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SOLAR, 9 years of operations as external payload on the ISS: The technical challenges overcome

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

SOLAR is a payload of the European Space Agency (ESA), 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 spectral solar irradiance in the wavelength range 17 to 3080nm.

The Belgian User Support Operations Centre (B.USOC) is the ESA Facility Responsible Centre that supported the operations for SOLAR throughout the whole mission, from the operations preparation to the first few commands sent, handling unexpected problems and operating the instrument with confidence to finally permanently switching it off after 9 years of successful operations. Nevertheless, the mission was of course not free of technical challenges, but these were always handled with the greatest attention to find a suitable solution that would have the least impact on the smooth continuation of the operations.

This paper will present the operations constraints experienced by the payload operations team while operating SOLAR and how these challenges were overcome. Constraints covered by the paper include problems related to the ISS attitude and orbit, the mechanical limitations of the instrument, the availability of the various ISS resources, the external influences to the payload operations coming from the ISS itself and from other payloads, the instrument's operational modes and the instrument's degradation with time. This list is furthermore complemented by an overview of the operations products needed for dealing with these constraints during operations. Additionally, the so-called Sun Visibility Window bridging will also be mentioned, describing how a scientific requirement that could initially not be fulfilled by the platform as-built could still be occasionally reached by requesting attitude changes of the ISS at well-defined seasonal periods of the year. The paper will be concluded with some valuable lessons learned drawn from the solid experience gained after a 9-year long mission, which can bring useful advise to other teams planning operations of external payloads on the ISS or even to internal payloads, as some encountered constraints can apply to them too.

This paper complements the abstract submitted by A. Michel et al. covering the evolution of the operational concept of the SOLAR mission.

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I. Nomenclature

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
SAA = South Atlantic Anomaly
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

II. Introduction

The story of SOLAR 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 on 7 February 2008, about 10 years ago, that the operational life of SOLAR started when it got launched together with the European Columbus Module to the ISS with the Atlantis Shuttle from Cape Canaveral Florida. Three days after the launch, 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, 8 USOCs spread around Europe, B.USOC was responsible for the operations preparations and operations execution of European scientific or technological experiments 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.

This paper presents the challenges and achievements that were experienced during the 9 years of operations. In section III the SOLAR payload will briefly be described, after which the Operational Technical Constraints encountered over the 9 years of operation will be outlined in Section IV together with some solutions that were found to overcome these constraints. In section V you will find an example of how constraints can also lead to achievements and section VI presents a list of operational products and tools that were used and developed during the SOLAR operations. The paper will be closed off with lessons learned in section VII and the conclusion in section VIII.

III. The SOLAR Payload

SOLAR is an ESA payload mounted on one of the external platforms of the Columbus module of the ISS (Fig. 1). 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].

Fig. 1 The European Columbus module on the ISS with the SOLAR payload in view of the external platforms of Columbus. [credits ESA/NASA]

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 capability. Compromises had to be made during SOLAR operations, taking into account thruster firings, structures present in the instrument's field of view, the instruments requirements for their sun observations, 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 10-12 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, three SOLAR modes were identified, each matching different SW modes of SOLAR and activities occurring on the ISS or operations planning. 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 available on a separate power line, while the CU would be off. 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 used the automatically received ancillary data from the ISS to point the SOLAR platform in the right direction and on time to catch the Sun on its apparent trajectory in order to correctly point the instruments at the Sun and start observations. The SW modes that identified the working condition of SOLAR itself were 'OFF', when the instrument was powered off, 'Setup and Configuration Mode' for maintenance activities, 'Software Maintenance Mode' in case of SW updates, 'Pointing Mode' in which the instrument could do science observations, and 'Standby Mode was a fall-back mode in case of anomalies, having only the basic functionality available (only the control unit active, no power to the tracking platform).

IV. Operational Technical Constraints

When planning operations, one tries to think of everything that could happen off the beaten track and be as prepared as possible for any type of situation and possible anomaly. Unfortunately, one can never be fully prepared and a mission that happens as expected and that does not come across a few hurdles, would not be a real mission. The SOLAR mission experienced its fair share of challenges, 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.

