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CHANGING THE ISS ATTITUDE TO MAXIMIZE SCIENCE RETURN OF THE SOLAR PAYLOAD

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Abstract

The Solar Monitoring Observatory, or SOLAR in short, is a payload of the European Space Agency that resides on one of the external platforms of the Columbus module of the International Space Station (ISS). The two operational instruments on-board the payload are designed to measure the solar irradiance in the wavelength range 16 to 3000nm. However, due to its unique location and because of the mechanical constraints of the platform, observations are only possible at most two weeks a month, for not longer than 20 minutes per ISS orbital revolution. Since the SOLAR mission will be operational for an almost complete solar cycle, it will provide data on the long-term evolution of the Spectral Solar Irradiance, important for, among others, atmospheric science. However, in order to study the short term variability it is important to have measurements covering a complete solar rotation. During the winter and summer solstices the time between two consecutive observation windows is the shortest. By changing the ISS attitude by only a few degrees from its standard Torque Equilibrium Attitude, this gap in the observations can be bridged. Between 30 November and 12 December, 2012, the ISS roll, and mainly yaw (about 7.5°) were modified, allowing the SOLAR instruments to monitor the Sun for more than 35 days in a row, covering a complete solar rotation. This event is historical as it was the first time ever the ISS rotated exclusively for a scientific experiment. The change of the ISS attitude was reached by solely using the Control Momentum Gyroscopes and did not negatively affect any of the other external payloads. This minimal effort resulted in a great scientific benefit. During this extended observation period data of the solar spectrum were intensively collected. A more complete dataset of the solar irradiance will contribute to a better understanding of the effect of the solar variability on the Earth's atmosphere.

I INTRODUCTION

Over the last decade an increasing effort has been invested in the study of the Sun-Earth connection. The cyclic variability of the solar magnetic field imposes modulations in the solar radiative output and changes in the interplanetary conditions. On the short term, the solar dynamic events can disturb the geo-magnetic environment, impact the Earth's atmosphere, or cause enhanced radiation levels in the near-Earth environment (Schwenn 2006; Pulkkinen 2007). On the longer term, the solar radiative output is determining the Earth's climate. Historical records and palaeoclimatological data indicate that there is a cor-

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relation between past changes in the Earth's climate and changes in the solar radiative budget (Engels and van Geel 2012). The Total Solar Irradiance (TSI) is an important radiative forcing factor of the climate, since it directly impacts sea surface temperature and the hydrological cycle. This is referred to as the bottom-up mechanism (Cubasch et al. 1997), as the surface temperature changes result in an upward coupling to the troposphere. Measurements of the TSI only became possible since the space-age, as about half of the incoming irradiance is reflected back to space or absorbed by the Earth's atmosphere. The first measurements date back from 1978 and more than three decades of TSI data show a variation in the TSI with the solar cycle of less than 0.1% (Fröhlich 2006). According to Gray et al. (2010), such a small variation in the TSI would result in a global mean temperature change of less than 0.1K over the course of the solar cycle. However, to explain the observed changes in the global sea surface temperature a three times higher heat flux is required than the one available from direct solar radiative forcing (White et al. 2003). This suggests an amplifying mechanism must be at work (e.g. Meehl et al. 2009). Most of the emission from the Sun is in the visible (VIS) and infrared (IR) part of the spectrum. However, the radiation at shorter wavelengths (UV, EUV, and even X-rays) is not insignificant for atmospheric physics. The radiation emitted by the Sun in the wavelength range below 300nm is completely absorbed by the Earth's atmosphere. It will heat up the upper and middle atmosphere and affect the middle and lower atmosphere's composition and chemistry. The variation over the solar cycle in the UV flux is ∼6%, and in the EUV and X-ray wavelength the change is even larger, up to 100% (Lean 2000), and thus the impact of solar variability is much larger in the upper and middle atmosphere than it is at lower altitudes. The resulting modulation in the stratospheric temperatures and winds will influence the underlying troposphere (top-down effect), and as such the Earth's weather and climate (e.g. Haigh and Blackburn 2006). However, the effect of solar variability on the Earth climate is complex and far from completely understood (Haigh 2007; Gray et al. 2010; Lockwood 2012). As noted by Rind (2002), in order to understand how the solar variability impacts the Earth's climate it is needed to have complete insight in 1) the short- and long-term solar variability and thus understanding of the solar dynamo; 2) the Sun-Earth coupling; and 3) the mechanisms that determine the response of the Earth's climate system.

