International Conference on Space Optics—ICSO 2018

Chania, Greece

9–12 October 2018

Edited by Zoran Sodnik, Nikos Karafolas, and Bruno Cugny

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International Conference on Space Optics — ICSO 2018, edited by Zoran Sodnik,
Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 11180, 111807F · © 2018 ESA
and CNES · CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2536186

A Ka-Band Single String Photonic Payload Flight Demonstrator for Broadband High Throughput Satellite Systems and an In Orbit Demonstrator of Optical RF distribution on board satellites

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ABSTRACT

This paper provides a summary of two on orbit demonstrators (IOD) for photonics payload technology hosted in two satellites respectively. A Ka-band Flight Demonstration Photonic Payload aimed for payload solutions for High Throughput Satellites (HTS) Systems was hosted in a GEO Communication satellite. An Optical RF Distribution flight demonstration was hosted in a second GEO satellite. This paper provides the design, parameter allocations and testing of these payloads. It describes the system and payload design solution overviews, identifies critical payload hardware, and summarizes key unit and payload performances for the Ka Band Flight demonstration payload and for the Optical distribution of RF signals. Both in-flight demonstrations are now flying as hosted payloads in two different GEO communications satellite recently launched.

Keywords: Photonic Payload, High Throughput Satellites, Ka band, Flight Demonstration, Frequency Conversion, Optical RF distribution.

1. INTRODUCTION

Global demand of broadband communication services is growing year by year with a forecasted double-digit growth in the coming decade so new satellite systems able to provide high capacity and flexibility are needed to satisfy every user on the network at the minimum in-orbit cost per Gbps. High Throughput Satellite (HTS) systems provide the optimally scalable solution to a wide range of bandwidth-intensive applications by combining regional and global beams for broadcast/multicast applications serving low-density traffic zones, and narrow spot beams for high-capacity broadband communications serving dense traffic zones. HTS systems are expected to supply more than a 1 Tbps of capacity by 2020, enabling service operators to compete with the cable-based infrastructure in price and service geostationary (GEO) satellites, and with fibre-like, low-latency connectivity with Medium Earth Orbit (MEO) spacecrafts.

State of the art HTS satellites offers capacities in the range of Gbps by using current RF and microwave technology. The multiplication factor required to achieve the Tbps capacity paradigm pushes the limits of the payloads and platforms cost, volume and complexity well beyond the nowadays affordable solutions with traditional technology. This is out-of-phase with the satcom market trend of dramatic cost reduction, light in weight spacecrafts and with enough flexibility to address the market changes faster than the traditional 15 years' vision.

Photonic technologies are key enablers to overcome the challenges required to provide the capacity and flexibility to dynamically manage future Terabit/s communication satellites payloads. The ability of Photonics to handle high data rates and bandwidth and very high frequencies is critical in this scenario, as well as its low power consumption, size and mass, especially when the optical fibre is included in the payload calculations instead of waveguides or coaxial cables.

DAS Photonics in collaboration with SSL (a Maxar Technologies company) and with the support of HISPASAT have developed a set of photonic technologies embarked in two Telecom Satellites as the first In-orbit demonstrations (IOD) of the photonic Local Oscillator distribution, fibre optic cabling of analogue signals and frequency conversion in Ka-band. These technologies are the core of the photonic payloads which could enable the order-of-magnitude improvement in mass, size and power consumption for the low power section of the next generation of telecom payloads.

2. PHOTONIC PAYLOAD CONCEPT FOR HTS

SSL and DAS Photonics are pursuing the introduction of payload equipment based on photonic technology within the commercial satellite market and are developing an architecture concept named V/Q-Band Photonic Converter Assembly (V/Q-PCA), which is **intended to fulfil the UHTS needs** with the following features:

