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OPTICAL FIBER SENSORS SYSTEM ON PROBA-2 AFTER 7 YEARS

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SUMMARY

The Fiber Sensor Demonstrator (FSD), for ESA's Proba-2 satellite is the first demonstration of a full fiber-optic sensor network in the space environment on a satellite. MPB Communications (MPBC) has developed the FSD as a lightweight (<1.3 kg) fiber-optic sensing system. It was launched on Proba-2 in November 2009 and is still completely functional, almost seven years after its launching. FSD contains also the first fiber laser in space, it is used to sweep the spectral range and read the intensity at each wavelength between 1520 and 1560 nm. The optoelectronic components and data acquisition board are about 500 g, and the rest (<800 g) is the mass of the protective monolithic aluminium enclosure that has to resist to the launching mechanical shock and vibrations.

The advantages of the FSD approach include a central interrogation module that is positioned remotely from the sensors and used to control a variety of different fiber-optic sensors, based on Fiber Bragg Gratings (FBG).

The FSD contains six parallel fiber lines multiplexed within the interrogation module. Sixteen specially-packaged FBG temperature sensors are distributed on four fiber lines. They monitor the temperature at different locations in the propulsion system and the spacecraft bus over the range of –60 °C and +120°C. The fifth fiber line is dedicated to a High-Temperature (HT) sensor to measure the transient temperature response of the SSTL thruster to beyond 350°C. The last fiber line contains an innovative Pressure/Temperature (P/T) sensor that provides both temperature and pressure measurements of the SSTL Xe propellant tank.

The fiber sensors are monitored periodically over the seven years of flight. Their measurements fit well with the standard sensors used by the satellite. The evolution of the FSD response in space shows the fibers and Interrogation module parameters are within 10 % variations, including the laser diodes power and the FBG sensors intensity. The total gamma radiation received by the FSD is about 7 krad, during the 7 years.

I. INTRODUCTION

The Fiber Sensor Demonstrator (FSD) provides temperature and pressure monitoring for various Proba-2 subsystems, including a hybrid propulsion system. It includes a redundant architecture developed for critical fiber-optic components, and a lightweight, ruggedized fiber-optic signal harness for use in space.

Spacecraft propulsion subsystems [1] require an array of different sensors to monitor the propellant tank pressure and integrity, the gas-line valve temperatures and status, the propellant mass flow rate and the thruster temperatures. This is currently performed using various electronic sensors at a substantial mass and performance penalty due to the shielding requirements of these sensors. The current electrical sensors have a number of drawbacks, including sensitivity to EMI, susceptibility to sparking, low sensor capacity per wire, sensor response times, and the proximity requirements for the associated electronics. The optical fiber sensors, provide an alternative that can solve many of these issues [2].

II. FIBER SENSOR DEMONSTRATOR SYSTEM DESCRIPTION

FSD has been launched on ESA's Proba-2 satellite in November 2009. It contains sixteen temperature sensors to measure the temperature at different locations in the satellite, and one High-Temperature (HT) sensor to measure the transient high temperature in the thruster, as well as one Pressure/Temperature (P/T) sensor to measure the xenon tank pressure. First set of on-orbit test data were obtained in January 2010.

The advantages of the FBG approach include a central interrogation module that controls the variety of different fiber-optic sensors including temperature, pressure, actuator status, and propellant leakage. The combination of both parallel signal distribution and serial wavelength division sensor multiplexing along single strands of fiber enables high sensor capacities.

Fiber-optic sensors employ a signal link via an optical fiber, allowing the subsequent electronic processing to be located remotely from critical areas of the spacecraft. This facilitates minimization of electromagnetic interferences and avoids the safety issues associated with electronics near the propulsion subsystem. Signals on a fiber-optic line are bidirectional, allowing a single fiber to carry both the source signal to the optical sensor and the reflected return signal back to the interrogation system. The temperature of FSD Interrogation module is also acquired through two internal thermistors AD590.

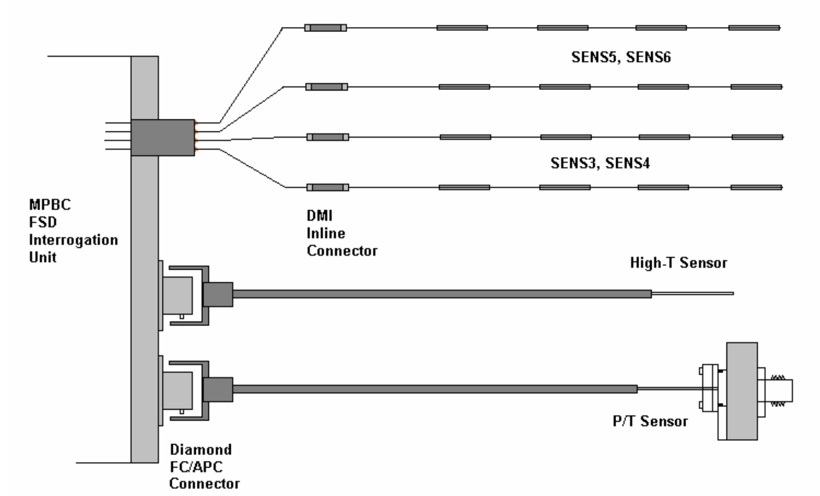

Fig.1 Schematic of FSD fiber-optic sensor signal harness.

