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SOLAR: Wrap Up after 9 Years of Successful Operations on the ISS

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Abstract

After exactly 9 years of operations, the SOLAR mission ended on 15 February 2017. This was an extraordinary achievement knowing the mission duration was originally foreseen for only 1.5 years!

SOLAR 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 SOLAR platform hosts three instruments built to observe the solar irradiance in the wavelength range 17 to 3080nm.

B.USOC is the Belgian User Support Operations Centre that conducted the operations for SOLAR throughout the whole mission. Over these 9 years, the operations team gained valuable experience in the planning, implementation and execution of the operations of this external payload, coordinating the mission with the scientists and the flight control teams of the different International Partners. This paper will first briefly present the SOLAR payload and then focus on the SOLAR mission as experienced by the B.USOC. The evolution of the operational concept will be outlined, highlighting achievements and encountered challenges and how these were overcome. The paper will be concluded with some valuable lessons learned that can only be gathered through solid experience such as only an end-to-end mission can bring.

Keywords: *ISS, Operations, SOLAR, B.USOC, Columbus, external payload*

Acronyms/Abbreviations

AIB	Analogue Input Board
B.USOC	Belgian User Support and Operations Centre
CART	Columbus Anomaly Resolution Team
Col-CC	Columbus Control Centre
CPD	Coarse Pointing Device
CU	Control Unit
DOR	Daily Operations Report
ESA	European Space Agency
ESR	Experiment Scientific Requirements
EUV	Extreme Ultra Violet
EVA	Extra Vehicular Activity
FCT	Flight Control Team
GMT	Greenwich Meridian Time
IP	International Partner
IR	Infrared
ISS	International Space Station
NASA	National Aeronautics and Space Administration
OSTPV	On-board Short Term Plan Viewer
PD	Payload Developer
PI	Principal Investigator
Sol-ACES	SOLar Auto-Calibrating EUV/UV Spectrometers
SOLSPEC	SOLar SPECtrum
SOVIM	Solar Variability Irradiance Monitor
SSI	Solar Spectral Irradiance
SVW	Sun Visibility Windows
TSI	Total Solar Irradiance
TYNA	The Yamcs Notification Add-on
USOC	User Support and Operations Centre
UV	Ultra Violet

1. Introduction

The story of SOLAR actually started 25 years ago, when a group of scientists, of Belgian, French, German and Swiss nationality, replied to an Announcement of Opportunity issued by the European Space Agency (ESA) for scientific research projects to be held on board of the International Space Station (ISS). But it is 9 years ago that the operational life of SOLAR started, on 7 February 2008, when it was launched together with the European Columbus Module to the ISS with the Atlantis Shuttle from Cape Canaveral Florida. Three days later, Atlantis docked to the ISS, the Columbus module was connected to the station and on 15 February 2008, SOLAR was installed on its designated external platform of Columbus. This was an important moment for the operations team on ground as it is from this moment onwards that the real-time operations started and that the operations concept as it was planned was finally going to be implemented and executed through all of the related operational products.

The payload, originally built to support an 18-month mission, went beyond expectations, ultimately offering 9 years of Sun observations, spanning almost a full Sun cycle. Besides the great benefit of acquiring scientific data over a long duration period, this extended mission enabled the control centre supporting the operations, the Belgian User Support and Operations Centre (B.USOC), to improve and adapt the original operational concept along the years and gain valuable experience.

The B.USOC was thus the Facility Responsible Centre for the SOLAR payload as assigned by ESA. Together with, at that time, eight other User Support & Operations Centres (USOCs) spread around Europe, B.USOC contributes to the operations of European scientific or technological experiments on-board Columbus. The overall planning of activities on-board the module and the control and monitoring of the Columbus systems is handled by the Columbus Control Centre (Col-CC), to which each USOC is individually connected.

At the beginning of the SOLAR mission, the experience in human space flight operations was at that time still limited at B.USOC and at Col-CC, as the Columbus module had just been installed a few days before SOLAR. Naturally, the operational concept, or the support provided by both centres evolved from the original planned concept to adapt to the evolution of the operational world and related agreements.

This paper presents the evolution of the operational concept as executed by B.USOC together with a selection of challenges and achievements that were experienced during the 9 years of operations. In section 2 the SOLAR payload will be briefly described, after which the 9 years of operations experience will be outlined in section 3. This latter section will be split into 3 subsections, the evolution of the operational concept, the challenges and the achievements. The paper will be closed off with lessons learned in section 4 and the conclusion in section 5.

