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ACTIVE OPTICAL CABLE FOR INTRASATELLITE COMMUNICATIONS

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***Abstract*— DAS Photonics and Airbus Defence and Space (Spain) have been working for more than six years in the concept of an Active Optical Cable (AOC) for copper cable substitution. The main advantages that AOC offers are significant mass and size saving, better flexibility and routing of the cable and immunity to EMI.**

***Index Terms*—Active Optical Cable, low mass, SpaceWire, high speed, fiber optic**

I. INTRODUCTION

Communication harness constitutes a major part in mass and volume of current satellite and onboard equipment. The main problems of the typical copper or coaxial cables used are the high mass and some problems derived of the technology, like low immunity to EMI or difficult to be routed. In order to assure the harness to be free of EMI or noise, it is needed to increase the diameter of the cables, increasing in consequence the volume/mass.

The limitations of the copper cables, as base for satellite harnessing, are used as main arguments to switch the actual technology from copper to optical fibre to be used for payload and potentially platform applications.

The first and most obvious benefit of harness reduction is a saving in the mass of the spacecraft. This could reduce launch cost significantly, may make the spacecraft easier to balance prior to launch, and reduces the fuel required to manoeuvre the spacecraft after launch. Moreover, harness mass savings could allow additional payloads to be flown, increasing the spacecraft capability.

Another benefit of optical cables is a decrease in the cable diameter, making it easier to route through the spacecraft. In addition, it does not cause or is affected by EMI and avoids ground loops. In contract to these interesting benefits, AOC need to be powered supply.

DAS Photonics and Airbus Defence and Space have been working together developing an opto-electronic conversion module to use fibre optic without impacting the current IF elements in on-board equipment[1][2][3].

The first demonstration of the technology was performed in a Spanish Space Program and the next steps done consisted in two in-orbit validations to verify the suitability of the technology under real space conditions.

Finally, in the frame of a GSTP activity, the development of an Active Optical Cable with reference to the specific application requirements of intra-satellite communications was performed. Three different AOC models were developed, SpaceWire, MIL-STD-1553 and CAN Bus.

Mainly, an AOC consist in two transceivers that manage the electro-optical conversion of equipment data, being connected using fibre optic.

In this paper are presented the main tasks performed on the design and technology verification, as well as related results to date.

II. FIRST DEVELOPMENTS

The first works were focused on the validation of the optical technology intended to be used in the opto-electronic conversion modules for digital communications. The initial developments consisted in a set of optical transceivers to fit low and medium signal speed:

- **Low Speed:** this solution, with a maximum data rate of 10Mbps, covers all control buses such as MIL-STD-1553 and CAN. Also is suitable to substitute other low speed links such as TM/TC signals or even low speed clocks.
- **Medium Speed:** this solution, with a maximum data rate of 500Mbps, covers all SpW data links (with low skew/jitter) usually used from 100 to 400 Mbps. Also is suitable to substitute other medium speed such a clocks or commands.

Due to the lack of qualified optical components, and in order to minimize the size and mass, commercial components were used in the design of the optical transceivers.

The developed models were submitted to several environmental and mechanical tests in order to validate the suitability of the technology for space use.

Fig. 1. First Active Optical Cable developed by DAS

III. TECHNOLOGY IN-ORBIT VALIDATIONS

The successful and promising results obtained in the first developments brought DAS two opportunities to validate in orbit a test bed of the AOCs.

A. TDP8 for Alphasat In-Orbit Validation

First flight opportunity raised under the frame of the TDP8 project, framed in the Alphasat mission, where DAS delivered a flight optical board with four optical transceivers for digital communications. The experiment allowed the demonstration of the performance of 4 optical links working @1Mbps and 4 optical links working @100Mbps.

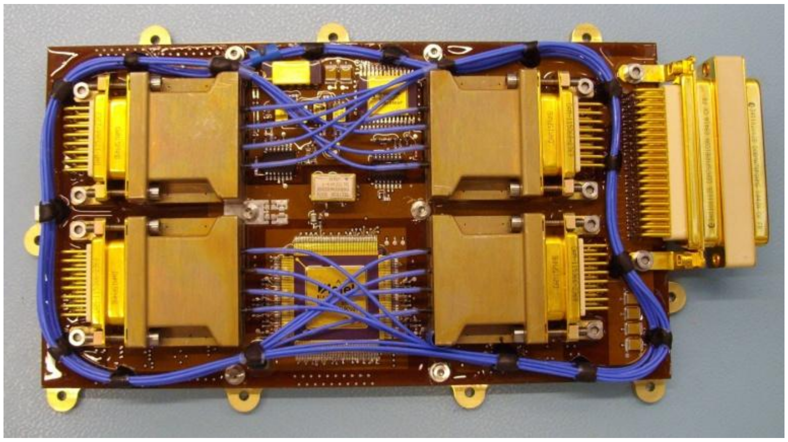


Fig. 2. Optical experiment boarded on TDP8 for Alphasat

As part of the in-orbit validation activities, the non space qualified components were submitted to a complete space assessment campaign with good results.

