On-orbit degradation of recent space-based solar instruments and understanding of the degradation processes

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ABSTRACT

The space environment is considered hazardous to spacecraft, resulting in materials degradation. Understanding the degradation of space-based instruments is crucial in order to achieve the scientific objectives, which are derived from these instruments. This paper discusses the on-orbit performance degradation of recent space-based solar instruments. We will focus on the instruments of three space-based missions such as the Project for On-Board Autonomy 2 (PROBA2) spacecraft, the Solar Monitoring Observatory (SOLAR) payload onboard the Columbus science Laboratory of the International Space Station (ISS) and the PICARD spacecraft. Finally, this paper intends to understand the degradation processes of these space-based solar instruments.

Keywords: Space-based solar instruments, PROBA2, ISS, PICARD, On-orbit degradation.

1. INTRODUCTION

A large number of space-based instruments operates in a very harsh and extreme environment. They are subject to the effects of the space environment such as atomic oxygen, ultraviolet, radiation, charged particles, debris, and temperature extremes. These environments on their own and in combination can cause, among others, degradation of optical components of the space-based instruments. Solar instruments are vulnerable because their optical elements are exposed to unshielded solar radiation. These solar instruments suffer particularly from the effects of contamination. By return on operating experience,[1] we learned that solar instruments may suffer of substantial degradation due to a combination of solar irradiation and internal instrumental and spacecraft contaminations. We can then wonder on the contamination control plan set up to define the overall contamination control requirements for the design, fabrication, assembly, integration, testing and operation of each solar instrument. There is a lot of possible contamination sources (molecular and particulate) at the various stages of the development (fabrication, assembly, integration, test, storage, transport, launch site, launch ascent, separation, on-orbit commissioning phase, *etc.*). Contamination sources from molecular origins are numerous (machining oils, fingerprints, air fallout and personnel, cleaning solvents, soldering, lubricants, bagging material, test facilities, purges, containers, venting, engines, spacecraft separation from the launcher and maneuvers, ultraviolet interactions, propulsion systems, attitude and orbit control systems, materials outgassing, *etc.*). All these sources of contamination represent a danger to the success of the mission. In order to control contamination and protect sensitive optical surfaces of the solar instruments, the use of covers and protective solar shields must be considered. Moreover, the use of minimal contaminating materials is required. Selected materials of solar instruments (near optical elements) need to respect drastic conditions such as a total mass loss less than 0.1% and a collected volatile condensable material less than 0.01% according to the European Space Agency guidelines for spacecraft cleanliness control (ESA-PSS-51). However, these requirements are not always sufficient for very sensitive solar missions. Moreover, the use of oils and organic lubricants is normally prohibited for this kind of space-based mission. These requirements highlight the difficulties in relation with the definition of solar instruments. Solar metrology missions are the most demanding.

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In this manuscript, we present analyses of three solar instruments' degradation. The instruments analyzed are:

1. The Large Yield Radiometer (LYRA) onboard the European Space Agency Project for On-Board Autonomy 2 (PROBA2) spacecraft, which was launched in November 2009;
2. The SOLar SPECtrometer (SOLSPEC) of the Solar Monitoring Observatory (SOLAR) payload onboard the Columbus science laboratory of the International Space Station (ISS), which was launched in February 2008;
3. The Solar Diameter Imager and Surface Mapper (SODISM) telescope onboard the PICARD spacecraft, which was launched in June 2010.

The causes of the degradation of the three space-based instruments are presented, when they could be identified. The consequences of degradation have an impact on the scientific results. Past experiences show that redundancy is useful in recovery from degradation and damage from different causes. As example, the LYRA instrument has several redundant observation channels that can help to monitor the degradation trends and to improve the analysis of the scientific data. Finally, the knowledge of the damage mechanisms and thresholds allows the selection of more promising design and material selection to realize new disruptive space-based instrument for next decades.

2. LYRA ONBOARD PROBA2

LYRA[2] is a space-based solar radiometer onboard the PROBA2 spacecraft, which is the second spacecraft in the European Space Agency's series of PROBA low-cost spacecrafts. PROBA spacecrafts are used to validate new spacecraft technologies while also carrying scientific instruments. LYRA was designed and manufactured by a Belgian-Swiss-German consortium (ROB-SIDC, PMOD/WRC, IMOMEC, CSL, MPS and BISA) with additional international collaborations (Japan, USA, Russia and France). LYRA monitors the solar irradiance in four broad spectral ranges across the ultraviolet (UV) and the extreme ultraviolet (EUV). These observations are relevant to Solar Physics, Space Weather and Aeronomy. More specifically, LYRA passbands are:

- The Zirconium channel 1–20 nm,
- The Aluminum channel 1–80 nm,
- The Lyman Alpha channel 120–123 nm,
- The Herzberg channel 190–222 nm.

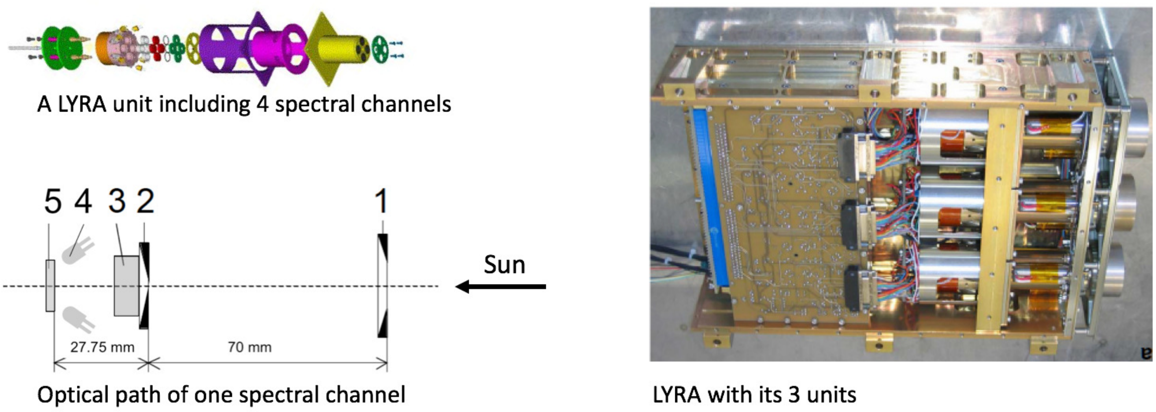

Figure 1: (left) LYRA optical path of one spectral channel and computer-aided design representation of a LYRA unit (four spectral channels). (right) LYRA with its three units during integration.