2. The SOLAR Payload

SOLAR is an ESA payload mounted on one of the external platforms of the Columbus module of the ISS (**Error! Reference source not found.**). The SOLAR mission had the aim to provide measurements with unprecedented accuracy of the Solar Spectral Irradiance (SSI) over a wide spectral range from the Infra-Red (IR) to the Extreme Ultra-Violet (EUV). The obtained data is to be used for two main goals: the study of the Sun itself and using the Sun's energetic output as a valuable input for climate models. The combination of these objectives makes SOLAR one of the few experiments studying both Earth and space, and serves several fields of research, such as solar physics, atmospheric physics, and climatology [1, 2].

Figure 1: The European Columbus module on the ISS with the SOLAR payload in view of the external platforms of Columbus.

To reach the objectives and such a wide spectral window, the SOLAR platform hosts three instruments that were designed to together cover the range of 17 to 3080nm. The Solar Variability Irradiance Monitor (SOVIM) was focusing on Total Solar Irradiance (TSI) data. Unfortunately, the SOVIM instrument was lost after a fatal hardware failure in the first year of the mission. The SOLar SPECtrum (SOLSPEC) instrument measured the SSI in three different channels: UV, visible and IR. Measurements of the SSI in the EUV part of the solar spectrum were taken by the SOLar Auto-Calibrating EUV/UV Spectrometers (Sol-ACES). The SOLAR instruments are mounted on a Coarse Pointing Device (CPD), a two-axes movable platform providing Sun pointing and tracking capabilities. The SOLAR Control Unit (CU) provided power, collected, formatted, and dispatched to ground the telemetry and science data generated by the platform and the instruments in dedicated telemetry packets. In the other direction the CU received ISS ancillary data and processed the ground issued tele-commands.

The ISS is not in an optimal orbit and environment for continuous Sun observation, there are more specialised vantage points like Sun Synchronous Orbits or orbits around Earth-Sun Lagrange points. The ISS was also not a platform dedicated solely to the SOLAR mission, many more missions are being supported simultaneously on the ISS. For the SOLAR instruments however, the SOLAR mission on the ISS was a unique opportunity to fly two well-proven instrument concepts (SOLSPEC and SOVIM) and one innovative EUV spectrometer including in-flight calibration (Sol-ACES) on a robust long-living platform with good power supply and data downlink capacity. Compromises had to be made during SOLAR operations, taking into account thruster firings, structures present in the instrument's field of view, ISS activities impacting its attitude and limiting the available power and the wide range of angles at which the Sun comes in over the course of the cyclic ISS orbit. The two-axis platform, together with the Sun Sensor, allowed for an accurate pointing to and tracking of the Sun. However, due to mechanical limitations, the Sun was only observable during at most 20 minutes per ISS orbit and this for about 10-14 consecutive days. This limitation resulted in so-called Sun Visibility Windows during which science data could be collected. In order to tackle all these constraints, a number of SOLAR modes were identified, each matching different configurations and activities occurring on the ISS. The *Survival Mode* was used when power was not available to SOLAR (power down due to maintenance or ISS power system anomalies or when maintenance or installation activities occurred on payloads sharing the same power lines as SOLAR). Keep-alive heaters were still be available on a separate power line, while the Control Unit would be off. The *Standby Mode* was a fall-back mode in case of anomalies or for maintenance activities, having only the basic functionality available (only the control unit active, no power to the tracking platform). For software updates of the SOLAR application software, there was also a dedicated mode called *Software Maintenance Mode*. In *Idle Mode*, SOLAR was in a stable waiting mode, until the Sun was back within its tracking range. Ancillary data from ISS allows the SOLAR platform to predict when the next tracking would be possible. Later in the mission, this mode also included the heating of the Sol-ACES instrument, as a mitigation for potential contamination of the instrument. Finally, the *Science Mode* was using the ancillary data automatically received from the ISS to position the SOLAR platform in the right position and on time to catch the Sun on its apparent trajectory in order to correctly point the instruments at the Sun.

3. 9 Years of Operations Experience

3.1. The Evolution of the Operational Concept

When designing a payload and preparing for operations, every possible scenario and any to-be-expected constraint are thought of and taken into account to the possible extent. Nevertheless, it is only with practical experience of the real-time operations that such constraints and consequences can fully be assessed. It is therefore only natural that the original payload operational concept evolves with time and gets changed to optimise the operations as the mission goes on.

