

Real-Time Monitoring of Fiber Optic Grating Sensors under Gamma Irradiation for Planetary Exploration

Patricia Mesonero Santos^{c*}, Tomás Belenguer Dávila^a, Andoni G. Moral Inza^b, Olga Prieto

Ballesteros^c, Raquel López Heredero^a

^a Space Optics Department, Instituto Nacional de Técnica Aeroespacial (INTA),

^b Space Programs and Systems Department, Instituto Nacional de Técnica Aeroespacial (INTA),

^c Centro de Astrobiología (CAB), INTA-CSIC

Ctra. Ajalvir km 4, 28850 Torrejón de Ardoz, Madrid, SPAIN

ABSTRACT

Optical fiber grating sensors are attractive candidates for monitoring physical and chemical parameters in radiation environments such as space missions and nuclear facilities due to their low weight, compact size, electromagnetic immunity, and multiplexing capability. Radiation-induced effects can affect the optical response of fiber grating sensors and should be characterized to enable compensation strategies and support sensor self-calibration for reliable operation in radiation-exposed space environments.

In this work, a gamma irradiation campaign was carried out to study the in-situ behaviour of fiber optic grating sensors under ionizing radiation exposure. The experiments were performed at the Co-60 gamma irradiation facility of the University of Santiago de Compostela (Spain), reaching a Total Ionizing Dose (TID) of 200 krad(Si), representative of planetary exploration missions. The study included long-period fiber gratings (LPFGs), tilted fiber Bragg gratings (TFBGs), and a radiation-hardened fiber Bragg grating (FBG) used as a temperature reference.

Real-time characterization was performed during irradiation. LPFGs exhibited a clear radiation-induced wavelength shift during exposure, reaching dip wavelength shift (DWS) values between 1.2 and 1.5 nm after the accumulated TID. Regarding TFBG sensors, the wavelength variations remained within temperature-induced fluctuations (~6 pm), indicating a high robustness under the applied radiation conditions.

The results demonstrate a continuous DWS increase with accumulated dose and confirm the importance of real-time monitoring in supporting the selection and calibration of fiber optic sensors for radiation environments, including planetary missions.

Keywords: Fiber optic sensors, LPFG, TFBG, Gamma irradiation, Radiation effects, Real-time monitoring, In-situ measurements, Space applications.

1. INTRODUCTION

This work presents a real-time monitoring study of the effects of ionizing radiation on different fiber optic sensors exposed to radiation dose levels typical of planetary exploration missions to Mars.

Fiber grating sensors are of interest for aerospace applications compared to conventional sensing technologies due to their well-known advantages, including electromagnetic immunity, compact size, low weight, multiplexing capability, remote sensing operation, and robustness in harsh environments [1,2]. Furthermore, they can be used to monitor different physical and chemical parameters, making them attractive candidates for planetary exploration missions.

Fiber optic sensors have been investigated for space applications including thermal monitoring, structural health monitoring and propulsion subsystems. In particular, FBG-based sensors have been evaluated for thermal monitoring of a NASA Mars rover antenna subsystem, highlighting their potential for future planetary exploration platforms. Since such missions operate in radiation environments containing gamma rays and ionizing particles, understanding the radiation response of fiber grating sensors is essential for their deployment in future planetary exploration missions [3]. In addition to gamma rays, space radiation environments contain ionizing particles such as protons, electrons and heavy ions. These particles can induce radiation-induced attenuation (RIA) and refractive index changes in silica-based optical fibers, which may affect the spectral response of fiber grating sensors [4].

Radiation-induced effects can affect the spectral response of optical fiber sensors, leading to changes in the measured parameters. Therefore, a proper characterization of these effects is essential for the development of compensation and calibration strategies that ensure reliable sensor operation in radiation environments, such as space [4,5].

In this context, real-time monitoring is a fundamental tool because it enables in-situ measurements during irradiation and allows the continuous tracking of sensor response as the accumulated dose increases.

