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The SOLAR attitude for the International Space Station: from a one-time experimental attitude change request to a standard ISS attitude to advance SOLAR science

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The Solar Monitoring Observatory, or SOLAR in short, is a payload of the European Space Agency, mounted 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 17 to 3080nm. 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 almost a complete solar cycle, it will provide data on the long-term evolution of the Spectral Solar Irradiance, important for, among others, atmospheric science. However, the monthly 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 rotation of the Sun. 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. After this successful first event, the SOLAR bridging operation was executed twice more, namely in July and December 2013. More bridging campaigns are envisioned, with the next one requested for the summer solstice 2014.

I. Introduction

With the Solar Monitoring Observatory (or SOLAR in short), the European Space Agency (ESA) has the aim to provide accurate measurements of the Solar Spectral Irradiance (SSI), covering a wide spectral range from the Infra-Red (IR) to the Extreme Ultra-Violet (EUV). The scientific objectives of the SOLAR mission cover different fields of research, such as solar physics, atmospheric physics, and climatology.[1] The solar spectrum reveals information on the composition and temperature of the different layers in the Sun's atmosphere (photosphere, chromosphere, corona). 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. Development of active regions on the solar surface and dynamic events in the solar atmosphere, both driven by the Sun's magnetic field, cause short term variation in the solar spectrum. On the longer term, the eleven-year cyclic variability of the solar magnetic field imposes modulations in the solar radiative output. 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%.[2] As noted by [3], 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.

SOLAR was mounted on one of the external platforms of the Columbus module on 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. 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.[4] 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[5] measuring the solar spectral irradiance (SSI) in three different channels: UV (165–370nm), visible (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.[6,7] Although the mission was initially granted for a duration of 1.5 years, a 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. By bridging two observation windows, data could be collected on a daily basis over a complete solar rotation period of 27 days.

This paper outlines the work of the B.USOC team to reach the goal of rotating the ISS purely for scientific purposes. The road to the SOLAR attitude, from the first idea till the actual implementation, is described in detail. After a successful first event in December 2012, the bridging experiment has been repeated twice more. A more detailed description of the SOLAR payload and its Sun pointing capabilities is described in II. The concept of the SOLAR bridging is outlined in III, while the executive aspect of the the three bridging campaigns is outlined in section IV. A discussion on the process and coordination on how to achieve the bridging is presented in V. The final section VI contains the concluding remarks.

II. The SOLAR platform

The SOLAR observatory is mounted on one of the external platforms of the Columbus module with the three instruments pointing to the zenith direction, i.e. away from the Earth. The SOLAR instruments are mounted on the Coarse Pointing Device (CPD): a two-axes moving platform, allowing the instruments to orient towards the Sun. In addition to the scientific instruments, a Sun Sensor is present on the CPD, which allows accurate alignment with the Sun vector. 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, of which the 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

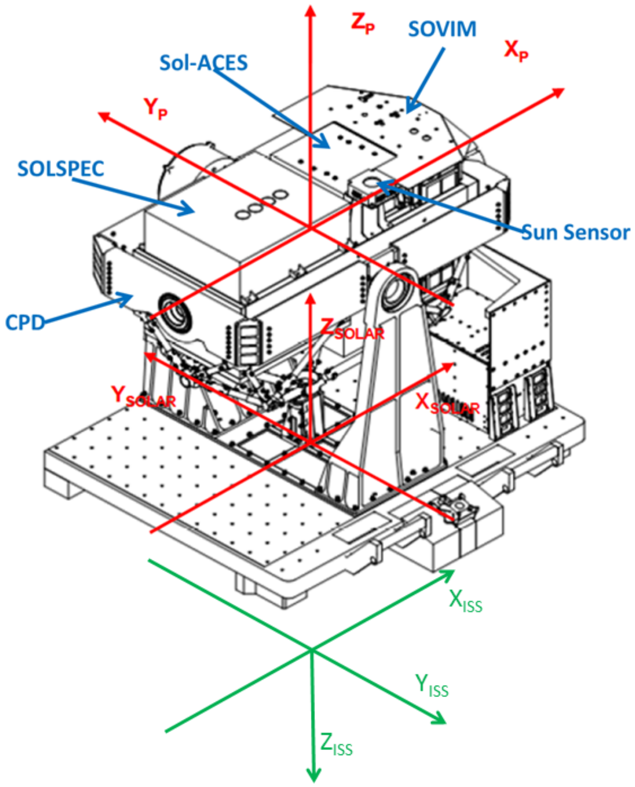


Figure 1. Schematic of the SOLAR payload, showing the location of the three instruments on the CPD. The SOLAR reference coordinate system is indicated by $(X_{SOLAR}, Y_{SOLAR}, Z_{SOLAR})$, and it is fixed to the static external platform. The reference frame attached to the instruments is indicated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

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 payload's commissioning phase.