The FSD employs a redundant temperature-compensated narrow-band reference FBG in series with the external FBG sensors (see Fig. 1) for each of the six sensor lines to provide an absolute wavelength reference. The FBG reference is kept in a small athermal packaging, keeping its wavelength practically independent from temperature (about 0.001 nm/C). The two thermistors ADS590, permit to confirm the accuracy of the FBG against long term potential shift of the FBG wavelength. In addition there are the readings of the laser diodes internal temperature provided by the diodes circuit. The thermistors, the FBG references and the temperature of the laser diodes give a good picture of the temperature evolution within the Interrogation module.

The Pressure/Temperature (P/T) sensor employs a heat-treated, orbitally-welded stainless-steel housing that is suitable for direct contact with propellants such as hydrazine. It can be employed for either single-ended or differential pressure measurements. The P/T sensor was proof-tested in N2 at 1200 psi, relative to the maximum operating pressure of 600 psi. The FSD innovative P/T sensor uses multiple FBG gratings with special mounting to provide simultaneous pressure (P-sense) and temperature (T-sense) measurements. The pressure readings are independent of the gas composition (see Fig. 5). The integral temperature measurements are employed to correct for the effects of temperature on the pressure readings.

The High Temperature (HT) Sensor measures the transient response of the SSTL thruster during firing, it is protected in a microtubing tip that is only 0.34 mm O.D. for minimal thermal mass.

The Four lines of Distributed FBG Sensors have a special proprietary packaging that was developed to nearly triple the effective sensor sensitivity to temperature ($\Delta\lambda/\Delta T \cong 0.03$ nm/°C), permitting a resolution of 0.05 °C.

Table 1: Specifications of the FSD Sensors.

Sensor	Description	Range	Wavelength Span	Resolution
MEMS/FBG Temperature	Pipeline temperature / propulsion system	-40 to 70 ^{o}C	5 nm per sensor	0.05 ^{o}C
Combined pressure/ temperature sensor	Xe Tank pressure	0 to 45 Bar	15 nm	2 mbar
		-40 to 70^{o}C	5 nm	0.05 ^{o}C
High-T FBG sensor	Thruster temperature	-40 to 350^{o}C	10 nm	0.1 to 0.2^{o}C

A tuneable Fabry Perot, controlled by a fast piezo-electric element, permits the fiber laser to sweep the spectral range and read the intensity at each wavelength between 1520 and 1560 nm. A fixed Fabry-Perot interferometer of 50 GHz follows the tuneable one and is the basic component to measure the wavelength of the FBGs. Its accuracy is a good sign of the sensor functionality in space.

Fig.2 presents the photographs of the location of the different sensors installed on Proba-2, and Fig.3 illustrates the Interrogation module box.