In order to investigate these effects, a gamma irradiation campaign was carried out at the Co-60 irradiation facility of the University of Santiago de Compostela to evaluate the behaviour of different fiber grating sensors, including Long-Period Fiber Gratings (LPFGs) [6], Tilted Fiber Bragg Gratings (TFBGs) [7], and Fiber Bragg Gratings (FBGs), under dose levels representative of planetary exploration missions.

The study focuses on two types of fiber grating sensors, LPFGs and TFBGs, whose responses under ionizing radiation were evaluated through real-time monitoring during irradiation [8,9]. A radiation-hardened FBG was also included as a temperature reference sensor to compensate for thermal variations during the measurements. The results provide a direct comparison of the radiation response of LPFG and TFBG sensors under gamma irradiation conditions representative of planetary exploration missions.

2. EXPERIMENTAL SETUP

This study focuses on the response of LPFGs and TFBGs to ionizing radiation. The sensors were fabricated using different inscription techniques, including UV laser and CO₂ laser inscription for the LPFGs and femtosecond laser inscription for the TFBGs. Their radiation response was evaluated using real-time monitoring during irradiation. A radiation-hardened FBG was additionally included as a temperature reference sensor to compensate for temperature variations during the measurements.

The irradiation campaign was carried out at the Co-60 irradiation facility of the University of Santiago de Compostela (Spain). The facility is composed of an irradiation room containing the Co-60 source and a separate control room. The sensors under test were connected by means of fiber optic cables to an optical interrogator located in the control room, allowing remote acquisition of the spectral response during the tests. A 1 cm thick RW3 plastic plate was positioned between the Co-60 source and the sensors to ensure appropriate irradiation conditions during the test. Depending on their position within the irradiation setup, the sensors were exposed for approximately 9 h and 3 min to dose rates of 22.1 krad(Si)/h or 19.1 krad(Si)/h, corresponding to source-to-sensor distances of 52 cm and 56 cm, respectively. Consequently, the accumulated dose received by each sensor depended on its position within the irradiation setup. This configuration allowed continuous real-time monitoring of the optical response throughout the irradiation campaign (Figure 1).

To reproduce the strain conditions applied during LPFG fabrication, a weight of 9.71 and 8.74 g was attached to one end of the LPFG-1 and LPFG-2 sensor, respectively, during the irradiation campaign. This configuration allowed recovery of the attenuation-band wavelengths observed after inscription and ensured stable and repeatable spectral measurements throughout the test.

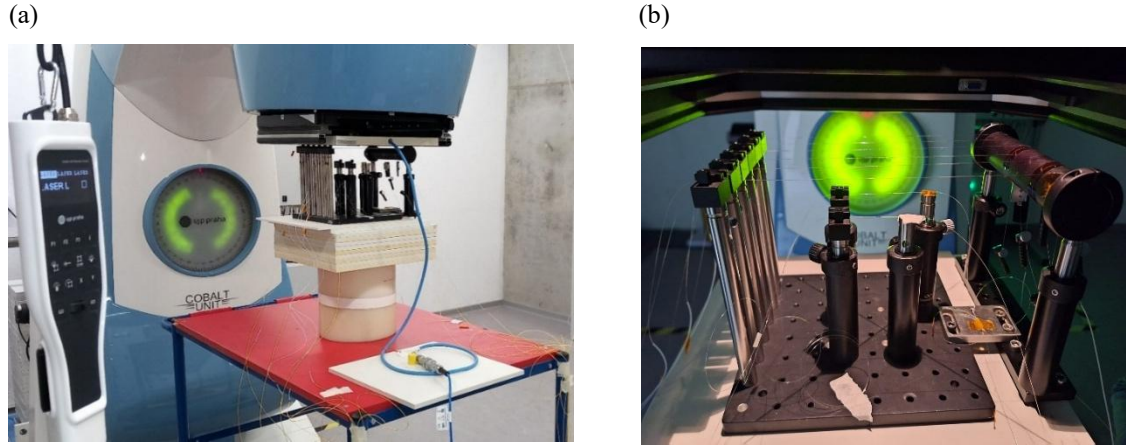


Figure 1. Experimental setup used during the irradiation campaign: (a) Co-60 irradiation facility at the University of Santiago de Compostela. (b) Optical fiber mounting configuration used for real-time monitoring during irradiation.