With the Solar Monitoring Observatory (or SOLAR in short), the European Space Agency (ESA) is contributing to this highly complex research domain. SOLAR was mounted on one of the external platforms of the Columbus module at the International Space Station (ISS) in February 2008 and is operated by the Belgian User Support and Operations Centre (B.USOC) since then. The SOLAR payload contains three instruments , each designed to observe the Sun in a specific wavelength range (Schmidtke et al. 2006a). The SOlar Variability Irradiance Monitor (SOVIM) is combining two types of absolute radiometers, providing TSI data, and filter-radiometers having three channels of 5nm bandwidth centred at 402, 500, and 862nm (Mekaoui et al. 2010). Unfortunately, the SOVIM instrument was lost after a fatal hardware failure in the first year of the mission. The SOLar SPECtrum (SOLSPEC) instrument incorporates three double spectrometers (Thuillier et al. 2009) measuring the solar spectral irradiance (SSI) in three different channels: UV (165–370nm), VIS (285–910nm), and IR (650–3080nm). Measurements of the SSI in the EUV part of the spectrum are made by the SOLar Auto-Calibrating EUV/UV Spectrometers (Sol-ACES). The instrument contains four spectrometers, together covering the wavelength range 17–226nm, and two ionisation chambers for calibration purposes (Schmidtke et al. 2006b). Although the mission was initially granted for a duration of 1.5 years, mission extension up to 2017 was recently approved. This means that the SOLAR mission is covering the end of solar cycle 23, including the deep minimum in 2009, and almost completely solar cycle 24. The data gathered by the three instruments are providing accurate measurements of the SSI and its variability as a function of solar activity. However, due to the particularity of the ISS and its orbit the instruments can collect data for at most 20 minutes per ISS orbital revolution and this for only 10 to 14 consecutive days, followed by a data gap of 10 to 22 days. The recurrent gap in the observations does not ease the modelling of the short-term variations in the solar EUV and UV flux, related to the development of active regions and the solar rotation. The total duration of one Sun pass is very dependent on the ISS attitude and it was noted that by temporarily changing the ISS attitude it would be possible to bridge two observation periods, benefiting the science data collection.

In this paper it is presented how the B.USOC team managed to rotate the ISS purely for scientific purposes and the scientific additional value of the extended observation window. A more detailed description of the SOLAR payload and its Sun pointing capabilities is described in section II. The concept of the SOLAR bridging is outlined in section III, where we also present our operational experience and preliminary scientific results. A discussion on the process to achieve the bridging is presented in **??**. The closing section IV contains the concluding remarks.

II THE SOLAR PLATFORM

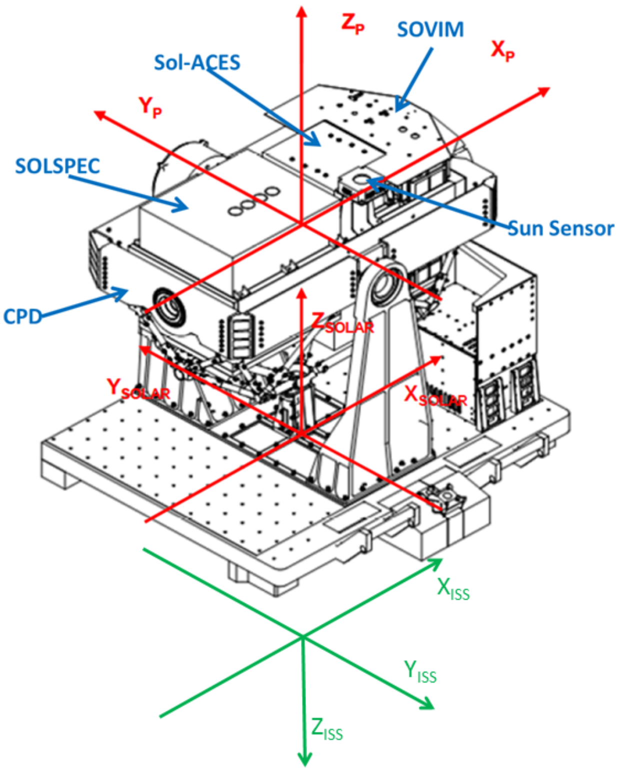


Figure 1: Schematic of the SOLAR payload, showing the location of the three instruments on the CPD. The SOLAR reference coordinate system is indicated by $(X_{SOLAR}, Y_{SOLAR}, Z_{SOLAR})$, and it is fixed to the static external platform. The reference frame attached to the instruments is indicated with (X_P, Y_P, Z_P). The orientation is the ISS attitude reference frame $(X_{ISS}, Y_{ISS}, Z_{ISS})$ is shown for completeness.