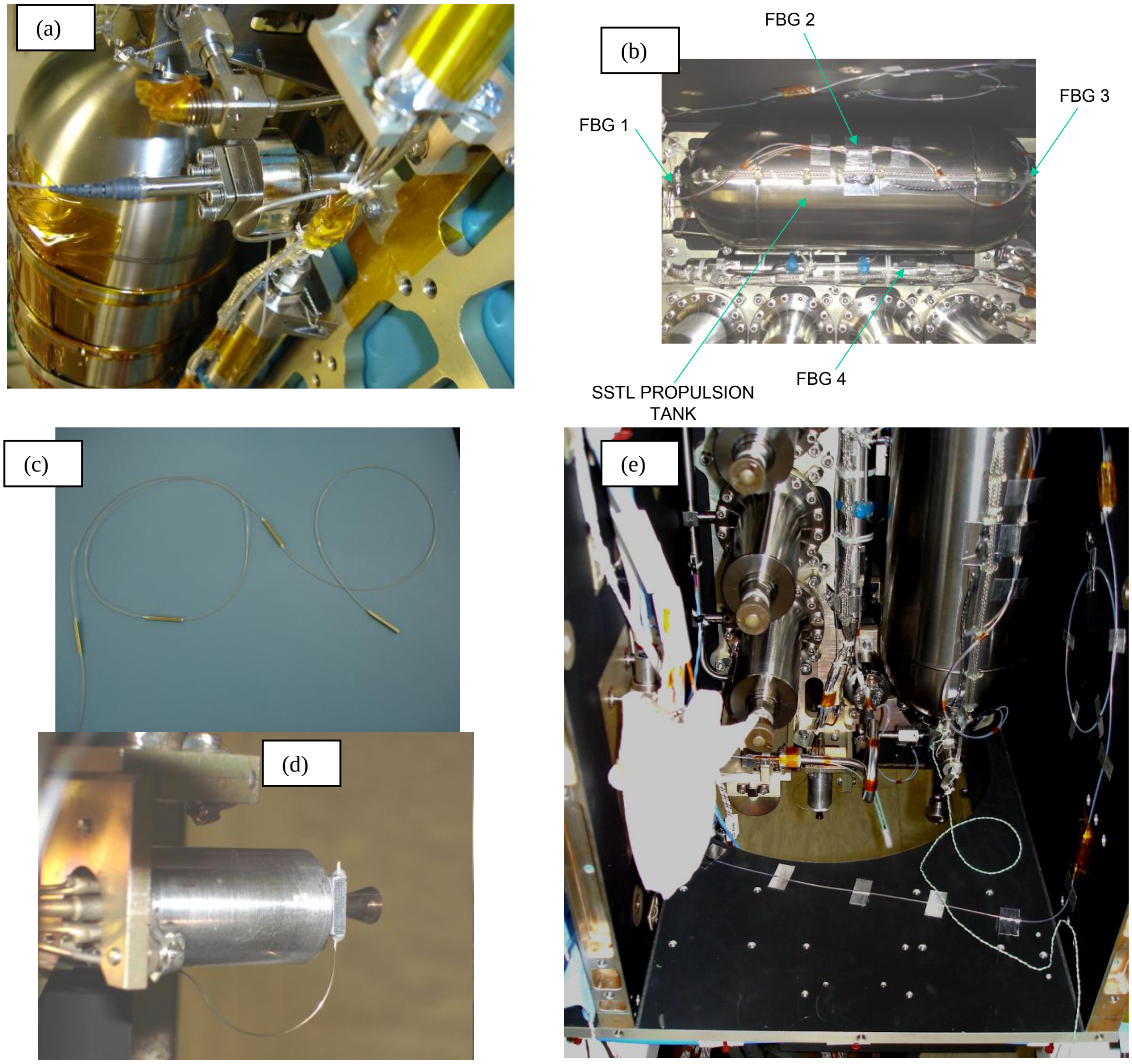

Fig. 2: Photograph of flight P/T sensor integrated with the SSTL propulsion system for Proba-2
(b) FBG Sensors integrated with SSTL Propulsion Subsystem
(c) Photograph of a packaged flight FBG T-sensor line with protective cabling and four sensors
(d) FBG Sensors integrated with Propulsion thruster
(e) Pressure/Temperature (P/T) and High Temperature (HT) sensors mounting on Proba-2

Fig. 3: Photograph of the Interrogation module

The interrogation module (15cmx17cmx12cm) is under 1.3 kg, and requires less than 2.5 W peak power.

The DAQ PCB is employing spacegrade and MIL-883 milgrade components for the critical functions, including a 16 bit A/D converter and serial interface D/A drivers from Maxwell. To minimize the power consumption, micropower op amps are employed for the analog signal processing. The DAQ PCB includes the control/monitoring electronics for the tuneable fiber-laser diode pumps and filters, as well as eight fiber-coupled InGaAs detector channels with individual preamplifiers for the six external FBG sensor lines and two internal reference lines.

III. ON ORBIT MEASUREMENTS

MPBC is monitoring periodically the performance of fiber laser and the FBG sensors. The FSD unit measures Proba-2 temperature variations in increments over an orbit, when requested by ESA. The following figures provide examples of the measurements.

- Fig.4 compares the temperature given by the HT fiber sensor, located on the exit of the thruster, with that provided by the standard thermocouple placed at the bottom of the thruster. They follow the same trend with a temperature about 50 °C higher at the HT position, in the peak of preheat experiment.
- Fig.5 shows the scan of the four FBG sensors monitoring the temperature on the Bus (Fiber Line_sens6), along with the first FBG reference (at 1530 nm). The wavelength shifts of the four FBG sensors are different indicating different temperatures seen by each of them. The four sensors sensors are spaced by 50 cm each and very probably they are affected by the sunlight and shadow differently.
- Fig.6 shows the evolution of the temperature during one orbit cycle as observed by these four FBG sensors on the Bus.
- Fig.7 presents a zoom of the 4000 pixels scanned by the tuneable Fabry Perot, over 45 nm (1520 nm-1565 nm). It compares the evolution of the intensity of the Fixed Fabry-Perot Interferometer signal (50 GHz, 0.4 nm). There is no difference between the intensity after integration on Proba-2, before the launch, and the first measurement in orbit a few months later [3]. The width of a single scan of the Fabry Perot on orbit is very similar to that on the ground, however the peak signal intensity is reduced by about 15-20% over the 7 years in space. This is the largest variation observed on any of the FSD parameters.
- Fig.8 illustrates the evolution of the main FSD parameters during the flight, since the last measurements on the ground. We can see the relative fluctuations of the Interrogation module inside temperature between 18°C and 32°C, and the slight linear slope of the increasing radiation level observed by the RADFET measurements.
- Fig. 9 gives the calibration of the RADFET according to the supplier at 20°C. It is about 1 krad/year, and fits globally with the predicted radiation measured by ESA [4]. The small fluctuations are due to the temperature changes.
- Fig.10 is similar to Fig.8 with the x-axis being the radiation (from RADFET) instead of the date.