- Use of photonic technology for the generation of multiple Photonic Local Oscillator and for its distribution via optical fibre
- Use of **photonic technology for the multiple, simultaneous signal mixing** (RF conversion to IF with a photonic Local Oscillator) **in a single device**, which enable to reduce the number of equipment
- Use of **photonic technology for the demultiplexing and routing of the different frequency conversions** (associated to multiple LOs). A schematic view of these characteristics is shown in the Figure 1.
- **Implementation of ultra-broadband electro-photonic interfaces covering from Ku to V band in a generic solution**, which enables to have a single photonic solution for any frequency band. This concept simplifies the architecture and reduces the need of "payload personalization" to the RF interfaces.
- Use optical fibre within a distributed architecture enables satellite designers to have a new degree of freedom and flexibility in the allocation of the hardware thanks to these characteristics of the optical fibre:
    - The propagation losses are independent of the lengths required in a satellite
    - Optical fibre is completely immune to RF interference, so it can be routed freely
    - The mass of the optical fibre is much smaller than coaxial cables and RF waveguides and is easy to route and bend.
    - Optical fibre can multiplex many channels/signals in a single fibre by using wavelength (de)multiplexing schemes (WDM) so the number of fibres can be reduced compared to RF cables (for example, all the LOs required in the architecture are multiplexed in a single fibre: the RF counterpart is to have a dedicated LO distribution network for every single LO).

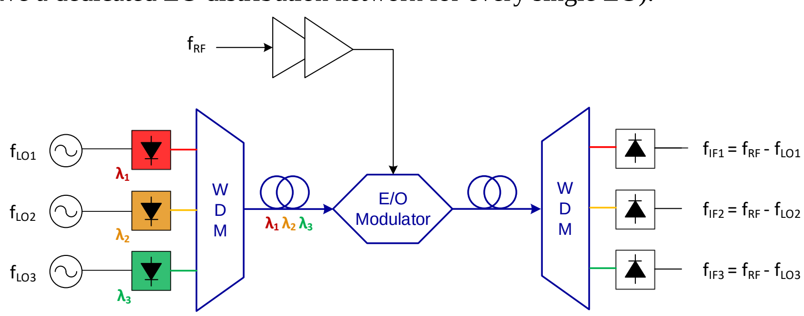


Figure 1. Concept of photonic frequency conversion with multiple LOs. Simplified scheme with 3 LOs modulated in three optical carriers, multiplexed (wavelength multiplexing), simultaneous mixing with the RF signal in an electro/optical mixer, demultiplexed and photodetected.

The product is a **Broadband Photonic Frequency Converter** from V/Q/Ka to Q/Ka band with photonic LO Module. The IODs achievements described in this paper are the first steps towards making this product a reality. The fundamental idea is to build generic photonic modules to demonstrate the key functionalities that are the core of the concept including LO generation and distribution, frequency conversion and fiber-optics remote delivery and distribution

3. PHOTONIC CLK AND LO DISTRIBUTION IOD

3.1 Optical Links for LO and CLK distribution

The technology demonstrator will accommodate two different lines of product for space applications. The two lines are:

- Analog optical links for reference signal distribution and transportation up to 2,5 GHz, but designed specifically for the demonstrator at 10MHz.
- Analog optical links for reference signal distribution and transportation up to 30 GHz, but designed specifically for the demonstrator at 10GHz.

The block diagram of the two analog links are shown in the following figure.

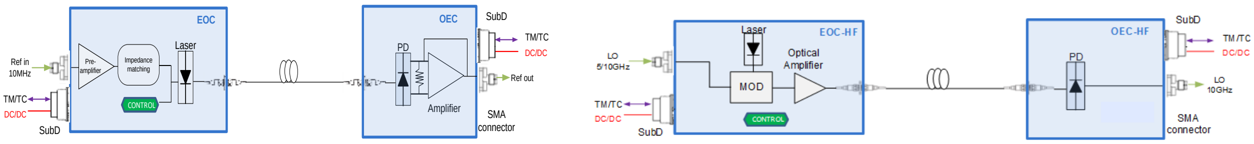


Figure 2: Block diagram of the optical link able to distribute signals up to 2.5GHz (*left*) and up to 30 GHz (*right*). (*EOC: Electro-optical converter. OEC: opto-electronic converter. HF: High Frequency*)

The concept of the optical link is based on an optical transmitter (EOC) that generates a modulated optical signal from an RF input signal. The optical signal is transported through fiber optic to an optical receiver (OEC) which converts the optical signal to electrical, recovering the signal. For links up to 2.5 GHz the RF signals can modulate directly the laser current which simplifies the optical circuit. For frequencies above 2.5 GHz an external optical modulator is use to modulate in amplitude a continuous wave optical carrier generated by a laser. Optionally, an optical amplifier could be placed after the modulator (or the laser for low frequency links) to compensate the optical splitting losses if an optical splitting is used to distribute the LO signal to multiple receivers (OECs). The main functional characteristics of the two links as shown in the following tables.