The SOLAR observatory is mounted on one of the external platforms of the Columbus module with the instruments pointing to the zenith direction, i.e. away from the Earth. The three SOLAR instruments are mounted on the Coarse Pointing Device (CPD): a two-axes moving platform, allowing the instruments to orient towards the Sun. Besides the scientific instruments also a Sun Sensor is present on the CPD, which allows accurate pointing towards the Sun. An overview of the SOLAR payload and its orientation with respect to the ISS is given in Fig. 1. On the figure, the X_{SOLAR}-axis is parallel with the X_{ISS}-axis of the ISS attitude reference frame, which origin is located in the geometric centre of the Integrated Truss Segment and its direction is nominally coinciding with the ISS flight direction, i.e. tangent to the ISS orbit. The Z_{SOLAR}-axis is pointing in the zenith direction, anti-parallel to the Z_{ISS}-axis, and is perpendicular to the X_{SOLAR}-axis. The Y_{SOLAR}-axis is perpendicular to both the X_{SOLAR} and Z_{SOLAR}-axis and completes the orthogonal set of the SOLAR reference vectors. This reference frame is static and has the origin located at the baseplate, where the payload is attached to the external platform. The SOLAR pointing reference frame (X_P, Y_P, Z_P) is initially parallel to the SOLAR reference frame, but it is moving together with the rotating payload cradle.

In order to have the instruments pointing at the Sun, the CPD has to compensate for the Sun's apparent motion. The rotation around the X_P-axis compensates for the elevation of the Sun over the orbital plane, which varies with the season and with the precession of the ISS orbit. In other words, to correct for the ISS β-angle: the angle between the Sun-Earth vector and its projection on the orbital plane. This rotation is referred to with the indexation angle α. The rotation over the Y_P-axis, on the other hand, compensates for the Sun's apparent motion along the orbit. This is called the de-rotation angle γ. The rotation over the Y_P-axis is limited to $\pm 40°$, which results in a maximum observation time of only 20 minutes per ISS orbital revolution. The ISS orbit has an inclination of $51.6°$ with respect to the Earth equator. This results in a β-angle that varies between $\pm 75.1°$ over the course of a year. However, the rotation over the X_P-axis is limited to $\pm 24°$, and as such Sun observation is only possible at specific periods of the year. A period of consecutive days of Sun pointing opportunities is referred to as Sun Visibility Window (SVW). The concept of SVW is illustrated in Fig. 2, which shows the evolution of the ISS β-angle over the year 2012. The SVWs are numbered incremental, where SVW#1 is defined as the first observation period after the commissioning phase.

In case the X_{ISS}-axis is perfectly aligned with the ISS

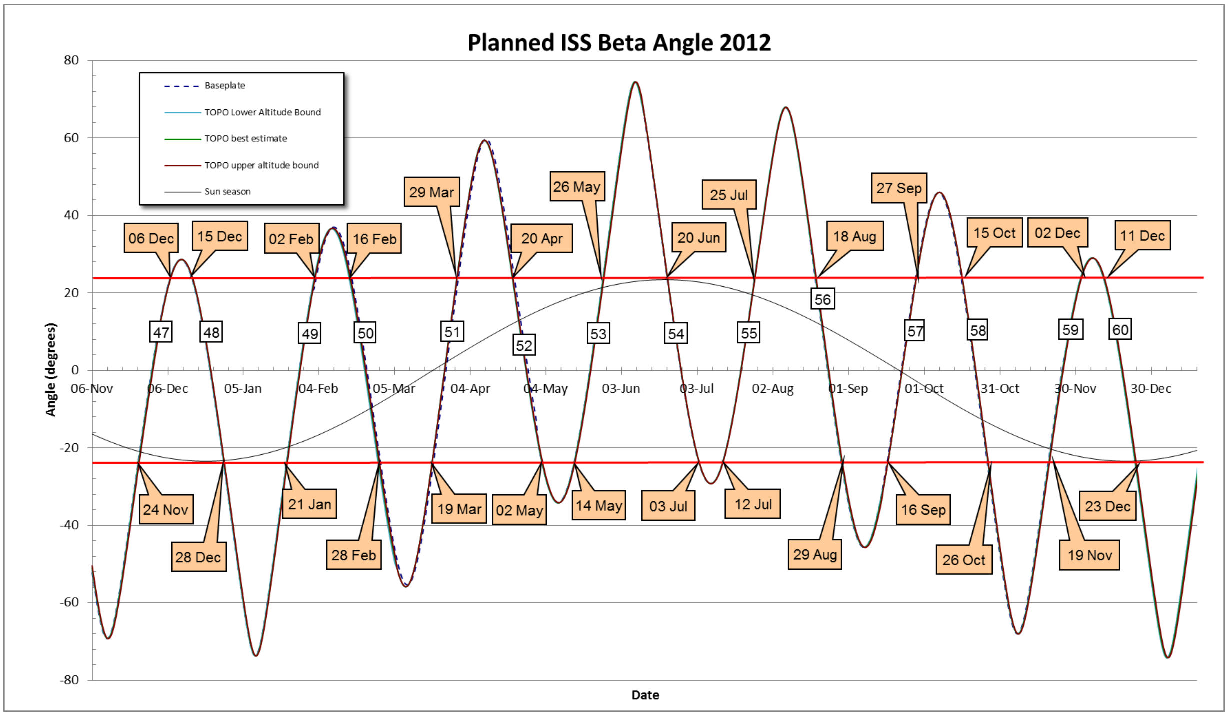
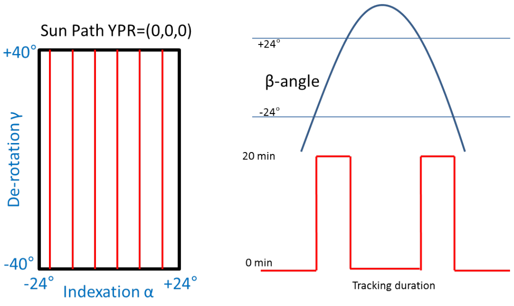


