, but this experience strongly suggests that improving the derating rules is a "Quick Win" solution that could deliver a harness mass saving from 5% to more than 20% depending of the spacecraft.

WHAT TO IMPROVE IN THE ECSS DERATING REQUIREMENT

Current ECSS Requirements

The ECSS standard [1] specifies:

- The voltage derating
- The maximum surface temperature in all conditions
- The maximum current in specific conditions:
    - Ambient temperature of 40°C
    - Single wire
    - Bundles of N wires with full current and P wires without current.

The derating factor was then determined by analyses and tests [2] to make sure that the maximum temperature at the surface of the hottest wire (usually the one in the centre of the bundle) will not exceed the acceptable temperature (including some margin).

It has to be noticed that the derating factor is very severe, especially for conductors within bundles: as shown on Fig. 4, the derating factor drops dramatically when the number of conductors in the bundles rises: for 10 wires, the derating factor is already below 0.5. This means that in a bundle of 10 conductors, a wire must be sized at less than half of the current it could have carried if it would have been alone.

One of the key issues in this requirement is that the derating factors are based on worst case configurations. This means that all the wires in the bundles are supposed to carry at the same time a steady state current equal to their individual maximum derated current. An additional assumption is that there is no thermal exchange at the ends of the bundle.

The bundle derating factor is a key issue because it generates some cumulative over-sizing effect for high power wires: due to the limitations of the crimping configurations for connector pins and splices, the effect of the bundle derating factors is to duplicate wires that in turn will change the derating factor to even more severe values.

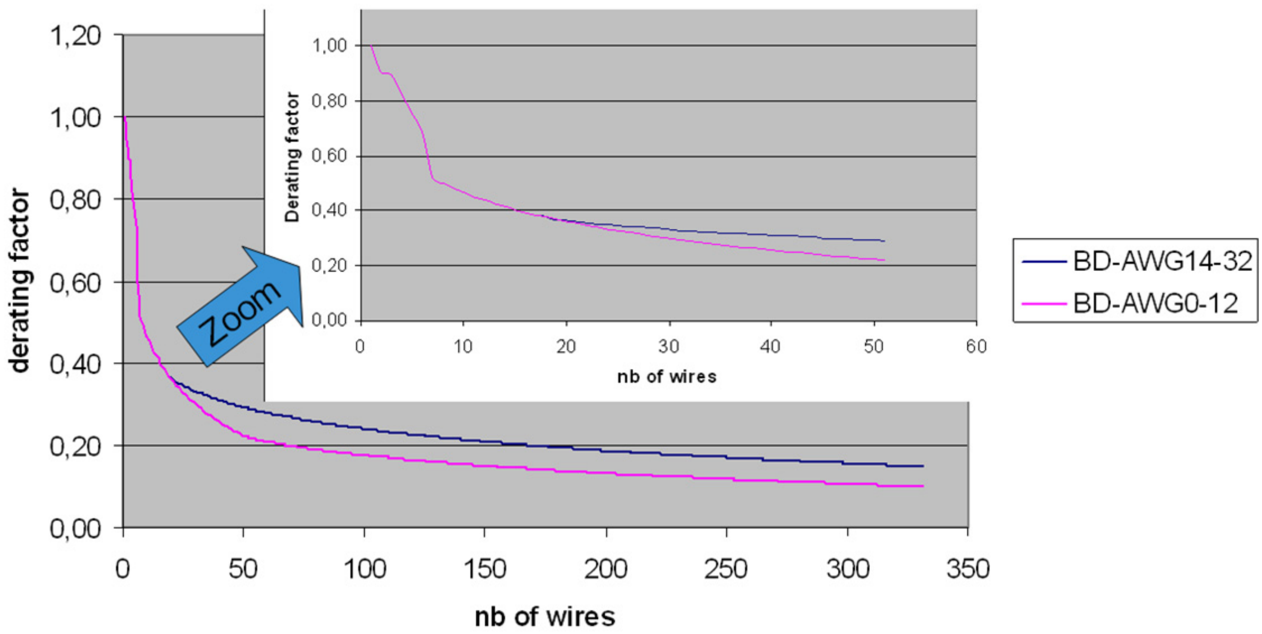


Fig. 4: Derating factor depending of the number of wires in the bundle

Room for Improvement

As highlighted before, the rating factor is mainly based on the acceptable **temperature of the wire**, which actually depends on:

- The environment conditions (temperature / solar flux / bundle protection / interface temperature)
- The load condition (current in each of the wire & ohmic resistance)
- The physical constitution of each bundle (shape, protection…)

Each of these elements can be considered as an opportunity for harness sizing optimization but they are not taken into account in all details in the ECSS wire & cable derating rules [1].

