Design of an optical sun sensor for a space application: a reliable passive sun tracking device for the SOLAR/SOLSPEC instrument

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ABSTRACT

SOLAR/SOLSPEC, a spectroradiometer measuring solar spectral irradiance is an instruments of the SOLAR payload mounted on the zenith external platform of the European Columbus module of the International Space Station. Solar flux is received by the SOLAR instruments thanks to the Coarse Pointing Device (CPD). A complementary Sun position tracking module, the Position Sensitive Device (PSD), is integrated in SOLAR/SOLSPEC. The PSD module has been a useful tool to monitor for misalignments between the CPD and the SOLAR payload. It is used in SOLAR/SOLSPEC's operations to follow the quality of the Sun tracking. The PSD module is also valuable to monitor for SOLAR/SOLSPEC's three spectrometers (ultraviolet, visible, infrared) angular response in orbit. We first give a detailed description of the PSD's functionalities. We then present the results of the PSD data analysis. We will show that the PSD module has, despite working in a severe space environment, preserved its full potential from 2008 up to 2017 thanks to its design and appropriate selection of components. We conclude that its robustness makes of the PSD module a simple, yet reliable, instrument useful for future long term space-based missions.

Keywords: Sun sensor, space missions, space degradation

1. INTRODUCTION

SOLAR/SOLSPEC[1,2] (SOLar SPECtrum) is a spectroradiometer measuring the solar spectral irradiance from 147 nm to 3088 nm. It is composed of 3 individual spectroradiometers, each one dedicated to a range of the solar spectrum. The Ultraviolet (UV) channel from 147 nm to 371 nm, the Visible (VIS) channel from 232 nm to 908 nm and the Infrared (IR) channel from 647 nm to 3088 nm. The spectral range of SOLAR/SOLSPEC covers $\approx 96\%$ of the Sun's Total Solar Irradiance (TSI). Together with SOVIM,[3] a TSI radiometer, and SOLACES,[4] measuring between 16 nm and 220 nm, the three instruments are part of the SOLAR platform mounted on the zenith external platform of the European Columbus module of the International Space Station (ISS). Initially planed for 18 months, the SOLAR mission ran during 9 years, between February 2008 and February 2017. The three instruments of the payload require accurate solar tracking in order to receive direct Solar flux. This is achieved thanks to the Coarse Pointing Device (CPD) (Fig. 1), wherein the 3 instruments are mounted. A complementary position tracking device, the Position Sensitive Device (PSD) is integrated in SOLAR/SOLSPEC. The PSD is a passive instrument with no feedback over the payload orientation. It uses a wide band-pass glass filter to attenuate the solar flux. The solar image is formed with a lens-triplet into a photodiode resistive surface where the Sun's image position is accurately detected. The PSD module was a useful tool to monitor the misalignments between the CPD and the SOLAR payload. It is used in SOLAR/SOLSPEC's nominal operation mode to monitor the quality of the Sun tracking. The PSD module is also valuable in the criss-cross operational mode achieved by depointing the CPD for a range of angular positions. This allows to monitor for SOLAR/SOLSPEC's three spectrometers angular response in orbit.

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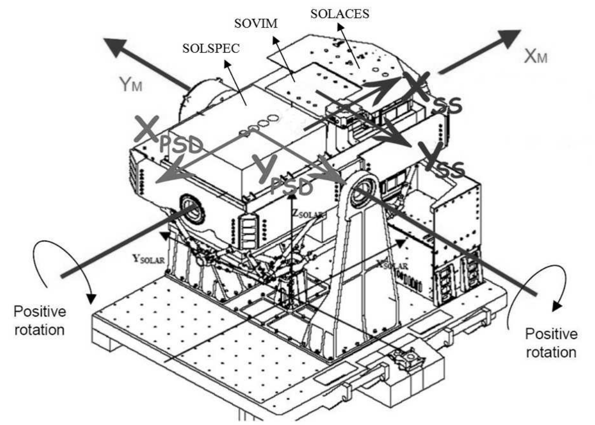

Figure 1. Layout of the 3 SOLAR instruments on the platform. The reference X and Y displacement and angular axis of the PSD and CPD, respectively are shown.