This section will review several aspects of the operational concept and explain the evolution those concepts underwent from the original concept to the final improved concept as it was in use by the end of the mission.

3.1.1. Internal Planning and Reporting

The internal planning and reporting at B.USOC is probably the point that has seen the biggest evolution throughout the mission. At the very beginning of the real-time operations, B.USOC operators worked with a post-it board on which they indicated the upcoming days' activities. This was quite a challenging way of planning, especially during periods where there was a possibility of a Shuttle docking as many reshufflings of the planning usually happen in such periods. The Daily Operations Report (DOR) was at that time a simple Word document which was usually written by the night shift.

As more operators joined the team over time, new ideas came along and the post-it board was soon taken out of the picture to be replaced by the SOLAR Mission tool, developed by the operators and which included a partial file configuration control system, semi-automated planning and automated DOR generation.[3]

This new mission tool was a big upgrade on the old-school post-it board solution, but not a solution that could not be improved even more. With the mission tool as a basis to build upon and the new experience on console from the operations team, several points of improvement were identified and a new tool was gradually developed, the SOLAR Predictor. This new tool had many features needed on console, such as an automated timeline review, an automated DOR generation, calculation of the individual Sun trackings, file configuration control, real-time planning, archive monitoring, etc.. This tool made life on console much more effective and productive and was used for the rest of the mission as the planning tool. [4]

3.1.2 Command windows

Each payload activity has to be scheduled in the ISS operations timeline, available for the Flight Control Team (FCT), crew and all International Partners (IPs) to be aware of what is happening on the ISS each day. At the beginning of the SOLAR activities, each single activity done with one of the instruments - e.g. powering-on an instrument, moving the platform, starting a certain observation, etc. - was indicated in the timeline with a separate commanding window for the duration of the activity and with a link to a dedicated procedure. As SOLAR had a scientific requirement of having at least 8 measurements per day during the Sun visibility window, this resulted in many command windows in the timeline and subsequently many timeline reviews to be done on the operators side. Furthermore, a "GO" had to be requested with the COL

Flight Director (COL FD) for each activity, which was interrupting the Flight Director a lot!

This planning cycle was very cumbersome and restricting. All experiment commands had to be included in the OSTPV (On-board Short Term Plan Viewer) with frequent daily rescheduling cycles due to unforeseen ISS events or changes of the science planning.

Luckily, with growing experience and confidence between the collaborating centres, B.USOC and COL-CC, the mode of operations evolved to a more realistic 'tele-science' concept allowing real-time commanding from the B.USOC during an allocated 24/7 command window, the 'SOLAR real-time commanding' window. Here, on a daily basis, a Flight Note had to be issued indicating the activities that would be performed that same day. The instruments' configuration activities for thruster events still had to be scheduled separately and activities still had to be coordinated and the status briefed with the COL FD, so it was not perfect, but this new concept was already an improvement compared to the previous one that included scheduling each single activity performed with SOLAR separately in the timeline.

This concept then evolved even further into the so-called 'SOLAR Ground Commanding' Window that would also last for a full day, but refer to the SOLAR Ground Command Procedures Book that encloses all the ground procedures that could be used in relation to the nominal and corrective SOLAR activities. This Ground Commanding Window gave B.USOC full responsibility over the payload with less restrictions from Col-CC than before. All that was left to do was for the operator to brief COL FD at the start of the shift, on the activities of the day and get a "GO" for the whole commanding window of that day.

This new way of working significantly facilitated and improved the work on console and soon paved the way for other payload operations, becoming a standard for ground only activities.

3.1.3 SOLAR modes and operation shifts

As seen in section 2, SOLAR had several operational modes in which it could be: idle mode, science mode, standby mode and survival mode. Full-time operations happened during a so-called Sun Visibility Window when the SOLAR platform could observe the Sun during intervals of roughly 20 minutes per orbit and science measurements could be performed. During this period of time lasting for about 2 weeks every month, SOLAR was kept in science mode, i.e. both feeders were powered and Sun Tracking was possible every orbit.