Table 1. Specifications of the low frequency (*left*) and high frequency (*right*) optical links embarked in the IOD.

Parameter	Min	Typ	Max	Units
Frequency Range	-	10	2.5	MHz
Operating Temperature	-10	-	65	ºC
Storage Temperature	-40	-	85	ºC
Power consumption (EOC+OEC)		4	5.5	W
EOC RF input power		10	-	dBm
Laser RF Input power		19	-	dBm
Laser optical Output Power		11	13	dBm
Operating wavelength		1550		nm
Optical input to Receiver		1	10	dBm
Input/Output Impedance		50		Ω
VSWR (Input/Output)		1.6:1	1.8:1	
RF link gain	-15	-10		dB
Added phase noise				
10 Hz	-130	-130		dBc/Hz
100 Hz	-149	-142		
1 kHz	-157	-151		
10 kHz	-161	-154		
100 kHz	-161	-154		
1 MHz	-161	-154		
10 MHz	-161	-154		
Allan deviation (10s<tau<100s)			$2 \cdot 10^{-12}$	
Power stability over T		±0.9		dB
EOL gain loss		3		dB (15y)
Weight		<0.5		Kg

Parameter	Min	Typ	Max	Units
Frequency Range	-	10	30	GHz
Operating Temperature	-10	-	65	ºC
Storage Temperature	-40		85	ºC
Power consumption		4	6	W
EOC RF input power	-	5	15	dBm
Operating wavelength		1550		nm
Optical input to Receiver		1	10	dBm
Input/Output Impedance		50		Ω
VSWR (Input/Output)		1.6:1	1.8:1	
RF link gain	-35	-25		dB
Added phase noise				
10 Hz		-70		dBc/Hz
100 Hz		-90		
1 kHz		-110		
10 kHz		-120		
100 kHz		-130		
1 MHz		-130		
10 MHz		-130		
Power stability over T		±0.9		dB
EOL gain loss		3		dB (15y geo)
Weight		<0.5		Kg

3.2 IOD description

The IOD consist on a piggy back demonstrator of Photonic Technology for On-board Reference, LO and RF distribution by using the low and high frequency links described above. The IOD will have the following characteristics:

- In-Orbit test of the optical links, including a fiber of 10 meters and a power splitter.
- Phase drift of 10 MHz reference by measuring the Allan deviation introduced by the optical link
- Power stability of both optical links (low and high frequency) tested at 10 MHz and 10 GHz.
- Health monitoring, measuring multiple parameters of the links (current(s) consumption, temperature, bias references…) and its environment.

In order to evaluate the behaviour of the optical links in real space environment, the system will comprise the following additional parts:

- **Power Supply Unit (PSU)**: The PSU extracts the voltages from the main power bus and generates secondary voltages needed in the different subsystems of the equipment.
- **Power Distribution Unit (PDU)** is the unit responsible for current sensing and limiting

- **Interface Control Unit (ICU)** is in charge of the communication between test Bed and satellite processor. by using the 1553 protocol
- **Optical Control Units (OCU)** control the optical links and monitors the status

The block diagram and the mechanical assembly and enclosure are shown in the following figure.