The experimental kit was composed of LPFG sensors fabricated using two different inscription techniques, UV laser and CO₂ laser inscription, in order to evaluate the influence of the inscription method on their response to gamma radiation. In addition, a femtosecond-laser-inscribed TFBG sensor was included in the kit to investigate the response of this grating technology under comparable irradiation conditions. A radiation-hardened FBG sensor was also incorporated as a reference for temperature monitoring during the irradiation campaign and thermal compensation of the response of the sensors. The optical transmission spectra of the fiber optic sensors included in the irradiation campaign are shown in Figure 2. The main characteristics of the investigated sensors are summarized in Table 1. For the TFBG sensor, the angle parameter corresponds to the tilt angle of the grating planes with respect to the fiber longitudinal axis.

Table 1. Fiber optic sensor specifications.

Fiber optic sensor type	Fabrication method	Fiber type	Period (μm)	Length (mm)	Angle ($^\circ$)
LPFG-1	UV laser	SMF-28 (Corning)	675	72	-
LPFG-2	CO ₂ laser	SMF-28 (Corning)	550	30	-
TFBG	Femtosecond laser	SMF-28 (Corning)	Not provided by manufacturer	8	6
Rad-Hard FBG	Femtosecond laser	RRSMFB (Fujikura)	Not provided by manufacturer	5	-

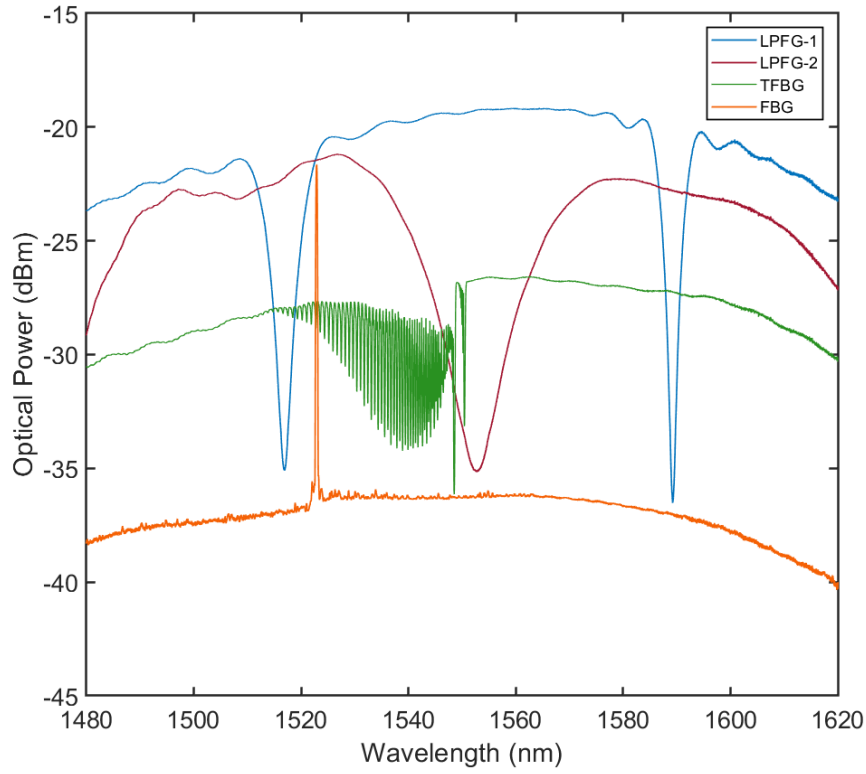


Figure 2. Optical transmission spectra of the fiber optic sensors included in the irradiation campaign.