In case the X_{ISS}-axis is perfectly aligned with the ISS 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), of which the yaw-angle is the largest, with a typical value of $-6°$.

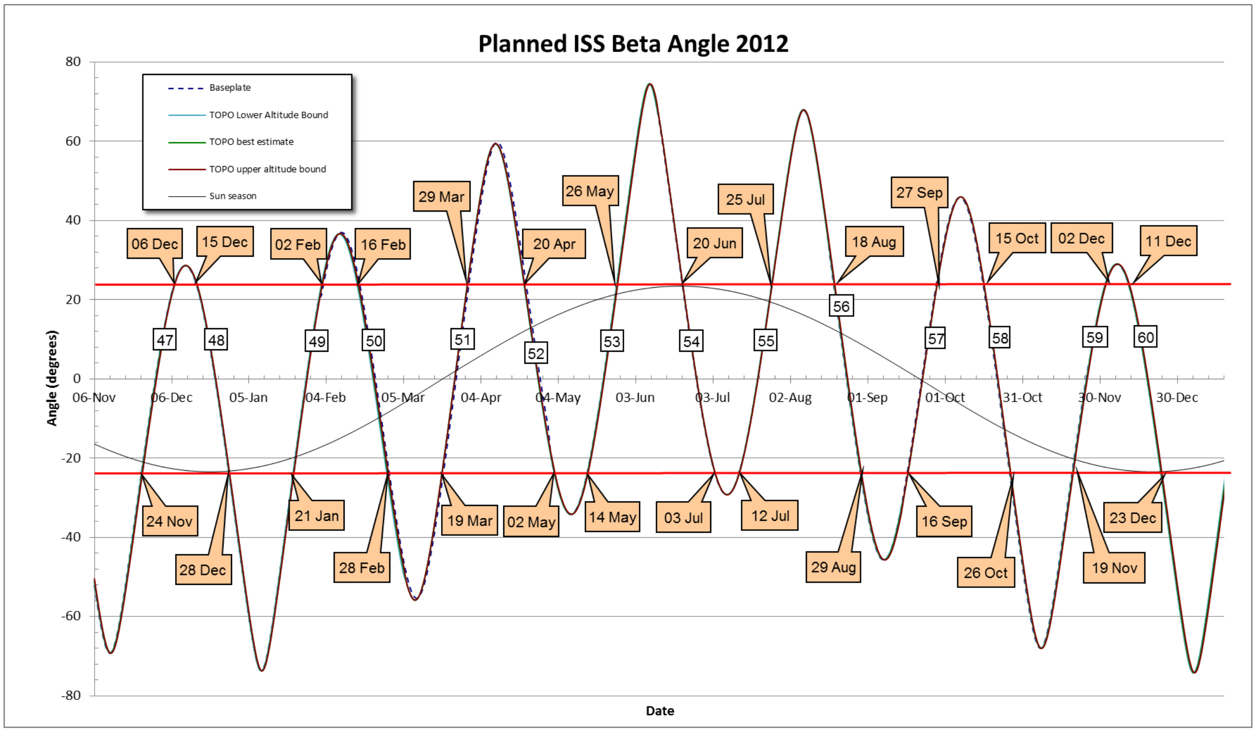
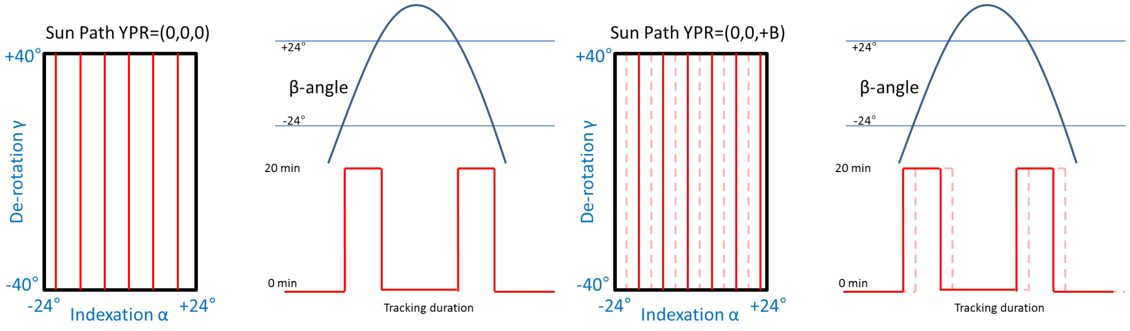


Figure 2. Variation in the ISS β-angle during year 2012. Sun observation by the SOLAR instruments is only possible when the ISS β-angle is in the range $[-24°, +24°]$, resulting in so called Sun Observation Windows (SVWs). Start and end dates of the SVW are indicated, as well as the SVW number. The value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

