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SOLAR, 9 years of operations as external payload on the ISS: The evolution of the operational concept

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In February 2017, the SOLAR mission ended after 9 years of operations onboard the International Space Station (ISS). SOLAR was delivered to the ISS in 2008, together with the European laboratory module, Columbus. Installed on the zenith external position of Columbus, the moveable platform, hosting 3 instruments (SolACES, SOLSPEC and SOVIM), tracked the Sun during so-called Sun Visibility Windows to observe the spectral irradiance from infra-red to extreme UV.

The payload, originally built to support an 18 months mission, went beyond expectations, ultimately offering 9 years of Sun observations. 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 Operations Centre (B.USOC), to improve and adapt the original operational concept along the years.

B.USOC was assigned by the European Space Agency (ESA) as one of the 9 control centres spread around Europe to conduct operations of European scientific or technological experiments onboard Columbus such as SOLAR. These control centres are then connected to the Columbus Control Centre (Col-CC), in charge of the Columbus system and of the overall planning of activities onboard the module.

At the beginning of the SOLAR mission, the experience in human space flight operations was at that time still limited both at B.USOC and at Col-CC. Therefore, the operational concept, or the support provided by both centres evolved from the original planned concept. In particular the planning cycle was very cumbersome and restricted. All experiment commands had to be included in the On-board Short Term Plan (OSTP) with frequent daily rescheduling cycles due to unforeseen ISS events or changes of the science planning. Later, with growing experience and confidence between the collaborating centres, the mode of operations moved to a more realistic 'telescience' concept allowing real-time commanding

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from the B.USOC during an allocated command window. This soon paved the way for other payload operations, and became a standard for ground only activities.

Another problem turned out to be the operations shift coverage: at the beginning of the SOLAR mission, B.USOC operators had to cover 24/7 shifts, whenever the payload was powered on. After gaining experience with the payload, and long negotiation between the centres, Col-CC took over the basic and essential monitoring of the experiment while no science was running (during the non-visibility period of the Sun), and therefore relieving the B.USOC personnel from shift-burden.

Later, Col-CC Flight Control Team was reduced and did not handle payload monitoring anymore. B.USOC then developed an automated notification tool (TYNA) to alert the operator on-call whenever critical parameters goes out of range, or in case of a ground segment failure.

After a brief presentation of the SOLAR mission and its scientific objectives, the paper will describe the evolution of the operational concept, from a rigid and cumbersome planning process of scientific activities to a telescience concept allowing almost full flexibility to conduct science operations. This will be complemented by the evolution of the tools allowing for a more automated operations support. Finally, the paper will gather the valuable lessons learned from this extended 9-year rich experience, which can be applied to similar long term missions.

This abstract complements the abstract submitted by G. Mariën et al. about the technical challenges during the SOLAR mission.

I. Nomenclature

B.USOC = Belgian User Support and Operations Centre
Col-CC = Columbus Control Centre
Col-FD = Columbus Flight Director
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
IR = Infrared
ISS = International Space Station
NASA = National Aeronautics and Space Administration
OSTPV = On-board Short Term Plan Viewer
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

After 9 years of successful operations onboard the International Space Station (ISS), the SOLAR mission was terminated in February 2017. Changes in the original operational concept are likely to be expected for a long duration mission in an international and dynamic environment such as the ISS. In the case of this specific space platform, changes were numerous and of different nature. The SOLAR mission started, together with ESA Columbus module, a new era where the different participating centres would learn and gain enormous experience in the Human Space Flight discipline.

This paper briefly presents the payload and its scientific objectives and provides an overview of the mission operations, the control centres, and the initial operational constraints. The evolution of the operational concept will be described sequentially along the years. Finally, the paper gathers the valuable lessons learned from this extended 9-year rich experience, which can be applied to similar long term missions.

III. The SOLAR Payload and Mission

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 Solar Irradiance as a valuable input for climate models. [1, 2]

SOLAR is an ESA payload, installed on the zenith external platform of Columbus, hosting three instruments (Fig. 1). The Solar Variability Irradiance Monitor (SOVIM) was focusing on Total Solar Irradiance (TSI) data [13]. The SOLar SPECtrum (SOLSPEC) instrument measured the SSI in three different channels: UV, visible and IR [12]. Measurements of the SSI in the EUV part of the solar spectrum were taken by the SOLar Auto-Calibrating EUV/UV Spectrometers (Sol-ACES) [14]. The 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 and, collected, formatted, and dispatched to ground the telemetry and science data generated by the platform and instruments in dedicated telemetry packets. In the other direction the CU received ISS ancillary data and processed the ground issued tele-commands.

