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S. Hernandez

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HERMOD: OPTICAL PAYLOAD TECHNOLOGY DEMONSTRATOR FLYING ON PROBA-V – OVERVIEW OF THE PAYLOAD DEVELOPMENT, TESTING AND RESULTS AFTER 1 YEAR IN ORBIT EXPLOITATION.

S. Hernandez[1], J. Blasco[2], V. Henriksen[3], H. Samuelsson[3], O.Navasquillo[2], M. Grimsgaard[3], K. Mellab[1]

[1]*ESA – ESTEC, Keplerlaan 1, 2200 AG Noordwijk, The Netherland – contact: stephan.hernandez@esa.int*
[2]*DAS Photonics, Cdad Politecnica de la Innovacion, 46022 Valencia, Spain*
[3]*T&G, Kirkeveien 25B, 1363 Høvik, Norway*

ABSTRACT

Proba-V is the third mission of ESA's Programme for In-orbit Technology Demonstration (IOD), based on a small, high performance satellite platform and a compact payload. Besides, the main satellite instrument aiming at Vegetation imaging, Proba-V embarks five technological payloads providing early flight opportunities for novel instruments and space technologies. Successfully launched by the ESA VEGA launcher in May 2013, it has now completed its commissioning and the full calibration of platform, main instrument and additional payloads and is, since last October, fully operational.

The High dEnsity space foRM cOnnector Demonstration or HERMOD is the last payload selected to fly on Proba-V. The payload objective is to validate through an actual launch and in orbit high-density optical fibre cable assembly, cumulate space heritage for fibre optics transmission and evaluate possible degradation induced by the space environment compared to on-ground tests. The future applications of this technology are for intra-satellite optical communications in view of mass reduction, the electrical grounding simplification and to increase the transmission rate. The project has been supported under an ESA GSTP contract. T&G Elektro (Norway) developed and tested the different optical cable assembly to be validated in the payload. The electro-optic modules, control, power and mechanical interfaces have been developed by DAS Photonics (Spain).

The payload contains four optical channels to be studied through the experiment, two assemblies with MTP/PC connectors and two assemblies with MPO/APC connectors. Optical data is transmitted in the four independent channels using two optoelectronic conversion modules (SIOS) working at 100Mbps including 2 full duplex channels each. A FPGA is used to generate, receive and compare the different binary patterns. The number of errors (if any) and Bit Error Rate (BER) is sent to the satellite TM interface. HERMOD successfully went through all mechanical and environmental tests before the integration in a very limited time. The telemetry data is currently sent to ground on daily basis. All the channels have survived the launch and no BER has been measured with the exception of channel 2, currently recording a BER of 3.06*10-16, that exhibits from time to time a burst of errors due to synchronizing issues of the initial data frame. It is expected to observe during the operating life of the payload the first errors within the channel 4 which was designed on purpose with reduced power margin

This paper will present the full overview of the HERMOD technology demonstrator including the development, testing, validation activity, integration, commissioning and 1 year in-orbit exploitation results.

I. INTRODUCTION

Fibre optics are widely used in the terrestrial market (Data networks and link, industrial systems, instrumentation and sensors). The fibre technology offers different type of application interesting for space usage such as optical communication, sensing, optical amplification, gyroscope, pyrotechnic. The advantages of using such links for optical communication are multiple and of interest for space applications. Optical harnesses are generally compacts, flexible, light weight and can offer almost unlimited bandwidth, galvanic isolation, immunity to EMI and no EM noise production. The introduction of this technology in spacecraft is quite recent and not adopted by the space community as a standard solution. Indeed, space community has limited heritage in usage of fibre optic technology and the availability of photonics space standards and qualified optoelectronic parts are for the moment very limited. The copper technology is mainly used as a primary solution for internal spacecraft communication as a reliable and well understood technology.