Figure 2: Variation in the ISS β-angle during year 2012. Sun observation by the SOLAR instruments is only possible when the ISS β-angle is in the range $[-24°, +24°]$, resulting in so called Sun Observation Windows (SVWs). Start and end dates of the SVW are indicated, as well as the SVW number. The value for the ISS β-angle is retrieved from various NASA sources, as indicated in the legend.

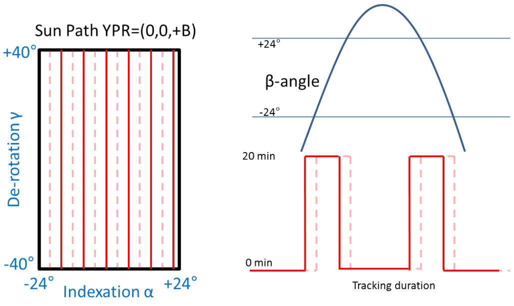
flight direction, thus tangent to the ISS orbit, the path of the Sun will describe a vertical line in the SOLAR Field of View (FOV), characterised by a constant indexation angle α, related to the β-angle. As the SVW progresses, the line will shift to higher or lower α-values, depending on the value of the β-angle at the start of the SVW. Each tracking has the same duration of 20 minutes. This is illustrated in Fig. 3(a), showing the path of the Sun in the (α, γ)-space. However, the ISS Torque Equilibrium Attitude (TEA) is not perfectly aligned with the flight direction, but shows a small yaw, pitch, and roll (YPR). Those numbers depend on the configuration of the ISS and the amount of vehicles docked to the station, of which the yaw-angle is the largest, with a typical value of $-6°$. A roll of the space station corresponds to a compensation in the indexation angle and will cause a shift of the start and end of the observation period (see Fig. 3(b)). At a non-zero yaw angle the path of the Sun in the (α, γ)-space becomes an oblique line. This results in shorter tracking duration at the beginning and end of the Sun observation window (Fig. 3(c)).

III THE EXTENDED SUN VISIBILITY WINDOW

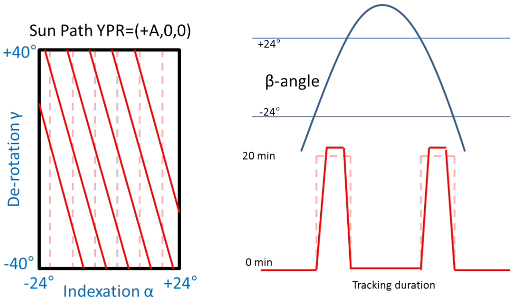
From a scientific perspective it is desired to have a minimum of interruptions in the observations. As can be deducted from Fig. 2 around the winter and summer solstices the gap between two consecutive observation periods is the shortest. As explained in Sect. II the ISS flight attitude has a considerable impact on the Sun observation, and as such the question was put forward if it would be possible to bridge two observation periods by simply changing the ISS attitude. The most straightforward attitude change is a transition to called ±YVV-attitude, in which the Y_{ISS}-axis is aligned with the velocity vector. In other words, a yaw of $\pm 90°$. In such scenario, the role of the X_{SOLAR} and Y_{SOLAR}-axes is reversed: Sun observations would be possible for a β-angle in the range $[-40°, +40°]$, albeit with a reduced tracking time, namely from 20 to 12 minutes. However, even with a tracking time of only 12 minutes the SOLAR science requirements can still be satisfied. A transition to



(a) Attitude YPR=(0,0,0)



(b) Non-zero roll YPR=(0,0,B)



(c) Non-zero yaw YPR=(A,0,0)

Figure 3: The effect of the ISS attitude on the Sun tracking by the SOLAR platform. a) The X_{ISS}-vector is aligned with the flight vector. The tracking is a vertical line in the SOLAR FOV. The tracking duration is constant during the SVW. b) A roll of the ISS will shift the start and end of the SVW compared to the YPR=(0,0,0) case. c) For a non-zero yaw angle, the Sun path will be an oblique line in the SOLAR FOV and will impact the tracking duration. The dashed lines in panels b) and c) represent the YPR=(0,0,0) case.

