SORCE Daylight-Only Operations

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On July 30, 2013 the Solar Radiation and Climate Experiment spacecraft entered into a new phase of mission operations when the degraded battery could no longer support the main computer through eclipse. Contrary to expectations at the time, this event did not mark the end of the successful SORCE mission, but instead the beginning of a new phase of operations. To save the spacecraft, the mission operations team had to quickly and efficiently address the spacecraft's fundamental needs every orbit. Responding to this anomaly was a combined effort from the mission operations team at the Laboratory for Atmospheric and Space Physics, Orbital-ATK technical support team, project management at NASA Goddard, and last, but not least the White Sands Communication Network schedulers. Seven months later the flight operations team at LASP deployed new flight software to restore the spacecraft to full-time science operations. The culmination of this work is a resourceful operations concept, called SORCE Daylight-Only Operations that has succeeded in extending the solar spectral irradiance and total solar irradiance climate records. This paper will address the work surrounding the design and implementation of a new operations concept for an end-of-life spacecraft with challenging hardware limitations.

I. Spacecraft Background

The Solar Radiation and Climate Experiment (SORCE) spacecraft launched January 2003 with a suite of instruments to characterize the solar input to the Earth's climate system. The LEOStar-2^{TM} spacecraft bus was developed by Orbital-ATK and the Laboratory for Atmospheric and Space Physics (LASP) built the instrument Microprocessor Unit (MU) and four instruments. SORCE's instrument suite consists of the Spectral Irradiance Monitor (SIM), the Solar Stellar Irradiance Comparison Experiment (SOLSTICE), the Total Irradiance Monitor (TIM), and the XUV Photometer System (XPS). The SORCE spacecraft is a 3-axis stabilized platform that is designed to point the instrument suite at the sun during orbit day for science observations. The spacecraft is controlled via the Onboard Computer (OBC) flight software (FSW), hosted by the Central Electronics Unit (CEU). In addition to the primary computer, a less sophisticated backup computer known as the Attitude Power and Electronics (APE) serves as the hardware interface and safehold computer. The APE computer was designed with several flight software banks, with Bank 0 containing an unmodifiable copy of the FSW version at launch, APE FSW6.3. Upon APE reset, swap or power cycle, the spacecraft is designed to default to the Bank 0 copy of FSW, and this behavior cannot be changed. The attitude control subsystem includes four reaction wheels (RWAs), two star trackers (ST), and sets of coarse sun sensors (CSS), magnetometers and torque rods. The power system is comprised of six solar array panels and a 23 Amp-hr Nickel Hydrogen (NiH2) battery with 11 common pressure vessels (CPVs).

During routine science operations the spacecraft uses Normal mode, controlled by the OBC with the ST incorporated in the attitude solution to achieve precision pointing. Contingency mode is also under OBC control, but uses only the CSSs for attitude determination resulting in a coarser pointing solution that will not meet science requirements. Finally, Safehold is a mode controlled by only the APE computer relying on CSS-only measurements for the attitude solution resulting in coarse pointing. Prior to 2013, SORCE spent the majority of its mission in normal mode with few excursions to contingency and only a handful of Safehold entries. The spacecraft was not originally designed to remain in Safehold for extended periods of time and as such the APE FSW was limited in scope, not containing complex logic like flight software driven heater control or data storage capabilities.

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Fig. 1 a) A view of the SORCE Spacecraft during assembly and integration testing. b) (top)The four solar instruments hosted by SORCE, (bottom) A view of the operations center at LASP

As with any spacecraft well into its in extended mission, some of flight hardware has shown degradation in the harsh environment of space. As the mission has evolved there have been several FSW updates to both OBC and APE to adapt to the changes in the performance of the hardware. As of 2018, only three of original four RWAs are in use and only one of the two star trackers is powered on and used in the attitude solution. Starting in 2008 the battery began to show symptoms of degradation that led the flight operations team to take make several operational changes to save power in eclipse between 2008 – 2013. Eventually, the lack of remaining capacity of the battery led to the SORCE spacecraft emergency mode in mid-2013 that was the catalyst for the Daylight-Only OPerations (DO-OP) development.

