

SMOS fiber optic harness: Modelling the impact of radiation after 15 years in orbit

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ABSTRACT

ESA's Soil Moisture and Ocean Salinity (SMOS) mission, launched in November 2009, was the first satellite to make extensive use of fiber-optic technology, an innovation that was novel in space applications at the time. Its payload, the Microwave Imaging Radiometer using Aperture Synthesis (MIRAS), incorporates an optical harness (MOHA) comprising fiber-optic cables and transmit/receive opto-electronic units. After more than 16 years of continuous operation, MOHA has performed flawlessly, effectively becoming a space-based test laboratory for all of its optical components. This paper examines the radiation environment experienced by different parts of MOHA to better understand its long-term performance in orbit and to assess the suitability of optical technologies for future space missions. To this end, a dedicated radiation-analysis tool was used together with a detailed model of the SMOS satellite. The results indicate an accumulated dose of approximately 15 krad over 15 years for most MOHA elements, although certain components were exposed to significantly higher levels. The paper also delves deep into the preliminary screening performed on the optical components selected for flight aboard SMOS. In summary, the experience gained over more than 16 years of flawless MOHA operation in orbit, together with the radiation-level simulation results presented in this paper, provides valuable guidance for adopting fiber-optic technologies and their associated transceivers as standard solutions for future space missions.

Keywords: SMOS, Fiber Optics, Radiation

1. INTRODUCTION

Fiber Optics have emerged as a new technology in Space with the commercial adaptation of fiber optic gyroscopes since 2014 [1] and the fiber optic digital communication links in 2021 [2]. Furthermore ARIANE-6 has adopted fiber optics for the pyrotechnics [3]. Fiber optics are also considered for application in the analog signal transfer and processing [4] and in fiber optic sensing [5]. These commercial applications have followed the pioneering operational demonstration for the use of fiber optics in SMOS [6] and PROBA-II [7] with their joined launch in 2009.

These two missions carry the longest in time data on behaviour of fiber optic links in Space and it is therefore important to see how they are faring 17 years into their missions. Reference [7] presented the status of the fiber optic links in the PROBA-II mission showing that essentially no degradation has occurred. The PROBA-II spacecraft was equipped with RAD-FET radiometer that provided real measurements of the levels in radiation that the spacecraft was subjected. Similarly, SMOS operates flawlessly for the same period of time providing confidence on the use of fiber optics and the associated opto-electronic devices in Space. However, the levels of radiation to which the SMOS optical harness was subjected to is not known as no radiation measurement equipment was installed in the SMOS spacecraft. Hence, the alternative was to simulate the levels of radiation using the most credible simulation tools. Simulations would have to assess the level of radiation in the various locations as the fiber optic harness spans over different parts of the spacecraft with different exposure to radiation. This is the topic of the paper. Chapter 2 provides a background and overview of the the SMOS mission and the Optical Harness in it. Chapter 3 presents the methodology used to assess the levels of radiation and Chapter 4 presents the main conclusions to be drawn by this work and its correlation with other studies.

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2. BACKGROUND OF SMOS MISSION AND THE OPTICAL HARNESS

2.1 SMOS and MIRAS

ESA's Soil Moisture and Ocean Salinity (SMOS) mission was approved for implementation as an Earth Explorer mission in May 1999 [8]. However, several early versions of its payload, the Microwave Imaging Radiometer using Aperture Synthesis (MIRAS), had already been under study, breadboarded, and experimentally tested since September 1992 [9]. The first MIRAS prototype consisted of 11 receivers and a correlator unit interconnected by an optical harness—MOHA (MIRAS Optical Harness) [10]. Aperture synthesis was achieved by sampling the receiver signals and digitizing them to 1-bit at approximately 55 Mbps, transmitting the digital streams to the correlator, and performing the cross-correlation of all possible signal pairs.

Optical cables were initially selected to simplify the deployment of the three arms of the envisaged space instrument, achieving a final aperture of 8 m diameter. However, extensive field experiments later revealed a far more compelling reason for adopting an optical solution: self-electromagnetic compatibility [9]. The harmonics generated by the digital signals transmitted from all receivers to the central correlator extended to high frequencies and, when copper coaxial cables were used, leaked back into the receivers through coupling or ground loops, severely degrading the correlation results. Additional shielding proved insufficient, highlighting the high risk associated with coaxial cabling for MIRAS. In contrast, prototypes built with optical fibers delivered much cleaner and more stable correlation values [11]. Consequently, when SMOS was approved for implementation, an optical harness was baselined for MIRAS.