±YVV is not straightforward, as it consumes propellant, has a major impact on other external payloads, and exposes a larger area of the ISS to micro-meteorite impact. A second option would be a limited change in the ISS attitude, mainly yaw and roll, resulting in a shift of the observation window and an impact on the duration of Sun Tracking. In this way, it would be possible to merge two SVWs when the observational gap is the shortest, being around the time of the solstices. This second option has much less impact on the other payloads, and can even be achieved solely by the use of the Control Moment Gyroscopes (CMGs). The drawback of this configuration is that there will still be a gap in the observations of 4 to 5 days, where the tracking time will be less than 7 minutes. The original requested attitude change was from equilibrium attitude YPR=$(-4°, -1.9°, +0.6°)$ to a biased attitude YPR= $(-11°, -2.6°, -0.3°)$ around the period of the winter solstice. It turned out that this configuration is not compliant with the requirement of a one fault tolerance for the CMGs. The alternative attitude suggested by the Attitude Determination and Control Officer (ADCO) was YPR= $(-11.5°, -1.9°, -0.1°)$. This attitude could be achieved by using the CMGs, with the proviso that desaturation burns could occur when external torques need compensation of the momentum management system requiring more than 95% of the CMG capacity available at that moment. The attitude change appeared in the Attitude Timeline (ATL) as "SOLAR attitude" and the manoeuvre to the biased attitude took place on 18:30GMT 30 November, 2012, and lasted until 00:30GMT 12 December, 2012, bridging SVW#59 and SVW#60. An overview of the predicted tracking time for the extended SVW#59-60 is presented in Fig. 4. The biased attitude lasted for more than 11 days and only during a period of 5.5 days the tracking time dropped under 7 minutes, with a predicted minimum of 4min35s.

III.I The Operator's perspective

The extended SVW#59-60 lasted from 19 November, 2012, to 23 December, 2012. The minimum tracking time dropped to 4min31s on 6 December, 2012. This yields a total observation period of 35 days. The science team prepared dedicated instrument commands, in order to retrieve valuable observations even during the period of reduced tracking. Unfortunately, observations had to be interrupted several times for thruster events and vehicle dockings. During such an events, SOLAR has to be reconfigured, with SOLSPEC switched off and Sol-ACES

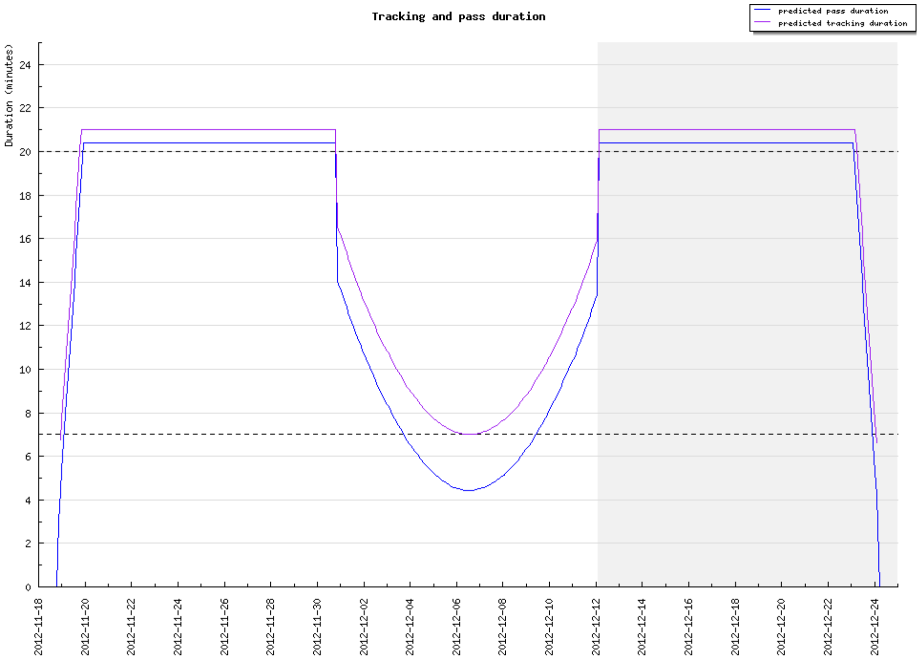


Figure 4: The predicted tracking duration for SVW#59-60. Predictions are based on the ISS attitude as per Attitude Timeline. The purple curve indicates the time the sun is in the FOV of the Sun Sensor, while the blue curve represents the duration of perfect alignment with the Sun vector.

in a heated state, to avoid instrument damage. Even cancelled ISS events have impact on the science timeline as they involve significant rescheduling and require up to 20 hours of transition to ensure a good payload configuration. For Sol-ACES, science can only be resumed at least 12 hours after the thruster firing as the instrument needs to cool down to its operational temperature range. Table 1 shows an overview of the thruster events that occurred during SVW#59-60.