SMOS (Soil, Moisture, Ocean Salinity) [1] successfully launched on November 2009, is the first European space mission to extensively use on-board fibre-optic communications [2]. The principal objective of the SMOS mission is to provide global maps of soil moisture and ocean salinity with high accuracy. For that purpose the SMOS payload which is still operating normally, also called "Microwave Imaging Radiometer by Aperture Synthesis" (MIRAS), employs 69 microwave receivers to captures images of the radiation of the surface of the Earth and 168 fibre-optics to interconnect the different sub-systems. For this specific application, the fibre-optic cables offered significant advantages compared to the electrical ones:

- Practically zero electro-magnetic emission of the cabling, which is of utmost importance because of the highly sensitive microwave receivers.

- Flexibility of the cabling (as well as its low mass), offering less resistance at the hinges, and therefore facilitating the deployment of the instrument's arms.
- Galvanic isolation between the units, as well as insensitivity to ground differential voltages.

Following SMOS successful outcome, some activities under GSTP have been initiated in 2010 by TEC-Q department in order to consolidate this flight heritage by focusing on the reliability through evaluation of cable assembly optical processes and development of ESCC and ECSS standard.

In the frame of Proba-V In Orbit Demonstration (IOD), the Proba-V manager called for an unique opportunity to embark a last Technology demonstrator (5^{th}) on-board of Proba-V. A Technology Demonstrator has been proposed to complement an already ongoing GSTP activity on the evaluation of optical cable assembly capability by European manufacturers. This demonstrator aims to validate multi-point optical assembly for which end-users have expressed an high interest. High density optical links with 12 fibers would already allow to reduce considerably the number of cables and connectors and save space for some specific interconnection configuration such as in SMOS project. The demonstrator should add some flight heritage to this type of assembly by confirming all the on-ground evaluation activity. The demonstrator will allow as well to validate the full digital optical transmission chain through the high density assembly by using optical transceivers.

This paper will start by giving the background and objectives of Proba-V mission and HERMOD, the 5^{th} technology demonstrator payload. Then, the full overview of the HERMOD technology demonstrator will be presented including development, testing, validation activity, integration, commissioning and 1 year in-orbit exploitation results.

II. MISSION BACKGROUND AND OBJECTIVES

1. Proba-V

The Proba-V mission [3] has been developed in the frame of the In-Orbit Demonstration activities of the European Space Agency, funded through the General Support Technology Program (GSTP). The main objective of Proba-V is to be an operational mission to continue the data acquisitions of the Vegetation Instruments on-board the CNES SPOT 4 and SPOT 5 satellites in activity since 1998.

In the second half of the last decade, in fact, the large community of over 10.000 institutional, scientific and commercial Vegetation data users distributed over the entire World expressed the need to continue, without interruption, the acquisition of Vegetation data after the de-commissioning of SPOT 4 and SPOT 5 foreseen for mid-2014. The main domains of applications interesting the Vegetation community are:

- Land use and coverage and its associated changes,
- Vegetation behavior in response to strong meteorological events (e.g. severe drought) and climatic changes (long term behavior of vegetation),
- Disaster management (detection of fires and surface water bodies),
- Biophysical parameters for the development of models devoted to water budget and primary productivity analysis (agriculture, ecosystem vulnerability, etc.).

Proba-V had then been identified as a "gap filler mission" between the decommissioning of the Vegetation instrument on SPOT 5 and the start of operations of Sentinel-3, providing the necessary risk reduction of data availability in case of gap between these two missions.

With decisive support from the Belgian Scientific Policy Office, Proba-V Phases B, C and D activities were initiated in early 2009, with an industrial consortium composed by Belgian, Canadian and Luxembourg companies, under ESA contract for the development of the full mission (Flight, Ground and Users' Segments).

Beside the principal mission's objective, Vegetation data acquisition, and following the footsteps of its predecessors, Proba-1 and Proba-2 [3,4]. Proba-V has also been, since its initial design phases, required to fly a number of innovative technologies on-board the platform, and to host promising pioneer payloads demonstrators. In total five technological payloads positions were reserved on-board Proba-V for these technology demonstration payloads. As a consequence, Proba-V has the unique objective to simultaneously be an operationally and technologically demonstrative mission.