2.2 MOHA and Optical Component Qualification

The optical harness of MIRAS is described in detail in [6] and its block diagram is shown in Fig. 1. MOHA provides two main functions, highlighted with different colours in Fig. 1: distribution of the reference clock to all 72 LICEF receivers and to the 12 Control and Monitoring Node (CMN) units, which generate the local oscillator for six receivers each (in green), and I/Q data transmission from the receivers to the bit de-multiplexers of the Central Correlator Unit, CCU (in yellow). In total, MIRAS incorporates approximately 756 m of fiber-optic cabling, supporting 84 uplinks (plus 12 redundant links to the CMNs) and 72 downlinks between the correlator and the receivers, along with the corresponding lasers and photodetectors located at each end of these links. Therefore, MOHA comprised five distinct elements:

- (a) a MOHA/LICEF unit hosted in each of the LICEF receivers, to receive the reference clock and to transmit the raw samples;
- (b) a MOHA/CMN unit hosted in the CMN to receive the reference clock used to generate the local oscillator;
- (c) the MOHA/CCU to receive all the optical raw signals;
- (d) optical splitters
- (e) optical fiber cables

The optoelectronic and photonic devices included are as follows [from 6]:

- The transmitter comprises
 - a laser driver integrated circuit (Maxim MAX3668EHJ)
 - a 1310 nm single-mode fibre coupled Fabry-Perot laser diode with a nominal output power of 1.5 mW (Modulight ML1310CSTCZZZ)
- A cascade of passive optical splitters (Sifam CSA004_OEMT662103101-003 and CSA005_OEMT6Y2103102-003)
- Fiber optic pigtail sleeving and tubing (Diamond AVIM D-6206.6 Connector and Hytrel Tubing)
- Each optical receiver (Hamamatsu G8340-22) comprised of:
 - single-mode fibre coupled pin-diode (InGaAs)
 - trans-impedance amplifier (pin-TIA)
 - an optimised band pass filter
 - and a discriminator integrated circuit (Maxim MAX3268CUB)

Figure 1. Block diagram of the Optical Harness of the MIRAS instrument on board the SMOS satellite

In parallel to these standard development and verification activities, a component qualification programme was executed during Phases A through C for two reasons: in the first place, fiber-optic and optoelectronic components (splitters, receiver modules, laser diode modules) were not available off-the-shelf with a suitable qualification; in the second place, the stringent power consumption and mass requirements required the use of reasonably recent (at that time) commercial integrated circuit technology for two electrical component types (laser driver and discriminator). All the mentioned commercial components were therefore subject to a dedicated campaign, comprising:

- Commercial component evaluation testing, to find out – among several candidates – the component most suitable for the application.
- Qualification testing, to demonstrate that each component could meet its performance requirements for the specified lifetime.
- Procurement of the flight components and their constituents from a single production lot, in order to eliminate as far as possible any process variations.
- 100% screening and burn-in of the flight components, in order to stabilise their characteristics and to detect early failures.
- LOT acceptance testing on samples of the flight lot, to ensure that it met the defined quality requirements.

2.3 SMOS Mission Radiation Environment

The radiation environment anticipated during the development of MOHA is described in this section. ESA/ESTEC's Space Environment Information System (SPENVIS) was used to determine the expected radiation spectrum for each of the MOHA elements including the fluxes of protons and electrons with a launch assumed in 2007 and a life duration of three years, as well as the corresponding doses as a function of shield thickness: ionizing dose (in Table 1) and Non-Ionising Energy Loss (in Table 2),

Single Event Effects (SEE) were considered, concluding that the CMOS amplifiers in the receivers could be susceptible to SEL (Single Event Latch-up) and SET (Single Event Transient), and the discriminator (Maxim MAX3268CUB), made in bipolar technology could be susceptible to SET. MOHA had to be free from single point failures causing a permanent failure in the operation of the MIRAS instrument, as for example, no reference clock delivery to the CCU, or to one (or more) CMNs or failure of one (or more) channels (loss of one or more LICEF), SEL became a point of concern. Hence, MOHA was designed with components which would not lead to (or would be protected against) any destructive latch-up. Furthermore, it was estimated that, in the worst case, up to 3 SELs could happen per receiver during the entire mission duration (assumed of three years). As for the SETs, they could affect the bit error rate (BER) as the receivers in the CCU might translate a SET into a wrong bit. The $BER < 10^{-10}$ requirement translated into a number of SETs per hour smaller than 12 (per channel) – the typical SET would be 20 ns long [14] compared to 10 ns bit duration (hence 3 bits might be affected by one SET).

2.4 Radiation Tests Performed on MOHA

The radiation tests that were performed on MOHA had three main objectives: (a) ensure the correct functioning of the component under space radiation conditions during the intended mission time; (b) provide information on any radiation induced changes in equipment characteristics (optical, electronic, or other) and (c) determine whether (and to which extent) the device was sensible to single event phenomena (SEL or soft error rates).

Table 1. SMOS ionizing doses for each of the MOHA elements

Module	Shielding [mm]	EADS/CASA (3years, sectoring analysis) [krad (Si)]	ESA (3 years) [krad (Si)]
MOHA/LICEF	1.9	10	11.9
MOHA/CMN	1.2	15	28.1
MOHA/CCU	2	<9	11.9
Splitter	1	-	34.3
Optical Cable	0	-	1850

Table 2. SMOS Non-Ionizing Energy Losses

Shield [mm Al]	Radiation Type	NIEL [MeV/g(Si)]	Equivalent 10MeV Proton Fluence [cm ⁻²]
0	NIEL of charged particles	$5.62 \cdot 10^8$	$8.15 \cdot 10^{10}$
1	NIEL of charged particles	$5.52 \cdot 10^7$	$7.99 \cdot 10^9$
2	NIEL of charged particles	$4.09 \cdot 10^7$	$5.93 \cdot 10^9$
3	NIEL of charged particles	$3.49 \cdot 10^7$	$5.06 \cdot 10^9$
4	NIEL of charged particles	$3.17 \cdot 10^7$	$4.59 \cdot 10^9$

The test set-ups, pass criteria and radiation level for each of the optical components are presented in Tables 3 through 7, including the discriminator connected to the output of the optical receivers and the laser driver.