2. PSD MODULE DESCRIPTION AND DESIGN

2.1 Detector description

The PSD module developed for SOLAR/SOLSPEC, described in depth in 2, is an improved version of the passive solar tracker that was integrated into the SPICAM[5] instrument in the Mars 96 mission. The new module is an opto-mechanical device supporting an imaging system and filtering optics for the control of the solar flux incident on the detector. The new design was the result of a collaboration between the Belgian Institute for Space Aeronomy (BIRA-IASB) and the Lambda-X[*] company. The main component, element 5 in Fig. 2 is a photosensitive Hamamatsu S2044 PSD detector[†] with an active surface of $4.7 \times 4.7mm^2$. Its pin cushion type format greatly reduces the effect of optical aberrations rendering not only the total output signal intensity quasi-independent of the light spot position on the detector but also, reducing the barrel and pincushion distortion of a grid image (quasi orthoscopic optical system). The absence of gaps at the detector surface (different design than four-quadrant type detectors) allows for uninterrupted optical power detection and thus, continuous position determination. The pointing resolution, at nominal conditions, is of $0.6\mu m$.

2.2 Optical components

An optical layout of the PSD module is shown in Figure 2. The optical components are:

- The first optical surface, element 1 in Fig. 2, is a SCHOTT BG18 radiation resistant filter previously used for VIRGO on SOHO.[6,7] It is a broadband filter with a full width half-maximum (FWHM) of 250 nm and a peak transmission centred at 501 nm. On the external surface exposed to the space environment, a deposit of a dichroic coating blocks unwanted IR radiation. On the internal surface, a neutral coating with an optical density (OD) of 0.8 was used. The choice of the filter's OD was done taking into account the need to limit the photocurrent from the detector to $100\mu A$. An accurate estimation of the exo-atmospheric irradiance at 501 nm was determined for this calculation.

- A Cooke triplet, elements 2, 3 and 4 in Fig. 2 is used as imaging system. The calculation of the lenses specifications was done in order to reduce distortions and off-axis aberrations of the Sun's image on the detector. The lenses materials (SCHOTT SK4-G13 and BK7-G25) are also radiation resistant. The focal length ensuring a field-of-view (FOV) of 12° for the Sun image is 19 mm. Another factor taken into account in this calculation is the need to work with an off-focus to reduce the density of optical power of the Sun's image on the detector in order to minimize detector degradation.

[*] www.lambda-x.com
[†] www.hamamatsu.com

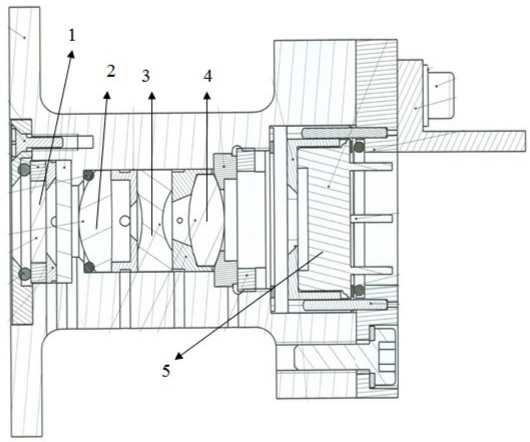

Figure 2. Cross-section of the PSD module design where the integration of the optical components, (1, 2, 3, 4) and the detector (5) in the mechanical structure can be seen.

2.3 Electronic read-out

The PSD detector yields 4 photocurrents , each of them being read-out by a separate amplifying circuit. To obtain the spot position on the detector one should use the following equations:

$$PSD_x = \frac{(I_2 + I_3) - (I_1 + I_4)}{\sum I_{1...4}} \frac{L}{2} \quad (1) \qquad PSD_y = \frac{(I_2 + I_4) - (I_1 + I_3)}{\sum I_{1...4}} \frac{L}{2}, \quad (2)$$

The PSD signal is the sum of the 4 individual photocurrents corrected for the dark current (DC), given by the following equation:

$$I_{PSD} = \sum_{i=1}^{4} (I_i - DC_i) \quad (3)$$

3. RESULTS

3.1 Assessement of SOLAR platform integration

Figure 1 depicts the integration of the three instruments of the SOLAR payload on the CPD platform. The PSD module has been integrated into SOLAR/SOLSPEC with a residual well known offset between it and the optical reference axes of the three spectrometers. Thanks to this well characterized integration, the PSD is used as the reference optical surface for the alignment of SOLAR/SOLSPEC. This reference was particularly important during the first weeks of the space mission when, it helped to identify and correct for a misalignment during integration of the SOLAR platform in the CPD, shown in Figure 3.