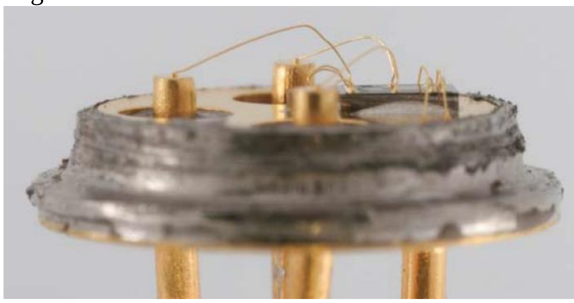


Fig. 3. Constructional analysis of photonic component

Although the satellite suffered some delays, finally was launched in 2013. At this moment DAS is receiving telemetry from the experiment with some error burst detected. Since each channel has a different optical power margin DAS is investigating the cause for these errors and if they are produced by events in the FPGA or because disturbances in the transceivers.

Table 1. Optical experiment on TDP8 @SAT, detected errors

TT	SIOS_BER1	SIOS_BER2	SIOS_BER3	SIOS_BER4	SIOS_BER5	SIOS_BER6	SIOS_BER7	SIOS_BER8
10-12-2013 23:39:57	0	0	0	0	0	31	1023	1023
18-12-2013 22:10:21	0	0	127	1023	1023	1023	1023	1023
20-12-2013 22:20:45	0	0	0	1	1023	1023	1023	1023
18-01-2014 16:26:21	0	0	0	0	0	0	0	1
15-03-2014 02:58:21	0	0	0	0	0	0	0	3
24-03-2014 10:40:13	0	0	0	0	0	3	1023	1023
09-04-2014 20:42:29	0	0	0	0	0	0	0	511
12-04-2014 18:43:01	0	0	63	1023	1023	1023	1023	1023
12-04-2014 18:53:01	0	0	0	0	63	1023	1023	1023
19-04-2014 11:35:17	0	0	0	0	0	0	0	1023
18-05-2014 11:39:57	0	0	0	0	0	31	1023	1023

The table shows the events when errors were detected and the number of them. SIOS_BER1:4 are 1Mbps channels and SIOS_BER5:8 are 100Mbps channels. Each channel has different optical power margin from 3.87dB up to 7.38dB. Since each number of detected errors is always a burst of '1' (ex: 127='1111111') followed by another set of '1' for all remaining channels the most probably cause for this is a SEE in the FPGA that causes a set of bit upsets storage word before to be sent to the platform. Therefore no error bit occurred in the optical links.

B. HERMOD for Proba-V In-Orbit Validation

The second flight opportunity, HERMOD, was in Proba-V satellite, where DAS and T&G Elektro developed a test bed to validate MTP connectors and multi-fibre cables. Thanks to the good results during TDP8 activity, T&G trusted DAS to design and manufacture an experiment that allowed both companies to demonstrate the feasibility of the technology for future space applications.

This flight opportunity consisted in single equipment with 4 optical channels SpW compatible working at 100Mbps and interconnected through four MTP connectors. Each optical channel was configured with different power margin between transmitter and receiver in order to check the complete losses (including MTP connector) in the channel.