2.1 The LYRA radiometer design

The optical path of all LYRA channels is similar and illustrated in Figure 1. It consists in a cover (not shown on the schema), a view-limiting aperture (1), a precision aperture (2), a filter (3), and a detector (5). Two light-emitting diodes or LEDs (4) at respectively 375 and 470 nm are also inserted sideway between the filter and the detector to check in-flight the evolution of the rejection of visible light.

The LYRA instrument has been designed with a triple redundancy. It is composed of three heads or units, each protected by an independent cover, that encompass the same four bandpasses as described above. Only one of these units is used in continuous. The two other units are respectively opened for specific scientific campaigns that require a less-degraded instrument and for calibration.

The only difference between the three units is the combination filter–detector used to reach those bandpasses. One of the LYRA's objectives was indeed to assess the use of innovative wide-bandgap detectors (PIN diode and photoconductor (metal-semiconductor-metal or MSM)) in space conditions. More details are given by BenMoussa et al.[3] To be able to compare the technology performances, the nominal unit is provided with those diamond detectors, while the campaign unit is provided with conventional silicon photodiode detectors (AXUV from IRD), and the calibration unit with a mix of both.

2.2 The LYRA on-ground calibrations

The radiometric responsivity of each LYRA channel has been determined during a set of ground-based calibration campaigns. The instrument was calibrated in the radiometry laboratory of the Physikalisch-Technische Bundesanstalt (PTB) at the Berliner Elektronenspeicherring-Gesellschaft für Synchrotronstrahlung II synchrotron (BESSY II) before the launch.[4] In-flight, regular acquisition of dark current, LED signal (370 nm and 470 nm), and signal from the calibration unit are performed to track the effects of instrument aging.

2.3 Observables and process of degradation

The LYRA radiometer observes the Sun since January 2010 when its covers were opened. Since then, LYRA has undergone a strong signal decrease that progresses with the Sun exposition. The contamination is the main source of degradation on LYRA. It caused a dramatic loss of signal that affects all units, although not identically. It is particularly prominent in the nominal unit that is used in a non-interrupted way, even causing the loss of the Lyman Alpha and Herzberg channels. The status of contamination as of February 2016 is illustrated in Table 1 and in Figures 2 to 4.

Table 1: Loss of signal caused by contamination as of February 2016.

Channel	Unit 1 – calibration	Unit 2 – nominal	Unit 3 – campaign
Lyman Alpha	62%	0.6%	61%
Herzberg	75%	0.03%	9%
Aluminum	100%	3%	19%
Zirconium	100%	30%	71%

The detector aging is assessed by observing an evolution of the dark current sensitivity to temperature and of the LEDs response. Both the dark current sensitivity to temperature and its evolution with time differ strongly from one channel to the other. So does the response to LED signal.

Globally speaking, PIN diamond detectors proved to be very resistant to aging effects, with almost no evolution of dark current or LED signal.

Si photodiodes showed a consistent increase of dark current, proportional to the exposition to Sun that might be attributed to damages in the Si–SiO2 interface caused by ionizing particles or UV radiation. The change of the photoresponse to the onboard LEDs differs from channel to channel.