Thanks to the analysis of the PSD signals it was possible, via an iterative process over the CPD orientation, to determine the optimal offset to apply to the CPD offset that optimizes the angular response of SOLAR/SOLSPEC spectrometers and the other two instruments.

3.2 Criss-Cross results

Other than the Sun tracking solar mode, the CPD allows to execute a criss-cross (CC) measuring mode in which the CPD describes a cruciform trajectory (depicted in Fig. 4), rendering the Sun out of the optical axis of the spectrometers and measuring their angular response through the FOV of the entrance optics by a well-known angular displacement. The primary goal of this mode is to monitor the angular dependency of the response of the spectrometers. Additionally is also useful in detecting the angular dependency of the PSD own detected

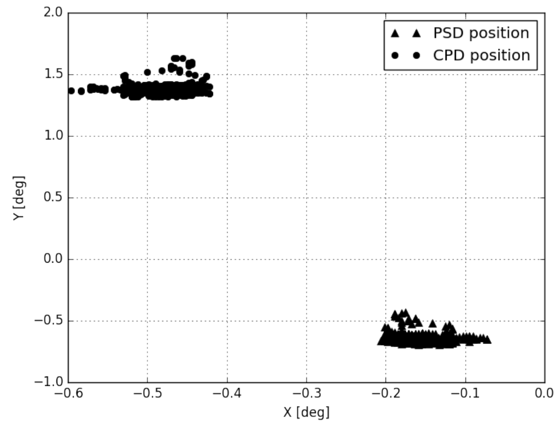

Figure 3. Depiction of the remaining offset between the PSD and the CPD coordinates observed during one of the first solar measurements.

signal. This is achievable thanks to the capability of accurately measuring the position of the formed image (Eq. 1 and Eq. 2) independently of the total incoming signal's intensity (Eq. 3). Figure 4 shows the variation of the PSD signal for a range of off-axis positions. The total PSD signal varies of $\sim 2\%$ between the nominal and the optimal CPD offsets.

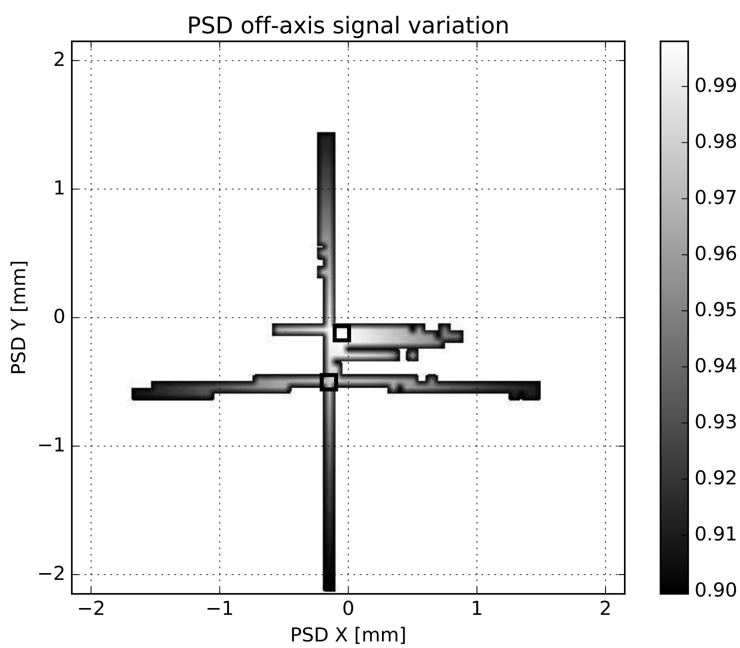

Figure 4. Depiction of criss-cross measuring mode. Coordinates data are binned into $0.05 \times 0.05mm^2$ bins. The value of each bin is computed relative to the bin of maximum signal and the respective scale is shown by the gray-scale bar on the right. The nominal CPD offset (cross center) and the optimal three-instrument offset positions are represented by squares.