A. Constraints related to the ISS attitude and orbit

The visibility of the Sun for the SOLAR platform depended on two factors. The first and most important one was 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 was the position of the SOLAR platform and its mechanical limitations. When the ISS was in its nominal XVV position and taking into account the limitations of the X-axis of the platform, SOLAR observations were possible when the beta angle was between -24 and 24 degrees (Fig. 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. Fig. 2 represents the ISS beta angle with time and SVWs are the period in between the two red lines.

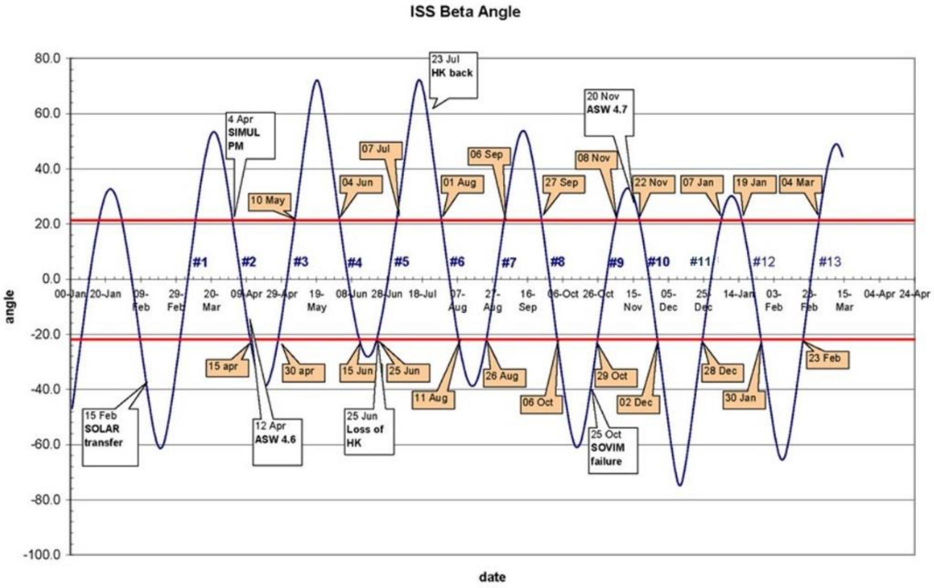


Fig. 2 ISS Beta Angle with time showing the periods of the year when the Sun is visible to the SOLAR platform (between -24 and 24 deg).

During the SVWs, the instruments could point towards and track 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.

SVW were periods of solar observations lasting no more than 10-12 days a month, alternated with an average of 20 days of the Idle Mode of SOLAR. This lead to an important scientific requirement not being met: the observation of the Sun continuously over the 28-day solar cycle [3].

B. Mechanical limitations of the Instruments

The mechanical construction of the platform revealed a limitation during real-time operations. It had been found that the Sun sensor, that allows the platform to detect the Sun and then track it for observations, was not perfectly aligned with the different instruments, which amongst themselves were also not perfectly aligned. For each instrument, a different offset had to be applied to the Sun Sensor alignment, otherwise the instruments would be off-centred compared to the Sun and therefore make invalid observations. In June 2010, few months after the start of the operations, 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. The operations concept was then modified accordingly and it was made sure the Sun sensor offset was changed to the right value and checked to correspond to the right instrument before the start of each new observation.

C. Availability of ISS resources

SOLAR heavily relied on the resources it received from the ISS. This was not only power, but also all communication capabilities for sending commands and getting telemetry. The ISS power provision is nevertheless not something continuous and powerdowns of the Columbus systems are regularly scheduled due to events like the locking of the ISS solar panels for thruster events, high beta angles or power anomalies. Luckily, these powerdowns rarely impacted SOLAR power, but the rare times it did, the impact had its toll on SOLAR operations. Whenever Columbus Systems had to be powered down SOLAR had to be kept in Survival Mode for that whole period, meaning no science could be performed. Indeed, in the 9 years of SOLAR operations, the planned science activities had to be halted due to long power downs. The one with the biggest impact was in December 2013, a major anomaly with one of the ISS cooling loops happened for which a lot of Columbus systems had to be powered down for several weeks. Due to this anomaly, the foreseen winter solstice SVW bridging, Nov-Dec 2013, could not be performed. This meant a loss of observations over 2 consecutive SVWs or of 36 days of observations. [4]

D. External influences from ISS activities and other payloads

As seen in section C., SOLAR operations were not only influenced by SOLAR specific limitations or anomalies, but external factors could also affect the nominal operational configuration of SOLAR. These effects were either due to some instrument constraints linked to factors such as thruster events and ventings, or were due to ISS reconfiguration activities or ISS system anomalies.