Proba-V (Figure 1) was launched from Kourou, as main passenger of the second ESA Vega launcher's flight, on May 7th, 2013 at 02:05 UTC, and precisely injected into its operational orbit 55 minutes later, over Perth, Australia.

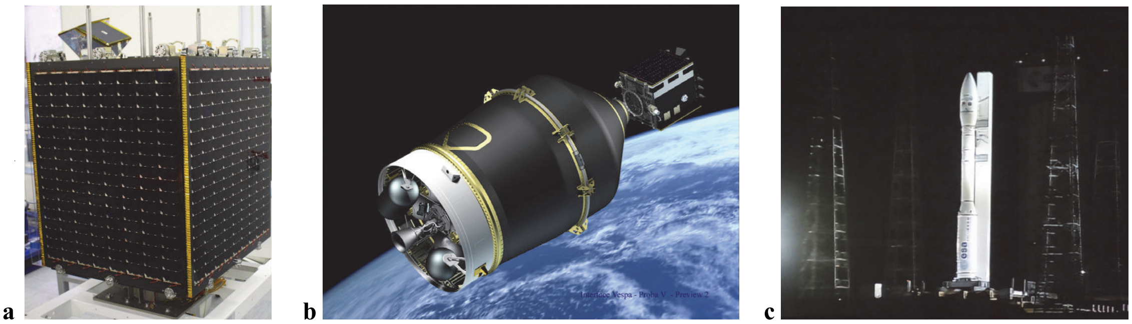

Figure 1: *a)Picture of Proba- V during last Integration Stage showing outer panels, b) Proba-V view after released from Upper Stage of Vega/VESPA, c)Picture of Vega before the launch.*

The overview of Proba-V mission including the 1 year commissioning results of the main Vegetation instrument and the 5 demonstrator payloads are available in a recently published [5].

2. 5th Payload Demonstrator

The interest of using optical communication for space has increased during the past years. The associated technology being already very well established on telecom for terrestrial application, the Photonics Working Group identified the need of having the technology compatible for space applications. Therefore, since 2010, ESA Product Assurance Department has initiated some activities dedicated to the validation and qualification of optical fiber assembly.

T&G is running one of this activity supported by the ESA GSTP and STRIN programmes. The tasks have been completed and the final presentation and deliverables are expected for end of 2014. The activity has been divided into two phases: the first phase aimed at confirming the need of the space end-users in term of optical assembly application and performing a survey of the components available in the market (connectors, cables, fibres). Based on the outcome of the first phase, a list of different possible assembly combinations was selected and proposed for testing during a second Phase. The second phase that has just been completed consisted in the assembly of the different selected technical solutions followed by on-ground validation testing. The endorsement of the proposed test plan for on-ground validation of optical assembly and associated deliverables will be used as input for future ESA standard related to optical assembly testing.

In the frame of Proba-V In Orbit Demonstration (IOD), the Proba-V team proposed an unique opportunity to embark a last Technology demonstrator (5th) on-board of Proba-V. A consortium between T&G (Norway) and DAS Photonics (Spain), supported by ESA under a CCN to the initial GSTP contract with T&G, has been established for this purpose. The multi-point optical assemblies for which European end-users expressed their highest interest have been selected to be validated into the demonstrator. This experience will allow as well to validate the full digital optical transmission chain through the high density assembly by using optical transceivers. This proposal was given significant interest by the Component Technology Group (CTB) and the relevant ECSS [6] and ESCC [7] systems. A final in space demonstration would allow to move quickly the confidence in the technology to a higher level with limited but still relevant flight heritage on Proba V. From a qualification system point of view a successful flight demonstration would definitively confirm the pertinence of the validation /qualification /certification standards under development and help in their recognition and application by the European Space Community.

A small and flexible team involving engineers from T&G, DAS Photonics and ESA worked together to fulfill this challenging project for which the very tight schedule of 6 months was very demanding. The 5th payload has been the last Technology Demonstrator opportunity to embark on-board Proba-V. This payload has been named HERMOD (High dEnsity space foRM cOnnector Demonstration) who is a Messenger in Norse Mythology.