The real harness applications are most of the time far from the worst cases that have been used to establish the ECSS derating factors:

- The wires are usually not equally loaded in the bundle
- All of them may not carry current at the same time
- The bundles may have different shapes: e.g. flat bundles as shown on Fig. 5 and Fig. 6 (Courtesy Astrium).
- Small bundles may be bunched together
- If the bundle is short, thermal exchanges at the ends of the bundles could help to cool it down, as usually the temperature of the terminations on units and structure is lower than the maximum wire temperature.

On the other hand, there may be a few factors that are not explicitly taken into account in the ECSS wire & cable derating rules but may have negative effects on their temperature:

- The environment temperature may be different from 40°C.
- Some of the cables may be shielded
- Some of the bundles may be surrounded by over shields, protective braids, double insulation…
- Some harness may be exposed to solar flux

Fig. 5: High power Satcom harness split in five AWG12 flat bundles to reduce the derating factor.

Fig. 6: Flat bundle made of two layers of four AWG12 wires

AVALIABLE TOOLS

The problem of bundle thermal simulation has been investigated during the last few years and several solutions have been developed.

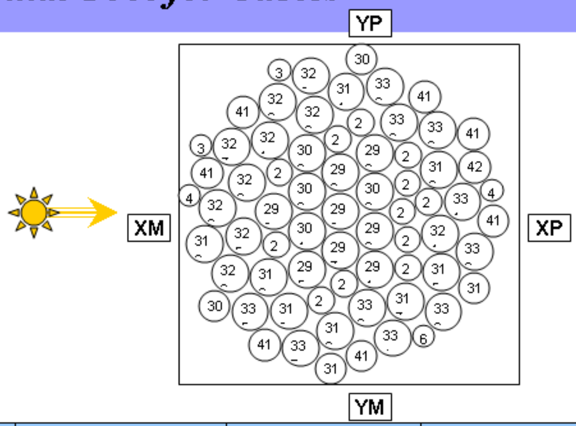
The National Aerospace Laboratory in Netherlands developed a software module for thermal analysis of wiring in aircrafts [3]. Astrium has also developed a significant experience and dedicated software tools for conducting thermal analyses on harness bundles. All of these tools allow modelling precisely the shape of the bundles, the real current in each wire and the environment conditions for a large range of bundle configurations. Examples of simulation results and bundle configurations are provided below in Fig. 7 and Fig. 8 (Courtesy Astrium).

Thermal Tool for Cables

Run process: OK

Environment Input Data

T_XP (K)	328,15
T_XM (K)	328,15
T_YP (K)	328,15
T_YM(K)	328,15
SOLAR FLUX (W)	0
SOLAR ANGLE (°)	180
EXTRA ISOLATION	OFF
RADIUS (m)	0,006365



Cables Output Data

Cable Number	T Conductor (K - °C)		T Dielectric (K - °C)		Solar Power (W)	Electrical Power (W)	I (A)
61	345,09241	71,942407	345,089254	71,939254	0	0,005057	0,2
208	356,0883	82,9383	356,053855	82,903855	0	0,072418	1,068
209	355,5096	82,359596	355,475214	82,325214	0	0,072286	1,068
210	355,27573	82,125732	355,241375	82,091375	0	0,072233	1,068
211	355,77324	82,623237	355,738826	82,588826	0	0,072346	1,068
212	354,02614	80,876136	353,991916	80,841916	0	0,071948	1,068
213	356,25959	83,10959	356,216082	83,066082	0	0,091475	1,2
214	355,60888	82,458879	355,574486	82,424486	0	0,072309	1,068
215	353,67664	80,526641	353,642458	80,492458	0	0,071868	1,068
216	353,65466	80,504664	353,620483	80,470483	0	0,071863	1,068
217	353,11061	79,960614	353,076492	79,926492	0	0,071739	1,068
218	352,44274	79,292742	352,408693	79,258693	0	0,071586	1,068
219	357,13625	83,986251	357,092623	83,942623	0	0,091727	1,2
292	359,17461	86,024611	359,096976	85,946976	0	0,233507	3
293	356,57459	83,424586	356,497581	83,347581	0	0,231613	3