Table 3. Test set-up, pass criteria and gamma radiation level for the radiation tests of the optical fiber cable.

Optical Fibre Measurement	
Measurements	• Variation of photo diode current versus incident light at 1310 nm (with modulated signal) • Dark current • Ambient temperature
Equipment Required at Test Facility	• Photodetector shielded enclosure • Diode laser & power supply • Fibre splitter to provide reference arm • Test jig to hold fibre • Power meter for measuring reference arm optical power
Pass Criteria	• Fibre Attenuation of less than 100 dB/km
Mounting	• The fibre will be mounted in such a way that the fibre is exposed to the radiation, but the connectors are not.

Step	Dose rate [krad/h] (Si)	Exposure time [h]	Exposure time (cumulated) [h]	Total dose [Mrad] Si
1	36	25.6	25.6	0.92
2	36	25.6	51.2	1.85
3	36	51.2	102.4	3.70

Table 4. Test set-up, pass criteria and gamma radiation level for the radiation tests of the optical receivers.

Fibreoptic Receiver Measurement	
Measurements	• Variation of photo diode current versus incident light at 1310nm • Dark current • Ambient temperature
Equipment Required at Test Facility	• Diode laser & power supply • Optical fibre to couple light to photo diode • Test jig to hold photodiode • Fibre splitter (1 in 2 out) to provide reference arm • Power meter for measuring reference arm optical power
Pass Criteria	• Photo diode efficiency degrades less than 1.5 dB • Dark current increases insignificantly (no effect on links)
Mounting	• The photo diode will be mounted in such a way that the semiconductor is exposed to the radiation, but the leads and connections are not. • The photo diode will be orientated such that a laser beam from a shielded fibre can be directed towards the active surface

Step	Dose rate [krad/h] (Si)	Exposure time [h]	Exposure time (cumulated) [h]	Total dose [krad] (Si)
1	3.6	2.1	2.1	7.5
2	3.6	2.1	4.2	15
3	3.6	4.2	8.4	30

Table 5. Test set-up, pass criteria and gamma (and proton) radiation level for the radiation tests of the optical transmitters.

Fibreoptic Transmitter Measurement				
Measurements (Not In-flux)	- Variation of diode laser optical output power versus operating current – including calculation of both Threshold Current and Slope (measured before step 1 & at the end of each radiation step) - Diode laser wavelength (measured before step1 and after step 3 only) - Temperature of diode laser (measured before step1 and after step 3 only) - Ambient temperature (measured before step 1 & at the end of each radiation step)			
Equipment Required at Test Facility	- Diode laser power supply - Optical Spectrum Analyser - Integrating Sphere or Large Area Thermopile Power Monitor - Single mode optical fibre and lens system to couple light from laser - Optical attenuators			
Pass Criteria	- Diode laser slope efficiency degrades less than 1.5 dB - Diode laser wavelength change (temperature corrected) is less than 10 nm			
Mounting	The diode laser will be mounted in such a way that the semiconductor is in the radiation, but the leads and connections are not.			
Procedure	The diode laser operating current versus optical output power will be measured prior to the first radiation step and after each subsequent radiation exposure step. All other measurements will be taken prior to the first radiation step and at the end of the total radiation exposure.			

Step	Dose rate [krad/h] Si	Exposure time [h]	Exposure time (cumulated) [h]	Total dose [krad] Si
1	3.6	1.4	1.4	5
2	3.6	1.4	2.8	10
3	3.6	2.8	5.6	20

Step	65 MeV Beam flux [cm ⁻² s ⁻¹]	Beam time [s]	Beam time (cumulated) [s]	Cumulative Fluence
1	1*10 ⁷	508s	508s	5.08*10 ⁹
2	1*10 ⁷	508s	1016s	1.17*10 ¹⁰
3	1*10 ⁷	1016s	2032s	2.34*10 ¹⁰

Table 6. Test set-up, pass criteria and gamma radiation level for the radiation tests of the discriminator.

Discriminator IC				
Measurements (Not In-flux)	- Step response of discriminator IC (measured before step 1 & at the end of each radiation step) - Ambient temperature (measured before step 1 & at the end of each radiation step)			
Equipment Required at Test Facility	- Testboard to connect Discriminator IC - power supply			
Pass Criteria	- Sensitivity in accordance with manufacturer's data sheet - Output signal complies with LICEF input signal requirements			
Mounting	The discriminator IC will be mounted in such a way that the semiconductor is exposed to the radiation, but the leads and connections are not.			

Step	Dose rate [krad/h]	Exposure time [h]	Exposure time (cumulated) [h]	Total dose [krad]
	Si			Si
1	3.6	2.1	2.1	7.5
2	3.6	2.1	4.2	15
3	3.6	4.2	8.4	30

Table 7. Test set-up, pass criteria and gamma radiation level for the radiation tests of the laser driver.