III. HERMOD

1. Description and design

a) Experimental description

HERMOD consists in a transmitter/receiver plus a bit error counter implemented in a FPGA used to generate four different patterns continuously, one for each single channel, at a data rate of 100Mbps. The transmitted pattern is selected with the aim to assure a DC level of 0 at the output and to be representative of the protocol used (maximum number of consecutive identical bits). This binary stream is injected into the optoelectronic conversion module, which converts it into an optical data signal. Each transceiver has two full-duplex channels independent between them leading to 4 channels on which the optical signal is transmitted at 100Mbps. The receiver channel from the other optoelectronic conversion module receives the optical data signal and converts it back into electrical signal with the appropriate levels, and leads the electrical signal to the FPGA. The FPGA receives back the binary stream and compares it to the expected pattern. If a bit error is detected, the error counter will be updated consequently and stored. The FPGA will send to the satellite interface the number of errors (if any) to calculate the BER. A simplified schematic of the experience is depicted in Figure 2.

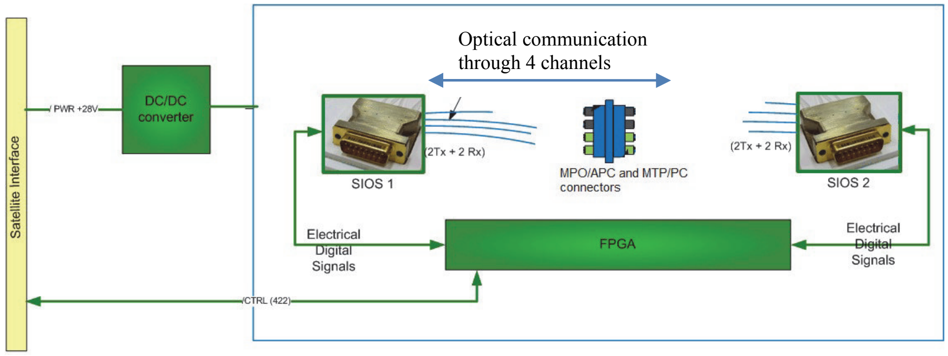

Figure 2 *Simplified building block of the experience.*

b) Electronic and mechanical design

The electronic design comprises the power interface with the satellite, the TM/TC data and the experimental area. The design has been completed to meet the different budget requirements from Proba-V and make the experience possible by using available space grade EEE parts and already assessed opto-parts. The main requirement on the electronic design was to make sure that all interfaces with the satellite are protected against single failures by avoiding any propagation to the platform.

From a mechanical point of view, HERMOD consists in an aluminum box divided in 2 layers by an aluminum plate (Figure 3). The upper stage is dedicated to the optical assembly and the fiber routing. The bottom layer accommodates the electronic components allowing dissipating the heat directly to the interface with the platform.

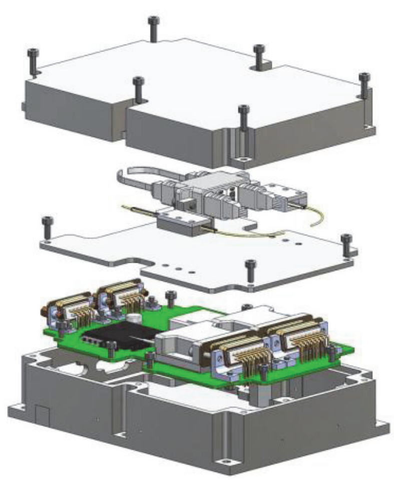

Figure 3 *Exploded view of HERMOD box including the optical (upper) and electronic (lower) layers.*

Additional information from the FMECA, thermo-mechanical and radiation analyses have been used to complement the electro mechanical design. Main requirements for HERMOD design with associated measured value on the manufactured Flight Model are given in Table 1.