Real-time characterization was performed during irradiation using an optical interrogator (HYPERION si255), providing a wavelength-tracking accuracy of 1 pm and a spectral resolution of 8 pm. The temperature in the irradiation room was maintained within ± 0.5 °C during the test.

3. RESULTS AND DISCUSSION

The results presented in this section are based on in-situ measurements acquired during gamma irradiation. Real-time monitoring allowed the continuous tracking of the sensor response as a function of accumulated dose.

The investigated optical fiber grating sensors exhibited distinct responses under gamma irradiation, depending on the grating type and inscription technique. The LPFG sensors exhibited a clear wavelength shift during gamma irradiation while the TFBG sensor showed wavelength shifts of only a few picometers. The following sections present the response of the different sensors as a function of the accumulated dose.

3.1 LPFG Sensors

The LPFG sensors exhibited a clear wavelength shift during gamma irradiation, demonstrating their sensitivity to ionizing radiation. The wavelength shift increased continuously throughout the irradiation campaign as the accumulated dose increased.

The UV-inscribed LPFG sensor (LPFG-1) presents two attenuation bands within the monitored spectral range. Both attenuation bands were monitored during the irradiation test, showing a progressive wavelength shift as the accumulated dose increased up to 200 krad(Si), as shown in Figure 3.

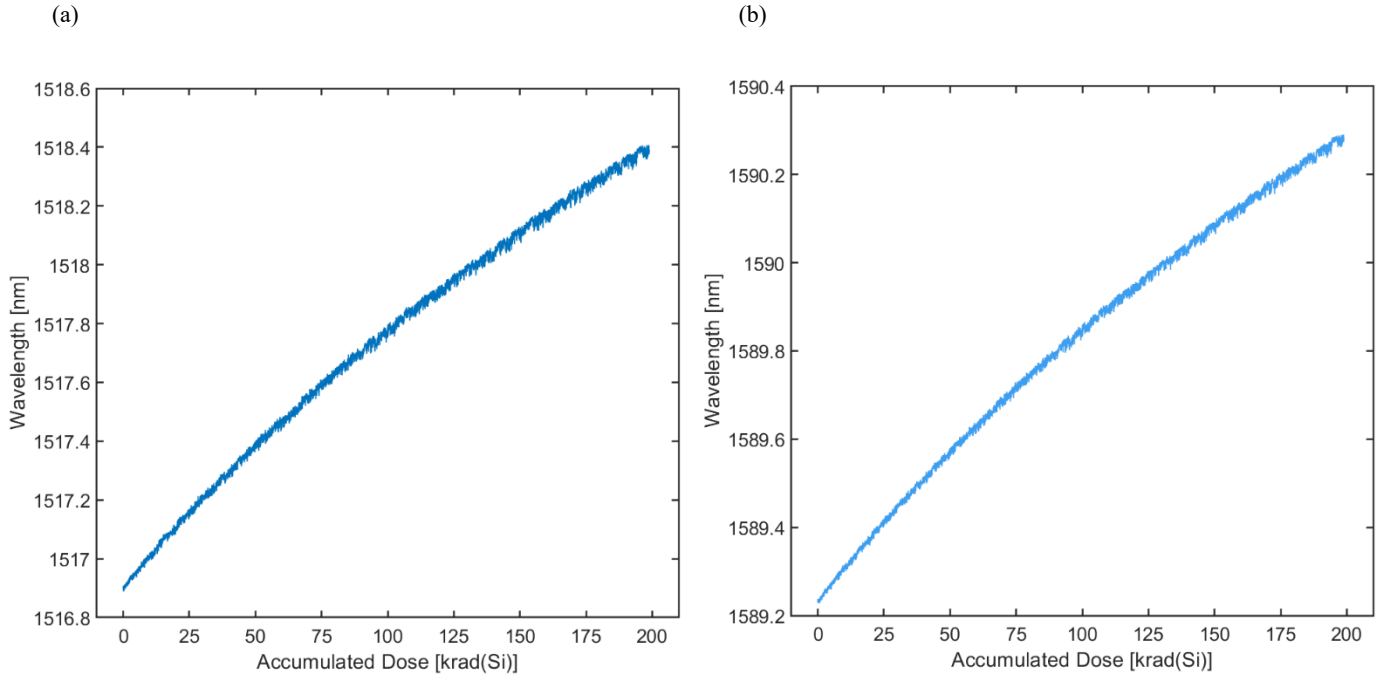