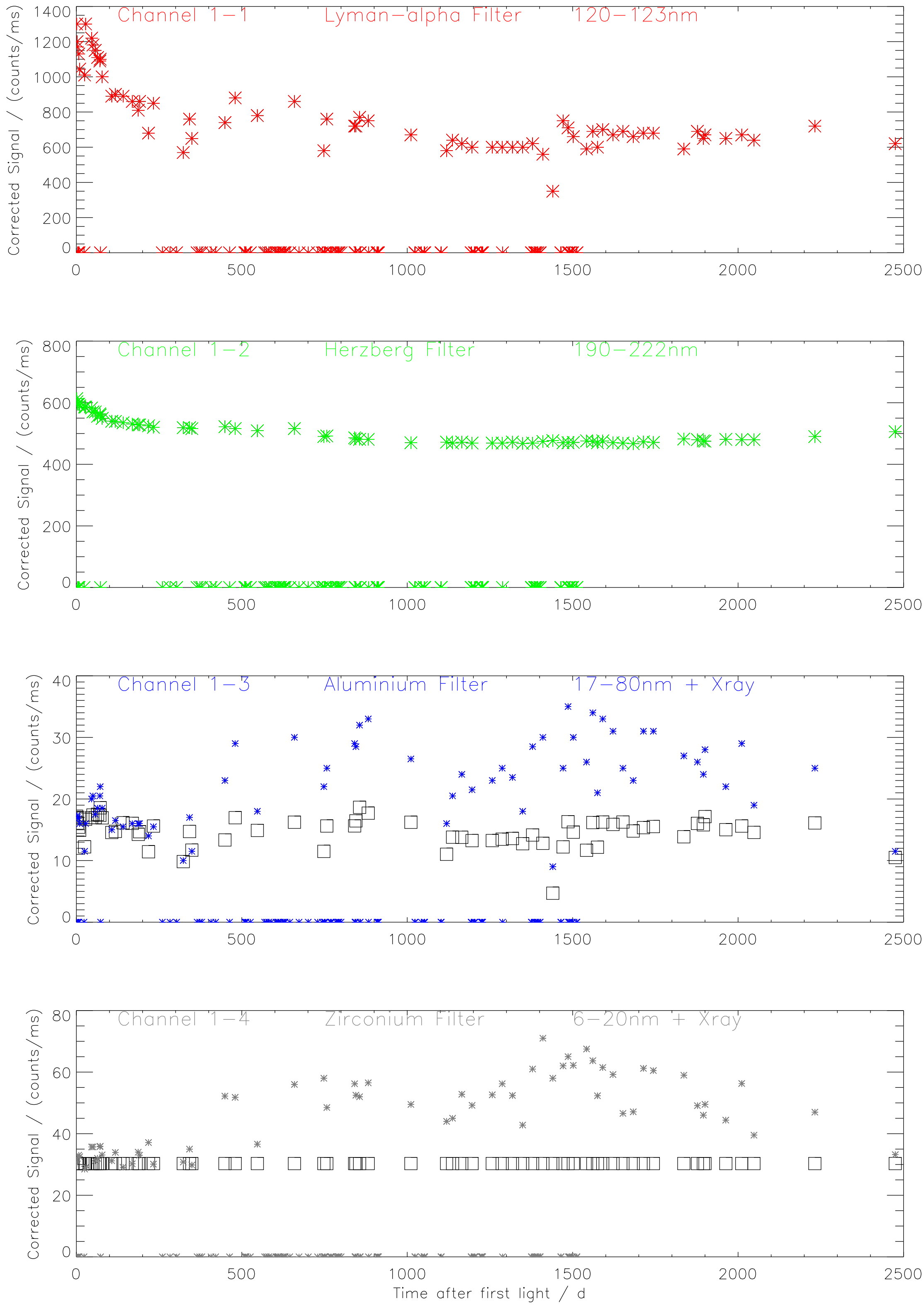

Figure 2: Evolution of unit 1 signal before (stars) and after (squares) removing the solar activity contribution.

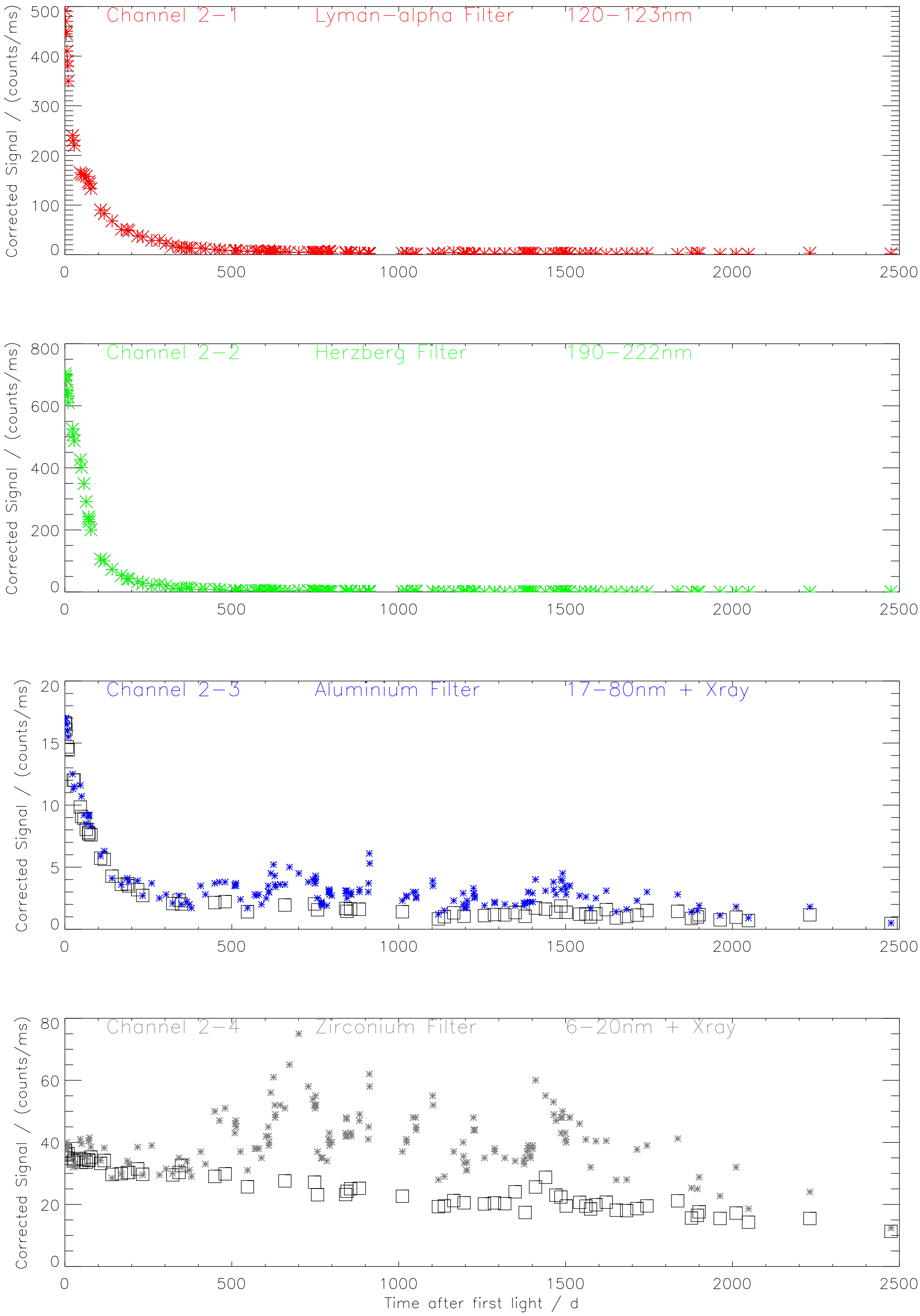

Figure 3: Evolution of unit 2 signal before (stars) and after (squares) removing the solar activity contribution.