HERMOD	Requirements	Measured value on the FM
Dimensions (mm)	160x115x51	160x115x51
Mass (g)	<1000	922
Power consumption (W)	<5	3.37 @ 85ºC

Table 1: *HERMOD requirements for dimension, mass and power consumption.*

c) Optical assembly design

MPO/MTP's are multi-fibers COTS connectors used in large scale in LAN and Telecom applications and have been selected to be validated through HERMOD experiment. Compared to single fibre connectors, multi fibre connectors as MPO/MTP's, can considerably improve weight/mounting wall area for connectors only. Additional savings will be introduced by validating ribbon/bundle fibre structure. A number of 12 fibres per connector is sufficient and less than 10 Gbit/s is maximum bandwidth requirement for typical communication purposes. Multi Mode (MM) 50/125 μm fibres were selected due to these requirements and also due to more tolerances in axial misalignment compared to Single Mode (SM). For potential need of higher fibre counts, Multi fibre connectors technology can today offer fibre count up to 72.

Due to the different behavior during vibration, different polishing types have been selected, standard physical contact (PC) polish and over-polished angled physical contact (APC) polish. Both types survived extensive environment testing, but probably margins are higher with APC polish as forces between ferrules are mainly picked up by ferrules and not fibres. In addition, stability during temperature stress and temperature cycling is slightly improved with APC polish.

The connector ferrule is made by composite. New processes such as pre-conditioning, epoxy outgassing, special fibre stripping methods, ultrasonic cleaning and special polishing process, have been introduced to improve the reliability and make the connector compatible with space requirements. Special high temperature Gore cable has been selected, however simpler cables might be as well suitable for space environment.

Each channel was configured with a different power margin in order to obtain additional information from the experiment.

The design of the optical assembly including the selected parts is depicted in Figure 4.

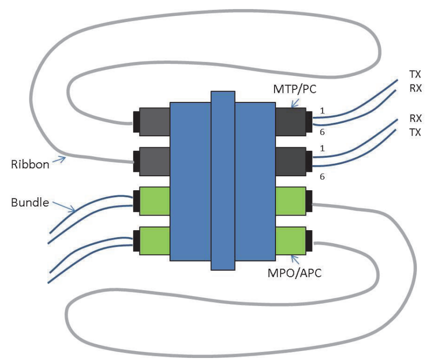

Figure 4 *Design of the HERMOD optical assembly including the 4 channels.*

2. Manufacturing

Two modules have been manufactured: the Engineering BreadBoard (EBB) and the Proto Flight Model (PFM). The EBB has been developed to validate the design through module functional testing and integration testing with the Proba-V platform. The PFM has been exposed to validation testing and integrated on-board of Proba-V for flight.

The lead time for the procurement of the critical components for the PFM was similar to the duration of the project (6 months). Therefore, the EBB architecture has been designed to be as close as possible from the PFM but using some parts with different quality level in order to reduce the procurement time. T&G was in charge of the manufacturing of the optical assembly and DAS Photonics for the electronic, SIOS modules and the EBB-PFM assembly.

The manufacturing has been done according to the materials, components and processes declared on the respective lists (DML, DPL and DCL) approved by ESA. Although all the electronic components have been procured with space qualified level, no space qualified optoelectronic parts was used (not yet existing). The opto-parts from the SIOS module have been selected based on a previous assessment study in preparation of the Alphasat project TDP8. The processes (optical cable assembly, fiber splicing, cable routing,..) and selection of parts for the optical cable assembly have been previously validated on ground by T&G under an activity with ESA.

The Print Circuit Board (PCB) manufacturing and mounting of the EEE components were performed by ESA certified companies: Printca and Matra Electronique (Figure 5). The final view of the manufactured PFM before closure can be seen in Figure 6.