Figure 3. Radiation-induced wavelength shift of the two attenuation bands of LPFG-1 as a function of accumulated dose up to 200 krad(Si): (a) attenuation band 1 and (b) attenuation band 2.

Different radiation sensitivities were observed for the two attenuation bands. The first band reached a maximum dip wavelength shift (DWS) of 1.494 nm at the end of the irradiation campaign, whereas the second band exhibited a lower DWS of 1.054 nm.

Temperature fluctuations during the irradiation campaign remained around 0.5 °C, corresponding to estimated thermally induced wavelength variations below 36 pm and 22 pm for the first and second attenuation bands, respectively. These contributions represent only 2.4% and 2.1% of the measured DWS values, confirming that the observed wavelength shifts were dominated by radiation-induced effects.

The response of a CO₂-inscribed LPFG sensor (LPFG-2) was also evaluated during the irradiation campaign. A wavelength shift of 1.349 nm was observed at an accumulated dose of 200 krad(Si) (Figure 4). The progressive red shift observed with increasing accumulated dose confirmed the sensitivity of the sensor to ionizing radiation.

Temperature fluctuations during the irradiation campaign remained around 0.5 °C, resulting in an estimated thermally induced wavelength variation of approximately 19 pm. This contribution represents only 1.41% of the measured DWS. As observed for LPFG-1, the measured DWS was dominated by radiation-induced effects.

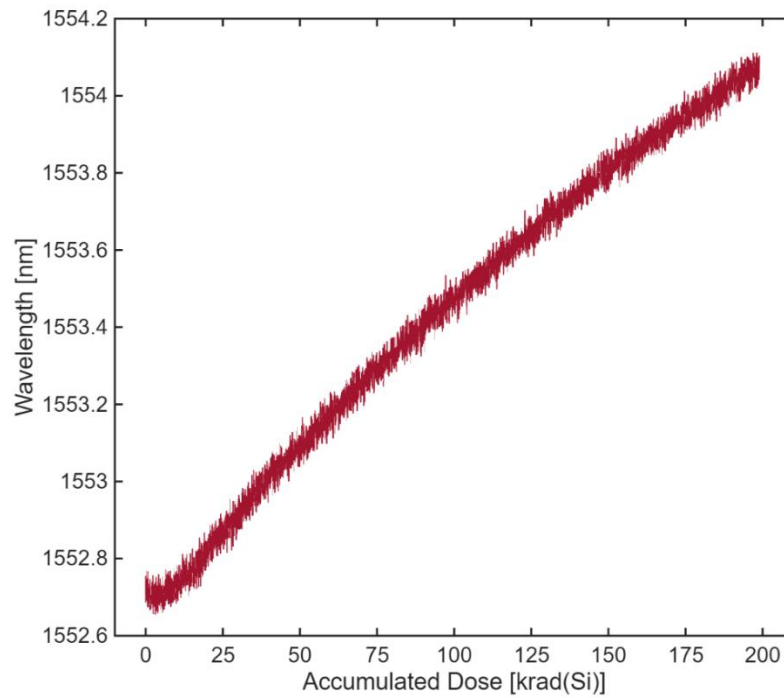


Figure 4. Radiation-induced wavelength shift of LPFG-2 as a function of accumulated dose up to 200 krad(Si).