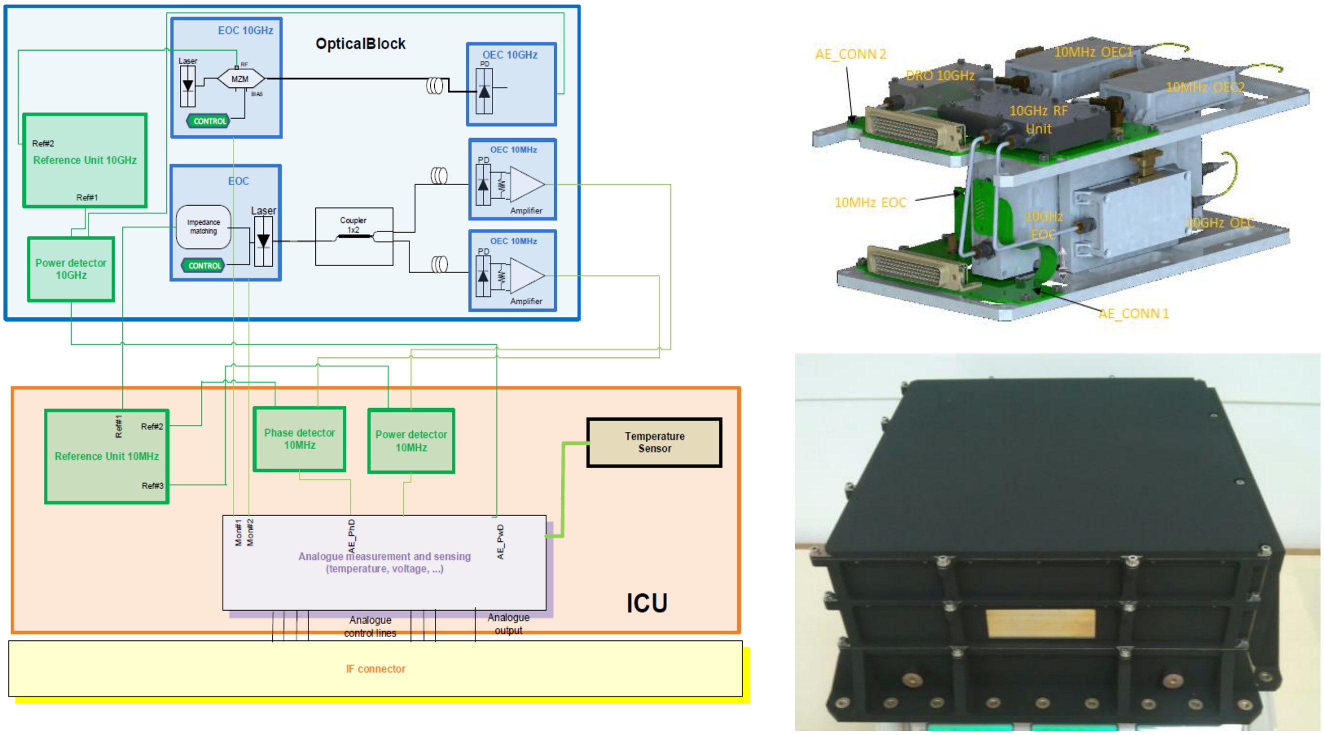


Figure 3: Block diagram(*left*), 3D view of the optical assembly including the optical links and the 10 GHz oscillator and power detector (*right-top*) and a photograph of the enclosure of the flight unit (*right-bottom*).

4. PHOTONIC FREQUENCY CONVERTER IN KA-BAND IOD

4.1 Photonic Frequency Converter

The Photonic Single Frequency Converter, or Single String Photonic Payload (SSPP) is a distributed system composed by two assemblies interconnected by optical fiber. Each assembly has its own DC power and TM/TC interfaces, as well as the specific optical and electrical ports. These assemblies are:

- Photonic Local Oscillator Module (PhLO)
  - This assembly oversees generating an optical local oscillator using in the photonic frequency conversion process
  - Basically, it is an optical transmitter that convers an electrical Local Oscillator to the optical domain similar the High Frequency EOC described in the previous section.
  - A booster optical amplifier and a 1 to 16 optical splitter has been included in the module in order to demonstrate the capability of LO distribution.
  - An optical multiplexor (WDM) has been included to be tested in orbit, although only one input port is used.
- Photonic Downconverter Module (PhDOCON).
  - This assembly is basically a photonic mixer that mixes the photonic LO with an RF signal to generate a set of mixing product and a photodetector that generates the IF signals. In this process only 1RF+/-nLO spurs are produced.
  - This assembly integrates optical amplification (pre and post amplification) and optical demultiplexer to demonstrate the impact of the demultiplexing in orbit

- Uses SSL pre- and post-amplifiers to achieve >17.5 dB Conversion Gain and OIP3 > 21 dBm

The photonic circuitry has been packaged in small boxes which are named PhLO component and PhDOCON component. The PhDOCON component also includes the SSL's pre and post-amplifiers. The Ph components are integrated in two modules together with its respective digital control electronics. In the case of the PhLO, an RF amplifier for the LO signals has been also integrated within the module. In the following figure the block diagram of the photonic assembly is shown as well as 3D views of the PhLO and PhDOCON components and the final flight assembly.