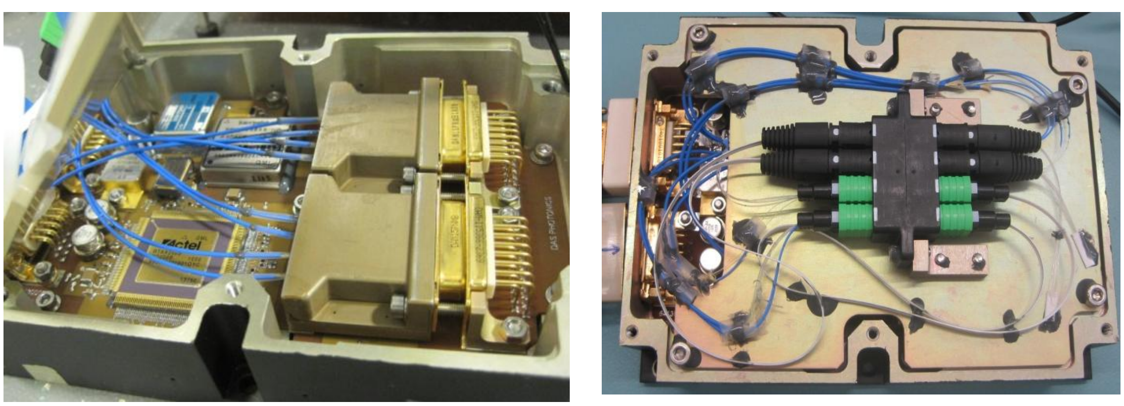


Fig. 4. Optical experiment boarded on Proba V

This experiment was executed within a very stringent schedule of 6 months. The Proba-V satellite was launched in April 2013. Collected data from the experiment telemetry allows to have more than one year of results producing representative BER information of the optical channels.

TABLE 2. 1 YEAR PROBA-V EXPERIMENT BER

Optical channel @100Mbps	BER values
1	<3.06E-16 (no errors)
2 (max. power margin)	<2.82E-12
3	<3.06E-16 (no errors)
4 (min. power margin)	<3.06E-16 (no errors)

No errors have been detected in any channel except for the channel_2, but since the error distribution is centered in each equipment switch on, it seems that the error is produced due to a bad start of the equipment. The start procedure was changed on flight, and no errors were detected beyond this change.

IV. GSTP ACTIVITY FOR ACTIVE OPTICAL CABLES DEVELOPMENT

With the information collected from previous activities DAS and Airbus DS started the GSTP focused on the development of AOC for buses and point-to-point protocols. Target buses were MIL-STD-1553 and CAN, being SpW the selected target protocol for point-to-point applications.

The AOCs developments assure key points in satellite harness and satellite performance itself, such as:

- Reduced mass, volume and transmission losses compared to copper harness
- Compliant with current BUS and point-to-point data rates. This will allow substituting the copper harness without impacting performances of equipment (the terminal connectors of the equipment).
- Compatible with current equipment interfaces. One important point is not to modify the current on-board equipment.
- Immunity to EMI. Both ways of EMI have been considered, radiated to the equipment and induced from them.
- No ground loops. Since each AOC's transceiver uses its own ground reference and the light transmitted does not need the same ground reference, two transceivers connected by optical fibre do not need to share ground signal, avoiding ground loops.
- Minimize AOC power consumption

A. AOC Design Development

The design of AOCs has been relied on the information and knowledge acquired in previous activities by DAS and Airbus DS. The selection of components followed a conservative approach using EEE qualified, if possible. Components that are not qualified were submitted to a verification test campaign to assess their behaviour under space environment.

MIL-STD-1553, CAN and SpW are protocols well known and used in intra-satellite communications [4]. The key points of the AOC design were to improve such points where optic fibre has strong advantages against copper, minimizing the impact on the equipment in terms of power consumption and signal integrity.

Necessary optical and electronics components to implement the electro-optical conversion are integrated inside the connector backshell. So, another key point was the reduced electrical connector used in SpW and CAN Bus. The uD-9 has very low profile and this fact constrained the mechanical design of the AOC in order to have the same size than the uD9 connector plus the backshell. AOC can be assembled almost in every kind of connector.

The AOC transceiver will perform the electro-optical and the opto-electronic conversion in order to be able to transmit optical signal through a fiber optical cable.

The figure below shows the block diagram for the SpaceWire DATA link, the STROBE link is identical. The internal architecture of bus transceivers is similar just adapting the drivers to be compliant with target protocol.

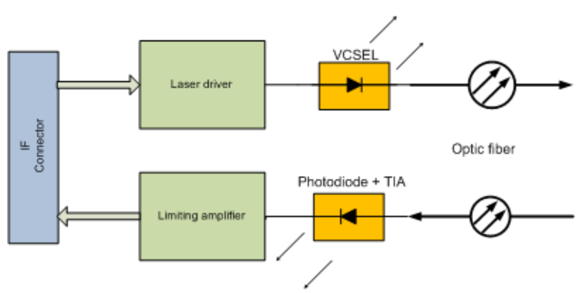


Fig. 5. AOC transceiver block diagram

Current AOCs design considers that modules are externally power supply at 3.3V, but power supply could also be provided through a connector spare pin since current load of each transceiver is quite low, less than 100mA.