Several system anomalies occurred during SVW#59-60, among others: glitches causing the abrupt end of Sun tracking; a failure of the Analogue Input Board (AIB) requiring a power cycle of the platform for recovery; missing ancillary data; Sol-ACES instrument badly initialised; SOLSPEC communication error causing a reboot of the platform. Despite some anomalies, some delays in the planning, or reshuffling of activities, all science requirements could be achieved. In Fig. 5 an overview is presented of SVW#59-60. The green crosses indicate the predicted tracking time by the platform, while the red crosses represent the actual tracking time and are a measure for the number of observations. The anomalies are indicated with red boxes. The interruptions of the tracking due to the Sun Sensor glitch on 20 November, 2012, and the AIB failure during Sun Tracking on 26 November, 2012, can be clearly spotted. The longer than predicted tracking duration during the bridging period and at the beginning and end of SVW#59-60 is due to the strong pointing drift that occurs when the platform is moving to the limits of its pointing capabilities. The light blue bars indicate when SOLAR was in pointing mode, and thus ready to track the Sun. In total, more than 80 SOLSPEC solar mode measurements were made and more than 90 SOLSPEC calibrations were performed. Sol-ACES took 4 spectrometer scans, and performed more than 150 calibrations.

III.II Scientific results

The bridging during the winter solstice of 2012 was an opportunity to 1) verify by cross-comparison the ability of the instruments for measuring the right amplitude of the variability of the solar irradiance, and 2) to contribute to

Start date	End date	Event
16 Nov GMT05:27	16 Nov GMT06:10	Soyuz thruster test
16 Nov GMT13:45	16 Nov GMT16:00	Debris Avoidance Manoeuvre (DAM)
18 Nov GMT20:40	19 Nov GMT02:05	Soyuz undocking
13 Dec GMT13:08	13 Dec GMT15:08	Pulsed DAM demo (cancelled)
16 Dec GMT12:14	16 Dec GMT14:14	Pulsed DAM
17 Dec GMT06:14	17 Dec GMT07:07	Dedicated thruster test
18 Dec GMT23:57	19 Dec GMT02:07	Pulsed DAM (cancelled)
21 Dec GMT12:25	21 Dec GMT15:05	Soyuz docking
23 Dec GMT10:10	23 Dec GMT12:20	Progress reboost

Table 1: Overview of the different thruster events and vehicle dockings that occurred during SVW#59-60.