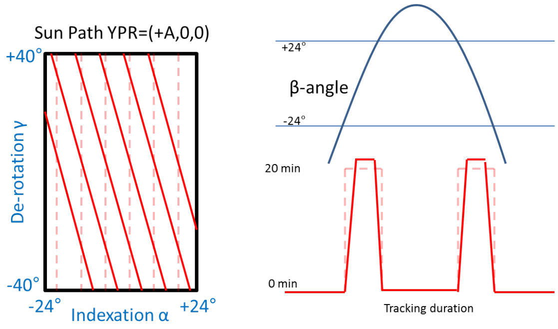
Those numbers depend on the configuration of the ISS and the number of vehicles docked to the station. A roll of the space station corresponds to a compensation in the indexation angle and will cause a shift of the start and end of the observation period (Fig. 3(b)). At a non-zero yaw angle the path 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 minimise the number of interruptions in the observations. Around the winter and summer solstices the gap between two consecutive observation periods is the shortest (Fig. 2). As explained in section 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 the so-called ±YVV-attitude, in which the Y_{ISS}-axis is aligned with the velocity vector. In other words, to change the yaw of the ISS to ±90°. In such a 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 ±YVV is not straightforward, as it consumes propellant, has a major impact on other external payloads, and exposes a larger unshielded area of the ISS to potential micro-meteorite impacts. 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, which is the minumum tracking time required to gather useful data by the instruments. 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



(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.

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.

IV. The Operator's perspective

IV.A. Bridging number 1: SVW#59-60

The extended SVW#59-60 lasted from 19 November, to 23 December, 2012, yielding a total observation period of 35 days. A minimum tracking time of 4min31s was reached on 6 December, 2012. The science team prepared dedicated instrument commands, in order to retrieve valuable observations even during the period where the tracking duration dropped below 7 minutes. Several constraints needed to be taken into account when scheduling the science activities:

1. SOLSPEC and Sol-ACES instrument should not take observations of the solar spectrum simultaneously, as the instruments are not perfectly aligned.
2. SOLSPEC should not be operated during South Atlantic Anomaly (SAA) passage, since the SOLSPEC photometers are highly disturbed when passing the SAA.

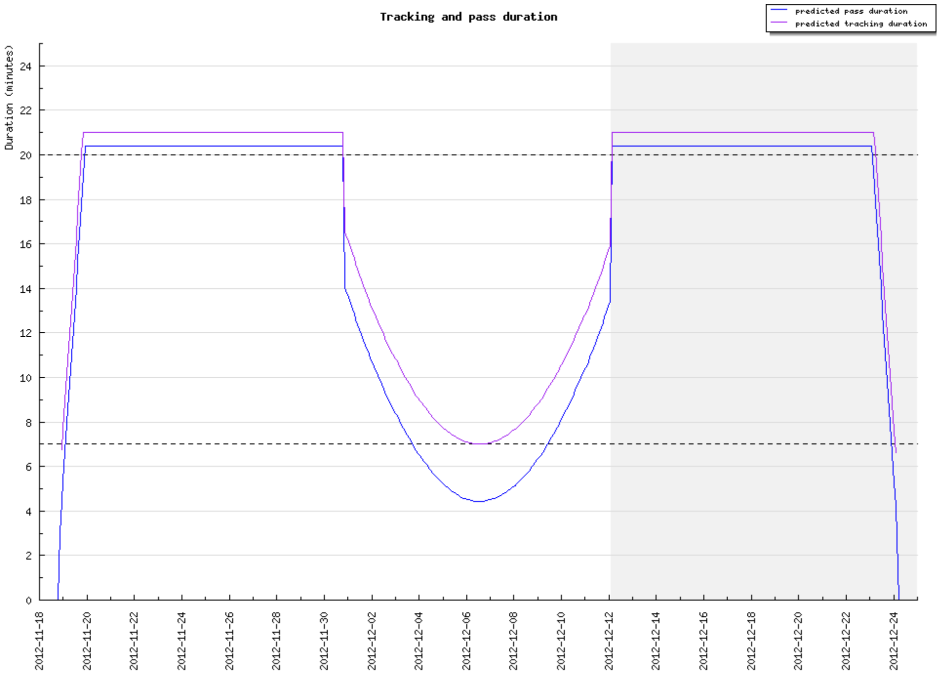


Figure 4. The predicted tracking duration for SVW#59-60. Predictions are based on the ISS attitude as per Attitude Timeline. The purple curve indicates the time the sun is in the FOV of the Sun Sensor, while the blue curve represents the duration of perfect alignment with the Sun vector.

3. The SOLAR software did not allow the execution of the new instrument commands provided by the SOLSPEC science team via an automatic schedule, i.e. a file containing a series of time stamped commands. Instead, the instrument commands had to be sent directly by the B.USOC operator. Since the timing of the command with respect to the start of Sun tracking is important, these activities could only be scheduled when there was sufficient S and Ku-Band coverage.

4. During thruster events and vehicle dockings, SOLAR has to be reconfigured, with SOLSPEC switched off and Sol-ACES in a heated state, to avoid instrument damage due to potential contamination.