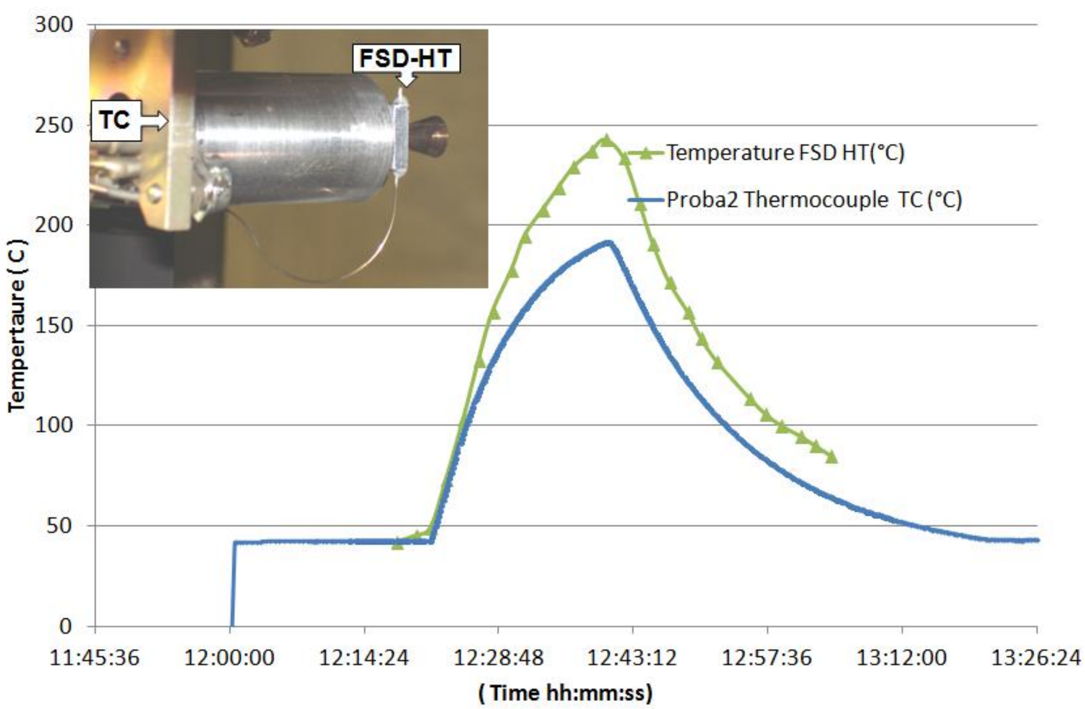

Fig. 4: Temperature measurements with FBG sensor at the thruster top, and a thermocouple at the thruster bottom, during a preheat experiment