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 problem, 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 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 Laborary in the US Lab had to be tracked in order to cease Sol-ACES and SOLSPEC operations during venting activities crossing a certain treshold.

For some of the thruster events, the ISS attitude had to be changed to another orientation. In this new attitude of the station, SOLAR was unable to perform any possible scientific observation due the mechanical limitations of the platform.

Early in the mission, it was noticed that at times the Sun tracking was aborted a few minutes earlier than expected for unknown reasons. After several of those occurrences, it was found out that the common element of those occurrences was the parking location of the ISS robot arm which was 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 the operations of the robot arm had of course priority over payload operations. It was then decided to add SOLAR to a pool of systems (like antennae and cameras) to be warned in advance in case the robot arm would come into the field of view of those systems. This allowed us to know when to expect shadowing from the robotic arm and plan the SOLAR operations 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 anomalies that happened with these payloads. The Columbus module can support up to four external platforms and in the history of SOLAR, the following payloads were attached and/or detached on the platforms: EuTEF (attached and detached), HDEV (attached) and Rapidscat (attached). The provided power from Columbus to external payloads 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 amount of 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 SOLAR instrument's 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 powerloss problem 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. [4]

E. The degradation of the instruments

1. The Loss of SOVIM

On 26 October 2008, the current of the SOVIM instrument outlet went to 0A. This anomaly 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.

2. The Calibration lamps of SOLSPEC

The SOLAR instrument SOLSPEC had 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 rapidly investigated and determined as ageing. A workaround was luckily quickly found by the SOLSPEC Team by using protective quartz plates and the hollow cathode tube to cover the calibrations that used to be 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.

3. *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.

4. 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, PD 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.

5. 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 Control Unit 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.

As mentioned, this failure happened at random times, but when plotting the occurences with ISS Attitude on a worldmap (Fig. 3), it can be seen that a bigger concentration of AIB failures happened when the ISS was flying over the South Atlantic Anomaly (SAA) region. Having more AIB failure in that region would make sense as this is a region higher amount of radiation and the AIB failure is due to a radiation sensitive optocoupler.