Fig. 7: Thermal simulation of a real flight bundle (69 conductors)

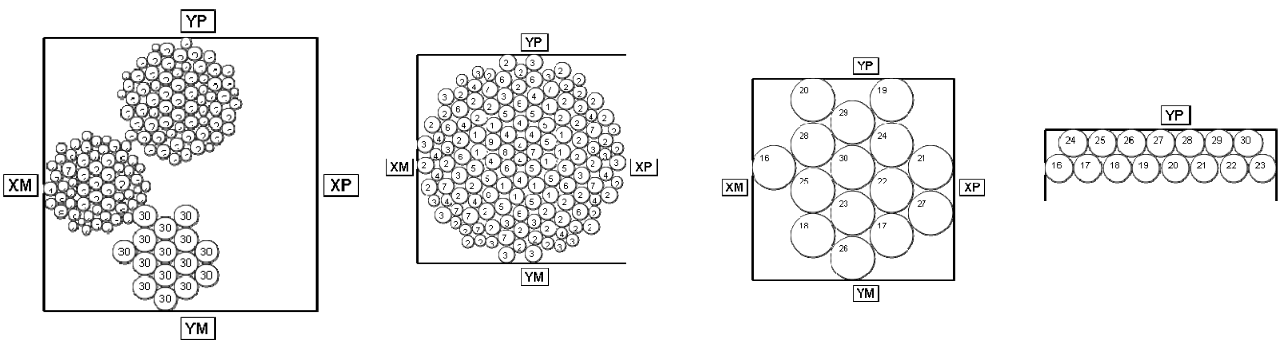


Fig. 8: Examples of bundle shapes for thermal simulation

NEXT STEPS TOWARD THE REVISION OF WIRE & CABLE DERATING RULES

As explained before, it's now clear that a revision of the derating rules specified in [1] would provide significant saving on the harness mass and would reduce the complexity of space harnesses.

However, upgrading the ECSS standard is a quite long process to go, with several steps as:

- Derating standards review & software tools assessment
- Identification of the main use cases, simulations & test validation campaign to define new rules for derating in bundles.
- It should be appropriate at that step to crosscheck the new derating rules for wires with the ones related to the connectors to assess the consistency between the currents allowed in the wires and in the pins of connectors.
- Last step would be a proposition of an update of ECSS wire & cables derating rules.

The first step has been initiated through RFQ/3-13902/13/NL/PA proposed by ESA and the following objectives are listed in the statement for work [4]:

"

- *Consolidate the status of the applicability of the ECSS harness derating rules. This should be done through comparison to rules applied in aerospace and industrial applications (ECSS, NASA, MIL, JAXA, aircraft, automotive…),*
- *Provide an assessment of available modelling or software tools,*
- *Define experiments that should provide data for relaxation of the derating rules and software validation.*

"

This study should start in September 2013 and be completed within five months. The study outcome shall be used to trigger the next phase of analyses, simulations and validation tests with the final target of upgrade the wire & cable derating rules in the ECSS standard [1].

SUMMARY

The mass and the complexity of the spacecraft's harness are increasing with the power and capacity of the space systems. The requirements and constraints on the harness design are as well very high, therefore solutions shall be found to reduce and optimize the harness.

Improving the sizing of the harness is seen as a "quick win" solution, as it does not require any hardware change nor qualification of new passive components.

The ECSS derating rules for wires and cables [1] are based on a conservative approach and do not closely cover all operating conditions. Avoiding over design by improving these rules is seen as a real opportunity to generate very significant savings on the harness mass and would help to reduce its complexity.

Thermal simulation tools are already available to assess the temperatures of wires in different types of bundles under various loads and environment conditions. They could be used to support the upgrade of the derating rules for wires & cables.

ESA initiated a study starting in September 2013 granted to the National Aerospace Laboratory of The Netherlands and Astrium to review the existing standards and assess the existing tools. The results should allow starting a new study in order to establish by analysis, simulation and validation tests a proposal for an update of the ECSS derating rules for wires & cables.

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