B. Component assessment

Since photonic and some EEE parts used in the optical transceivers are non space qualified because of the lack of available parts for these technologies [5][6], a components assessment was needed to be performed. The obtained results along with the previous information from other activities, the viability of the use of the parts will be determined for future missions.

Previous data results from other activities were used to complement the GSTP components assessment:

- Outgassing and residual gas test
- Catastrophical Optical Damage
- Thermal Vaccuum Cycling
- Heavy Ions
- Life test
- Thermal Conductance analysis

The life test of 1000 hours @85ºC was performed on 20 samples of each component type used in the AOC. No major degradation was observed during the life test and all components survived to the test.

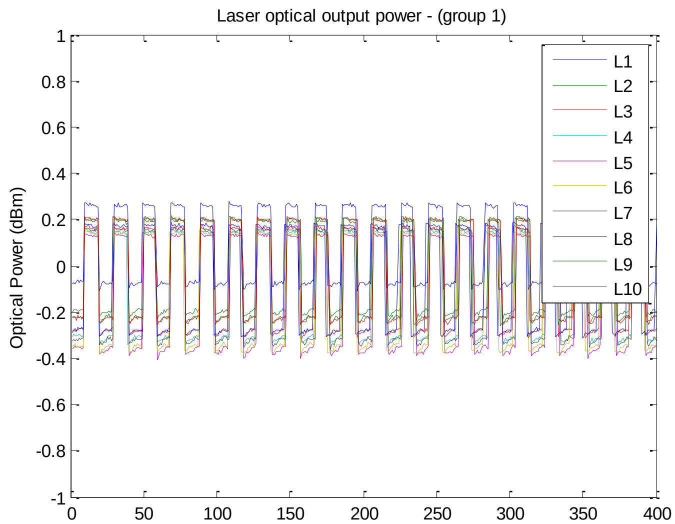


Fig. 6. Life test, output optical power of first set of 10 lasers

Also, a verification programme of the soldering process for the assembly of micro-D connector to the board inside the transceiver of the AOC was performed. Since in order to optimize the size of the optical transceiver an approach not supported by ECSS[7][8]was needed to be used. This verification programme produced successful results and the process was validated for this application.

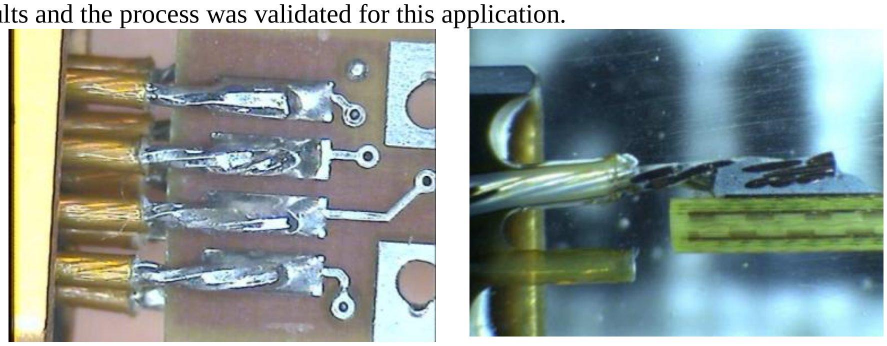


Fig. 7. uD9 soldering assement

C. AOC bus issues

Both buses, CAN and MIL-STD-1553, presented similar technological barrier from an architecture point of view. Copper buses are easy to implement since each terminal connected to the bus can transmit the information bidirectional to all terminal but optic fiber has directionality and the protocol architecture from bus to ring but with lower mass cost than the copper architectures. The total mass of the bus will be decreased from a classical bus with copper wire. This change in the topology does not affect the communication among interfaces; each one will maintain perfectly the communication with BC and all RTs.