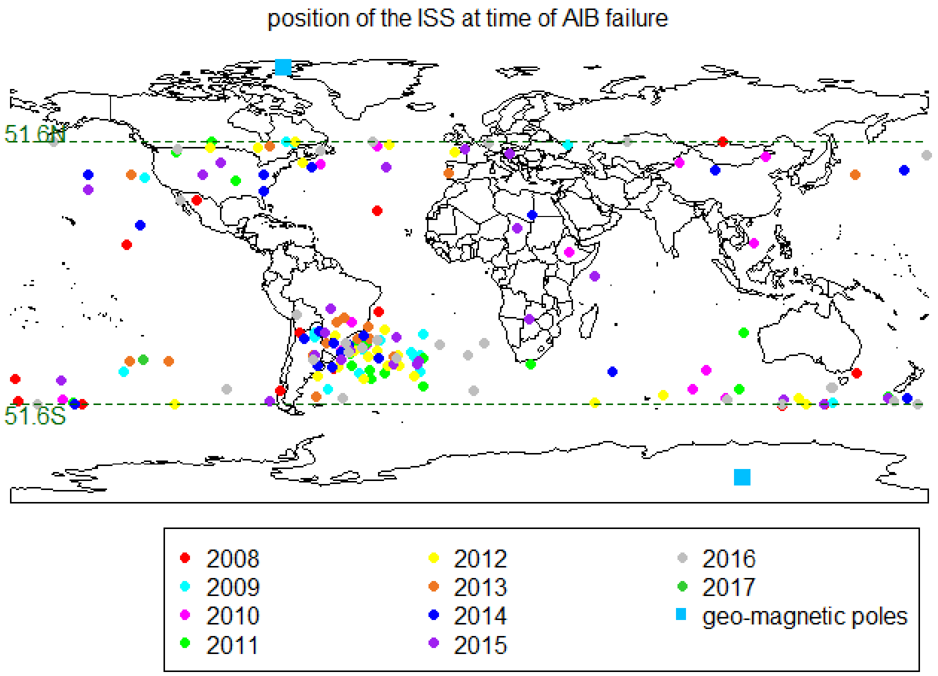


Fig. 3 Position of the ISS over the World at times at which AIB failures occured on the SOLAR instrument, from 2008 to 2017.

V. Achievements as a result of constraints

Constraints do not always only have a negative impact. Sometimes the search to a solution leads to something better or the realisation of a feat, unthought-of of before. For SOLAR, such an achievement was reached with its famous SVWs Bridging. As mentioned in section IV.A , One of the original scientific requirements of the SOLAR mission was to observe a full 28-day rotation of the Sun [3]. 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 four 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. [11]

After a successful first attempt in 2012 (bridging shown in Fig. 4), 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, the 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

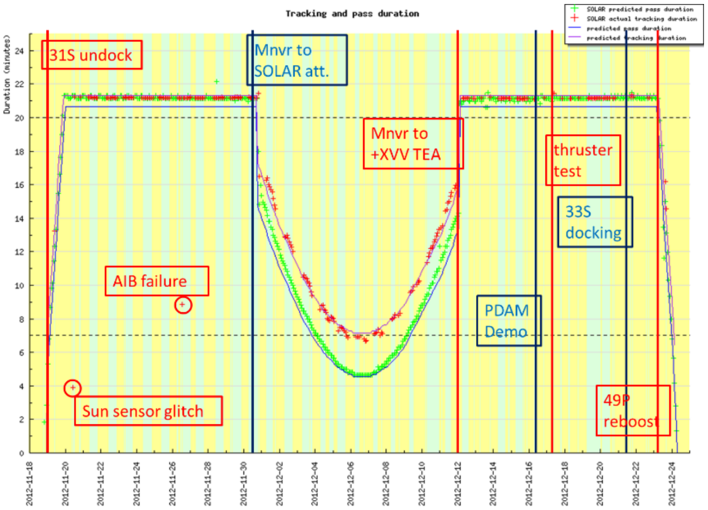
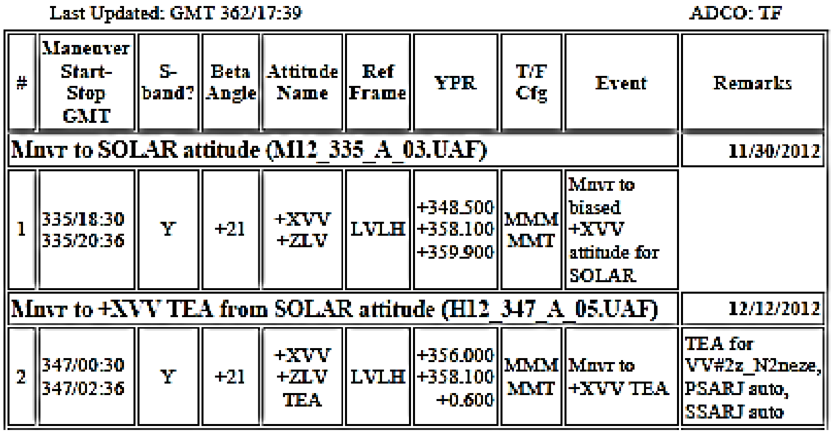


Fig. 4 Tracking and Pass duration for the SOLAR platform by date, SVW#59-60, 19 November to 23 December 2012.

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 Fig. 5.



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

Fig. 5 The ISS attitude timeline showing the schedule manoeuver to move the ISS to the 'SOLAR attitude' in order to bridge two Sun Visibility Windows.