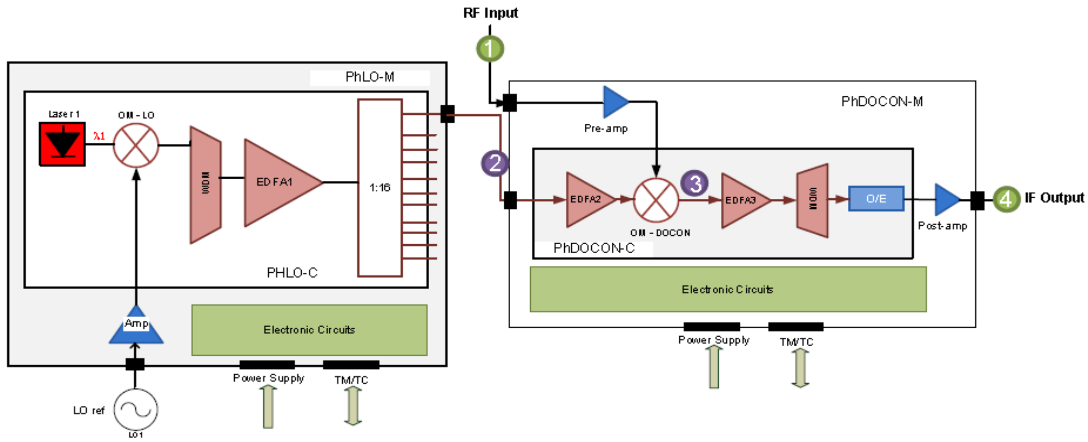


Figure 4: Ka-band Single String Photonic Payload block diagram. The PhLO module (*left*) is connected with the PhDOCON module (*right*) with optical fibre (point 2). External LO reference at 3.25GHz is injected at the input of the PhLO, which generates 16 replicas of the optical LO signal. On replica is mixed (point 3) with the incoming Ka-band signal (point 1) to generate the IF signal at the output (point 4). The RF amplifiers (LO, DOCON pre and post-amps) are shown in blue.

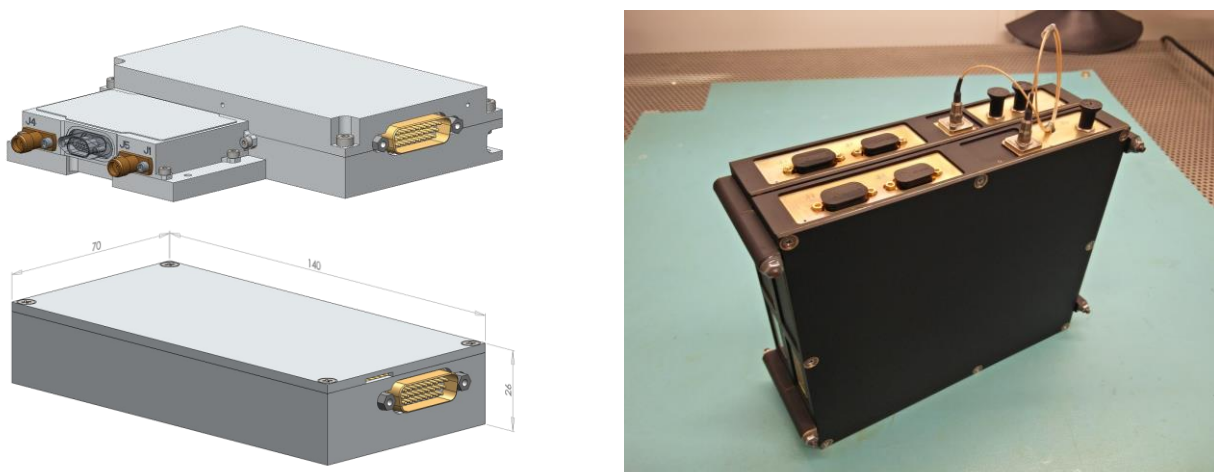


Figure 5: 3D view of the PhDOCON component integrating the pre and post-amplifiers and the optical circuitry in a single box (top-left). 3D view of the PhLO component, including the size in millimeters (70x140x26). The box was designed to allocate three multiplexed PhLO together but only one was populated for the IoD (bottom-left). Picture of the flight assembly. The PhLO and PhDOCON modules are stacked together as a single assembly. The connection between the units are done by optical fibre (right).