During the first extended observation window, several thruster events took place. Even cancelled ISS events have an impact on the science time-line as they involve significant rescheduling and require up to 20 hours of transition to ensure a good payload configuration, as Sol-ACES needs to be heated up. 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 payload 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 SOLAR for recovery; missing ancillary data; Sol-ACES instrument incorrectly initialised; SOLSPEC communication error causing a reboot of SOLAR; unexpected behaviour of one of the Sol-ACES valves. Despite these 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

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

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	Pre-determined DAM (PDAM) demo (cancelled)
16 Dec GMT12:14	16 Dec GMT14:14	PDAM
17 Dec GMT06:14	17 Dec GMT07:07	Dedicated thruster test
18 Dec GMT23:57	19 Dec GMT02:07	PDAM (cancelled)
21 Dec GMT12:25	21 Dec GMT15:05	Soyuz docking
23 Dec GMT10:10	23 Dec GMT12:20	Progress reboost

150 calibrations.

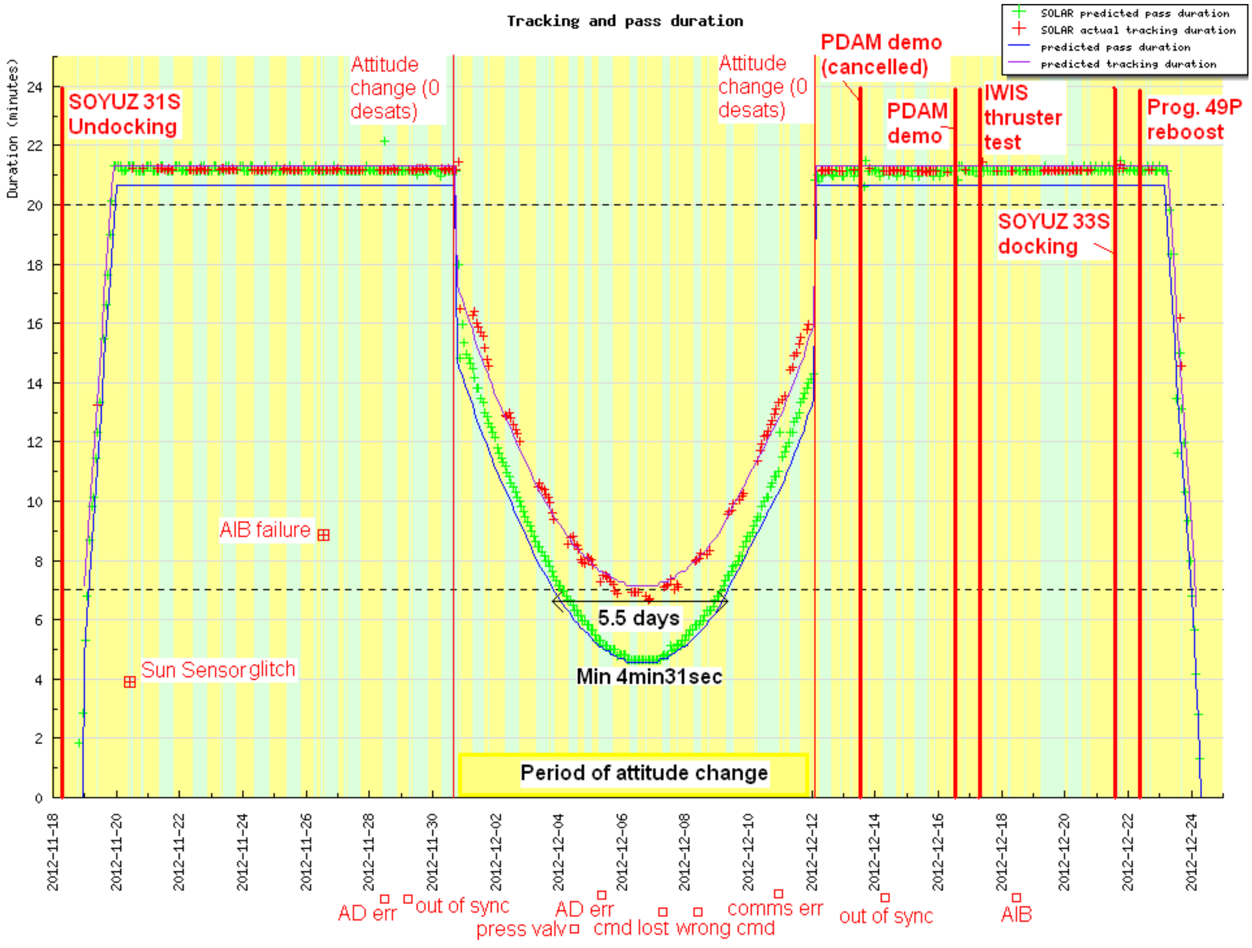


Figure 5. Overview of SVW#59-60, showing the evolution of the tracking duration. Vertical red lines indicate relevant ISS events. Green crosses: the predicted tracking duration by the platform; red crosses: the actual tracking duration, being a measure for the number of observations. The light blue bars indicate when SOLAR was in pointing mode; yellow bars: SOLAR in idle mode, no tracking of the Sun. Different anomalies are indicated by square boxes.