VI. Operational products and tools to deal with constraints during operations

In order to deal with all possible technical challenges over the time of a mission it is necessary to be well-prepared with a complementary team and a good set of operational tools and products that will support every aspect of mission operations and ensure a smooth run of operations during nominal and non-nominal events. Most of these tools are already existing at the start of the mission, but some will evolve with the mission or be created during the mission in order to improve the ongoing operations. This section gives an overview of the operational products and tools that were used, improved or created during the SOLAR mission.

A. Operational Products

The operations of ISS missions are governed by operational products. These products set out the “rules” to follow for everyone to be on the same page and have the same understanding of operations, they act as guidance to prepare and execute to operations in nominal and non-nominal cases and they document the operational concept of the different missions. The main types of Operations Products are [4]:

1. *Operations Interface Procedures and Joint Operations Interface Procedures*

These are documents that describe the interactions between the different international partners in case of the Operations Interface Procedures (OIPs) and between the different teams within Europe in case of the Joint Operations Interface Procedures (JOIPs). They can also be seen as sort of agreements on how the various Control Centers cooperate and interface. They also contain payload-specific agreements such as e.g. how to handle the “real-time commanding window”. [5] [6]

2. *Flight Rules*

Flight Rules (FRs) are ISS wide laws which are agreed upon and have to be followed by all IPs under normal circumstances. They are divided by ISS elements and help to guide the flight control teams in operations preparation and how to react in case of anomalies. They are developed to guarantee crew and vehicle safety, and prevent hardware damage to ISS systems. [7]

3. *Payload Regulations*

The Payload Regulations are sort of the level down of Flight Rules. They are the FRs for specific payloads and will point out the “rules or laws” to which to abide in order to have safe and efficient operations, with minimal adverse interference. They are developed by the involved International Partner responsible for a particular Station Element, like ESA for the Columbus module. [8]

4. *Ground Rules and Constraints*

The Ground Rules and Constraints (GR&Cs) are again a level down compared to the Payload Regulations and FRs. These “laws” that are published on ESA side and guide the Flight Control Team with the needed information to prepare their operations in way that will lead to safe and efficient missions.

5. *Operations Procedures*

Any activity planned on the station has to be executed following a procedure that has been prepared and validated in advance. When performed from ground, the payload operator can only send commands to a payload following that validated procedure. Initially, all procedures, ground or crew, were formatted in ODF (Operations Data File) standards, and for Columbus payloads, the ESA Payload ODF (PODF) is published to the whole ISS community through the International Procedure Viewer (IPV). In order for a procedure to be certified for execution, it needs to be reviewed by different parties, validated and distributed via IPV. From 2014 onward, the “Ground Commanding Procedure Book” was introduced, which should reflect a predefined set of step-by-step instructions used by flight controllers on ground only. GCPs are published within the ESA Operational environment only and require a simplified verification and review cycle. [9] [10]

6. *Timeline*

About 6 months before the start of an increment (period between two subsequent Soyuz undockings on the ISS), the planning of the on-orbit operations for crew and ground controlled activities starts with the On-Orbit Operations Summary (OOS). This document gives an overview of all activities, uploads and downloads that will happen during a specific increment. All scheduled activities are thus identified and are expected to have a PODF associated to them. This pre-increment timeframe will then be transferred into an execution timeframe by releasing the Weekly Look-ahead Plan (WLP) in OPTMIS, a sort of calendar providing access to the day-to-day schedule of onboard (ISS) and ground (MCC) activities in the form of a timeline that includes links to procedures and detailed notes on the activities. The WLP will put an exact execution time on all activities one week before the start of the week of execution. After this, further reviews are done 7, 3 and 1 days before execution. It is possible to ask for changes to this integrated Columbus / ISS timeline and the information included about the activities at each review cycle, but the closer to the day of execution, the more difficult and less appreciated of course and a good rationale will be needed.

For SOLAR, the flexibility of the implementation of routine operations was improved through a “real-time commanding window” called the ‘SOLAR Ground Commanding’ Window which would last for a full day and 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. On console, the operator would just 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. A new way of working that greatly reduced the restrictions B.USOC had to plan and execute the many science observations of SOLAR during one day of a SVW.