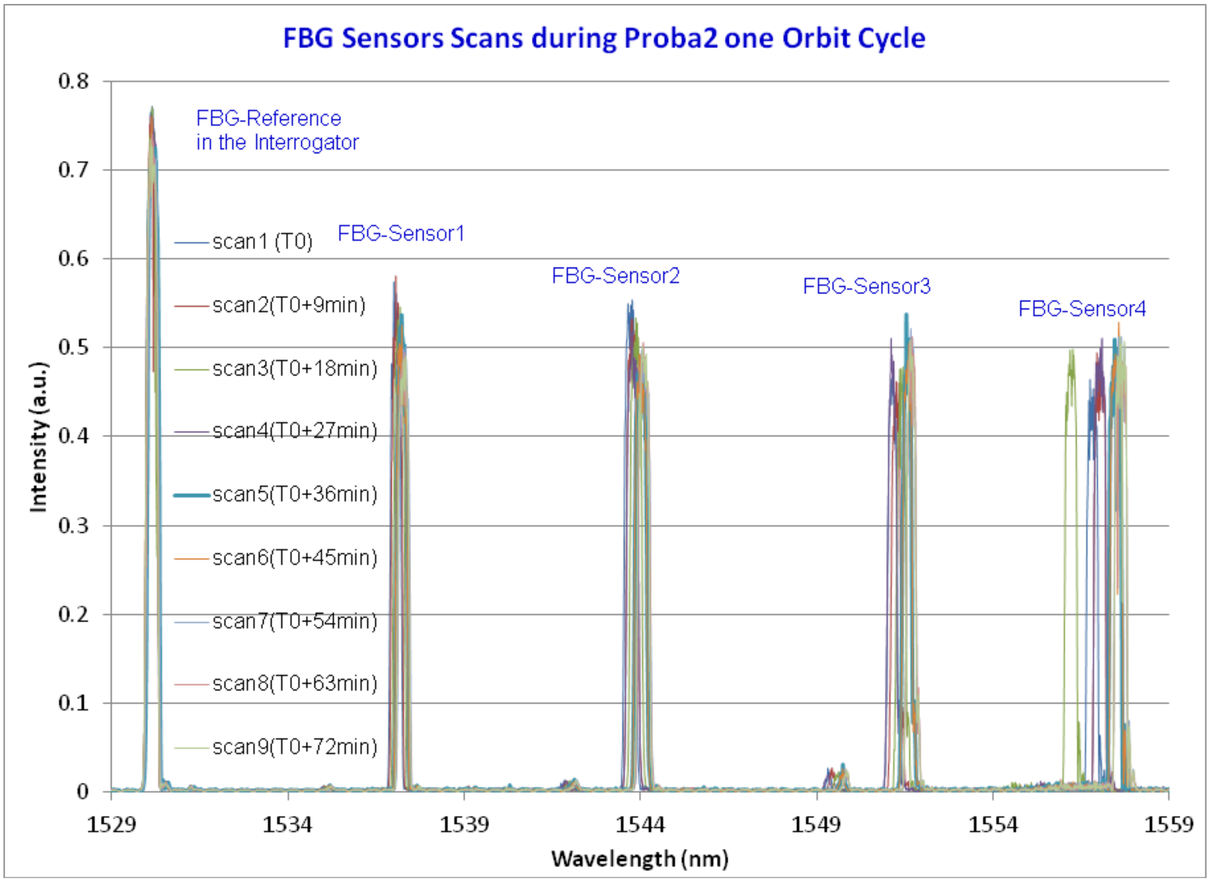

Fig. 5: Scan of the wavelengths of the Line during the orbit cycle

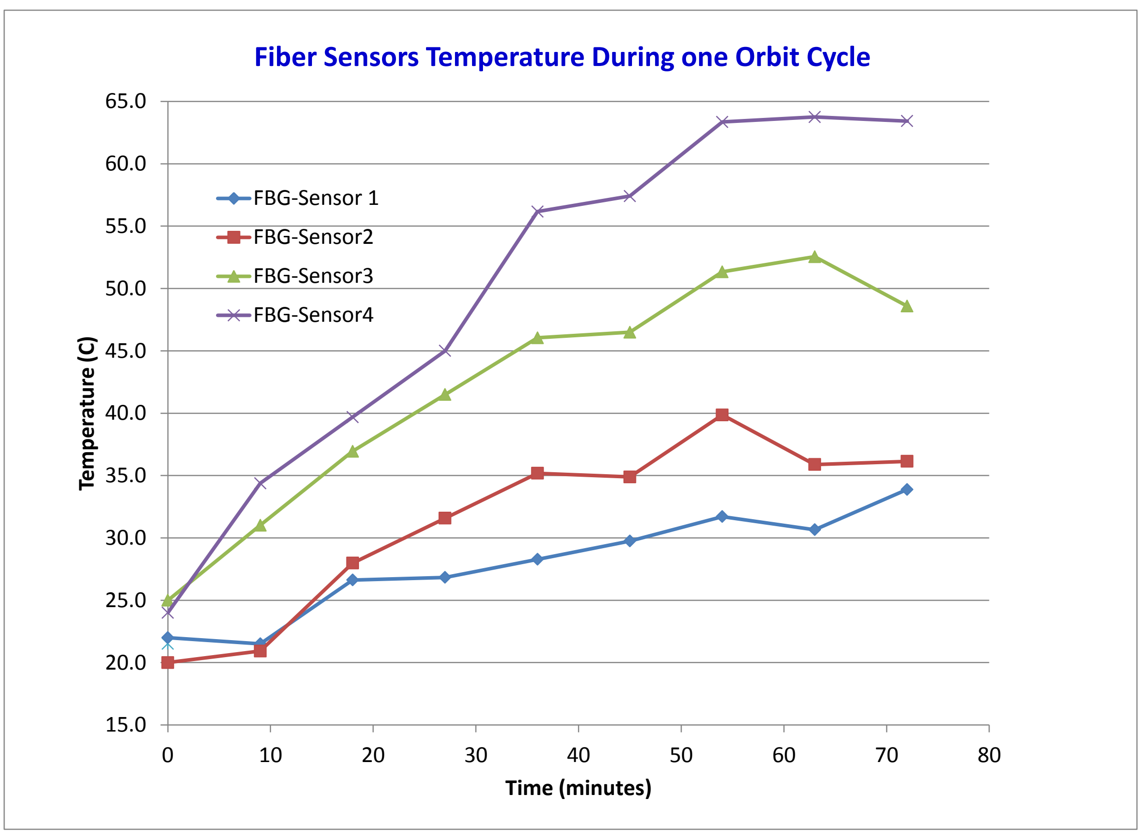

Fig. 6: Temperature measurements provided by the four sensors of Fiber Line_sens6(Bus)