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

Due to ISS orbital mechanics and due to the mechanical limitations of the SOLAR CPD, the Sun is not always observable by SOLAR. Tracking capability of the platform is mainly dependent on the ISS beta angle (the angle between the line connecting the ISS and the Sun and the orbital plane of the ISS), and while the ISS attitude is nominal, SOLAR tracked the Sun continuously for 10 to 12 days per month. In these periods of solar observations, called "Sun Visibility Windows" (SVWs), the instruments were pointed to the Sun for a duration of 20 minutes each ISS orbit. [6].

Other major operational constraints of SOLAR were initially documented as follow:

- Survival heaters of SOLAR must be powered on at all time to keep the payload within operative temperature ranges.
- Since SOVIM acquired data even while the Sun was not at sight, the science team requested to keep the instrument powered on at all time.
- No science operations could be conducted with SOLSPEC over the South Atlantic Anomaly (SAA), its photometers were too sensitive in this area of high levels radiation.
- No major operational constraint for the Sol-ACES instrument.
- And for any thruster firing, usually associated with a vehicle docking/undocking, Extra Vehicular Activity (EVA) or a reboost, science operations had to be paused and the platform had to be parked in home position motor controlled [5].

The Belgian User Support and Operations Centre (B.USOC) was the Facility Responsible Centre for the SOLAR payload as assigned by ESA. The overall planning of activities on-board the European module and the control and monitoring of the Columbus systems are handled by the Columbus Control Centre (Col-CC), to which B.USOC is connected.

B.USOC is part of the USOC network, a decentralized infrastructure adopted by ESA in the nineties, to conduct the payload operations onboard the European module. The network, was at the time, composed of 9 centres spread around Europe, each of them having different field of expertise (i.e: human physiology, fluid physics, solar physics...).

IV. The Evolution of the Operational Concept

Before describing the series of evolution the SOLAR operational concept faced throughout the years, one should define the meaning of the term: “operational concept”. The operational concept is, in this paper, referred to as the way in which the payload operations are conducted, resulting in the determination of the on console support, planning of activities, required tools and products.

The development and optimization of such a concept depends on many, also external, factors. Indeed, the way operations are conducted (planning and execution) is determined with respect to the payload operational constraints (as briefly summarized in Section III), and the agreements on how the various control centres cooperate and interface with each other (documented by Joint Operations Interface Procedures).

Moreover, the console support, or the moment the operator will be sitting on console to conduct operations or be on-call, is, on its turn, determined by to the payloads planned activities, the availability of an automated monitoring tool and, finally, the ESA budget allocated to SOLAR flight operations.

The evolution of the operational concept is presented below in a chronological and historical way, introducing the major evolutions throughout the years.

A. February 2008 – The beginning

At the beginning of the Columbus era in February 2008, the centres involved had limited experience in Human Space Flight. All payload activities had to be included in the On-board Short Term Planning (OSTP), together with crew or system activities, and required the “Go” from the Columbus Flight Director (Col-FD) before being initiated. [4]

The Columbus planning cycle starts two weeks before an activity execution, where all requests for nominal commanding are collected in the Weekly Look-ahead Plan. Then in the near-execution timeframe, revision of the timeline is requested seven, three and one day prior to execution. Each activity showed on the OSTP Viewer is associated to a procedure defining a fixed sequence of steps and commands.

The science planning is, on the other hand, not that predictable. Science operations are very much dependent on the previous experiment results. Based on the data acquired, changes of instrument configurations or sequence of activities are often requested by the science teams. Such requests implied a modification of the start time and on the procedure.

In addition, SOLAR payload being impacted by thruster events on the station, the planning uncertainties of vehicle docking and undocking demanded several reshuffling of the activities.

This cumbersome and restricted planning cycle led to substantial workload on console, to insert on daily basis the right experiment commands at the most appropriate time. At the time, B.USOC operators worked with a post-it board on which they indicated the upcoming day’s activities, a process that was time consuming and error-prone.

Concerning the console support, SOLAR operators sat on console 24 hours, 7 days a week (27/4), independently of the Sun Visibility Windows. SOLAR needed to be continuously powered and continuously monitored as, following an ISS Flight Rule [5], manual action from ground was required whenever certain 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.

At that time, the B.USOC human resources were limited to three certified operators and three trainee operators that weren’t allowed to command yet.

Furthermore, the first version of the Mission Control System was unstable, and not adequate for operations around the clock [9].