4.2 IOD description

The IOD is a flight demonstration of BSS Photonics Receiver installed on a separate switchable path (in parallel to the primary BSS RF receiver) with no interference to RF payload and with monitoring of the Photonic Downconverter Module telemetry over life time operation in order to gain photonic technology experience in space environment and providing performance for 1 year minimum, 5 years as a goal.

The scope of the IOD included:

- Perform PFM level testing per specific satellite environmental requirements
- Pre environmental Functional Test
    - Vibe and TVAC Test
    - EMC Test (RE/RS, CE/CS) to ensure no inter-payload interference
    - Post Environmental Functional Test
- Component screening, analysis and test
    - Meet minimum of 1 year and maximum of 5 year life
    - No failure propagation from Photonic Receiver to the interfacing elements of the satellite
- External interface components (interfacing with standard flight hardware) to be fully space qualified part to prevent failure propagation

The Photonic Receiver amplifies a low power RF input signal and frequency converts to the downlink frequency combining the mature NF performance of established RF front end parts with the advantageous spurious characteristics of Photonic mixing. This IOD version does not fully take advantage of photonic SWAP characteristics because large digital electronics with extensive health monitoring on the photonic system has been included in the modules together with the photonic components.

The key requirements of the BSS transponder are:

- RF In: 24.7 – 25.2 GHz
- RF Out: 21.45 – 21.95 GHz
- Gain: 55 dB min
- Noise Figure: 3 dB max @ 60C

The final photonic assembly installed in the transponder also included a DC/DC converter and a Ka-band LNA. The transponder architecture and a photo of the flight unit photonic assembly are shown in the following figure.

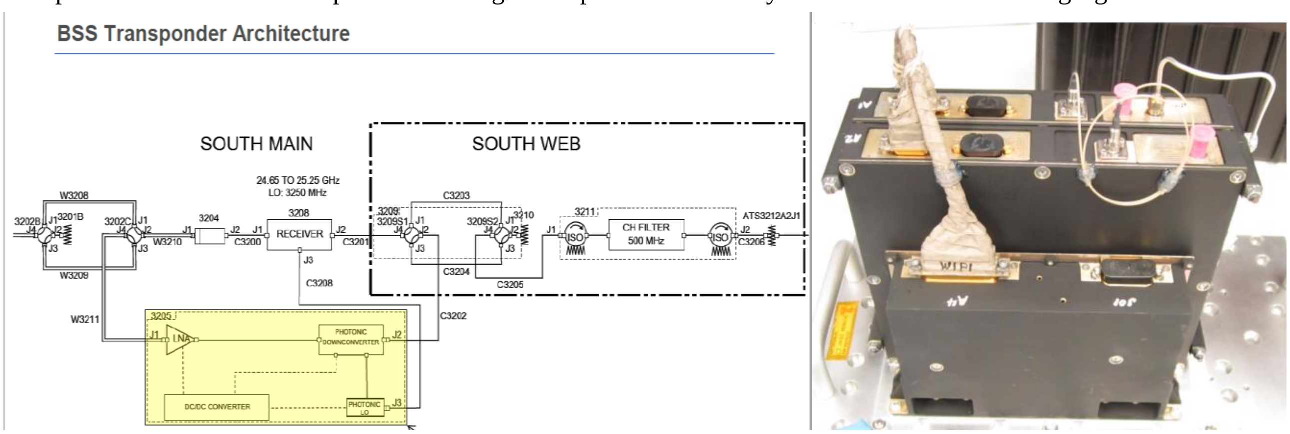


Figure 6: Transponder architecture (*left*) and a photo of the flight unit photonic assembly (*right*).

4.3 Photonic Payload Qualification assessment

The hardware was constructed with Level 1 Hi-Reel EEE and RF parts at the interfaces and Level 3 for the rest. The photonics parts used in the payload were submitted to a qualification campaign and a space assessment (flight readiness assessment), defined to ensure that all the parts will satisfy the requirements in terms of compatibility with the S/C and the space environment before PFM manufacturing. This Space Assessment comprises the following tests, at parts level (including lasers, photodiodes and passives such a couplers, passives or filters):

- Hermeticity
- Thermal Cycling Test
- Thermal Conductance
- Outgassing

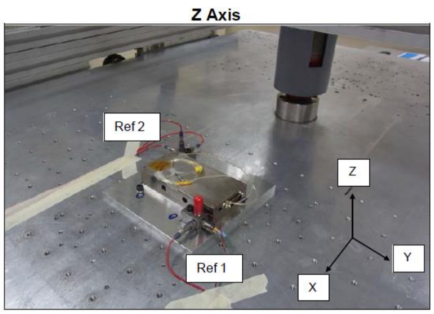
- Radiation TID (150KRad @360rads/hour)
- Radiation: Protons (Protons energy: 60-100-200MeV)

At component level (PhLO component and PhDOCON component), the tests performed were:

- Vibration
- Shock
- Thermal Vacuum Cycling (TVAC) tests

The fight assembly was also submitted to TVAC and to vibration tests.