7. *Mission Database, Displays and Command Stacks*

The Mission Database (MDB) is a Central repository for all configuration data required for Columbus operations and is used to configure and control the ground and on-board configuration at Col-CC, ESC and the USOCs. It contains all telemetry, telecommands and all associated parameters and limits. The validated MDB is used to prepare the payload's displays and the command stacks, which are used by the payload operators to monitor and control the payload.

B. Operational Tools

During real-time operations, several tools are used to support the operations. The main tools used during SOLAR operations are listed below:

1. *The Predictor*

As more operators joined the team over time at B.USOC, the internal planning of operations evolved from the use of a simple old-school post-it board to an online tool. Operators first developed the SOLAR Mission tool which included a partial file configuration control system, semi-automated planning and automated DOR generation. [12] With time and more experience, several improvement points were pointed out and the mission tool got upgraded to a newer version, 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. [13]

2. Yamcs

In mission control centers, a major part of the ground segment is the front-end and back-end software which is used to assist payload and system operators in their daily tasks. Yamcs (which stands for "Yet Another Mission Control System") is a software package which has been created for long-term payload operations and works as an extension to ESA's standard Mission Control System (MCS) for Columbus. Yamcs integrates into the existing USOC architecture, fulfilling specific mission related needs that the standard MCS is not capable of. It allows the SOLAR Operators to monitor the telemetry, quickly browse the data archive, and to perform replays of events. It also provides secure access to telemetry/telecommanding by remote users[8]. [14]

3. *TYNA*

Due to cost saving measures at the Columbus Control Centre in Munich end 2013, SOLAR would not be monitored anymore by COL-CC outside periods of science measurements. This meant that as of January 2014, B.USOC was obliged to revert back to providing a 24/7 on-console service, putting a huge workload on the understaffed team for such a configuration. To solve this constraint and form of stress on the team, B.USOC created an extension to the Yamcs software that would work as a notification tool allowing for operators to not have to do night shifts anymore or be on-console on days of no science, but just be on-call. The tool was named "The Yamcs Notification Add-on" (TYNA) and actively monitored all the SOLAR telemetry data and the connections between the different servers. In case of an anomaly, the operator on-call would then be notified by phone. As the SOLAR telemetry was remotely accessible from any workstation with the Yamcs software, the SOLAR Operator was able to quickly assess the nature of the anomaly as being a payload problem, an on-board system anomaly, or a ground segment problem, and inform the counterparts and take adequate countermeasures.

The TYNA software has proven to be so useful that it will continue to be used for the other payloads under B.USOC's responsibility planned after SOLAR. Furthermore, it has been validated to interface with the commonly used ESA MCS tools applied in the Columbus Payload Data Center (CD-MCS) and to monitor the other ESA payloads and Columbus System Telemetry. Both Yamcs and TYNA, developed with the support of ESA, are open source software and free of use for the ISS payload community [15].

VII. 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 getting comfortable with the work of the operations world within the Flight Control Team and an increasing knowledge of SOLAR instrument and its perks. This paper described the constraints that were encountered during the mission and how they were solved or how the operations were adapted to accommodate these deviations from the expected operations at the preparation phase.

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[8] http://www.yamcs.org/

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 that all factors in mission operations should be represented in payload design and 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. Especially at the start of a mission flexibility is key. The real-time partners should have the possibility to optimise and finetune their operations concept for payloads like SOLAR. To achieve 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.

VIII. Conclusion

The SOLAR payload got installed on the external platform of the European Columbus module of the ISS in February 2008. Originally planned to last 1.5 years, the mission went beyond expectations and got extended twice to end up with total duration 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 gain valuable experience in operations preparation and execution.

The gained experience would certainly not have been as valuable, if it wouldn’t have been for the hurdles encountered on the way. Indeed, constraints force you to know your instrument, the functioning of the ISS operations and the used operational product very well in order to be able to react fast and correctly. An extensive knowledge of the working environment is thus very important, but wouldn’t be effective without a solid and dedicated team that can take on the encountered challenges, troubleshoot them and find solutions in the shortest timeframe possible with good coordination and communication between the different teams working on the project.

Acknowledgments

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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