IV.B. Bridging number 2: SVW#66-67

The second bridging campaign merged SVW#66 and SVW#67, starting 18 June, 2013, and lasting until 24 July, 2013. On 30 June, 2013, the ISS was brought into the yaw-biased SOLAR attitude with YPR=

$(-11.5°, -2°, 1.3°)$. The originally foreseen date to transition back to nominal TEA was 11 July, 2013. However, an Extra-Vehicular Activity (EVA) was scheduled on 9 July for which the ISS was configured to nominal +XVV TEA (YPR= $(-6°, -2.3°, 0.6°)$). It was decided not to transition back to the yaw-biased SOLAR attitude after the EVA, as the tracking time was already sufficient to do useful science. Moreover, an ATV-4 reboost was scheduled for 10 July, 2013. Compared to the first bridging, the upgrade of the SOLAR Applications Software was an important improvement, considerably facilitating the operations. From now on, a sun sensor glitch during sun tracking is no longer causing an interruption of the tracking and the SOLSPEC commands that needed to be sent manually before, can now be included in an automated command schedule, resulting in more planning flexibility. This second bridging went extremely smooth. Only one calibration measurement for the Sol-ACES instrument was lost, due to an AIB failure. Sun tracking was ended prematurely on 28 June due to the Canadian robotic arm casting a shadow over SOLAR. However, all science data were already collected for that specific pass, and thus there was no impact on the operations. In Fig. 6 the overview of SVW#66-67 is presented in the same format as Fig. 5. Six thruster events took place during this extended observation window (indicated with vertical red lines in Fig. 6). The discontinuity in the tracking duration on 9 July, 2013, is due to the transition to nominal TEA for the EVA. In total, the SOLSPEC instrument performed 82 solar spectrum measurements, and 82 calibrations. Sol-ACES performed 5 spectrometer scans, and 165 calibrations.