At the beginning of the mission, up to 2011, outside of SVW periods, SOLAR would be put in survival mode, while during the SVW or Science Mode periods, B.USOC provided a 24/7 on console staffing following science. The 24/7 shift coverage was needed due to thermal constraints of the instruments and the motors of the platform. These constraints needed the SOLAR payload to be continuously powered and continuously monitored as, following the ISS Flight Rule B19-104, manual action from ground was required whenever these temperatures would go out of limit. Furthermore, in case of an anomalous situation where the telemetry could not be monitored anymore, the SOLAR Operator had to support recovery actions or set up a work-around to put SOLAR back in a nominal state and, if possible, to regain telemetry [5].

This setup was followed by an agreement that was established between ESA, COL-CC and the B.USOC, to optimize the SOLAR on console support in the light of the science requirements [6]. Since the Columbus Flight Control Team at the COL-CC is in charge of the Columbus Laboratory, the COL-CC has visibility of a limited number of Health and Status data of all payloads, such as power consumption, critical temperature sensor readings, etc., including those SOLAR temperature readings listed in the Flight Rule B19-104. In the light of the science requirements the agreed console support for SOLAR was:

- During SVWs and science operations, the B.USOC provided 16/7 SOLAR on console support; During the night, Col-CC monitored the payload and contacted the SOLAR Operator on-call whenever the platform showed an out of limit telemetry or whenever an external event occurred which could impact the SOLAR payload.
- Outside SVWs or periods of no science measurement, B.USOC provided 8/5 on-console support and be on-call with Col-CC monitoring the payload the rest of the time.

This set-up was applied until December 2013.

At the end of 2013, the B.USOC received the information that SOLAR would no longer be monitored by COL-CC outside periods of science measurements. B.USOC had to take back the monitoring of SOLAR on a 24/7 basis, putting a lot of stress on the understaffed team for such a configuration.

As solution to this delicate situation, an agreement was set up between ESA and B.USOC where B.USOC would support a full 24/7 console coverage for a period of a maximum of six months and use that transition period to develop a notification tool that would allow the automated monitoring of the payload when not performing science measurements.

The notification tool called TYNA (The Yamcs Notification Add-on) got created and used for the rest of the mission, relieving operators from night-shifts, only being called on console in case of an anomaly [5].

With the success of TYNA and as part of a larger USOC cost saving exercise, ESA finally requested to extend the SOLAR Automated Notification Tool to a more generic notification tool that would be usable by all USOCs and not rely on the Yamcs mission control system as is the case for the B.USOC/SOLAR [5, 7].

3.2 The Challenges

As already mentioned in this paper, a mission that happens as expected and that does not come across a few hurdles, would not be a real mission. The SOLAR mission had its fair share of challenges too, but thanks to the hard and dedicated work of the operations team, these constraints were always taken care of in due time while trying to minimise the impact on the ongoing science operations. A list of encountered challenges is given in this section together with the solution adopted by the operations team in order to overcome the challenge in question.

3.2.1 Unplanned situations

- The Sun Visibility Window

The visibility of the Sun for the SOLAR platform depends on two factors. The first and most important one is the beta angle, which is the angle between the line connecting the ISS and the Sun and the orbital plane of the ISS. The second factor is the position of the SOLAR platform and its mechanical limitations. When the ISS is in its nominal XVV position and taking into account the limitations of the X-axis of the platform, SOLAR observations are possible when the beta angle is between -24 and 24 degrees (**Figure 2**). In practice this led to the so-called Sun Visibility Windows (SVW), which were the periods during which science observations were possible using the SOLAR instruments. **Figure 2** represents the ISS beta angle with time and SVWs are the period in between the two red lines.

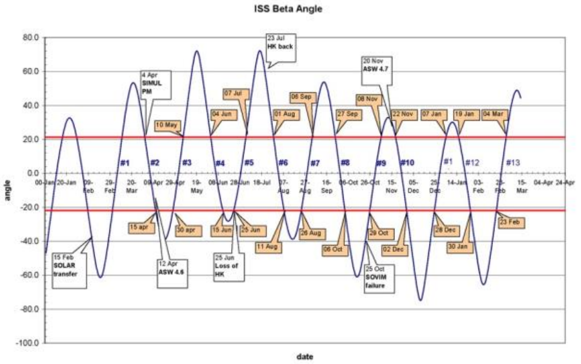


Figure 2: ISS Beta Angle with time showing the periods of the year when the Sun is visible to the SOLAR platform (between -24 and 24deg)

During the SVWs, the instruments were pointed to the Sun for a duration of 20 minutes each ISS orbit. This 20-min duration was imposed by the Y-axis limitations of the platform.