Laser Driver				
Measurements (Not In-flux)	- Step response of Laser driver (measured before step 1 & at the end of each radiation step) - Ambient temperature (measured before step 1 & at the end of each radiation step)			
Equipment Required at Test Facility	- Testboard to connect Laser driver - power supply			
Pass Criteria	Loss in optical output of diode due to laser driver degradation <1.5 dB			
Mounting	The Laser driver will be mounted in such a way that the semiconductor is in the radiation, but the leads and connections are not.			

Step	Dose rate [krad/h]	Exposure time [h]	Exposure time (cumulated) [h]	Total dose [krad]
	Si			Si
1	3.6	1.4	1.4	5
2	3.6	1.4	2.8	10
3	3.6	2.8	5.6	20

2.5 PROBA-II Mission

The technology demonstration PROBA-II mission was launched together with SMOS in November 2009 carrying the first Fiber Optic Sensor Demonstrator (FSD) system made by MPBC, Canada. The FSD included several photonic and optoelectronic devices like fiber lasers and fiber Bragg gratings applied to different sensors. It was originally built for 2 years of mission and, as reported in [7], has been working flawlessly ever since 14.5 years after and to the best of our knowledge even until the moment this paper is written almost 17 years after its launch. PROBA-II had a RADFET instrument for measuring the radiation levels over the mission years. The complete analysis on the impact of radiation on the FSD is presented in detail [7] with the main findings repeated here as they were of interest for correlating with the present work for SMOS. Specifically:

- The laser diodes power decreased by 10%.
- The Fabry Perot sweeping intensity at the end of the optical line before the FBG decreases by about 30% (this includes the laser diode effects of 10% plus the radiation effects on the Erbium Doped Fiber laser (EDF), and probably the effect of aging of optical components.
- The total gamma radiation received by the FSD, and measured with a RADFET, is 14.7 krad, i.e. about 1 krad/year in concordance with the estimation deduced from the modelling.
- The FSD can follow the detailed variations of the effect of small temperature variations, a few degrees °C during the orbit cycle, on its components such as the laser diodes and the RADFET and gives the variation as a function of the temperature.
- Having a manual command (bootloader) was very helpful in identifying and solving the issues caused by the catastrophic single-event effects. It would also probably help to solve other issue cases, by following the test of execution of single commands.

3. METHODOLOGY FOR ASSESSMENT OF RADIATION

3.1 Modelling strategy and simulation parameters setup

To accurately estimate the Total Ionizing Dose (TID) and Displacement Damage Equivalent Fluence / Total Non-Ionizing Dose (DDEF/TNID) accumulated by the MIRAS Optical Harness (MOHA) over its operational lifetime, a 3D ray-tracing radiation simulation was conducted. The analysis utilized FASTRAD® (version 4.2.3), applying a sector analysis calculation based on the slant path method.

The ray-tracing analysis implemented 10.000 rays (100 theta count and 100 azimuth count) evenly distributed over 4π steradians per analysis point, from now on called as “detectors”. This sampling density significantly exceeds the minimum requirement of 1.800 rays per detector defined by [12].

The structural model was derived from the detailed 3D CAD geometry of the SMOS-MIRAS instrument (Fig. 2). The baseline model mass evaluated in FASTRAD® was 165.89 kg, representing approximately 47.4% of the total SMOS mass budget (~350 kg). In accordance with [13], simulation models accounting for less than 70% of the nominal equipment mass can be considered conservative. The original SMOS platform 3D model is not included in the FASTRAD® simulation model. The TID and TNID analysis demonstrated that the inclusion of a 5 mm aluminium equivalent bottom panel to simulate the satellite platform had a negligible impact on the simulation results. Hence, to remain conservative, all the reported results exclude additional platform shielding.

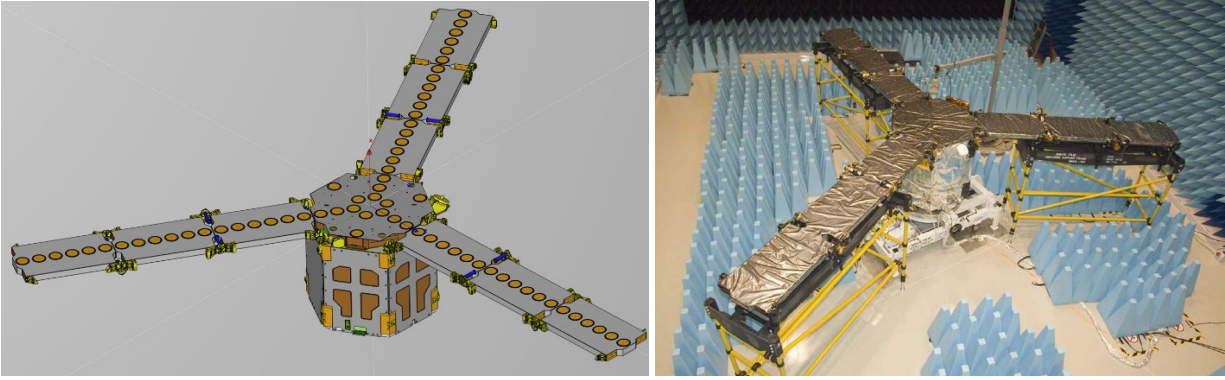


Figure 2. Detailed 3D FASTRAD® model of the SMOS-MIRAS instrument (left) and MIRAS payload at the Maxwell EMC chamber of ESTEC.