The analysis of the criss cross measurements allowed to establish the relation between the Sun angular position given by the CPD and the PSD linear position given by Eq. 1 and Eq.2. The results of these measurements, determined with good quality linear regressions, and its comparison to pre-flight measurements are shown in

Figure 5 and the corresponding angular coefficient shown in Table 1. The space measurements confirm those determined during the pre-flight characterization. The four coefficients in Table 1 agree withn 0.3%

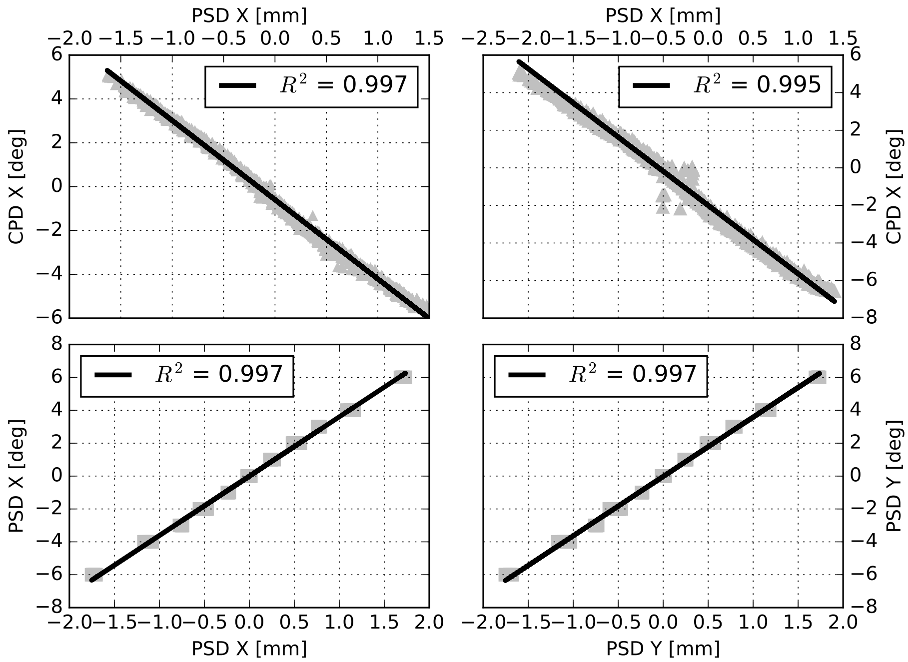

Figure 5. Results of the measurements destined to determine the linear to angular conversion coefficients of the PSD. These coefficients are equal to the slope (Table 1) of the linear regression performed over the measurement points; the correlation coefficient, R^2, is shown in each plot. Top panel: results in orbit obtained with the criss-cross measurements. Bottom panel: results obtained during the pre-flight characterization.

Table 1. Table showing the conversion factors between linear and angular position of the detected Sun spot on the PSD surface. This values represent the slopes of the linear regression shown in Fig. 5. The values determined at pre-flight confirm the linear to angular relation observed in orbit. The four presented values agree within 0.3%

	X coordinate factor $[deg.mm^{-1}]$	Y coordinate factor $[deg.mm^{-1}]$
Pre-flight	3.609	3.608
Orbit	3.613	3.636

3.3 PSD signal analysis

As described in Section 1, due to the expected harsh conditions in space, more specifically in the ISS environment, precautions were taken when designing the PSD module. Figure 6 depicts the process of treatment of the PSD signal (Eq. 3). The temperature coefficient used in the correction shown in Fig. 6 (panel C) was obtained from the analysis of thermal behaviour tests during the first trimester of 2016 in which SOLAR/SOLSPEC was left operating for an exceptional long period to measure the effect of a large but controlled temperature increase. The determined coefficient of photo sensitivity of $-0.021\%°.C^{-1}$, agrees with the curves published by the manufacturer. The coefficients of correction for the different CPD set points were determined with the criss-cross measurements as explained in Section 3.2

The above explained process of data treatment yields a virtually stable signal, shown on Fig. 6 (Panel D). This signal has a quasi-gaussian distribution, shown in Figure 7. The peak-to-peak (3σ) variation of the corrected signal is $\sim 0.6\%$.