A clear radiation-induced wavelength shift was observed in both UV-inscribed and CO₂-inscribed LPFG sensors, reaching values between approximately 1 and 1.5 nm at the end of the irradiation campaign. These results are consistent with previously reported gamma-irradiation responses of LPFG sensors [10].

In all cases, the contribution of temperature fluctuations remained below 3% of the measured response, confirming the high radiation sensitivity of LPFG sensors under gamma irradiation.

Table 2. Summary of the LPFG sensor response during gamma irradiation.

Sensor ID	Inscription technique	DWS (nm)	Thermal contribution (%)
LPFG-1 Band 1	UV laser	1.494	2.4
LPFG-1 Band 2	UV laser	1.054	2.1
LPFG-2	CO ₂ laser	1.349	1.4

3.2 TFBG Sensor

The response of a femtosecond-laser-inscribed TFBG sensor was also evaluated during the irradiation campaign. In the case of the TFBG sensor, minimal wavelength shifts were observed, as shown in Figure 5. The measured wavelength shifts were comparable to the temperature-induced variations associated with the thermal fluctuations measured by the radiation-hardened FBG sensor used for temperature monitoring. Therefore, the observed response can be mainly attributed to thermal effects rather than to radiation-induced changes.

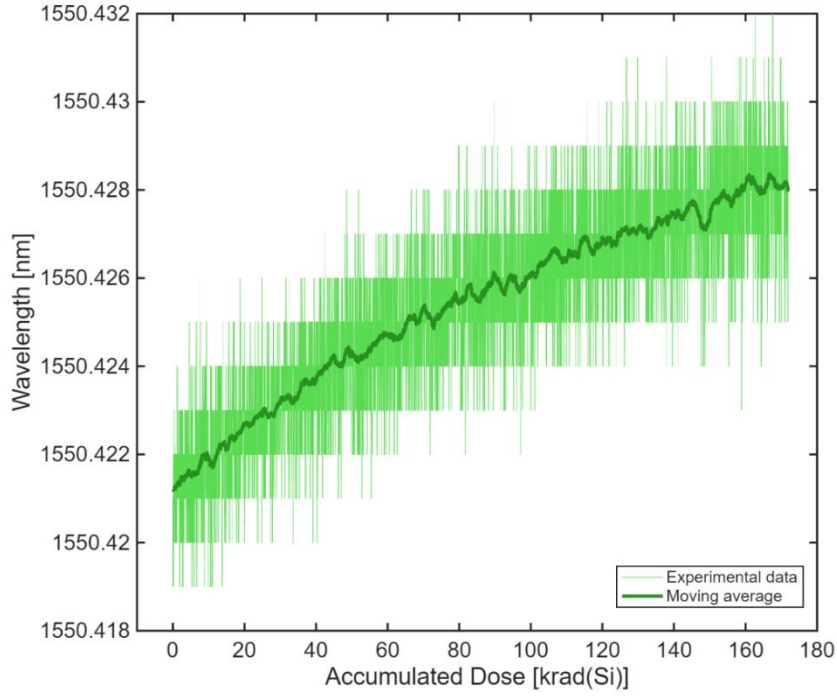


Figure 5. Radiation-induced wavelength shift of the TFBG core mode as a function of accumulated dose up to 170 krad(Si). The experimental data are shown together with a moving-average curve, calculated in MATLAB®, to show the global wavelength evolution during irradiation.

The core mode reached a maximum DWS of approximately 6 pm at an accumulated dose of 170 krad(Si). Temperature fluctuations remained around 0.5 °C, resulting in an estimated thermally induced wavelength variation of approximately 5.5 pm. Since both values are of the same order of magnitude, the observed wavelength shifts can be mainly attributed to thermal fluctuations. Similar wavelength variations of around 6 pm were observed for the monitored cladding modes, supporting the conclusion that the TFBG response was dominated by temperature fluctuations rather than radiation-induced effects.