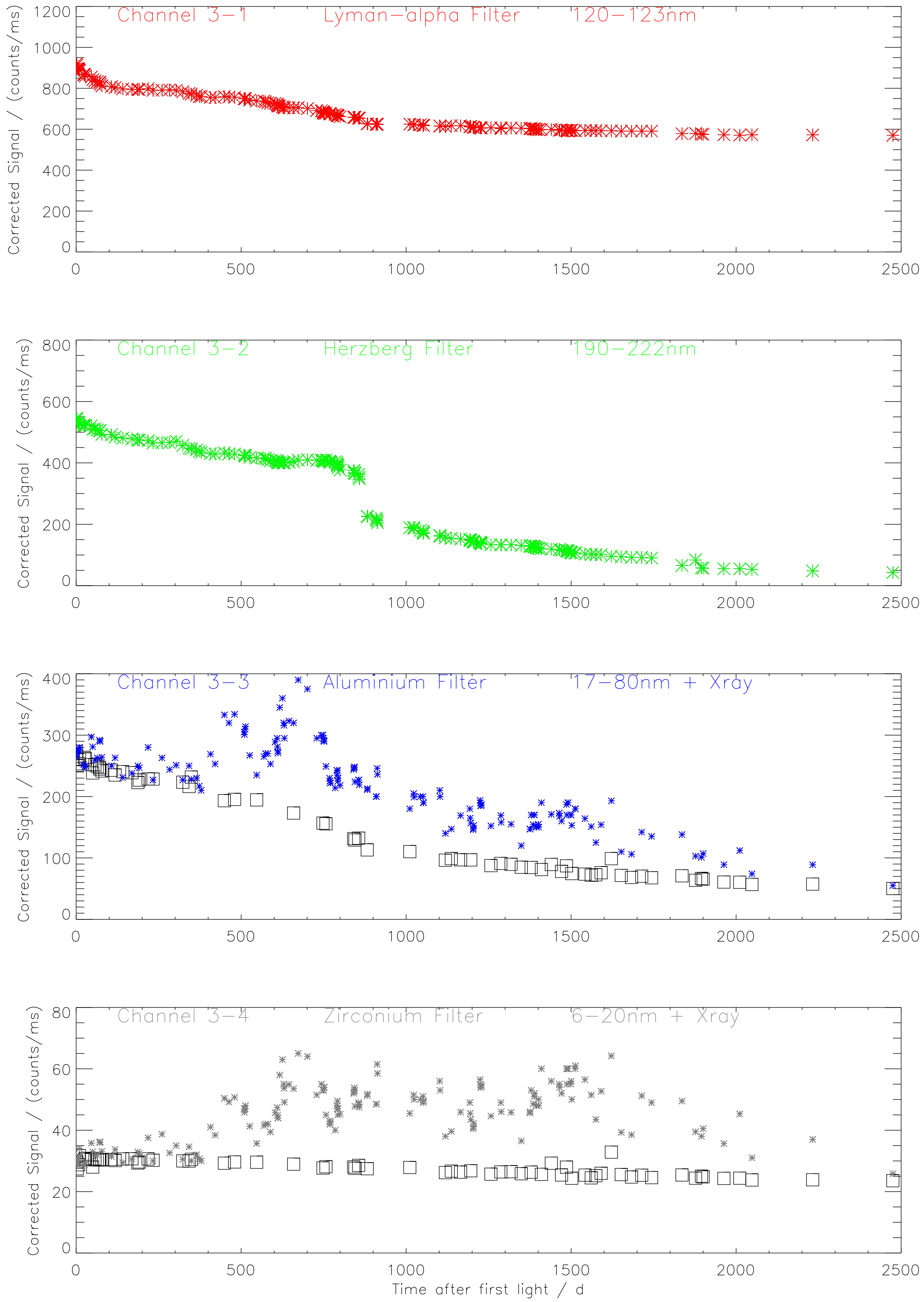

Figure 4: Evolution of unit 3 signal before (stars) and after (squares) removing the solar activity contribution.

The situation with diamond MSM photodiodes is less clear, as the evolution of both dark current varies strongly with the channel considered. In most cases, the dark current was found to decrease with time at a given temperature, contrarily to what was anticipated. The mechanism at play is not assessed yet. However, a possible explanation could be related to desorption of surface contaminants (mainly water) that increases conductivity. An example of dark current evolution in a MSM detector is illustrated in Figure 5. Only one channel showed some evolution of its LED response, and it was indicating an increase of the NUV–VIS rejection.

The MSM (metal-semiconductor-metal) photodetector is built with a planar configuration of the electrodes, making their production simpler than PIN. It should be added that diamond MSM detectors are more sensitive to the ambient environment and to surface contamination than PIN diodes. Special precautions were taken to keep the diamond MSM detectors in a dry inert environment by purging LYRA continuously with nitrogen and keeping covers always closed during on-ground activities but this was perhaps not sufficient.