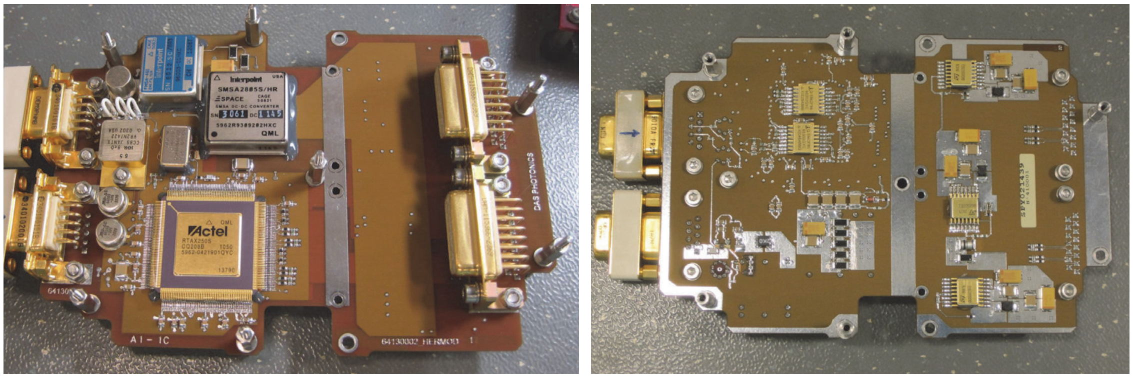

Figure 5: *Front and back view of the HERMOD PFM PCB just after the components being mounted.*

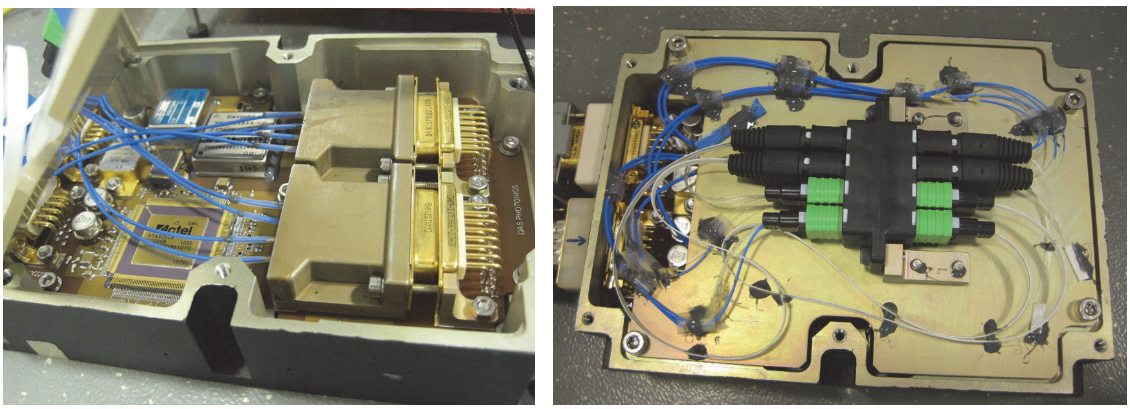

Figure 6: *Electronics and SIOS modules (left), optical assembly and fiber routing on the upper layer (right).*

3. On-ground testing and integration

HERMOD module went successfully through Validation testing according to Proba-V test requirements based on the position of the payload into the satellite. The validation testing has been performed on both models EBB and PFM as summarize in the Table 2. Due to the tight schedule, the PFM being manufactured 1 week before integration, the Shock and EMC testing have been run on the EBB while the PFM was under Thermal Vacuum Cycling (TVC) and vibration testing.

Model	**Visual inspection**	**Functional tests**	**Shock**	**Vibration (Sine and random)**	**TVC**	**EMC**	**Compatibility testing**
Optical assembly	MPO-01	MPO-02	MPO-03	MPO-04	MPO-05 (TC)		
EBB	EBB-01	EBB-02	EBB-03			EBB-04	EBB-05
PFM	PFM-01	PFM-02		PFM-03	PFM-04		PFM-05

Table 2: *Tests performed on the optical assembly, EBB and PFM. The reference number indicates that the test has been performed.*

The environmental tests at module levels have been performed according to Proba-V validation requirements in different location:

- Shock and vibration on the different axis (INTA, Spain): Sine vibration (range 50-100Hz @20g), Random vibration (26.27g RMS) and Shock (100Hz@20g, 1250Hz@1000g, 10000Hz@1000g).
- EMC (ESA-ESTEC, The Netherlands): Bonding, grounding and isolation measurements, Conducted emissions, Conducted susceptibility and Radiated emissions.
- TVC (ESA-ESTEC, The Netherlands): 6 cycles between (-40,+70)ºC with a survival temperature of (-50,+80)ºC, switched ON @ -50ºC.