3.3 Radiation-Hardened FBG

A radiation-hardened FBG sensor was included in the irradiation setup to monitor temperature fluctuations during the irradiation campaign (Figure 6). These measurements were used to estimate the thermal contribution to the wavelength shifts observed in the LPFG and TFBG sensors, allowing a more reliable evaluation of radiation-induced effects.

The wavelength shift observed in the radiation-hardened FBG sensor was consistent with the temperature fluctuations recorded during the irradiation campaign. A maximum wavelength shift of approximately 6 pm was observed, corresponding to temperature variations around 0.5 °C. These results confirm the thermal stability of the irradiation conditions and provide a reliable reference for the evaluation of temperature-induced effects in the investigated sensors [11].

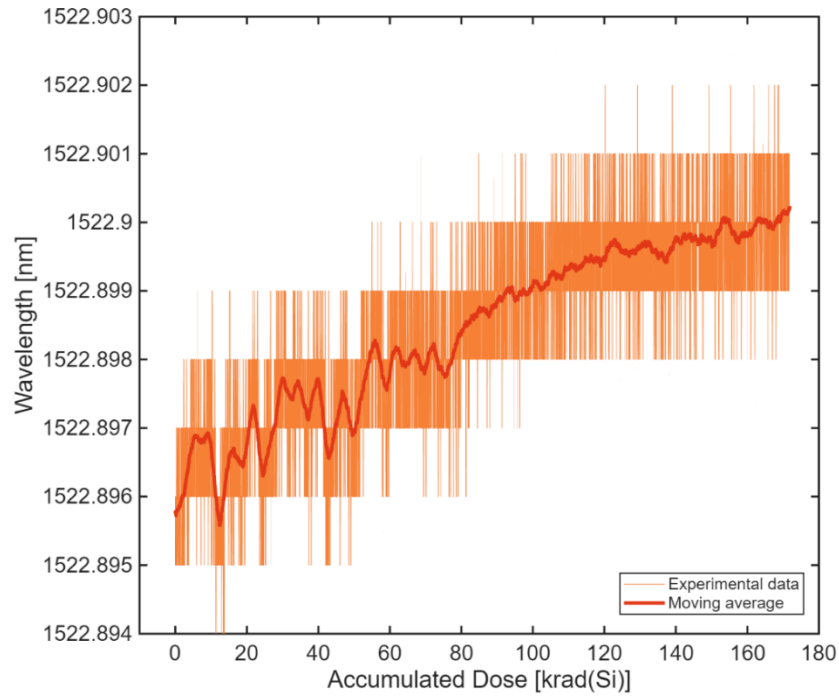


Figure 6. Wavelength shift of the radiation-hardened FBG sensor as a function of accumulated dose up to 170 krad(Si). The experimental data are shown together with a moving-average curve, calculated in MATLAB®, to show the global wavelength evolution during irradiation.

4. CONCLUSIONS

In this study, a gamma irradiation campaign was carried out to investigate the real-time response of LPFG and TFBG sensors under ionizing radiation levels representative of planetary exploration missions. Real-time measurements allowed the continuous tracking of the sensor response throughout irradiation and provided a direct comparison of the radiation response of LPFG and TFBG sensors.

The LPFG sensors exhibited clear radiation-induced wavelength shifts, reaching DWS values between approximately 1 and 1.5 nm at the end of the irradiation campaign. In contrast, the TFBG sensor exhibited wavelength shifts on the order of a few picometers, comparable to the wavelength shifts observed in the radiation-hardened FBG reference sensor used for temperature monitoring. In the case of the TFBG sensor, the results suggest robustness under the applied ionizing radiation conditions.