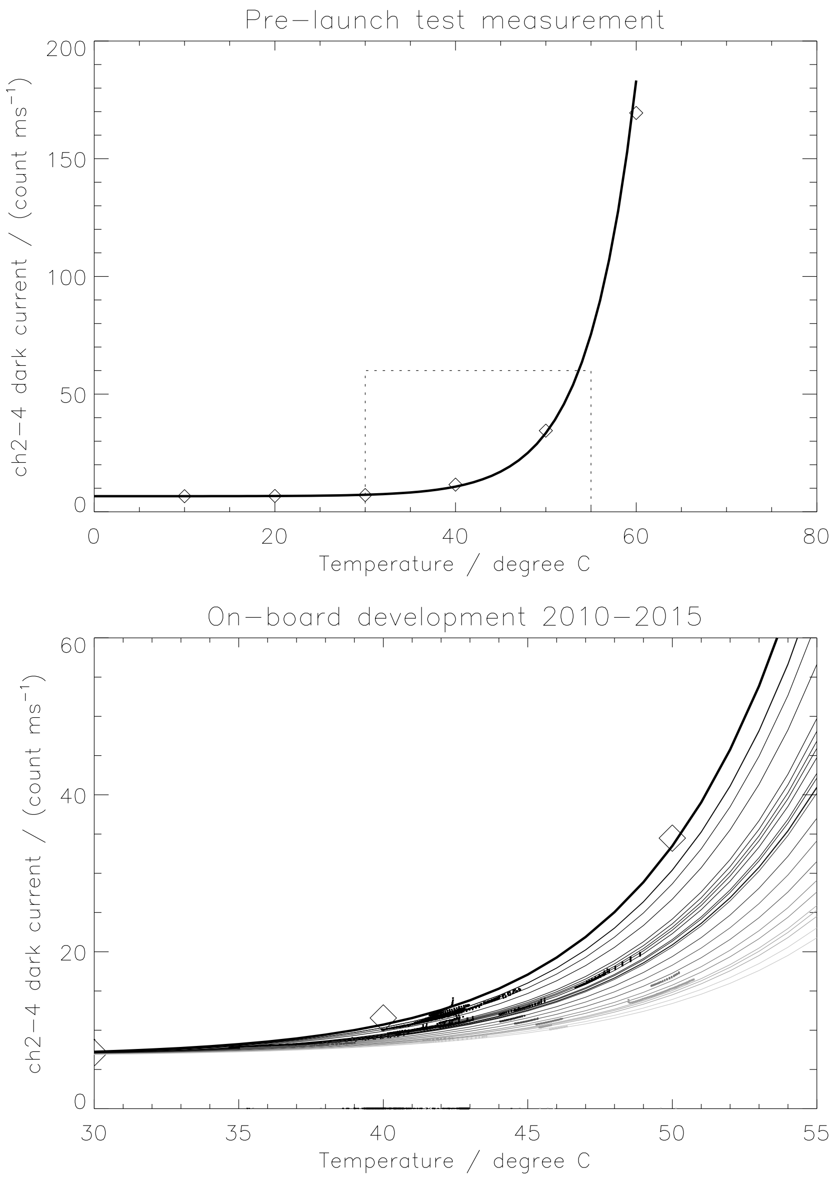

Figure 5: Pre-launch measurement (top panel) and time evolution (bottom panel) of the dark current sensitivity to temperature for the Zirconium channel of Unit 2. The lighter colors correspond to more recent measurements. The temperature range of the bottom panel is highlighted by a dashed rectangle in the top panel.

2.4 Understanding of the degradation processes

The following degradation processes have been identified:[5]

1. Contamination of the entrance filters, probably by a deposit of silicium (Si) and carbon (C);
2. Potential oxidation of the entrance filters;
3. Impact of the desorption of surface contaminants (mainly water);
4. Silicon based-detector aging.

3. SOLAR/SOLSPEC ONBOARD ISS

SOLAR/SOLSPEC[6,7] is a space-based spectro-radiometer of the SOLAR payload onboard the ISS Columbus science laboratory. SOLAR/SOLSPEC is designed to measure the solar spectral irradiance (SSI) from 165 to 3088 nm with a high spectral resolution. This instrument was developed by CNRS-LATMOS (France) and BIRA-IASB (Belgium) with a major collaboration of the Heidelberg Observatory (Germany).

3.1 The SOLAR/SOLSPEC spectrometer design

The SOLAR/SOLSPEC space-based spectrometer consists of three channels ('UV', 'VIS' and 'IR') that cover the wavelengths domain extending from 165 to 3088 nm. Each channel of the SOLAR/SOLSPEC instrument is associated with a double monochromator, which uses concave holographic gratings to minimize the scattered light. The optical path of SOLAR/SOLSPEC is illustrated in Figure 6. The SOLAR/SOLSPEC instrument has not been designed with redundant channels (impact on the mass, the volume and the power).

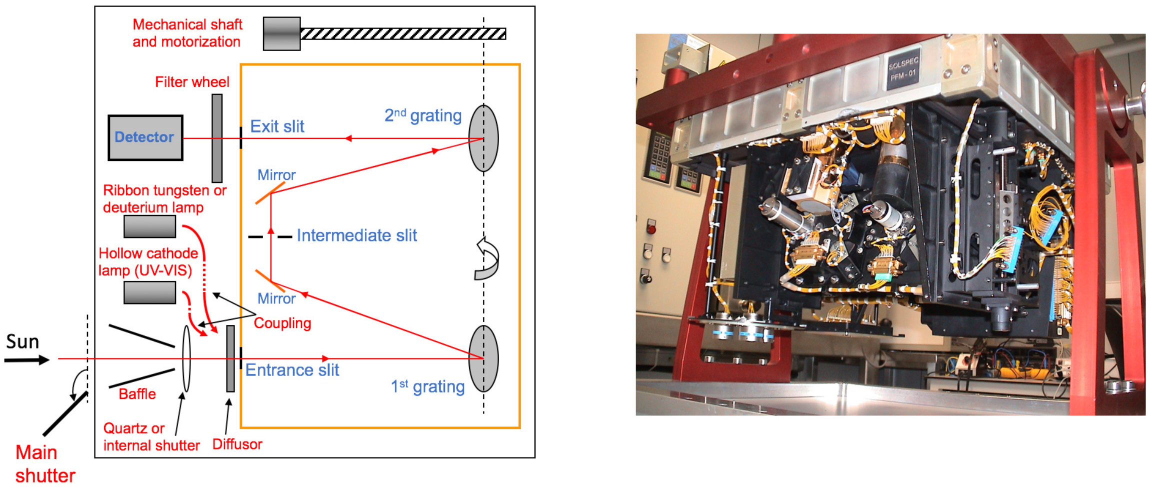

Figure 6: (left) SOLAR/SOLSPEC optical path of one spectral channel (double monochromator). (right) The SOLAR/SOLSPEC instrument with its three units during integration.