The evaluation of the optical assembly technology (Shock/Vibration/TVC/temperature step stress) has been performed by T&G at their premises and in Kongsberg (Norway). During evaluation, the parts are extensively stressed in order to determine the failure mechanisms and margins for the technology (tested to destruction whenever possible). The complete evaluation including additional testing (torsion, retention, radiation, optical measurements during vibration) has been completed in the frame of the initial GSTP activity.

The test vehicles used for testing include a combination of 12 fibers connectors (MPO/MTP), polishing angles (PC-APC) and cables (Ribbon or bundle) which are represented in

Figure 7.

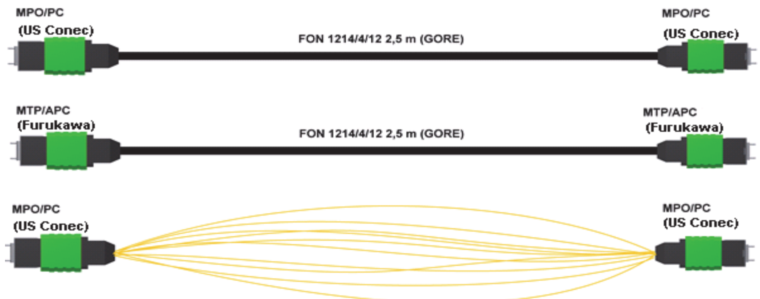

Figure 7: *Different test vehicles used for on-ground evaluation testing of the optical assembly*

The compatibility testing of HERMOD EBB and PFM with the platform took place in Qinetiq Space (Belgium). The flight payload has been successfully integrated into the spacecraft on the day of the deadline (Figure 8). HERMOD has been integrated on the top panel of the platform which offers a higher level of mechanical stress during the launch to validate the experiment.

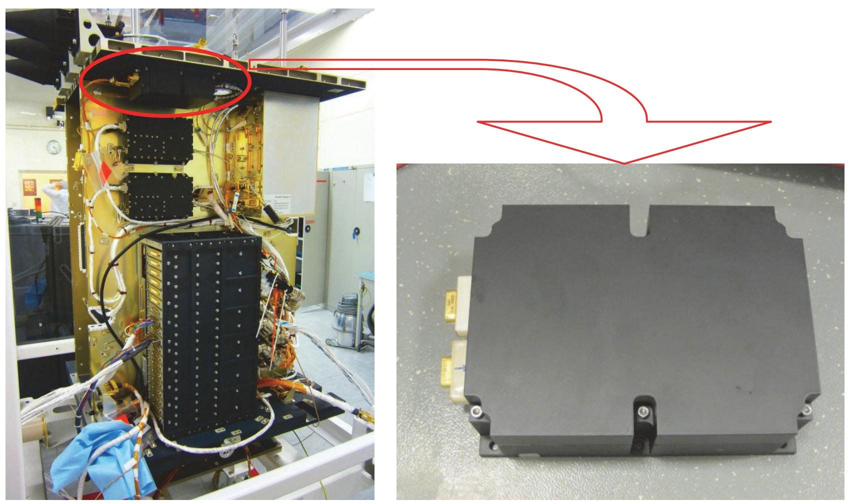

Figure 8: *HERMOD PFM payload before(right) and after (left) integration on Proba-V platform.*

4. In-flight results – Operation

Proba-V has been launched from Kourou on the 7th of May 2013 at 02:57 UTC with Vega launcher. The data related to the 5 technological payloads are downlinked, together with the satellite housekeeping telemetry, on the S-Band channel to ESA Redu Ground Station in Belgium. The data are de-commuted at the Mission Control Centre (MCC) located in Redu and placed automatically and securely on a dedicated web server, where the payload data together with the necessary platform ancillary information can be downloaded. The HERMOD related data are automatically downloaded on daily basis from the webserver. The data are then processed and analyzed by an automated software. Consequently, the updated information related to the operation of the payload and the cumulated number of errors on the 4 channels are available every days to the HERMOD team.