Every unit to be studied was modelled as a simple aluminium box with a certain thickness, typically between 1.2 mm and 2 mm, depending on the unit design (Fig. 3). Inside the units, several Printed Circuit Boards (PCBs) were placed according to their flight model design. The PCBs were considered as polyamide with a typical thickness of 1.2 mm.

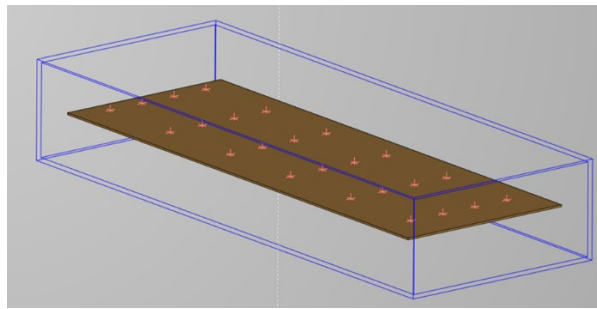


Figure 2. Example of a SMOS unit modelled in FASTRAD®. In blue, the aluminium housing (wireframe view). In brown, the PCB. The points in red are the grid of detectors.

3.2 Detectors placement strategy

Radiation analysis detectors were strategically placed throughout the instrument CAD model across two main domains:

1. *Equipment PCBs*: Simulation detectors were arranged in a regular matrix grid on both top and bottom sides of the PCBs of all the equipment analysed, including the CCU, CMNs, LICEF receivers, Noise Sources, Power Dividers, and Splitters. The component packages are not used in the FASTRAD® simulation model.
2. *Optical Harness Routing*: Multiple detectors were placed continuously along the physical routing of the optical fibers in the following areas: inside the three different segments of an arm, in the arms hinges, along the structure struts and inside the SMOS structure. In the arm hinges, optical harness is not directly exposed to the radiation environment but slightly protected by the thermal hardware. In order to take into account this protection, these detectors have been placed inside a Kapton material sphere of 0.0508 mm (1 mil Kapton).

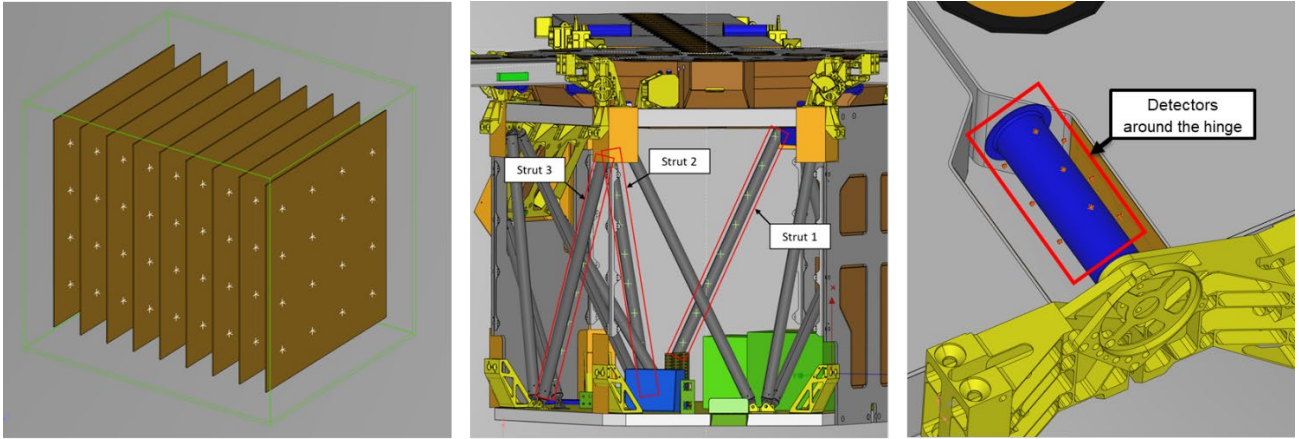


Figure 3. Examples of different detectors placement in the FASTRAD® simulation model.

3.3 Environmental inputs for the analysis

The SMOS radiation environment curves for TID and TNID, together with the DDEF 10 MeV equivalent proton fluence have been used as the environment input in FASTRAD® for the ray-tracing analysis. Simulations were executed for both the nominal 3-year mission and the extended 15-year operational duration.

3.3.1 TID and DDEF Results

The overall results demonstrate a clear difference to radiation exposure between the analysed points inside the different units of study and the analysed points along the optical harness routing.

The results showed that about 1 krad/year was impacting the different equipment that included the optoelectronics for the transmit/receive parts as well as the passive photonic devices like splitters and most of the fiber cables. The accumulated radiation was about 15 krad in 15 years, being up to about 26 krad the maximum accumulated TID in certain detectors analysed. The maximum DDEF reached inside these units is 2.32E^{+10} p/cm² [10 MeV].