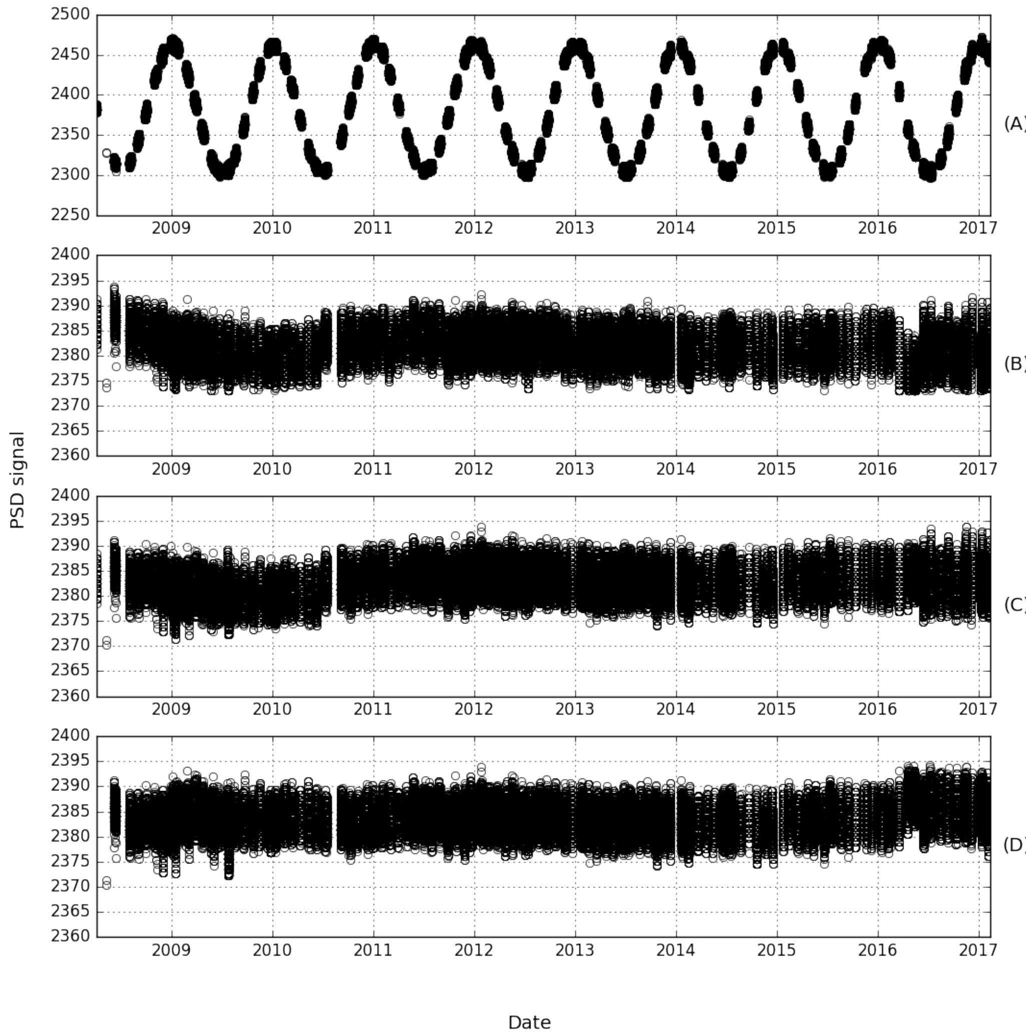

Figure 6. The PSD signal is the sum of the 4 individual photocurrents. Panel (A) shows the raw measured signal during solar operations. Panel (B) shows the raw measured signal corrected for the Earth to Sun distance. Panel (C) shows the signal corrected for the Earth to Sun distance and for the temperature variations. Panel (D) shows the application of the two previous corrections as well as the correction for the different CPD set points used during the mission.