The following figures shows some pictures and information about the mechanical tests done on the photonic components.



Shock Requirement		
Frequency, Hz	SRS Acceleration, g (Q=10)	
	Flight	Protoflight & Qualification
200	37	52
4000	3000	4200

Figure 7: Test set-up for Z axis shock test on the PhDOCON component (*left*) and shock requirements (*right*). The levels used were the qualification ones up to 4200g at 4000Hz.

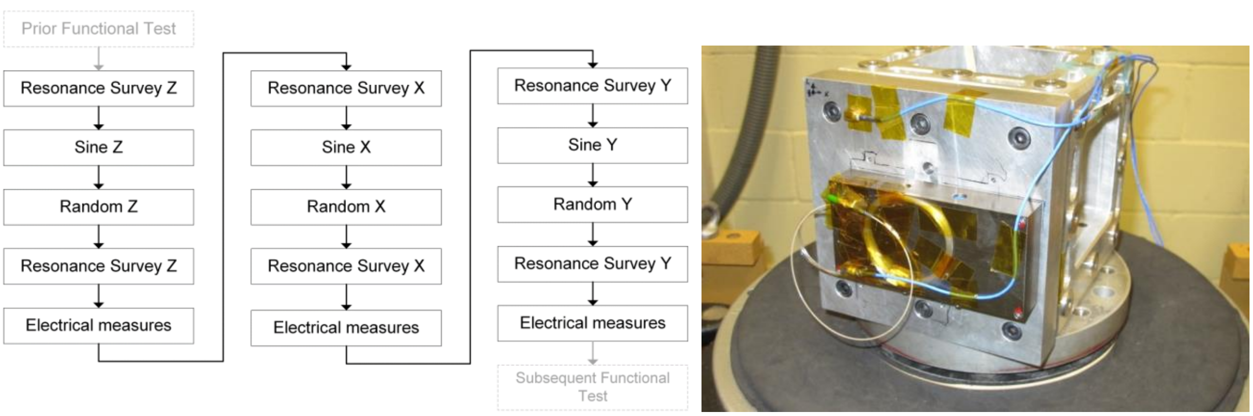


Figure 8: Qualification Vibration Test Flow done for the Photonic Components (*left*) and photo of the PhLO component on the vibration test set-up (*right*).

4.4 RF transfer performance

The figure 9 shows the conversion gain tested at different temperatures (cold, ambient and hot) and the noise figure tested at ambient temperature. The LO frequency was 3.25 GHz and the input and output frequencies tested were 24.7 – 25.2 and 21.45 – 21.95 GHz respectively. The maximum noise figure at ambient was lower than 29.5dB. The minimum gain was higher than 17.5dB.

In the figure 10 the third order linearity performance of the photonic converter (not including LNA) is shown, either the IM3 and the OIP3, measured in the 500 MHz frequency band under test. OIP3 in the order of 17dBm was measured and IM3 lower than -55dBc.