3.2 The SOLAR/SOLSPEC on-ground and in-flight calibrations

The radiometric responsivity of each SOLAR/SOLSPEC channel has been determined during a set of ground-based calibration campaigns. The instrument has been calibrated at PTB (Braunschweig, Germany) before the launch. The pre-flight absolute calibration of each SOLAR/SOLSPEC channel was carried out with the BB 3200pg blackbody of PTB. In-flight, regular acquisition with lamps system were performed to track the effects of instrument aging. The deuterium lamp (nominal or spare) allows a calibration of the UV spectral band. Similarly, the tungsten ribbon lamp (nominal or spare) allows a calibration of the VIS spectral band. Two tungsten ribbon lamps (nominal and redundant) are associated with the IR spectral band. A Argon hollow cathode lamp controls spectral resolutions and wavelength scales for the UV and the VIS spectral ranges. The SOLAR/SOLSPEC spectro-radiometer has onboard standards (*i.e.* a lamp system) for calibration to identify possible SSI long-term changes.

3.3 Observables and process of degradation

SOLAR/SOLSPEC was exposed to sunlight for the first time on April 5, 2008. The spectrometer observed the Sun from April 2008 to February 15, 2017 (end of life). The duration to record a solar spectrum (165–3088 nm) was less than 17 minutes. During less than one decade, around 800 solar spectra were acquired. The degradation of the SOLAR/SOLSPEC instrument is easily detectable with the 'UV' channel. The contamination is one of the main source of degradation on SOLAR/SOLSPEC. It caused a loss of signal that affects mainly the 'UV' channel of the instrument. The status of contamination during the full mission is illustrated in Figure 7. Until April 2009, the degradation of the instrument was very important. This dramatic aging is probably due to the use of the deuterium lamps (instrument contamination). The temperature of the SOLAR/SOLSPEC instrument can have also influenced the evolution of the signal presented in Figure 7. In all cases, there was a potential high materials outgassing of the deuterium lamps (glue, *etc.*). When the deuterium lamps were switch off after April 2009 due to a power supply failure of the lamps, the aging of the 'UV' channel was less important.[8] We can then wonder on the contamination control plan set up to define the overall contamination control requirements for the in-flight calibration approach.

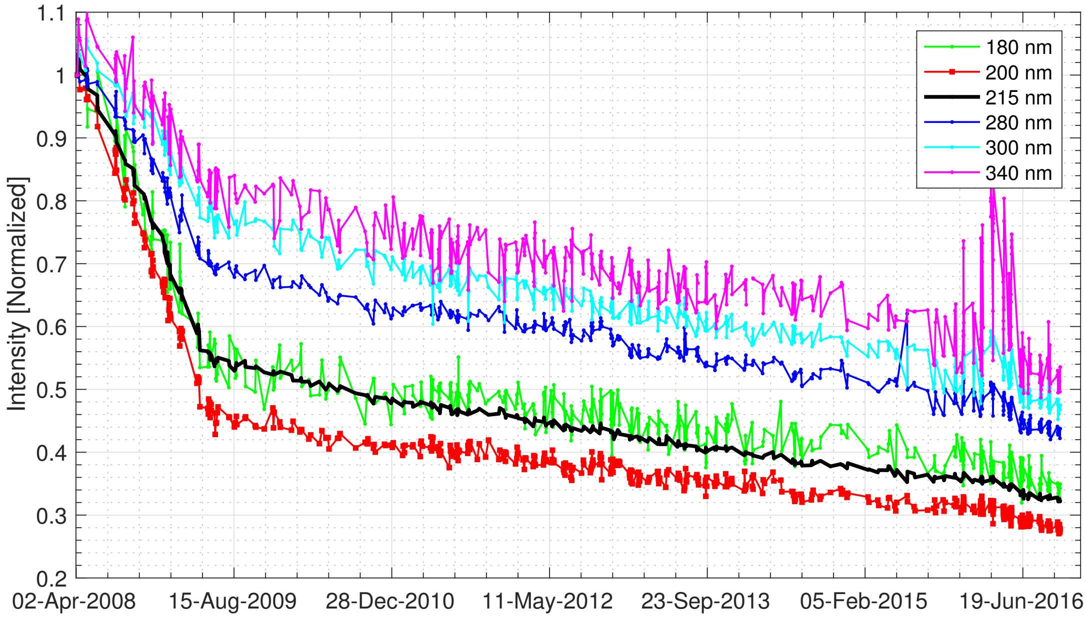

Figure 7: Evolution of the SOLAR/SOLSPEC degradation with time for different UV wavelengths. The temperature of the SOLAR/SOLSPEC instrument can influence the evolution of the signal over time.