This SVW was not foreseen in the operational concept. Originally, it was required for the instruments to observe the Sun continuously over the 28-day solar cycle [8]. Unfortunately, when operations started, it was observed that the Sun was not always visible and the reason for it was soon calculated. Luckily, this was just a matter of orientation and these SVWs could be calculated with precision and thus accounted for, allowing for us to make the most out of the available observing time. Nevertheless, this resulted in science to be done only for 10-12 days a month, alternated with an average of 20 days of Idle Mode of SOLAR.

- Comprised Sun Sensor offset

The mechanical construction of the platform also revealed another limitation during real-time operations. It had been found that the Sun sensor, that allows the platform to identify the Sun and then track it for observations, had to be at a different starting angle for the different instruments. Without accounting for this starting angle offset, the instruments would be off-centred with the Sun and therefore make invalid observations.

In June 2010, the best solution for this problem was found to be to integrate a Sun Sensor offset for each instrument and not to have two measurements of different instruments happening at the same time.

3.2.2. The degradation of instruments

- The loss of SOVIM

On 26 Oct 2008, the current of the SOVIM instrument outlet went to 0A. This issue was identified as the power board failure of the instrument. After some further investigation, the instrument had unfortunately to be declared lost and no further activation was attempted.

The operations nevertheless had to continue and after some re-adjustment related to some SOVIM constraints that were not applicable anymore and other constraints that still applied, such as the different modes of SOLAR, the operations were back on track with only two working instruments on the SOLAR platform, Sol-ACES and SOLSPEC.

- The Calibration lamps of SOLSPEC

The SOLAR instrument SOLSPEC has 6 calibration lamps: 2 Deuterium (D1 and D2) and 4 tungsten (W1, W2, W3 and W4). On 26 April 2009, part of the Light Power Supply feeding the Deuterium lamps failed. This resulted in it being impossible to re-ignite the lamps D1 and D2. The anomaly was soon investigated and determined as aging. A workaround was luckily quickly found by the SOLSPEC Team by using protective quartz plates and the hollow cathode tube to cover the calibrations otherwise performed by the deuterium lamps.

On 29 July 2015, the lamp W1 was lost due to the tungsten ribbon that broke. This was discovered by the scientists after analysing the data of the measurement using this lamp. A decrease in temperature was noticed just before the end of the warming period and no measurable signal after the period nor during the next measurement. The other lamps, W2, W3 and W4, were nevertheless still operational and were used to nominally continue the science measurements with SOLSPEC for the rest of the mission. From SVW#92 onwards all measurements which included the W1 lamp were therefore removed from the science planning.

- Decrease of Sol-ACES' spectrometer efficiency.

Early 2011 the Sol-ACES science team reported a strong decrease in the efficiency of the spectrometers and they assigned this initially to the pollution of the optical surfaces by internal or external contamination. As a countermeasure, the Sol-ACES science team requested to keep Sol-ACES heated outside of the observation periods. This resulted in a change of the operational concept, as SOLAR had to be continuously powered. As the B.USOC team did not have the resources to support a 24/7 service outside Sun Visibility Windows, the compromise was to reduce the support to 16/7 during science windows, and 8/5 outside. When not on console SOLAR was monitored by COL-CC as described in Section 3.1.3.

- SOLACES ionisation chamber Temperature

On 20 April 2015, the temperature of one of the Sol-ACES ionisation chambers was seen to increase drastically during a Sol-ACES spectrometer calibration. When the temperature reached a magnitude of 130degC, a fast shutdown of the instrument was executed in the hope for it to stop increasing and starting to decrease again. The temperature did decrease, but the instrument being unpowered, the temperature soon went close to the lower temperature limit set for a safe configuration of the instrument. Indeed, for the survival of the instruments, it is important to keep them warm and Sol-ACES was therefore powered on again but closely monitored to make sure the temperature of the electrometers would not go over 85degC.

What followed was a very long troubleshooting process including all parties of the FCT, operators and PIs. A period in which several Columbus Anomaly Response Team (CART) meetings were held and troubleshooting operations on the instrument. In the end, the result of the analysis was that this high temperature reading was not a realistic number and due to a failed component, but not a showstopper for operations. Only the front part of the ionisation chamber was affected and calibrations could be performed with the back part only. So after four months of discussions and troubleshooting, the anomaly report could finally be closed and Sol-ACES activities resumed.