The results confirm that ionizing radiation can affect the spectral response of LPFG sensors and therefore, this effect needs to be considered when these sensors are employed in planetary exploration missions. The implementation of compensation and self-calibration strategies remains essential to distinguish radiation-induced effects from variations associated with the physical or chemical parameter under measurement, allowing a more accurate interpretation of the sensor response in radiation environments, including space missions. In contrast, the response observed in the TFBG sensor shows its potential for sensing applications in radiation environments.

ACKNOWLEDGEMENTS

Authors would like to thank the Agencia Estatal de Investigación (AEI) of the Spanish Ministry of Science, Innovation and Universities for the support provided through MICIU/AEI/10.13039/501100011033 and ERDF/EU grant PID2022-142490OB-C33. The authors also acknowledge INTA (TOCDE 18002) for funding support of all the activities described in this paper.

REFERENCES

- [1] Rovera A, Tancau A, Boetti N, Dalla Vedova MDL, Maggiore P, Janner D. Fiber Optic Sensors for Harsh and High Radiation Environments in Aerospace Applications. *Sensors*. enero de 2023;23(5):2512. doi:10.3390/s23052512
- [2] Mihailov SJ. Fiber Bragg Grating Sensors for Harsh Environments. *Sensors*. febrero de 2012;12(2):1898-918. doi:10.3390/s120201898
- [3] McKenzie I, Ibrahim S, Haddad E, Abad S, Hurni A, Cheng LK. Fiber Optic Sensing in Spacecraft Engineering: An Historical Perspective From the European Space Agency. *Front Phys*. 15 de noviembre de 2021;9:719441. doi:10.3389/fphy.2021.719441
- [4] Girard S, Kuhnenn J, Gusarov A, Brichard B, Van Uffelen M, Ouerdane Y, et al. Radiation Effects on Silica-Based Optical Fibers: Recent Advances and Future Challenges. *IEEE Trans Nucl Sci*. junio de 2013;60(3):2015-36. doi:10.1109/TNS.2012.2235464
- [5] Gusarov A, Hoeffgen SK. Radiation Effects on Fiber Gratings. *IEEE Transactions on Nuclear Science*. junio de 2013;60(3):2037-53. doi:10.1109/TNS.2013.2252366
- [6] Bhatia V. Applications of long-period gratings to single and multi-parameter sensing. *Opt Express*. 24 de mayo de 1999;4(11):457. doi:10.1364/OE.4.000457
- [7] Guo T, Liu F, Guan BO, Albert J. [INVITED] Tilted fiber grating mechanical and biochemical sensors. *Optics & Laser Technology*. abril de 2016;78:19-33. doi:10.1016/j.optlastec.2015.10.007
- [8] Esposito F, Srivastava A, Campopiano S, Iadicicco A. Radiation Effects on Long Period Fiber Gratings: A Review. *Sensors*. 2020;20(9):2729.
- [9] Stancalie A, Esposito F, Neguț CD, Ghena M, Mihalcea R, Srivastava A, et al. A New Setup for Real-Time Investigations of Optical Fiber Sensors Subjected to Gamma-Rays: Case Study on Long Period Gratings. *Sensors*. enero de 2020;20(15):15. doi:10.3390/s20154129
- [10] Esposito F, Stăncălie A, Neguț CD, Campopiano S, Sporea D, Iadicicco A. Comparative Investigation of Gamma Radiation Effects on Long Period Gratings and Optical Power in Different Optical Fibers. *Journal of Lightwave Technology*. septiembre de 2019;37(18):4560-6. doi:10.1109/JLT.2019.2910639
- [11] Kuhnenn J, Weinand U, Morana A, Girard S, Marin E, Périssé J, et al. Gamma Radiation Tests of Radiation-Hardened Fiber Bragg Grating-Based Sensors for Radiation Environments. *IEEE Transactions on Nuclear Science*. agosto de 2017;64(8):2307-11. doi:10.1109/TNS.2017.2673023