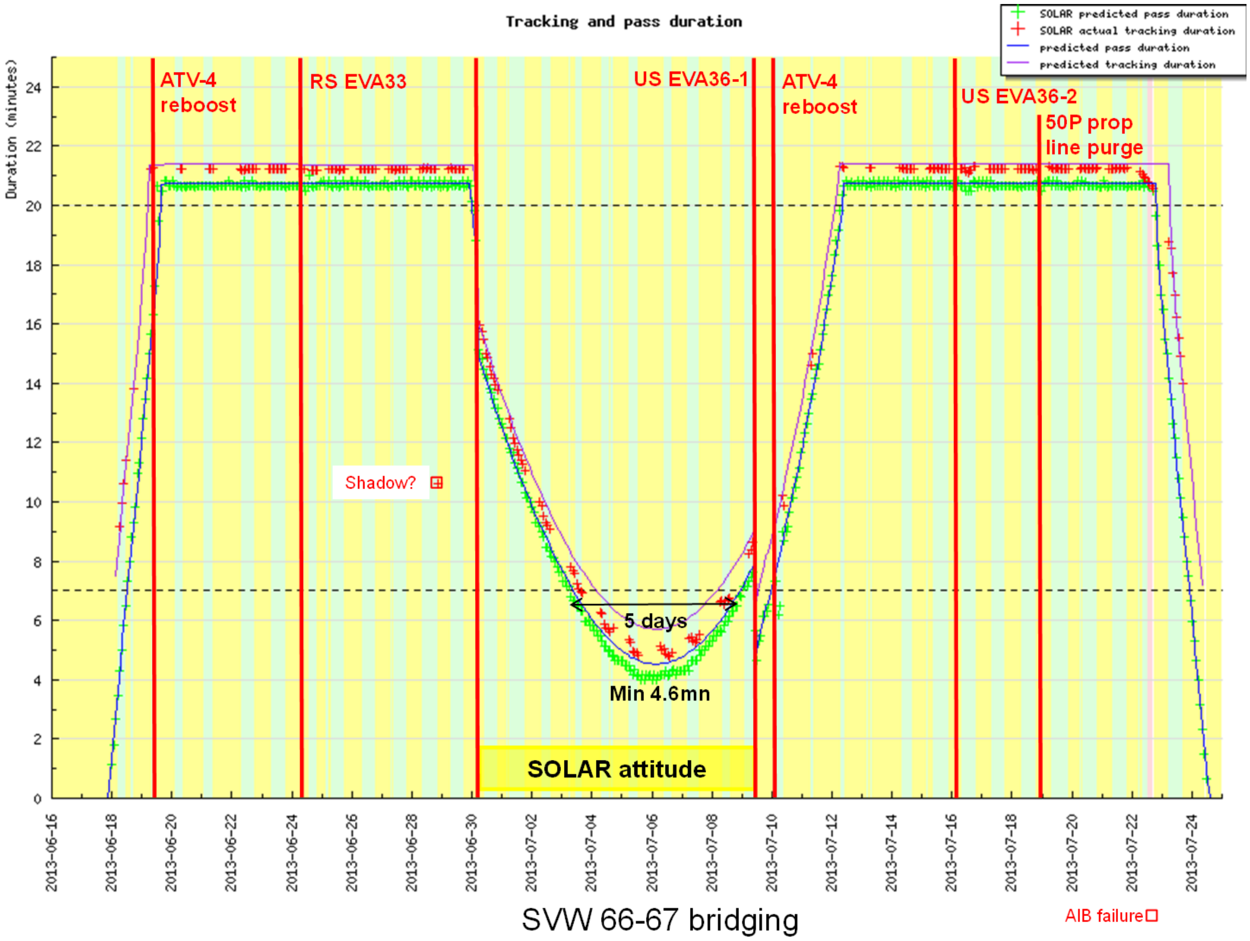


Figure 6. Overview of SVW#66-67, showing the evolution of the tracking duration. Vertical red lines indicate relevant ISS events. Green crosses: the predicted tracking duration by the platform; red crosses: the actual tracking duration, being a measure for the number of observations. The light blue bars indicate when SOLAR was in pointing mode; yellow bars: SOLAR in idle mode, no tracking of the Sun. Different anomalies are indicated by square boxes.

IV.C. Bridging number 3: SVW#71-72

The third bridging campaign merged SVW#71 and SVW#72, making SOLAR observations possible from 16 November until 22 December, 2013. The ISS retained the yaw-biased attitude of YPR= $(-11.5°, -2.6°, -0.1°)$

between 30 November and 10 December, 2013. Only three thruster events were scheduled during this extended SVW. No additional changes were made to the SOLAR software, and the instruments were performing similar measurements as in the previous two campaigns. The planning and execution of the activities was straightforward and smooth. Three AIB failures occurred, but all when SOLAR was not performing science. However, on 11 December, 2013, a major system failure on the ISS occurred. Due to a problem with a flow control valve in one of the ammonia coolant loops, a power down of the Columbus Power Distribution Unit 1 was necessary. This resulted in a cut-off of the SOLAR nominal power, and consequently a transition of SOLAR to survival mode. All SOLAR science activities were halted. SOLAR had to stay in this configuration up to 31 December, 2013. Therefore, from a scientific perspective, this bridging campaign was the least successful as almost the complete SVW#72 was lost. The merged SVW lasted for only 25 days, instead of the expected 36 days, during which 55 SOLSPEC solar spectrum measurements, 59 SOLSPEC calibrations, 4 Sol-ACES spectrometer scans, and 131 calibrations were performed. Figure 7 presents the overview of SVW#71-72 in the same format as Fig. 5 and 6.