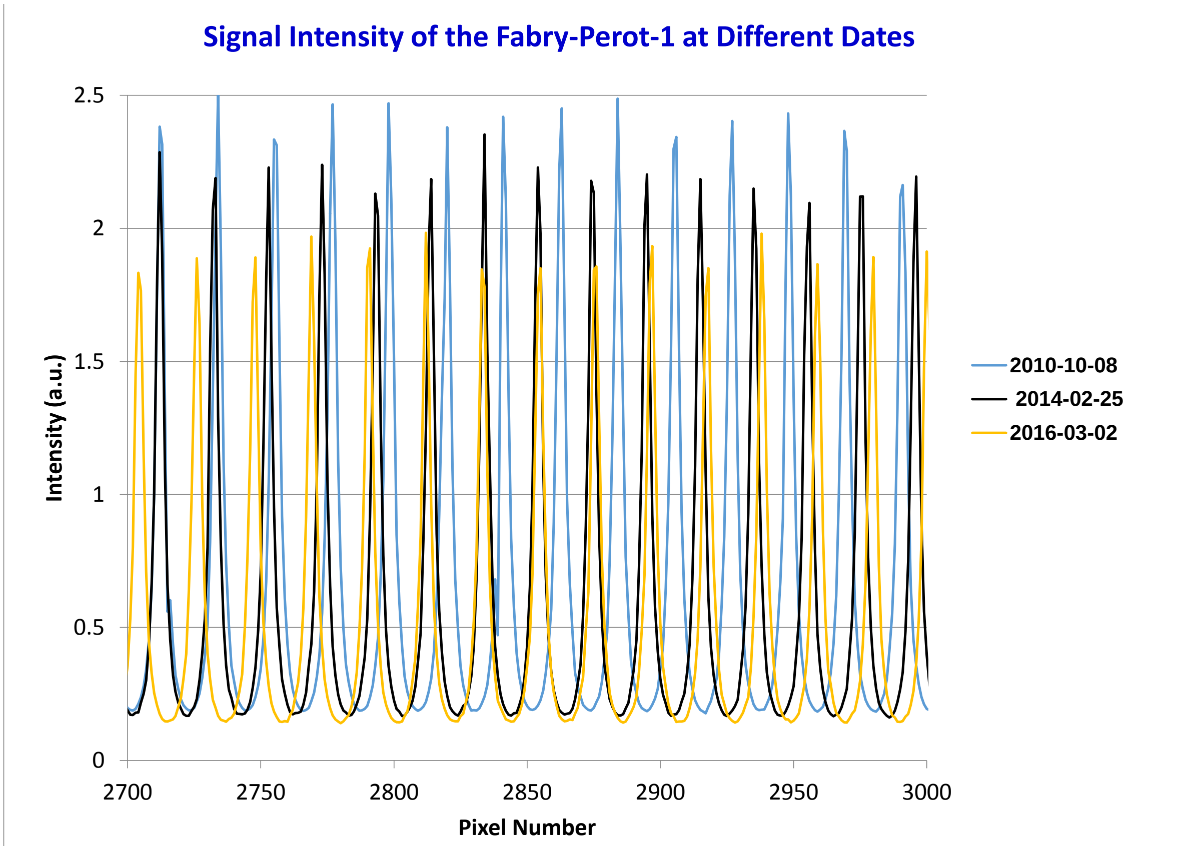

Fig. 7: Intensity of the fixed Fabry Perot Scans (50 GHz/scan) in a Zoom over the pixels 2700-3000 of the tuneable Fabry-Perot (total 45 nm/ 4000 pixel width)

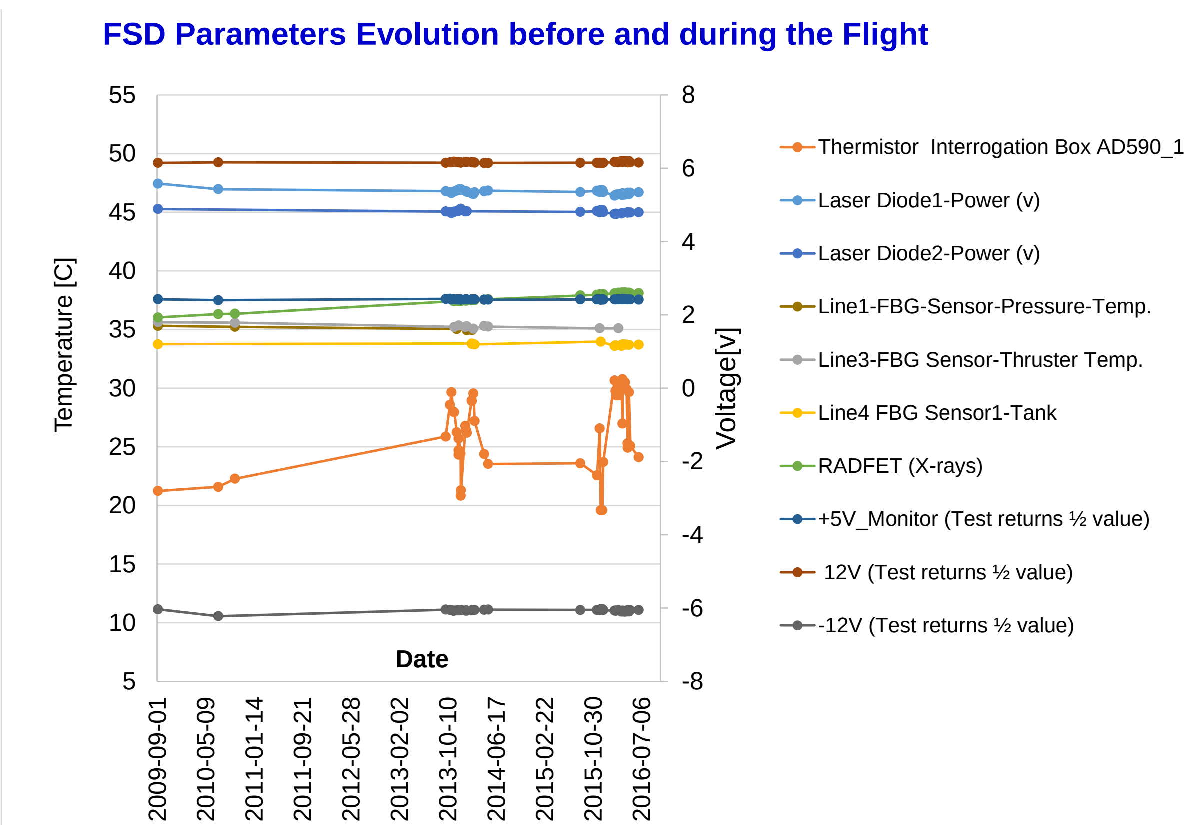

Fig. 8: Main FSD parameter evolution since the last on ground measurement. Only the temperature follows the primary vertical axis (left side), all the other parameters follows the secondary axis (right)