B. June 2008 – Introduction of the Idle mode

SOLAR operations are clearly divided into predicted periods of science and non-science operations. The SVWs are periods of solar observations where the operator has an active and continuous role. In between the SVWs, beside a weekly calibration of SOLSPEC, no science operations were conducted and the operator had mostly a passive role monitoring the telemetries.

With the limited number of personnel allocated at the time, the 24/7 support was not sustainable. Especially in the light of the passive periods of SOLAR, an optimized console setting was required. Therefore, B.USOC, ESA and Col-CC started discussing a more optimized concept that would release the B.USOC operator while no science was running.

Since the Columbus Flight Control Team (FCT) at 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 SOLAR temperature readings.

Hence it was agreed that the Columbus FCT was going to take over the monitoring of the essential parameters of SOLAR outside nominal working hours during the shadow periods, i.e. periods were no science measurements were performed. This was called the SOLAR Idle Mode.

This was a sudden and significant relief of workload. Human resources were used in a more efficiently way, and were allocated to off-line work such as anomaly resolution, updates of operational products or general operational improvements.

From June 2008, two different operational modes were possible:

- The SOLAR Science Mode during SVWs: SOLAR is powered and perform Sun tracking ideally every ISS orbit; B.USOC is on console 24/7.
- The SOLAR Idle Mode outside SVWs: SOLAR is powered, platform is kept in home position, and instruments are not performing Sun measurements; B.USOC is on console 8/7, the rest of the time Col-CC is monitoring the payload and B.USOC is on-call.

C. October 2008 – Introduction of the Survival mode

On 26 Oct 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 investigation, the instrument had unfortunately to be declared lost and no further activation was attempted.

Since SOVIM was the sole instrument requiring to remain powered on at all time, with its loss and in consultation with the scientists and the payload developer, there was no need to keep SOLAR powered continuously. This resulted in another operational mode being introduced, the so called SOLAR Survival Mode, defined as follow:

- The complete SOLAR payload, platform and instruments, is powered off, only the survival heaters remained on.
- Operator is on-site 8 hours a week (8/5), and on-call the rest of the time.

With the introduction of the Survival Mode, Table 1 shows a typical month of SOLAR operations:

Timeframe	~ 6 days	1 day	~ 6 days	1 day	10-12 days
Mode	Survival Mode	Idle Mode	Survival Mode	Idle Mode	Science Operations
SOLAR Configuration	Powered off	Powered on, motor controlled No science measurements	Powered off	Powered on, motor controlled No science measurements	Powered on, motor controlled Science measurements
Console support	8/5 on site, on call outside	8/7 on console, on call outside	8/5 on site, on call outside	8/7 on console, on call outside	24/7 on console
SOLAR Activities	None	Weekly check of temperature Ensure good	None	Ensuring the instruments temperatures are	Science measurements following science input

Timeframe	~ 6 days	1 day	~ 6 days	1 day	10-12 days
		configuration for thruster firings Weekly SOLSPEC calibration		within operational ranges and that all necessary command schedules are available for SOLAR	

Table 1: Typical month of SOLAR operations

D. End of 2008 – Introduction of the SOLAR Mission Tool

With the hiring of new personnel, new ideas came along, the SOLAR Mission tool was progressively introduced to replace the post-it board [7]. The tool embedded in a spread sheet and developed by the operators, included a partial automation of the planning process, a limited configuration control system, and the generation of the Daily Operations Report (DOR).

E. February 2009 – Introduction of the Real-Time commanding window

With growing experience and confidence between the collaborating centres (B.USOC and COL-CC), the concept of 'SOLAR real-time commanding' window was put in place. A daily 24 hours command window allowed a more realistic 'telescience' concept, and consequently eased significantly the science planning process. 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 pre-coordinated with Col-FD to request his/her go, but this new concept was already a big improvement. [4]

F. End of 2010 - Introduction of the SOLAR Predictor

With the new experience on console from the operations team, several points of improvement were identified and a new tool, based upon the SOLAR Mission tool was gradually developed, the SOLAR Predictor. Initially designed to provide an accurate prediction for the timing of the SVWs and the Sun observation opportunities within those, it slowly progressed to a full functional operations support tool. 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 [8]. It was under continuous development and improvement until 2012, and was used for the rest of the mission as the planning tool.

G. Early 2011 – Reduction of support for the Science Mode

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. Moreover the Sol-ACES science requirements were revisited following the decontamination, heavily reducing the amount of Sun observations. As such only daily calibrations would be performed with a maximum of 2 spectrometer measurements per SVW. The revised requirements resulted in the use of the Idle Mode again, where SOLAR was continuously powered. Moreover, the science requirements for both Sol-ACES and SOLSPEC showed that the majority of the activities could be performed within a 16/7 baseline. Hence the console support was reduced to 16/7 during science windows (Science Mode), with on call outside in case science measurements went beyond this window.