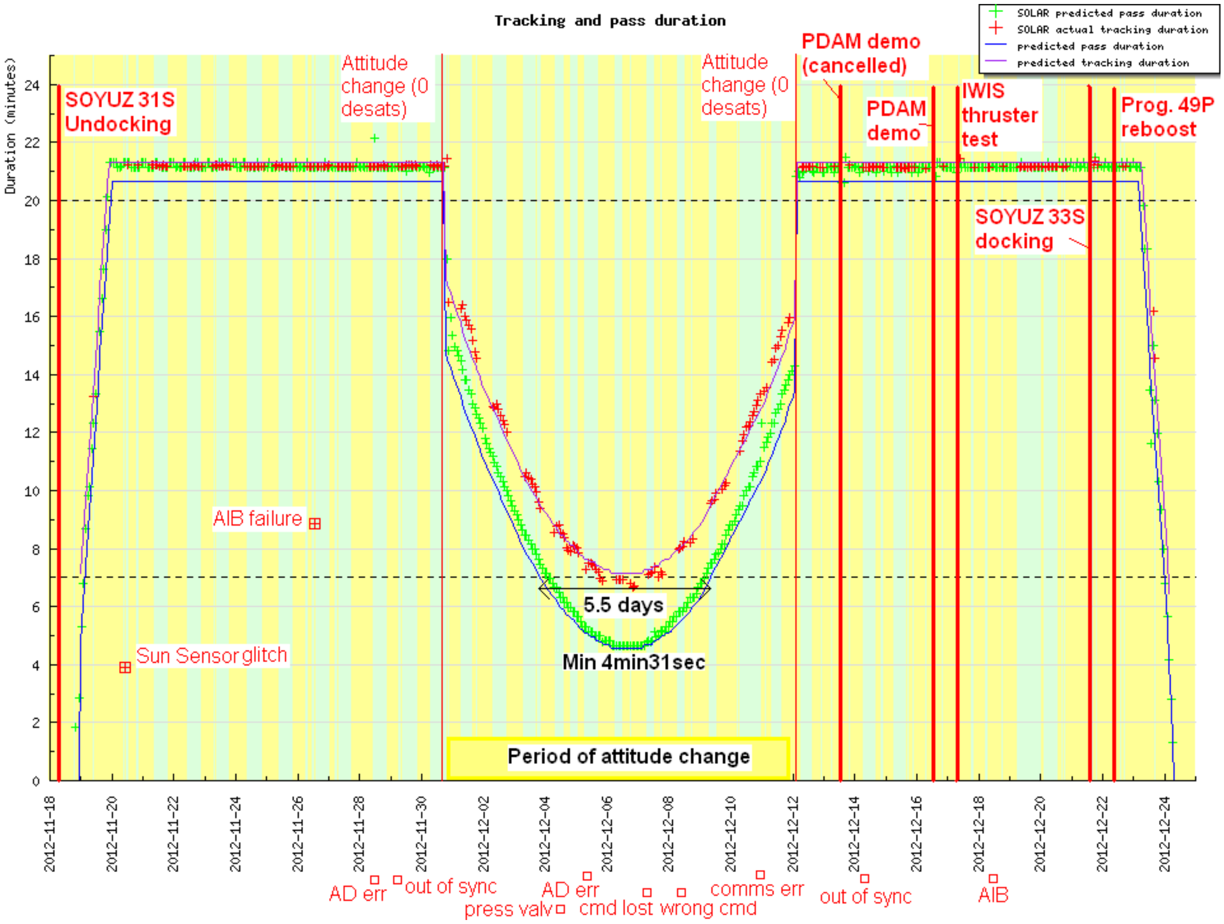


Figure 5: Overview of SVW#59-60 including the different ISS events. Green crosses: the predicted tracking duration by the platform; red crosses: the actual tracking duration and are a measure for the number of observations. The light blue bars indicate when SOLAR was in pointing mode; yellow bars: SOLAR in idle mode, no Sun tracking. Different anomalies are indicated as well.

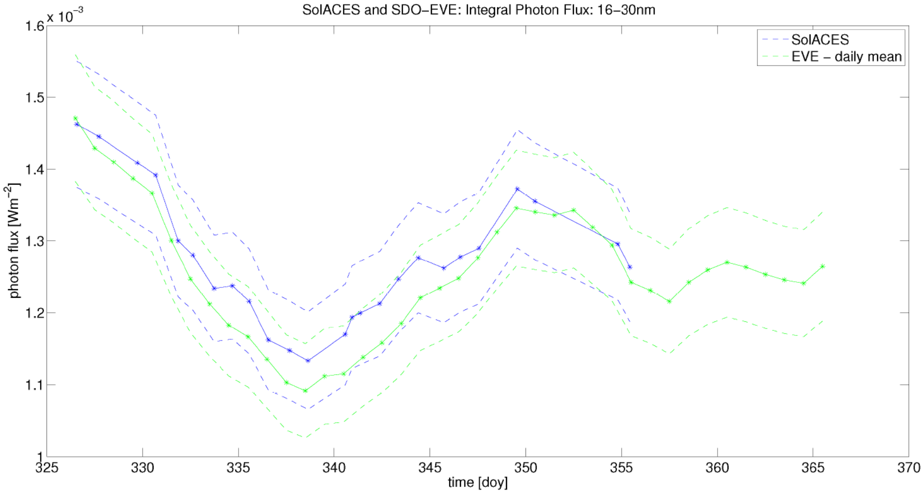


Figure 6: Inter-comparison between Sol-ACES data (blue asterisks) and SDO/EVE data (green asterisks) for the period of SVW#59-60. The dashed lines represent the ±10% error levels for both instruments.

the modelling of sunspots, faculae and their effect on UV irradiance for a better prediction of solar activity. More specific, for Sol-ACES this was an opportunity for inter-comparison of extreme UV irradiance measurements as provided by the Solar Dynamics Observatory (SDO) in order to reduce uncertainties of absolute scales; SOLSPEC could perform an inter-comparison between the variability of UV irradiance and solar proxies such as the MgII index.