- AIB failure

There was one anomaly that was recurrent for SOLAR. This was the so-called AIB failure or the Analogue Input Board failure. This failure happened at random times and put SOLAR off working capability completely, the temperature readings would be off, the AIB status would be off and the platform would be put in Stand-by mode, not allowing the continuation of nominal operations. On top of this, if the failure would happen at the same time as a SOLSPEC measurement was running, the SOLAR platform would reboot.

The anomaly was not truly a failure of the Analog Input Board, but due to an anomalous activation of the VME reset line, due to a radiation sensitive optocoupler on the VME backplane. It got its name because a typical characteristic was that the AIB showed off in the telemetry, and in addition event messages related to the AIB were received. The failure would happen at random times, but could luckily be solved by a powercycle of the platform. The operations team got much acquainted to the recovery procedure and knew exactly what to do when this happened and always put the recovery in place as soon as possible in order for it to influence the ongoing science measurements the least possible.

3.2.3 Influences from external factors

Apart from the SOLAR specific limitations, instruments and platform anomalies and degradation, the SOLAR operations were also influenced by external factors. These were either due to some instrument constraints linked to those factors such as thruster events and ventings, or were due to ISS reconfiguration activities or ISS system anomalies, which affected the nominal operational configuration of SOLAR.

The events that had the most frequent impact on operations were the regular docking/undockings of crew spacecraft and re-supply cargo spacecraft, reboosts and Extra Vehicular Activities (EVAs). For each one of these thruster events, the ongoing SOLAR operations had to be ceased for a little longer than the duration of the event. From 2011 onwards, due to the Sol-ACES contamination issue, Sol-ACES even had to be heated-up during the event. The heating process needed to start a day in advance to reach the right temperature and the instrument needed to be kept warm between one to three days after the event depending on the amount of used propellant. When such event would happen during

SVWs, this proceeding resulted in quite a limited acquisition of scientific measurements for the SolACES instrument. Also, ventings from the Materials Science Laboratory in the US Lab had to be tracked in order to cease Sol-ACES and SOLSPEC operations during the venting activities.

For some of these thruster events, the ISS attitude even had to be changed to another orientation, for which SOLAR was unable to perform any possible scientific observations due the mechanical limitations of the platform.

Early in the mission, it was noticed that at times the Sun tracking was aborted few minutes earlier than expected for unknown reasons. After several of those occurrences, we found out that the common element of those occurrences was the location where the ISS robot arm was parked, in fact casting a shadow that moved towards the Sun Sensor of the SOLAR platform. When the shadow would reach the Sun Sensor, the platform would evaluate this dark patch as the Sun not being visible anymore and go back to the zero position. Discussions started with NASA to find mitigation actions, but of course operations of the robot arm had priority over payload operations, so it was decided to add SOLAR to a pool of systems (like antennae and cameras) to be warned in advance when the robot arm would come into the field of view of those systems. In this way, we knew when to expect shadowing from the robotic arm and allowed us to work around it.

Other events that have impacted the SOLAR operations were the come-and-go from other external payloads of the Columbus module, or some issues that happened with these. The Columbus module can support up to four external platforms and in the history of SOLAR, the following payloads were also attached and/or detached: EuTEF (attached and detached), HDEV (attached) and Rapidscat (attached). The provided power from Columbus is designed in such a way that all external platforms share two power outlets. The impact for SOLAR was that one or both of the power feeders had to be switched off for a certain time when another payload was installed or removed. In the case that both feeders were switched off at the same time, the ongoing reconfiguration activities had to be rigorously tracked by the operators to monitor that the temperatures did not drop beyond the limits as indicated in ISS Flight Rule B19-104. One specific example of such events, that heavily influenced SOLAR operations, was the failure of the Rapidscat payload on 20 August 2016. The consequence was that SOLAR had to be put in Survival Mode for a few days while the investigations for the power issues of Rapidscat were ongoing. Afterwards, several troubleshooting activities were held at separate times where each time SOLAR had to be powered off and on, until it was finally concluded that RapidScat was lost on 18 October 2016.