However, the analysis revealed that, at certain parts of the instrument, like the arm hinges, the optical fiber cables were exposed to remarkably higher radiation levels at the rate of hundreds of krad/year. The variation of the radiation received by the fiber optic cabling of the MOHA is hence relevant depending on the location of the routing. In unshielded or minimally shielded areas, the TID levels are significantly higher. While in the internal structural routings (struts, arms and inside the SMOS structure) reached a maximum TID of 362 krad to 724 krad over 15 years, the arm deployment hinges, shielded only by 0.0508 mm of Kapton, were exposed to higher TID levels. In these areas, the accumulated maximum TID was of 6.39 Mrad and a maximum DDEF of 2.97E^{+11} p/cm² [10 MeV] on the fiber optic cabling surface. It is important to remark that, depending on the cabling physical construction, the TID received inside the cable will be lower than the 6.39 Mrad reached in its surface, as the dose received gets reduced while crossing the different layers of the cable. Table 8 presents a summary of the TID and DDEF values at the different detector locations for a 3 and a 15 year mission.

According to tables 3 to 7, several tests were performed on the optical components up to the following irradiation steps:

- Optical Fiber: tested up to 3.70 Mrad
- Fiberoptic Receiver: tested up to 30 krad
- Fiberoptic Transmitter: tested up to 20 krad
- Discriminator IC: tested up to 30 krad
- Laser Driver: tested up to 20 krad

All the TID results obtained from the ray-tracing analysis with FASTRAD® are well below the tested values for a 3 year mission. Even for a 15 years mission, the vast majority of the TID levels reached inside the different units analysed are covered by the irradiation tests performed. With respect to the optical fibers, except for the detectors analysed in the hinges, the rest of the detectors along the routing, for a 15 years mission, receive a TID lower than the tested one of 3.70 Mrad.

Table 8. Summary of the TID and DDEF results of the different units and optical fibers location

	3 years mission			15 years mission	
	Max TID [krad]	Max DDEF [p/cm ²] 10 MeV		Max TID [krad]	Max DDEF [p/cm ²] 10 MeV
CCUs	1.804	3.67E+09		9.02	1.84E+10
CMNs	3.079	4.31E+09		15.395	2.16E+10
LICEFs	3.502	4.15E+09		17.51	2.07E+10
MOHA CCU	1.667	3.62E+09		8.335	1.81E+10
Noise sources	2.928	4.23E+09		14.64	2.12E+10
Power dividers	4.189	4.52E+09		20.945	2.26E+10
Splitters	5.247	4.64E+09		26.235	2.32E+10
Optical fibers Arm A	144.9	1.23E+10		724.5	6.15E+10
Optical fibers hinges	1277	5.94E+10		6385	2.97E+11
Optical fibers lower platform	72.56	7.97E+09		362.8	3.98E+10
Optical fibers struts	129.7	9.36E+09		648.5	4.68E+10
Optical fibers units platform	24.83	5.44E+09		124.15	2.72E+10

3.3.2 G_{kj} amplitude coefficients and relation with MOHA degradation through analysis of correlations

A decreasing trend in the amplitude of the correlation coefficients G_{kj} averaged for the 2556 baselines of MIRAS has been observed over the years of the mission (Fig. 5). This decaying trend was suspected to be linked to a possible degradation of the optical link due to radiation. The methodology to assess whether there was indeed such a link was based on the study of the evolution of the normalized correlations during the time span of the mission.

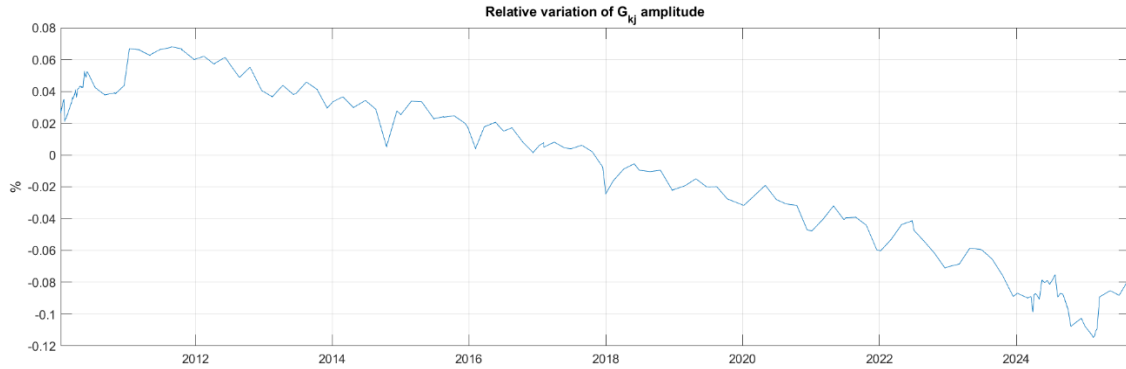


Figure 4. Relative variation of the amplitude of the G_{kj} terms averaged for the 2556 baselines in MIRAS over the years. The decaying trend and seasonal behaviour are apparent.

The analysis of the data revealed that the normalized correlations of the in-phase (I) and quadrature (Q) components of the signals with the deterministic signal "0" have progressively increased over the years. A consistent decrease of the normalized correlation of these signals with the deterministic signal "1" was also verified. An increase in the noise present in the fibers as a result of their degradation would translate into a change in the standard deviation of the signal entering the correlator. Such variation would not modify the value of the 1-bit correlation provided that the threshold considered in the correlation remains invariant and centred in 0. On the contrary, a variation of the threshold value would translate into a variation in the correlations as observed in the data (Fig. 6 and 7).