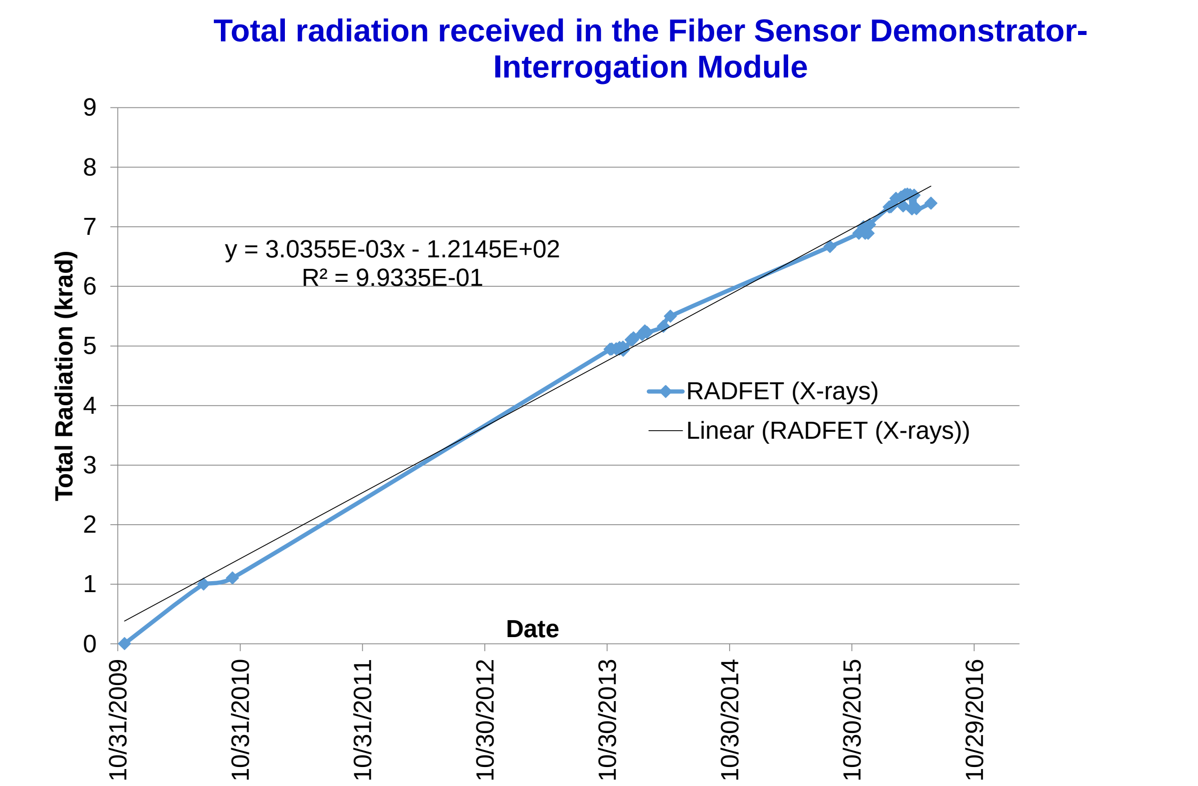

Fig. 9: Calibration of the RADFET vs the time spent in space

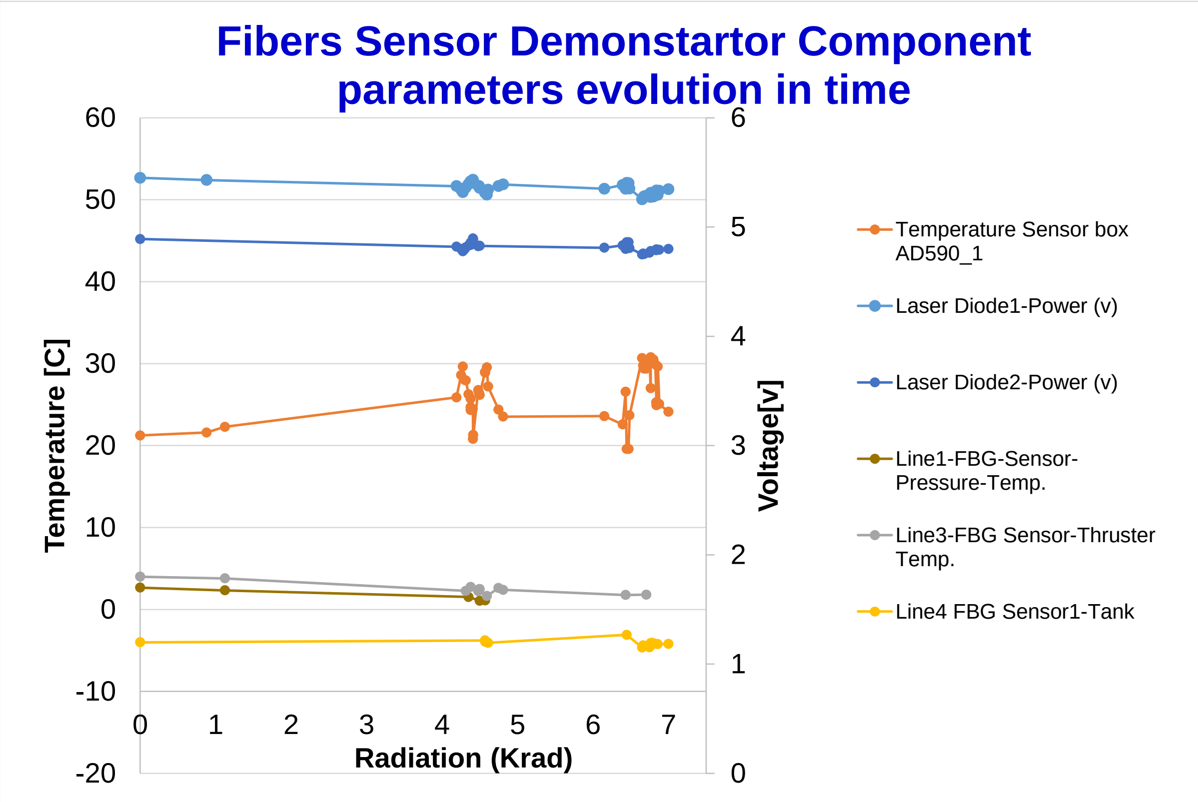

Fig. 10: Main FSD parameter evolution since the last on ground measurement

IV. FBG TEST WITH HIGH GAMMA RADIATION DOSE

A test was made by a third party (Kayser-threde, Germany) addressing the stability of the FBGs in equivalent harsh radiation -space environment. MPBC prepared three kinds of packaging:

- Bare FBGs (only 5µm polyimide coating)
- Medium thickness tube stainless steel (0.83 mm thick)
- Larger thickness stainless steel tube (1.37mm thick)

The FBGs were submitted to high radiation level (25Mega-rad at 420 krad/h) - 250 times larger than the 100 krad commonly requested. The effect on the FBGs was a small shift (200 pm, equivalent to the shift in the Central Wavelength (CWL). A second radiation test (250 krad, at 4.1 krad/h) confirmed the small CWL shift. For 100 krad the CWL shift is less than 5 pm at the 4.1 krad/h, and less than 10 pm at 420 krad/h.

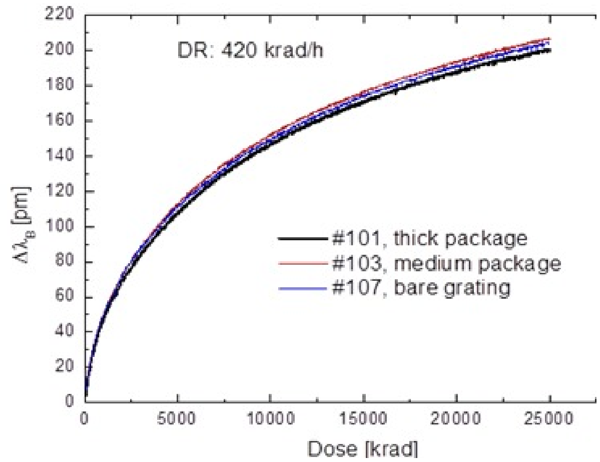

Fig. 11: Central-Wave-Length shift with 25 Mrad at a dose rate of 420rad/h