The quality of the SOLAR/SOLSPEC fine pointing may have influenced the signal observed by the instrument when deviations from the SOLAR/SOLSPEC line of sight were significant. A coarse pointing device (CPD) was the main component of the guiding system of the SOLAR platform, which allows a fine pointing of the SOLAR/SOLSPEC instrument. A complementary Sun position tracking module, the position sensitive device (PSD), was integrated in SOLAR/SOLSPEC. Figure 8 shows the evolution of the total signal seen by the PSD system over the full mission. During the second trimester of 2016, the PSD total signal was modified as the signal by the SOLAR/SOLSPEC (Figure 7). However, there isn't any relation between SOLSPEC's spectrometers signals and the PSD total signal. The quality of the pointing must be analyzed from the PSD x and PSD y coordinates and not from the PSD total signal as shown in Figure 8 (as a reminder, the pointing system is not the subject of this manuscript). The PSD has a negative temperature coefficient on its signal, and the decrease in signal in the second trimester of 2016 is due to the overall increase of temperature of the instrument due to the long temperature duration tests. The reference temperatures of the instrument (central plate, main shutter, *etc.*) highlight this change.

Figure 8: Solar flux received by the SOLAR/SOLSPEC PSD, which is a useful tool to monitor the misalignment between the CPD and the SOLAR payload. The PSD is very useful if the position of the Sun image (x,y) is calculated but if we consider the sum of photocurrent, the PSD (if perfect: no non-linearities, no temperature dependence for the response, no aging) should be insensitive to Sun de-pointing. The change here, in the second trimester of 2016, could be related to the thermal tests that have led to a better understanding of the instrument.

3.4 Understanding of the degradation processes

The following degradation processes have been identified:

1. Possible contamination of the gratings and optics of SOLAR/SOLSPEC, probably by a deposit of the EC2216 glue used during integration of the calibration lamps and/or during the use of the lamps in space;
2. Contamination of the SOLAR/SOLSPEC optics, probably by a deposit of Si and C;
3. Potential degradation of the transmission of the diffusor by radiation and UV solarization. This is a possible but not certain hypothesis. As a reminder, the Suprasil is extremely resistant to radiation;
4. Potential oxidation of the filters;
5. Detector aging;
6. Impact of the end-to-end calibration methods with the deuterium lamps; other solutions could be implemented for the instrumental responsivity calibration for futures instruments (stellar, vicarious, redundancy, *etc.*).

4. SODISM ONBOARD PICARD

SODISM[9] is an imaging Ritchey-Chrétien telescope, which is a part of the PICARD spacecraft. SODISM was design to measure the solar diameter and the solar oblateness at several wavelengths (535.7, 607.1 and 782.2 nm in the photospheric continuum). The telescope performed also helioseismic observations at 535.7 nm to probe the solar interior. Images in the Ca II line (393.37 nm) were used to detect active regions of the Sun near the solar limb, which may impact the solar diameter measurements. These observations (393.37, 535.7, 607.1 and 782.2 nm) could be used to measure the solar spectral irradiance and the solar differential rotation as well as for space weather, together with images in the 215 nm wavelength. This instrument was developed by CNRS-LATMOS (France).

4.1 The PICARD/SODISM telescope design

SODISM is an 11-cm diameter telescope with a charge coupled device (CCD) at its focal plane. Figure 9 presents its optical layout. The front window protects the internal SODISM optics from the space environment and limits the solar flux into the instrument, thus restraining heating and degradation. This optical part has a great impact on the degradation process of the PICARD/SODISM instrument. Moreover, the telescope has not been designed with a redundancy (impact on the mass, the volume and the power).

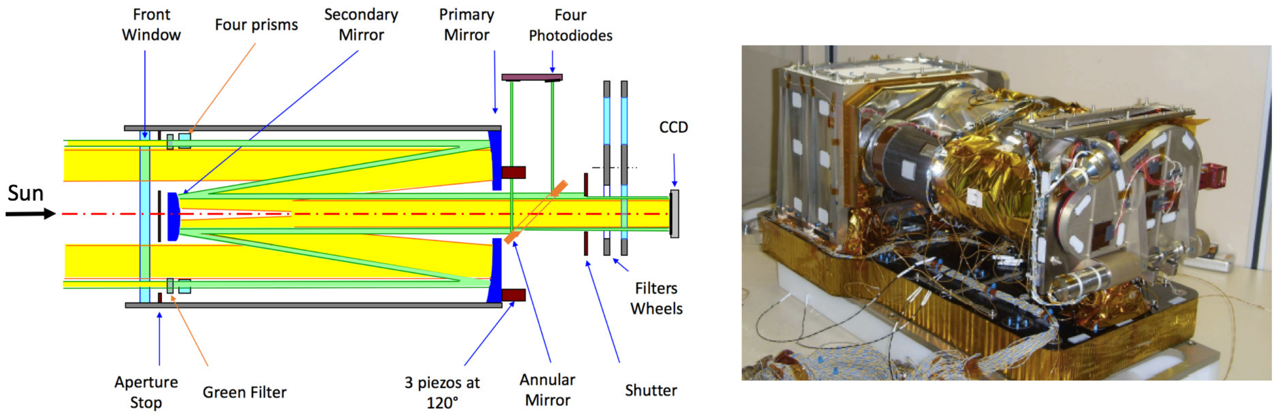

Figure 9: (left) PICARD/SODISM optical path. (right) The PICARD/SODISM instrument during integration.

4.2 The PICARD/SODISM on-ground and in-flight calibrations

The plate scale of the telescope has been determined during a set of ground-based calibration campaigns (solar collimator). In-flight, the plate scale has been determined during the transit of Venus,[10] which allowed an absolute determination of the solar radius.[10,11] However, there is no on-ground and in-flight calibrations of the signal evolution during the full mission.

4.3 Observables and process of degradation

PICARD/SODISM was exposed to sunlight for the first time on July 2010. The telescope observed the Sun from July 2010 to March 2014 (end of life). During less than four years, more than one million of images of the Sun at several wavelength were acquired. From 2010 to 2014, PICARD/SODISM has undergone a strong signal decrease in the UV that has progressed with the Sun exposition. The contamination of the front window is the main source of degradation on PICARD/SODISM. It caused a dramatic loss of signal that affect mainly the UV wavelengths. The status of contamination from July 2010 to March 2014 is illustrated in Figure 10.