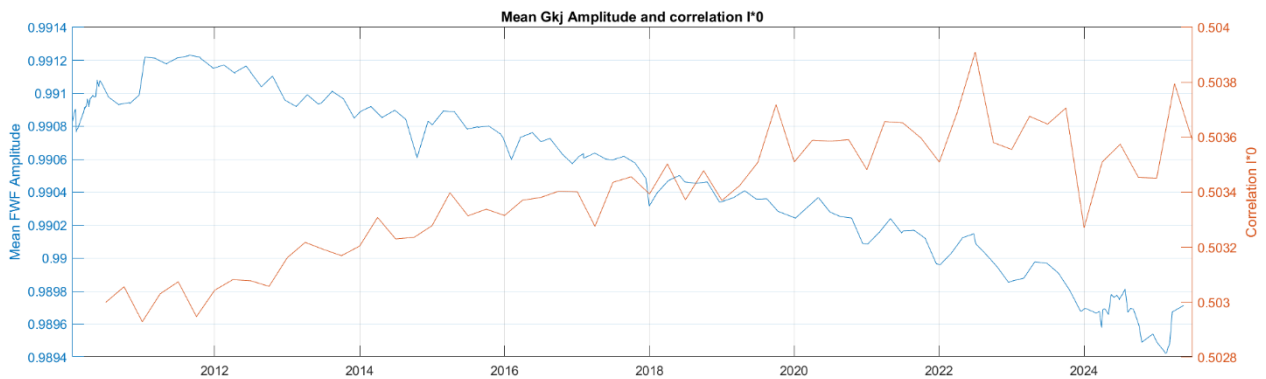


Figure 5. Blue: G_{kj} amplitude averaged for the 2556 baselines. Red: normalized value of the 1-bit correlation of I-component signals and "0", where each data point corresponds to the average of all baselines during one semi-orbit.

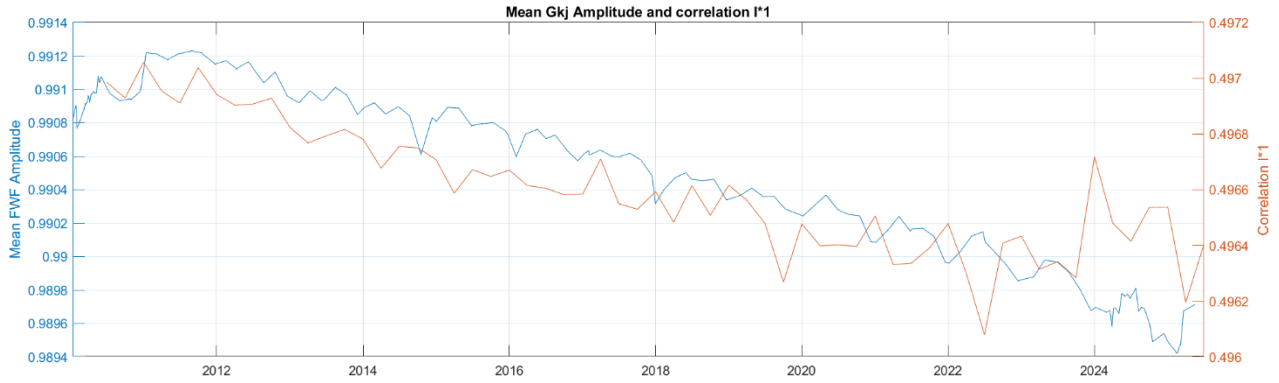


Figure 6. Blue: Gkj amplitude averaged for the 2556 baselines. Red: normalized value of the 1-bit correlation of I-component signals and “1”, where each data point corresponds to the average of all baselines during one semi-orbit.

In the light of the previous results, the next step of the analysis consisted of assessing the evolution of the offset due to the samplers threshold, which is noted as ΔZ within the context of SMOS processing (Fig. 8). The values of ΔZ were computed from the correlation data. They revealed that ΔZ has progressively increased over the years. In addition, its evolution shows local minima around the Winter Solstice every year and it is especially apparent since 2022. This evolution resembles the thermal profile observed in the equipment of MIRAS. It is worth reminding that the variation of ΔZ has no impact on science as it is compensated in processing. It is nevertheless a sign of instrument degradation, be it in the optical link or any other part of the instrument.