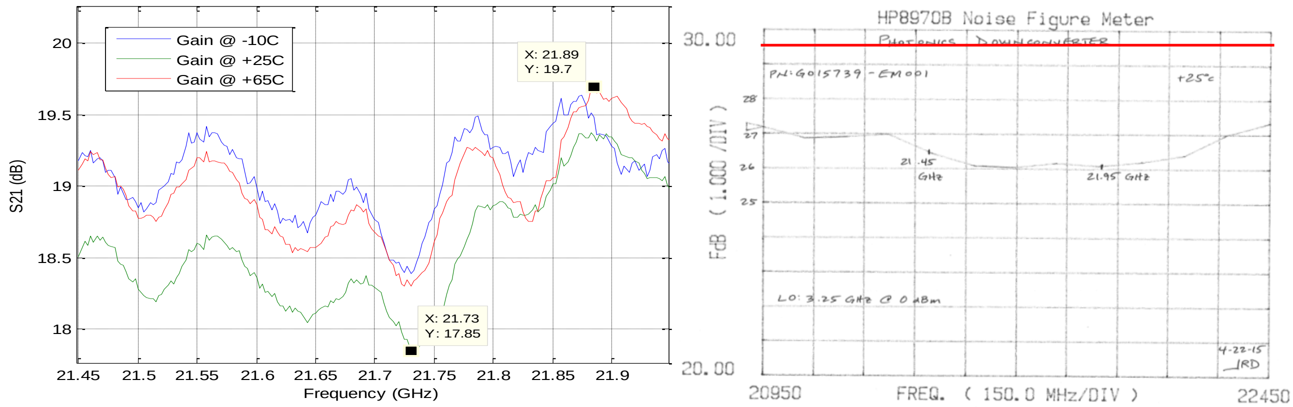


Figure 9: Conversion gain at ambient (+25ºC) , cold (-10ºC) and hot (+65ºC) temperatures (*left*) and noise figure at ambient (+25ºC) (*right*).

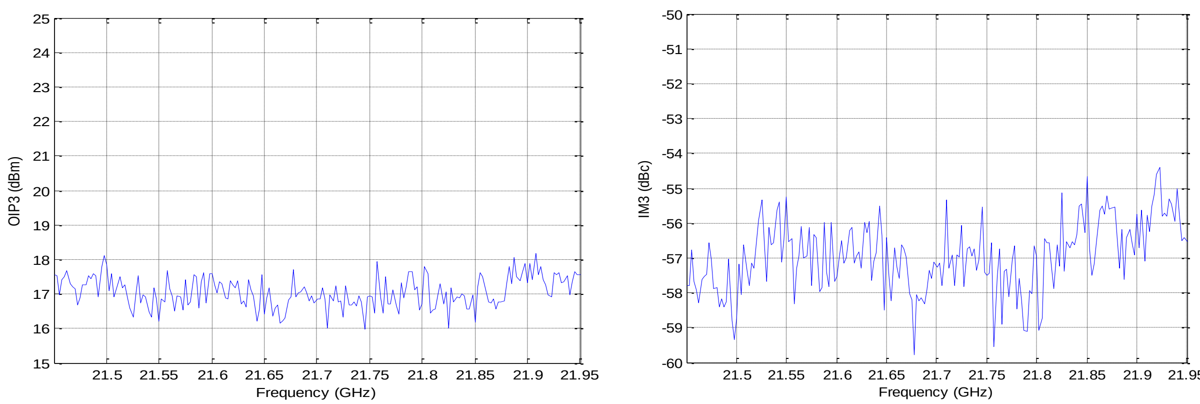


Figure 10. Ka1 band third order linearity performance of the photonic converter (not including LNA).

5. HISPASAT 30W 6 AND AMAZONAS 5 SATELLITES

These DAS Photonics hardware are part of SSL hosted payloads in SSL manufactured satellites for HISPASAT. The satellite Hispasat 1F hosts the Photonic Frequency Converter IOD working in Ka-band as redundant converter. The Amazonas 5 satellite host the photonic piggyback demonstrator for the photonic LO distribution links. Both spacecrafts have been successfully launched and tested in orbit and have been incorporated by HISPASAT to its fleet.

6. CONCLUSION

The IODs described in this paper have been the first demonstrations in space of the capabilities of the photonic technologies to perform the functionalities of photonic LO generation and distribution and photonic frequency down-conversion in the Ka-band required in telecom payloads. These are also a good example of industrial collaboration between the equipment manufacturer (DAS Photonics), the satellite integrator (Space Systems Loral) and the operator (Hispasat) to advance in the adoption of innovative technologies such as the photonic one.

In the case of the photonic frequency converter, although the in-orbit demonstration has been done in the Ka-band, the broadband capability of the electro-optical converters enables to have a single frequency-agnostic design for the photonic section, and to customize the solution case by case with the RF section. The interconnection between the photonic modules is done by optical fiber, which enables the replacement of segments of waveguides and/or coaxial cables in the payload, which reduces notably the overall mass and footprint of the RF harness.

Functional test results have demonstrated the operation of the photonic solution and its suitability for commercial telecom satellites, especially for HTS in which a large optimization of mass, size and power consumption is foreseen respect to a traditional RF implementation.