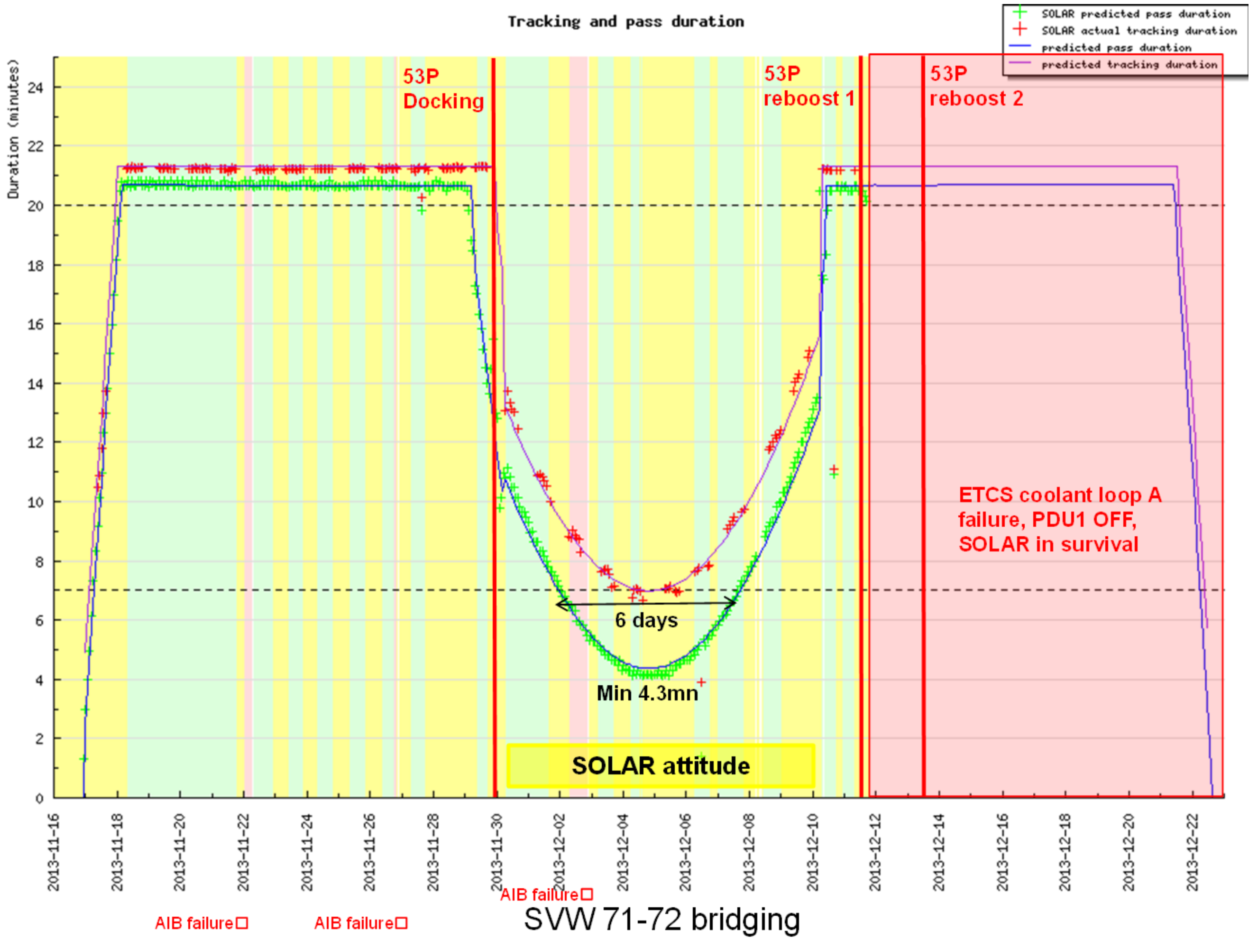


Figure 7. Overview of SVW#71-72, showing the evolution of the tracking duration. Vertical red lines indicate relevant ISS events. Green crosses: the predicted tracking duration by the platform; red crosses: the actual tracking duration, being a measure for the number of observations. The light blue bars indicate when SOLAR was in pointing mode; yellow bars: SOLAR in idle mode, no tracking of the Sun. Different anomalies are indicated by square boxes.

V. Discussion

The SOLAR bridging was not immediately realised: two and a half years have passed from the idea to the implementation of the first bridging. Intense pre-coordination took place between the different international partners (IPs) and the strong support from ESA was crucial at all times.

Once ESA was convinced of the additional scientific value of the SOLAR bridging, the request process could be initiated. The SOLAR Experiment Science Requirements document,[8] including the requirement to have measurements over a complete solar rotation period, was issued. A Change Evaluation Form was created in which two different options for the attitude were presented, as discussed in Sec. III. The ±YVV option has significant scientific benefits, since the observation period could be extended from 16 November, till 27 December, 2012, although with a reduced tracking time. To obtain such a long observation window, the YVV attitude is not only required to bridge the two SVWs, but also at the beginning and the end of the extended observation period. Tests performed on the SOLAR ground model by the payload developer have demonstrated that the implemented Sun Pointing algorithms are compatible with the ±YVV attitude and it was also confirmed by the payload developer that there are no thermal problems for SOLAR in the ±YVV attitude. Although this option was preferred by the scientists, it rapidly became clear that this option could be detrimental for some other external payloads. Moreover, a manoeuvre to ±YVV would consume a lot of fuel and as such the choice for YVV would require more resources. Also the NASA Vehicle Integrated Performance Evaluation Team (VIPER) team had its concerns for an attitude change to YVV. The ±YVV flight attitude was so far only applied during spacewalks to mitigate positive potential shock hazard. The ±YVV attitude is currently limited to no more than 100 hours per year, and this to reduce the risk of science loss for the attitude dependent payloads, but it is also an assumption for structural life assessment as a larger, more fragile area is exposed to micro-meteorite impacts. Additional time above 100 hours per year must first be approved by all IPs via different boards. Besides this, at the time a Soyuz docking was foreseen on 7 December, 2012, requiring a manoeuvre to XVV in the middle of the bridging period. From these perspectives it is clear that the yaw-biased +XVV attitude is preferred.