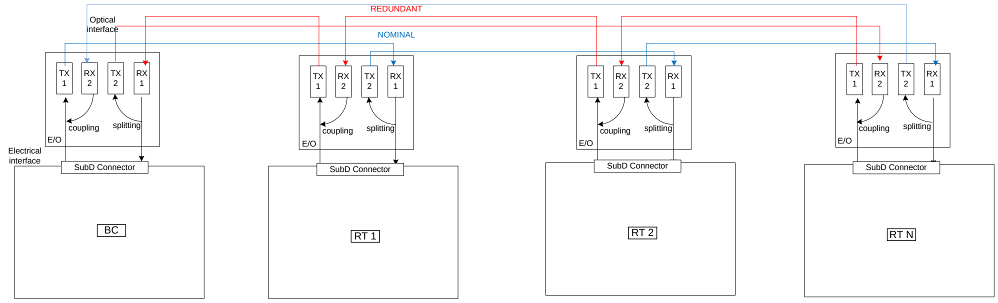
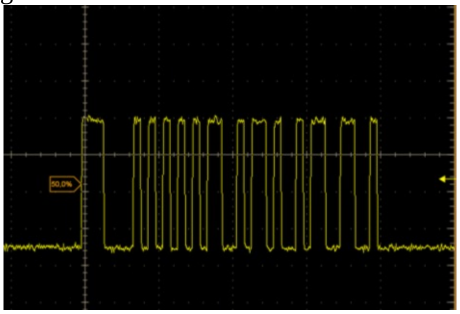


Fig. 8. Bus AOC transceiver block diagram

During the test phase, some issues were detected in both buses. Mainly, these issues were produced during IDLE time of the bus, since the low frequency of the line affected the photodiode and TIA response, causing glitches and loss of information.



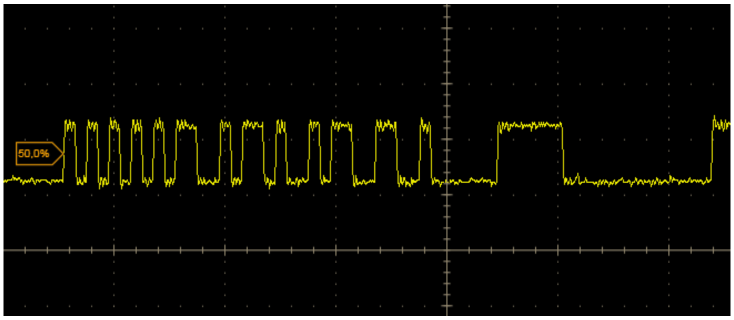


Fig. 9. Bus AOC issues, sent data and received with loss of information

The investigations showed that to remove these issues the transceiver shall be redesigned increasing the complexity since a special treatment of IDLE and low frequencies shall be implemented in order to be compliant with the optronic devices.
Whereas system integrators have not shown a commercial interest for 1553 optical solution, optical CAN Bus is very attractive for them. Therefore, further investigations are being performed to overcome IDLE and management issues in optical CAN buses.

D. SpaceWire AOC test campaign

Due to the issues found in optical buses, only SpW AOCs were manufactured and submitted to the test campaign. This test campaign was performed using representative values and profiles on all test in order to cover as much as typical application cases as possible for future flight missions.

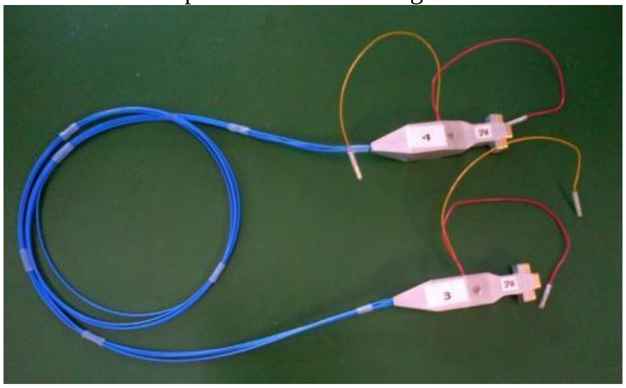


Fig. 10. SpW AOC

Test campaign at AOC level included the following tests [9][10]:

- Functional tests
- Mechanical tests (vibration and shock)
- TVC: 8 cycles -40/85ºC
- TID: 150Krad @ 360rads/min
- Single Events (protons): 60,100,200MeV with a flux up to 1E11 p/cm2

None of the tests comprised in the test campaign produced destructive or detectable degradation on the performances of the AOC.