Seven days after the launch, the first HERMOD related results have been received and analysed. The team was pleased to see that HERMOD and the 4 optical links survived the launch and were working correctly.

After the 6 months conditioning, the cumulated operating time of HERMOD was 145 days which provided us accurate statistical data for the optical transmission analyses of the 4 channels. No error was detected on 3 channels and very few on channel 4. These errors were detected in 8 bursts of 1023 in the first data packet after a start command was sent to HERMOD. These events coincided to the moment the operation and sending the start command to HERMOD was changed by QS. These few occurrences of error are most probably produced by a bad start and synchronizing of the FPGA after HERMOD received a different start command from initial procedure.

On the 14th of August, After 1 year, 3 months and 7 days (464 days), the cumulative operational time of HERMOD was 378 days. 3270 Tbits have been transmitted in each channel and still no error has been measured, excluding the few errors due to the initialization in channel 2. After 5000 passes around the Earth, the number of errors and Bit Error Rates (BER) associated to the 4 channels are indicated in Table 3.

Optical channel @100Mbps	**1**	**2**	**3**	**4**
Number of errors	0	9207	0	0
BER	<3.06E-16	<2.82E-12	<3.06E-16	<3.06E-16

Table 3: *Number of errors and associated BER for the 4 channels, 463 days after the launch. The worst case is provided assuming that the next received bit is an error.*

The channels are perfectly functioning with very low BER. However, we hope to observe some errors in channel 4 that was design on purpose with low power margin. Apparition of first errors would allow to quantify the degradation of the optical link and its associated optoelectronic emitting and receiving parts, based on the initial on-ground functional testing performed with different attenuators.

CONCLUSION

Proba-V was successful launched on May 7th, 2013 from Kourou on-board Vega. HERMOD technology payload demonstrator aims to validate digital optical transmission chain through a high density assembly by using optical transceivers. HERMOD payload and its 4 optical communication links are working properly and continuously since the commissioning. Future apparition of first errors on the 'weak' channel would however allow to provide some information on the in-flight degradation of the channels and opto-parts.

This successful space demonstration allow to increase the confidence in using high density optical cable assemblies for space and confirm all the on-ground evaluation activity for this technology. From a qualification system point of view, it confirms the pertinence of the standards under development and help in their recognition and application by the European Space Community.

This successful experience is building some additional space heritage for the usage of on-board optical fibre communication which offers additional advantages to the well-established copper media. This technology already very well established on-ground and its recent multiple utilisation for space application make it a good candidate to be considered in future missions.

In order to increase the confidence in this technology, the ESA Product Assurance department has been initiating activities over the last years to increase the evaluation and qualification of opto-parts and optical cable assembly to be available to the European space community. A better control of the quality process of the different manufacturers involved in the manufacturing of optical cable assemblies and opto-modules is considered by ESA through a potential recognition (certificate) that could be implemented with a newly issued certification scheme (Process Capability Approval) under the ESCC system.

REFERENCES

[1] M. Drinkwater et al., *The Soil Moisture and Ocean Salinity Mission. Exploring the Water Cycle of the Blue Planet,* 2009*,* ESA Bull-Eur Space, 137.
[2] K. Kudielka et al., *Fibre optics in the SMOS mission*, ICSO 2010, Rhodes, Greece.
[3] D. Gerrits D et al., *PROBA2, Two Years of In-Orbit Experience*, The 4S Symposium 2012, Portoroz, Slovenija,
[4] S. Santandrea et al., *PROBA2: Over Four Years of Autonomy, Technology Demonstration, Solar Science and Space Weather Monitoring*, The 4S Symposium 2014, Majorca, Spain.
[5] K. Mellab et al., *PROBA-V: An Operational and Technology Demonstration Mission – Results after Commissioning and OneYear of In-orbit Exploitation*, The 4S Symposium 2014, Majorca, Spain.
[6] http://www.ecss.nl/
[7] https://escies.org

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