4.4 Understanding of the degradation processes

The following degradation processes have been identified:

1. Contamination of the front window of the telescope (external side), probably by a deposit of Si and C from the spacecraft solar panels. There is also a potential impact of the contamination during the spacecraft separation from the launcher (general contamination of the spacecraft);
2. Contamination of the front window of the telescope (internal side), probably by a deposit of C from the tube of the telescope that is in carbon-carbon with its chemical vapor deposition silicon carbide;
3. Contamination of the internal filters;
4. Potential oxidation of the filters;
5. Impact of the radiation on the front window and filters;
6. Detector aging.

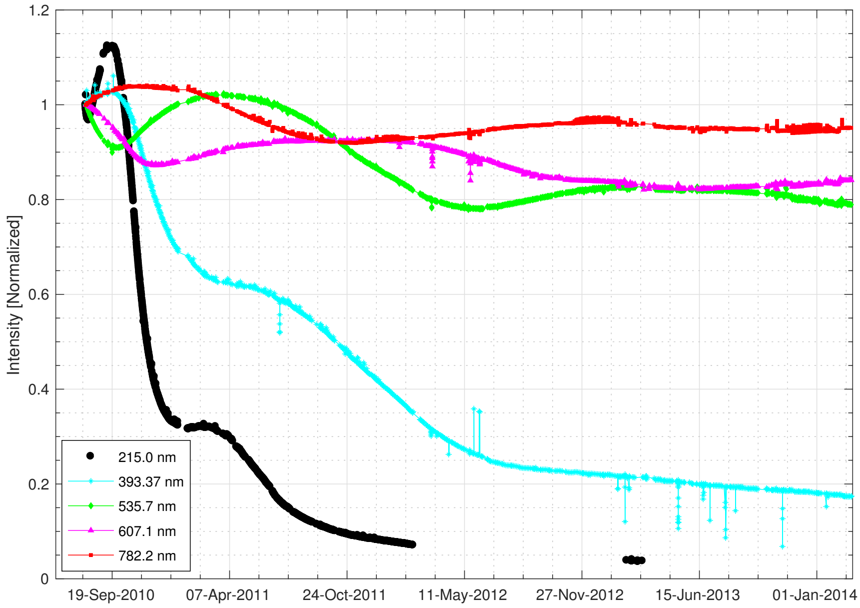

Figure 10: Evolution of the PICARD/SODISM degradation over the full mission.

5. CONCLUSIONS

Degradation of space-based solar instruments could be complex, and contamination is a particular concern for solar instruments. Currently, there is no possibility of mitigating contamination in space once molecules have settled irreversibly after UV-polymerization, which is a classical concern for UV solar instruments. However there are several approaches for assessing and monitoring the degradation that give good results and to largely recover the instruments calibration.

Taking advantage of the lesson learned of the past and ongoing space projects such as LYRA, SOLSPEC and SODISM, the most important preventive measures and strategies to minimize contamination and degradation can be summarized as follows:

–1– **Extreme cleanliness control** (at instrument and S/C levels), which includes careful material selection (*e.g.*, high radiation tolerance, ultra-high vacuum material quality with lowest outgassing values), minimization of organic material (bake-out), design (*e.g.*, purging with large venting hole, door, heater for detector bake-out, cold cup around the detector, *etc.*) and stringent cleanliness procedures of all hardware. It should be added that the ground-support equipment that will be in direct contact with the flight hardware must be submitted to the same rules.

–2– **Stability of the instrument radiometric calibration**. Intensive preflight calibration is crucial for such instruments. Pre-flight calibration can be achieved with detectors and transfer radiation-source standards, both traceable to a primary standard source found in synchrotron-radiation facilities, while the instruments themselves can be calibrated at the synchrotron facility or locally, at the instrument test facility, by transporting a transfer source standard to that facility.

Once a spacecraft is in orbit, the stability of calibration can be monitored by carefully planned observations. A careful initial calibration and meticulous tracking of the evolution of instrumental calibration are both very important. Onboard-calibration light sources have been essential to the success of many solar payloads, and similar devices should always be included in the design of space-based solar instruments. Multiple calibration light sources (lamps or LEDs) may be carried onboard and should be operated and exposed regularly to maintain an established calibration status. Alternatively, it is possible to track instrumental calibration by inter-calibration using observations from occasional rocket under-flights using similar instruments that can be carefully calibrated on the ground both before and after the flight. Finally, redundancy can be implemented at either component or instrument levels (such as LYRA). Past experience shows that redundancy is useful in recovery from degradation and damage from different causes.

–3– **Technological developments**. Specific design and technological development are particularly important for solar instruments and can reduce the impact of radiation exposure. For instance, the radiation effect at UV detector level is already anticipated with the use of wide band gap materials (WBGM) as used on LYRA. WBGM are the primary choice as the photosensitive material for high-energy photon detection (*i.e.*, soft X–ray–NUV range), mostly motivated by their advantages over Silicon. Furthermore there is a great need for optical elements of all kinds (filters, grazing reflectors, and mirrors) with improved radiation tolerance and spectral purity. This need is demonstrated by the rapid degradation of the UV filters on PROBA2 and PICARD.

–4– **Repeatability of observations and constant temperatures in space**. The detection of trends in solar variables requires observations with acceptable calibration uncertainty and repeatability over a long period of time. Operations on the spacecraft and instrument must also be repetitive. The choice of the orbit is important to minimize the temperature variations (no eclipse and halo orbit around the Sun-Earth L1 point that represents the best case such as for the SoHO mission).

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