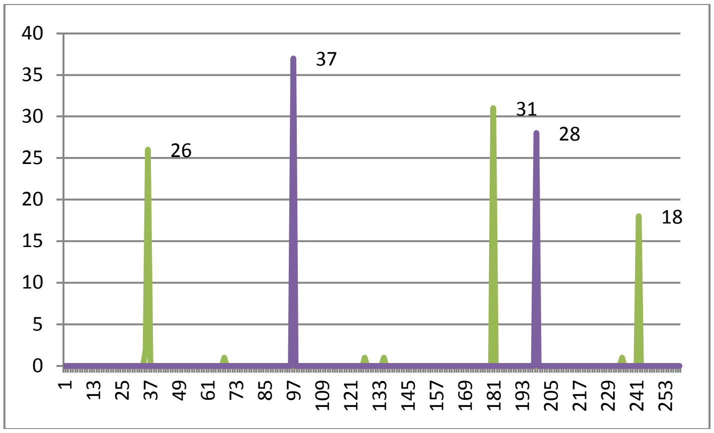


Fig. 11. Errors distribution at 200MeV, flux 1E8 p/cm2/s, fluence 1E11 p/cm2

For protons irradiation some errors were detected due to single events. This experimental data allowed inferring future behavior in flight mission extracting the expected BER figure. For a GEO mission (15 years) the expected BER will be from 3.6E-18 to 1.7E-16 and for a LEO mission (8 years) the expected BER will be from 5E-18 to 1E-15. Both values are much lower than the requirement for a SpW communication, 1E-12.

Radiation tests such as gamma and proton were performed upon the transceivers with and without the mechanical package in order to measure the different behavior of the AOC. No important effects were measured in both tests.

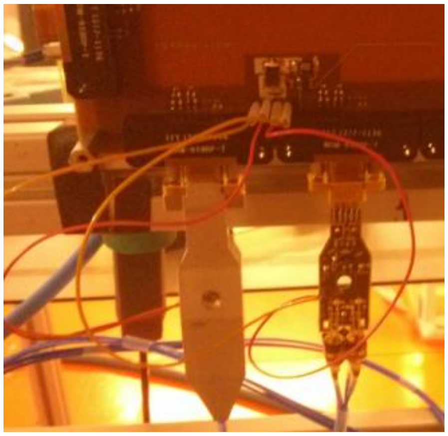


Fig. 12. TID test, transceivers with and without mechanical package

V. SPACEWIRE ACTIVE OPTICAL CABLE PERFORMANCES

As results of the GSTP activity was generated the first commercial version of an AOC for SpW copper cable replacement. Following table presents the current specifications of a copper cable and the measured values for the AOC for an example case of a 1 meter long cable.

Table 3. Copper SpW cable Vs AOC

Especification	Copper cable	AOC
Mass	87 grams	<30 grams
Data rate	<400Mbps	<400Mbps by design Tested up to 380Mbps
Jitter/Skew	2000ps	190ps
Power consumption	NA	<700mW @ 200Mbps
Bending radius	>45mm	>25mm
Temperature range	-200 to +180ºC	-40 to +85ºC

The scalability of the AOC allows to improve the mass saving with longer cable lengths since the mass cost of a copper cable is around 80-100g/m but for an AOC is 4-10 g/m.

A real study of mass saving was performed comparing expected mass figures of harness and connectors.

Table 4. Mass figures of SpW cable and AOC

		Connector mass (g)	Cable mass (g/m)
Copper cable	Min	9,5	83
	Max	23,5	100
AOC cable	Min	12	1,2 (x 4)
	Max	15	2,4 (x 4)

Using this table values the mass of a cable of 1m in copper will be around [102, 147]g whereas for optical fiber cable the mass is between [29, 39.6]g

This means a **mass saving of more than a 70% per cable.**

For longer cables the mass saving will be higher. For **10 m the mass saving could reach the 90%.**

VI. CONCLUSSIONS AND RECOMMENDATIONS

Based on the positive GSTP results, in can be concluded that AOC is becoming a real potential replacement for copper SpW cable in future applications for those scenarios where a mass reduction of current Spw harness is needed.

The major drawback of the AOC is the power consumption as well as the need of external powering since there are no spare pins available at uD9 interface connector. Next ECSS issue will allow the use of different connectors that changing minimally the mechanical package and the electrical design make possible to use a connector pin as power input to the transceiver.

At this moment DAS continues performing tests with debug equipment in order to complete all expected possibilities in future missions when connecting on-boarded equipments. After these tests DAS expects to have a flight opportunity to check the SpW AOC in real environment (not only the technology as in previous flight opportunities) in order to raise TRL level of the solution.

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