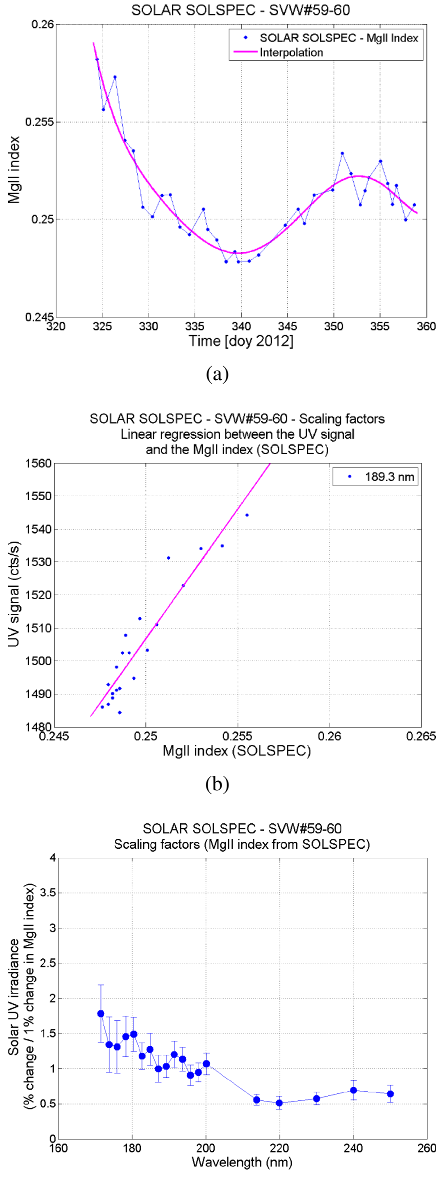
An inter-comparison between the Sol-ACES and SDO/EVE data are shown in Fig. 6. The figure shows the EUV flux in the wavelength range 16-30nm for the period of SVW#59-60. Deviations between the two instruments are within the range of 3%. This is an important result in EUV spectroscopy as the accuracy of the data could only be estimated in the past. The results show one of the best agreements ever obtained between two EUV space instruments, using different optics and calibration methods.

The MgII-index, as measured by SOLSPEC, is a proxy for the solar activity, as it relates to the emission from the chromosphere. The evolution of the SOLSPEC MgII index during SVW#59-60 is presented in Fig. 7(a). The multispectral study performed by SOLSPEC for the UV solar irradiance provided similar time series for each wavelength. The increasing UV variability with shorter wavelength can be revealed by comparison with the simultaneous MgII index measurements. The correlation between the MgII index and the UV emission in different wavelengths (see Fig. 7(b) for an example), can be used to extract the scaling factors that represent the percentage of change for the UV solar irradiance for one percent change of the MgII index versus the wavelength (Fig. 7(c)). These factors are the key parameters for modelling the solar irradiance variability from the MgII proxy (Thuillier et al. 2012).

IV CONCLUSIONS

On 30 November, 2012, at GMT18:30 the International Space Station made an attitude change. Thanks to this small change in roll, and mainly yaw (about 7.5°) the Solar Monitoring Observatory could perform measurements of the spectral and total solar irradiance uninterruptedly over a period of 35 days. This event is historical as it was the first time ever the ISS rotated solely for a scientific experiment. Without this small change in attitude, the maximum SOLAR observation period would not exceed 14 days due to the mechanical constraints of the platform. An entire rotation of the Sun was monitored quasi-continuously for the first time in history from the ISS and close daily collaboration was demonstrated between different International Partners for a common science goal.

The ISS is definitely not the most ideal environment for a Sun watching instrument. First of all, the typical ISS orbit makes it impossible to continuously monitor the Sun. Secondly, visiting vehicles, thurster firings,



(a)

(b)

(c)

Figure 7: Results derived from SOLSPEC data. a) Evolution of the MgII-index during SVW#59-60; b) the MgII-index versus the UV signal at 189.3nm; c) the derived scaling factor for a MgII-index of 0.25, clearly showing the increasing variability for shorter wavelengths.

and ventings might be harmful for the instrument optics.

Thirdly, since the ISS is not a dedicated platform to solar observations, other ongoing activities might interrupt the measurements, such as shadowing by movable structures. On the other hand, there are many positive aspects. The ISS offers a great opportunity to fly two well-proven instrument concepts (SOLSPEC and SOVIM) and one innovative EUV spectrometer including in-flight calibration (Sol-ACES). Moreover, the ISS is a long-living platform with good power supply and data downlink capacity and there is a possibility to return flown experiments for ageing and contamination analysis. Having quasi-continuous SOLAR observations is vital for a better understanding of the solar EUV/UV variability and will 1) provide data to investigate the impact of the solar variability on the Earth's climate; 2) contribute to the understanding of the complex processes taking place in atmospheric physics; 3) improve the modelling of the solar EUV/UV irradiance and its relation to solar active regions and flares, the solar-terrestrial connection, and certain aspects of the space weather. Therefore, it is important to repeat these bridging campaigns as much as possible, with an opportunity every solstice. The success of this event is attributable to the thorough support from ESA and the NASA counterparts, and the commitment of the science teams.

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