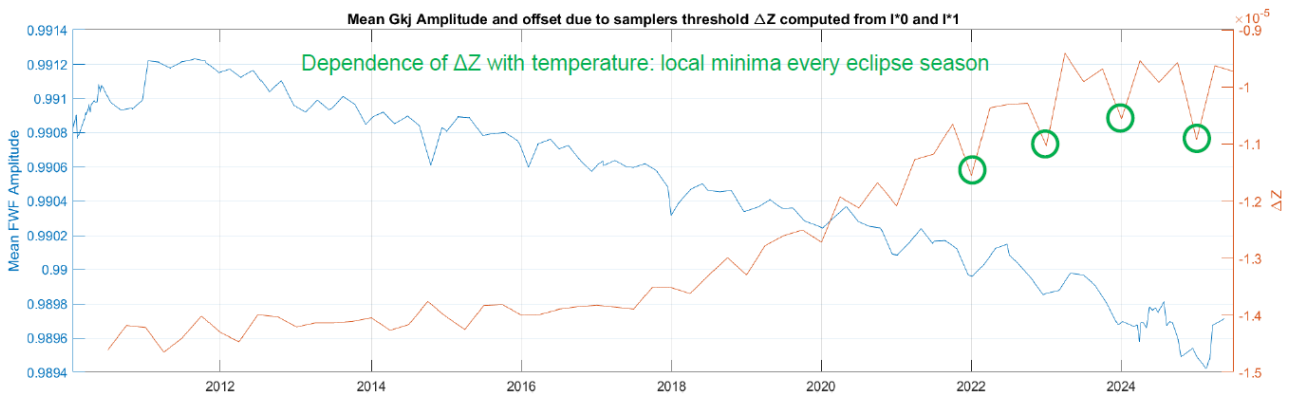


Figure 7. Blue: Gkj amplitude averaged for the 2556 baselines. Red: value of ΔZ computed from the correlations. The local minima in ΔZ around every Winter Solstice are highlighted in green.

The final stage of the analyses focused on trying to correlate the variation of ΔZ with the temperature evolution of the equipment mentioned before. The task successfully resulted in identifying a very accurate match between the evolution of ΔZ and the temperature profile of the CCU. In particular, the previously mentioned local minima of ΔZ around the eclipse season of SMOS match the minima in temperature of the CCU registered every year (Fig. 9). Both profiles show that these minima are especially noticeable since 2022. The findings described suggest that the evolution of the correlations with 0 and 1 over the mission duration is closely related to thermal effects rather than any potential degradation in MOHA due to radiation.

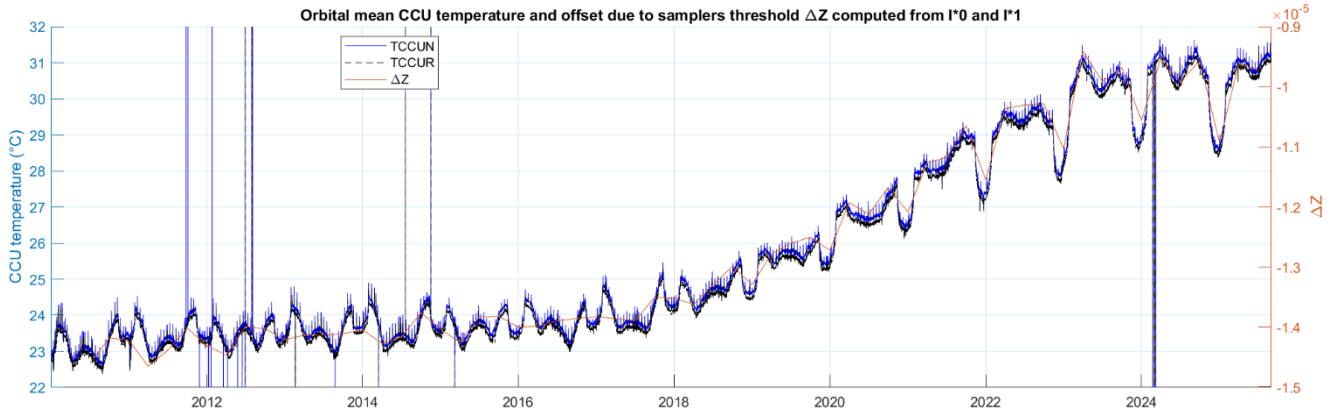


Figure 8. Thermal profile of the nominal (continuous blue) and redundant (discontinuous black) CCU together with the value of ΔZ over the years. The match between the thermal profiles and the samplers' threshold is accurate. In particular, both data show local minima during SMOS eclipse season which are especially apparent since 2022.

4. CONCLUSIONS

Based on the experience during the pre-development activities of MIRAS, it was decided to use an optical harness (MOHA) to avoid EMC issues which could severely degrade the performance of the SMOS payload, bringing also other mechanical advantages. After almost 17 years at the writing of this paper, SMOS mission is fully operational, becoming an excellent laboratory in space for evaluating radiation effects on opto-electronic components and optical cables (SMOS is as of March 2026 the longest flying-in-space operational earth observation satellite of Europe, after PROBA-I). The aim of this paper has been to estimate, by detailed simulations, the radiation levels experienced by the SMOS mission during its first 15 years of flight, comparing the simulated results to the levels measured by PROBA-II mission (in a very similar orbit than SMOS) as well as to the radiation levels with which the MOHA parts were tested and screened when building MIRAS. The paper has also presented evidence of the lack of any degradation in the correlation coefficients or the samplers threshold which could be linked to any deterioration of MOHA.

In conclusion, the MOHA components were tested to much larger radiation levels than those experienced over the entire mission duration (roughly 1 Krad/year), showing ample margin over the original design lifetime of SMOS (3 years), and no performance degradation is observed which could be attributed to any radiation effects on the optical harness parts. It is here noted that, since the clock and raw data signals transported by MOHA are digital, we cannot detect small degradation levels that pass unnoticed when evaluating the correlation performances of the instrument.

Looking back in the early 2000's when SMOS was designed, the use of fiber optics, as a first-timer technology with the impact of the space environment on it being unknown, was seen with high reservation. SMOS took a real risk. The experience, as witnessed today after nearly 17 years of flawless operation of MOHA in orbit, and confirmed by the simulation results on the level of radiation presented in the paper, provides guidance and confidence for the use of fiber optics and the associated transceivers in space as a standard technology.

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