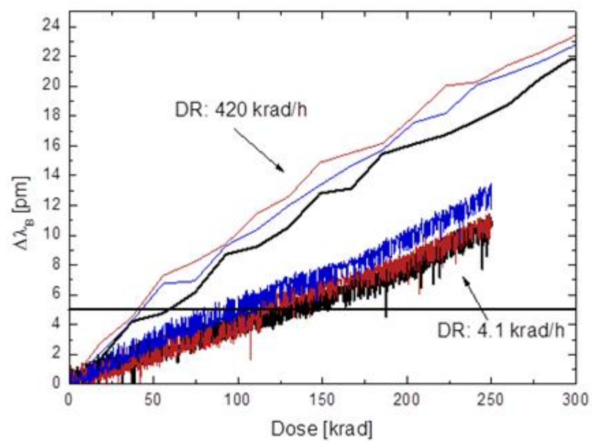

Fig. 12: CWL shift at 300 krad total dose, comparison of two dose rates (420 vs 4.1 rad/h)

V. DISCUSSIONS AND CONCLUSION

The Fixed Fabry Perot signal is reduced by 15-20% after the 6.5 years. All the other FSD parameters seem more constant, with a trend of decreasing signal of the Laser diode pumps by about 5-10% over the 6.5 years.

The FBG sensors are at the end of the circuit and shall see the effect of all the effects received by the other components in the opto-electronic circuits. The evolution of the FBGs peaks from three different lines showed about 3-10% reduction in their intensity (Fig.10), depending on the sensor itself.

The FSD confirmed the reliability to use Optical Fiber Sensors in space missions and demonstrate its capability to monitor different parameters such as pressure and temperature at different level. The FSD on Proba-2 opens the door to a variety of other fiber sensor applications such as launch vibrations, liquid level in tanks and high temperature atmospheric re-entry.

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