SOLAR heavily relied on the resources it got from the ISS. This is not only power, but also all communication capabilities for sending commands and getting telemetry. Regarding power provision, regular powerdowns of the Columbus systems were scheduled due to events like the locking of the ISS solar panels for thruster events, high beta angles or power anomalies. Luckily, these almost never impacted SOLAR power, but there was this one major anomaly with an ISS cooling loop in Dec 2013 for which a lot of Columbus systems had to be powered down for several weeks, and hence SOLAR had to be kept in Survival Mode. Due to this anomaly, the foreseen winter solstice SVW bridging, Nov-Dec 2013, could not be performed.
[9]

3.3 The Achievements

Besides dealing with and overcoming the several constraints and challenges that come with real-time operations as listed in section 3.2, which are already achievements on their own, there are two achievements that are worth mentioning separately as they had a big contribution to the success of the mission and reaching the scientific requirements. These are the two extensions that were granted to the mission and the accepted change of attitude of the ISS in order to be able to bridge two Sun Visibility Windows for SOLAR operations.

3.3.1 The extensions of the mission

The objectives of the SOLAR mission were to provide accurate measurements of the Solar Spectral Irradiance over a wide spectral range from the IR to the EUV. This was in order to study the Sun itself throughout its solar cycle and to use the data of the Sun's energetic output as input for climate models. With the original 18-month length of the mission and knowing a solar cycle lasts for about 11 years, the mission would only cover a small part of the Solar Cycle #24. Furthermore, a solar cycle maximum coinciding with an increase in the solar activity was expected to happen in 2013, which would of course be of high scientific interest to be able to observe with the SOLAR payload.

Both these reasons prompted to request an extension of the mission, in order to be able to observe the Sun the longest possible and cover as much as possible of a full solar cycle.

Three extensions were requested and two out of three were granted. The granted extensions were from July 2009 to 2013 and from July 2012 to February 2017. A third extension was requested in 2017, but was unfortunately rejected. Nevertheless, these two extensions allowed to convert an 18-month mission into a 9-year one, which made SOLAR the longest running scientific experiment to date on the COLUMBUS module of the ISS. An achievement to be proud of!

3.3.2 The bridging of SVWs

One of the original scientific requirements of the SOLAR mission was to observe a full 28-day rotation of the Sun [8]. Unfortunately, this came out to be impossible due to the attitude of the ISS and the limited movement of the SOLAR platform, which ultimately only allowed the platform to observe the Sun about 12 days per month, during the so-called Sun Visibility Window.

After some initial discussions during the SOLAR face to face meetings between the operators and the scientists and during shift handovers, an idea was formed that would give a temporary solution to the problem. The idea was to request a change of the ISS attitude in order to change the angle-position of SOLAR compared to the Sun allowing to bridge the 12-day observing windows of two consecutive months into a single observing period of five to five weeks. After some detailed analysis, a lot of support from ESA and NASA, B.USOC submitted the request and received the approval for the ISS to move to an attitude enabling the merging of two SVWs. This meant that a full 28-day rotation of the Sun would be observable and the originally requested scientific requirement met. [10]

After a successful first attempt in 2012 (bridging shown in **Error! Reference source not found.**), four more ISS attitude changes were requested throughout the SOLAR mission. In total, four out of five requested attitude changes were completed. The completed bridgings happened at the following dates:

-SVW#59-60 19 Nov- 23 Dec, 2012
-SVW#66-67 18 Jun – 24 Jul 2013
-SVW#71-72 16 Nov – 22 Dec, 2013 – interrupted because of the failure of the Cooling Loop A Flow Control Valve. Consequently power to SOLAR was interrupted and most of SVW#72 was lost
-SVW#78-79 17 Jun – 22 Jul, 2014
-SVW#102-103 10 Jun – 15 Jul, 2016

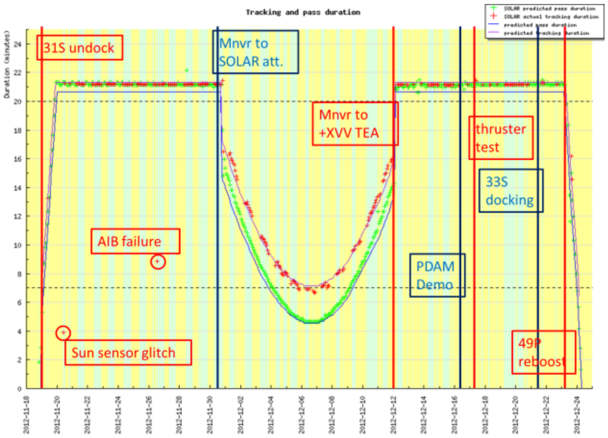
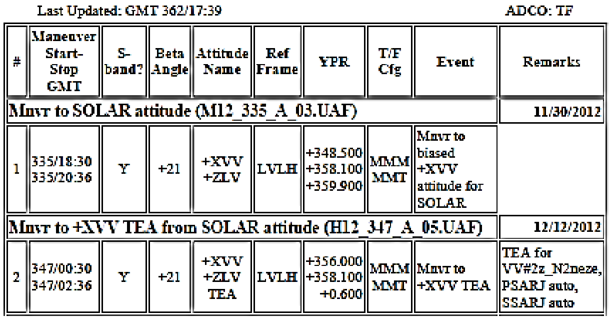