3.4 Sun-tracking stability

Being independent of the main tracking system and due to the high stability of its signal makes the PSD an ideal proxy to monitor the stability of the Sun tracking of the CPD during the 9-year space mission. Figure 8 shows the stability of the Sun tracking for both axes. One can observe well constrained stability, oscillating between 0.5 arcmin and 1 arcmin for the Y-axis, while for the X-axis the stability is inferior and deteriorates by around 25% during the mission.

4. CONCLUSIONS

The results achieved with the PSD module of the SOLAR/SOLSPEC highlighted the importance of the concept of redundancy in space missions. In the particular case of SOLAR/SOLSPEC the PSD proved, despite its passive

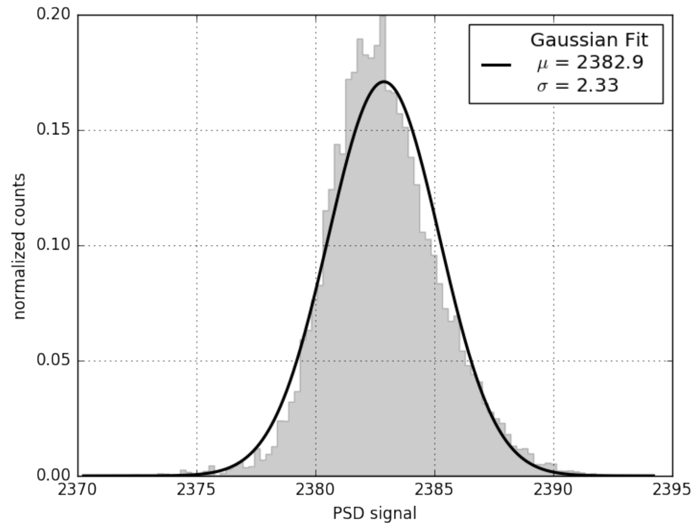

Figure 7. Distribution of the PSD signal shown in panel (D) of Figure 6 and the respective Gaussian fit over the distribution.

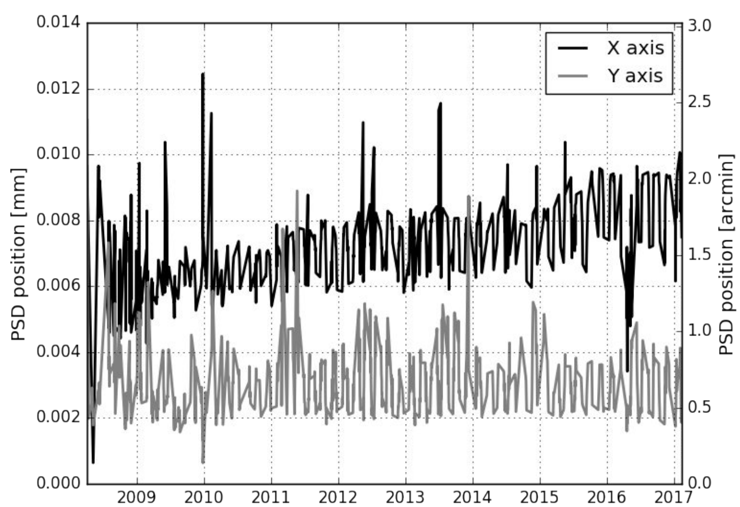

Figure 8. Evolution of the CPD pointing stability for the whole mission. For each solar measurement, the stability is measured as the standard deviation of the respective coordinate data points

nature, its usefulness not only as a complementary but also as a validation tool to the CPD functioning. This validation was particularly critical during the first days of mission, when an non-negligible misalignment of the payload during its integration into the CPD was detected. The current understanding of degradation of optical components in space and the heritage of past space missions knowledge allow to establish well defined criteria for the design of space instruments. The analysis of the stability of the PSD signal is a good indicator of the completion of these criteria. The extensive pre-flight conception and characterization work yielded a virtually stable instrument for a duration of 9 years. Although being out of the scope of this paper, the radiometric capabilities to detect Sun irradiance variabilityof such kind of instrument should be kept in mind in future space missions, as it is has been the successful case in other space missions.[8]

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