The proposed alternative attitude of YPR= $(-11.5°, -1.9°, -0.1°)$ can be reached purely by the CMGs; however, it will reduce the amount of CMG momentum margin. In case a torque cannot be handled with the available momentum margin, desaturation burns will occur. Usually, in momentum management steady-state control, only a dynamic operation or a failure would cause desaturation burns. In the nominal TEA +XVV attitude only 15-20% of the available CMG margin is used during steady state operations. During the period in biased attitude, it was estimated that it would be at 75% of the available capacity. This means there is much less ability to handle unexpected torques. However, during this time period dynamic operations that could cause desaturation burns were ruled out, so the only desaturation burns would come from a failure. During the two-orbit manoeuvre to and from the biased TEA, two or three desaturation burns were expected. In the coordination of the SOLAR attitude, these desaturation burns were of concern for the Sol-ACES instrument. During spectrometer measurements with high voltage on, an electric discharge, called the corona effect, will occur when the pressure inside the instrument exceeds 2.1×10^{-5}mbar. Such a corona effect will cause permanent damage to the instrument. However, the environmental experts assured that the CMG related desaturation burns are not in the direction of SOLAR and can impossibly create such an internal pressure in the instrument. Therefore, there was no reason to inhibit the desaturation burns. In any case, during the manoeuvre to the biased attitude SOLAR was not performing measurements to avoid that the released thruster gases impacted the data. During the bridging itself, no desaturation burns have taken place and the momentum capacity of the CMGs remained between 60-65% during the SOLAR attitude, well below the predicted 75%.

Another concern in preparation of the first bridging campaign, that required intense coordination between the different teams, was the parking position of mobile transporter (MT). The MT was planned to support the NASA-CSA payload Robot Refuelling Mission (RRM), and therefore the MT needed to be transitioned to Work Site (WS) #2. Having the MT at WS#2 would reduce the available CMG capacity from three (if MT is at WS#4) to 2.5 (at WS#2). The translation of the MT from WS#3 to WS#2 was initially scheduled for 13 November, 2012, and the MT would have to stay at WS#2 until January 2013, due to the limited crew on board (since a Flight Rule states that EVA capability should be available in case the MT gets stuck). Also, having the MT and Space Station Remote Manipulator System (SSRMS or robot arm) at WS#2, SOLAR would experience shadowing from the robot arm near the end of Sun tracking. The reduced CMG capacity would increase the risk of desaturation burns. Moreover, having the MT parked in WS#2 for almost two months increases the risk of Trailing Umbilical System (TUS) cable damage due to Micro Meteoroid Orbital Debris (MMOD) strike. A loss of the TUS cable would result in the loss of the capability to send commands to the SSRMS. In the end, it was decided to transition the MT to WS#4, which is according to a Flight Rule the preferred position for the MT, and the SSRMS was reconfigured to be not in the field of view of SOLAR.

Table 2 summarises the different milestones in the request for the first SOLAR attitude change. This request has been coordinated with the following stakeholders:

- ISS Payload Programme Office - Research Integration Management Office, Research Planning Office, Payload Operations
- Vehicle Integrated Performance and Resources (VIPeR) Standard Planning and Requirements Committee (SPARC) Panel
- Payload Engineering and Integration
- European Space Agency
- Japanese Aerospace Exploration Agency

Table 2. Overview of the milestones in the attitude change request

Milestones	date
Payload Integration Panel	14-Jun-2012
VIPER SPARC Panel	21-Jun-2012
Mission Integration and Operations Control Board (MIOCB)	21-Jun-2012
Space Station Programme Control Board (SSPCB)	17-Jul-2012
Joint Operations Panel	24-Oct-2012
ISS Mission Management Team	29-Nov-2012
Execute ISS Attitude Manoeuvre for SOLAR	01-Dec-2012

After the successful first bridging, ESA agreed to support two more additional bridgings. The process to require a second and third bridging were considerably simpler. At the MIOCB of 28 March, 2013, it was decided that the approval of the SSPCB was no longer required.

While preparing the second bridging, it turned out that the yaw-biased SOLAR attitude was an issue for the EVA planned on 9 July, 2013. As the ISS solar arrays are blocked during an EVA, power inhibits are in place taking out one of the four CMGs. Because of concerns regarding encroachment on the momentum manager margins while in the SOLAR attitude during the EVA, a decision was taken to transition back to TEA before the EVA and to remain in TEA for up to 15 hours before returning to the yaw-biased attitude. In the end it was decided not to return to the yaw-biased attitude after the EVA, as an ATV-4 reboost was on the schedule two days after and the tracking time was already sufficient in nominal TEA to gather useful science data.

Also the response in case a Debris Avoidance Manoeuvre (DAM) would be needed in the yaw-biased attitude was discussed in preparation of bridging campaigns. It was decided that a DAM could be executed in the biased attitude. However, for the case of a Pre-determined DAM, a transition back to +XVV TEA was required. Only after the software transition for the Russian Segment on 5 December, 2013, it was cleared that a PDAM could be initiated anywhere in the +XVV attitude envelope. Fortunately, during none of the bridging phases there was a need for a (P)DAM.

VI. 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. 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. 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 observing instrument. First of all, the typical ISS orbit makes it impossible to continuously monitor the Sun. Secondly, visiting vehicles, thurster firings, 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. After successful completion of the first bridging campaign, two more SOLAR bridgings have been performed with relative ease. Unfortunately, the third extended SOLAR Sun Visibility Window was interrupted after 25 days due to a major system failure on the ISS. A request has been made in the mean time to repeat the bridging experiment a fourth time during the summer solstice in 2014. 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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