Figure 3: Tracking and Pass duration for the SOLAR platform by date, SVW#59-60, 19 November to 23 December 2012.

These SVW bridgings were probably the biggest achievement of the SOLAR mission as with these the SOLAR community made history as the first ones to request and get approved a change of ISS attitude for scientific purposes. The changed ISS attitude even received the name of ‘SOLAR attitude’ as can be seen in the ISS attitude timeline as indicated in **Figure 4**.



Last Updated: GMT 362/17:39 ADCO: TF

#	Maneuver Start-Stop GMT	S-band?	Beta Angle	Attitude Name	Ref Frame	YPR	T/F Cfg	Event	Remarks
Mnvr to SOLAR attitude (M12_335_A_03.UAF)									11/30/2012
1	335/18:30 335/20:36	Y	+21	+XVV +ZLV	LVLH	+348.500 +358.100 +359.900	MMM MMT	Mnvr to biased +XVV attitude for SOLAR	
Mnvr to +XVV TEA from SOLAR attitude (H12_347_A_05.UAF)									12/12/2012
2	347/00:30 347/02:36	Y	+21	+XVV +ZLV TEA	LVLH	+356.000 +358.100 +0.600	MMM MMT	Mnvr to +XVV TEA	TEA for VV#2z_N2neze, PSARJ auto, SSARJ auto

Figure 4: The ISS attitude timeline showing the schedule manoeuver to move the ISS to the 'SOLAR attitude' in order to bridge two Sun Visibility Windows.

4. The Lessons Learned

The SOLAR mission ran for a total of 9 years of operations. This is certainly a substantial amount of time for strong experience to be collected by stepwise improvements of the operations concept and the increasing knowledge of SOLAR. This paper describes the constraints that were encountered during the mission and how they were solved or how the operational concept was adapted to accommodate these deviations from the expected operations at the preparation phase.

Several lessons learned were collected throughout the mission, stating what occurred, the background and root cause of the problem and how it was solved or the recommended action. When going through the list of these lessons learned, they actually all relate to the same general causes and hence one main advice can be set up from them for future operations mission preparation to-be-done by any USOC.

The main cause of hurdles or frustrations in a mission is some sort of miscommunication or bad coordination. From this, we learned that the most important in mission preparation and execution is to always be prepared for unexpected anomalies to happen and to be ready with a good team at hand and good support from the other entities such as the PIs, the FCT and Payload Developer (PD) engineers, to tackle the problem in the shortest amount of time possible. For this, a fluent communication flow between the teams is needed, a good interchange of action items tracking by all respective teams to be able to implement their actions and one that keeps all concerned parties up to date with all changes or decisions that might affect the payload.

5. Conclusion

In February 2008, the SOLAR payload got installed on the external platform of the European Columbus module of the ISS for a mission that was originally planned to last 1.5 years. The mission nevertheless went beyond expectations and extended the mission time to a total of 9 years! This long duration mission allowed for the acquisition of very valuable and interesting scientific data in the field of solar science, but not only. It also enabled the control centre supporting the operations, the Belgian User Support and Operations Centre (B.USOC), to improve and adapt the original operational concept along the years and gain valuable experience.

After 9 years of operational experience it can be concluded that no matter how well prepared a mission control centre is to support a scientific mission, there will always be constraints and challenges that will appear during the mission. The important part then is to have a solid and dedicated team that can take on those challenges, troubleshoot them and find solutions in the shortest timeframe possible with good coordination and communication between the different teams working on the project.

Acknowledgements

SOLAR was part of the ESA Human Space Flight Program, although the crew involvement was quite limited, the SOLAR mission was an incredible human adventure here on the ground.

Beside the great performance of the platform to sustain 9 years (instead of 1.5y), it is thanks to the dedication of the ground personnel, with their high flexibility, their engineer spirits and skills, to achieve the one goal of the success of the scientific mission.

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