H. End of 2012 - Introduction of the SVW Bridging

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 ISS attitude and the limited orientation of the SOLAR platform, which ultimately only allowed the platform to observe the Sun about 12 days maximum per month, during SVWs.

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 this requirement: to request a change of the ISS attitude in order to change the angle-position of SOLAR compared to the Sun and to allow a bridging of two consecutive SVWs. When possible, such ISS attitude change will replace two 12-day separate observing window into a single observing period of five to six weeks [6]. 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. After a successful first attempt in 2012, four more ISS attitude changes were requested throughout the whole SOLAR mission.

I. July 2014 - Introduction of the automated monitoring tool TYNA

At the end of 2013, following a cost saving exercise, Col-CC was no longer able to monitor SOLAR 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 team understaffed for such a configuration.

As a 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 maximum 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 in July 2014 TYNA was up and running, taking over the basic monitoring of the payload and of the ground segment [10]. The Science and Idle operational mode could be applied again, relieving operators from night-shifts, only being called on console in case of an anomaly.

J. May 2014 – Introduction of the ground commanding window

The concept of SOLAR Real Time Commanding Window evolved further into the so-called ‘SOLAR Ground Commanding Window’ that also lasted for a full day, but referred to the SOLAR Ground Command Procedures Book that enclosed all the ground procedures that could be used in relation to the nominal and corrective SOLAR activities [4]. This Ground Commanding Window gave B.USOC full responsibility over the payload with less restriction 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.

K. April 2016 – Reduction of the console support

In April 2016, another substantial ESA budget reduction, led to a reduction of the overall console support for SOLAR. In Science Mode, the Sun observations were to be performed only during the day. To reduce the impacts on science as much as possible, an optimized concept was set-up in agreement with the science teams. The SOLSPEC team required daily calibrations and a maximum of 1 Sun observation while the Sol-ACES team required at least 5 to 6 orbits in a row to conduct certain long observations. Following this exercise it was agreed to alternatively conduct a long and a short shift per day (9,5 hours and 6,5 hours respectively), still achieving the minimum objectives of the science teams.

This operational support was applied until the end of the mission, in February 2017.

V. Lessons Learned

Lessons learned collected throughout the years of the SOLAR mission can be applied to similar long term missions. They are summarized here:

- Six operators to support a full time console presence was inadequate to support long term mission, and was insufficient for a proper off-line support such as update of procedure, anomaly resolution, coordination with the science teams or reporting to ESA. Ideally, the size of the operators team should not be less than 10 to 12 people to support a 24/7 service. [11]
- The SOLAR Ground Commanding Window paved the way for other payload operations. It significantly facilitated and improved the work on console, it became a standard for all ground only activities of

payloads. Today, the 24 hours Ground Commanding Window together with a Ground Commanding Procedure Book are being used by B.USOC to support operations of the new ESA external payload Atmosphere-Space Interactions Monitor (ASIM).

- The 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 [6]. It also showed the importance of understanding the impacts of the ISS orbit and attitude on external payloads.
- In general, it is essential to have a detailed overview of the operational constraints the payload will be dealing with (internal or external), to better prepare the operations and the teams on the ground. These constraints could also influence design choices made during payload development to allow for easier and more flexible operations. [5]
- Eventually, budget cut can lead to a significant innovation. In 2014, it led to the development of TYNA, with a generic version available for the other USOCs. A monitoring and automated notification tool appeared to be highly valuable to monitor the payload in routine phase or when no science is ongoing, releasing the operator from doing purely passive tasks. [10]
- During the mission, time should be allocated to constantly look for optimization and improvements of operations on all aspects.

VI. Conclusion

SOLAR longevity went beyond expectation. From an original mission duration of 18 months, operations were conducted over 9 years. The mission ran into several obstacles, anomalies or budget cut, after which the operational concept had to be adapted.

All parties within the SOLAR mission underwent a learning curve, the scientists optimized their science requirements throughout the mission, with the objective to have a maximum science return while minimizing the degradation and anomalous behavior. The Payload Developer supported every request for further analysis to ensure the operations concepts could be achieved, even if these were not foreseen in the initial payload design. And finally, the B.USOC went from 24/7 on console to an alternative 6.5/9.5hrs on console for science measurements only. This reduction was always in the light of maximization of the science return, but also optimization of team resources.

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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