A. Emergency Mode Critical Accomplishments

To establish a new concept of science operations a series of technical challenges had to be overcome to stabilize the spacecraft. These challenges included reinforcing the health and safety of the spacecraft each sunrise, establishing new methods of capturing science data, and developing new processes to optimize ground communications with the spacecraft. Many of these challenges are discussed in depth in a paper submitted to the 2018 SpaceOps Conference, *Lessons Learned During the Transition of SORCE Science to Daylight Only Operations* by S. Ryan, which describes the SORCE spacecraft's state of emergency and gradual recovery. The following bullets will highlight some of the major accomplishments of the fall of 2013 that paved the way for DO-OP, but further details are not provided in this paper.

- A sequence to rapidly load the essential FSW patches to restore from the launch version of APE FSW6.3 to a safer version APE FSW6.9 was thoroughly tested and optimized for timing.
- Eventually an intermediate APE FSW7.0 was loaded to the spacecraft to establish new methods for enforcing loads on/off as a function of solar array current, battery operation heaters were modified to be used in Safehold, and new low watermark telemetry was established to record the minimum voltage and time associated with that voltage in eclipse.
- A momentum bias of 0.5 Nm/s was installed along the Z-Axis of the spacecraft. This update ensured the solar arrays, normal to the Z-Axis, would remain pointed within 45 degrees of the Sun at sunrise.
- A new downlink data rate was added to allow the science telemetry to flow to the MOC in real-time using the Tracking and Data Relay Satellite System(TDRSS) constellation.

The SORCE emergency endured for 78 days of 24x7 coverage before the spacecraft reached a routine, safe configuration each orbit that did not require manual intervention. At this point, the flight operations team (FOT) turned their attention to salvaging the mission by redefining the way SORCE collects science each orbit.

II. Development of the DO-OP Concept

While spacecraft health and safety challenges had to be prioritized, in the background other work was underway to enable the new concept of science operations. Four major design efforts that are essential to the success of DO-OP are summarized in the following section including development of autonomous mode transitions to science attitude, new science collection methods, data collection techniques and finally resourceful uses of fault protection in autonomy.

A. Achieving Science Attitude Autonomously

One of the major engineering problems to be solved was how to safely promote the spacecraft out of APE-controlled Safehold to OBC-controlled contingency mode, and then onto Normal mode in order to establish the precision pointing control required for science collection. Up to this point in this mission, each of transitions mentioned above were manually commanded and carefully observed operations that could take several orbits to accomplish. In DO-OP, a new concept was developed to accomplish these transitions autonomously, safely and efficiently in order to maximize science return during the ~65-minute orbit day period. As the spacecraft enters the sunlight each orbit day in Safehold the spacecraft nulls rates and searches for the Sun using its CSS measurements. Once the Sun's location is determined, the spacecraft will stabilize, pointing the solar arrays towards the Sun. As the spacecraft settles into solar pointing, this mode change triggers a telemetry monitor (TMON) onboard the spacecraft that looks for stability in this configuration. If the spacecraft is able to maintain solar pointing for sixty seconds, the TMON will take action and call a relatively timed command sequence to exit Safehold and enter Contingency mode under OBC control. In addition, rather than let the OBC FSW cycle through its nominal progression of nulling rates, searching for the sun and stabilizing in sun point, a series of commands in the onboard relatively timed sequence (RTS) will force a rapid promotion to stable contingency sun point. Onboard checks verify the spacecraft is quiescently sun pointed or if the rapid progression was unsuccessful the spacecraft will autonomously take care of itself by regressing to its default state of nulling rates before beginning the cycle again. The interactivity of the newly designed onboard sequences and TMONs, enables the spacecraft to promote from Safehold to Contingency mode within minutes of sunrise.

For the spacecraft to achieve its nominal science attitude in Normal mode, also referred to as NormalTargetSun, it is first necessary to load a state vector to the spacecraft via the absolutely timed sequence (ATS). An ATS is generated by the ground planning software for each orbit day and autonomously loaded using ground software. Ground autonomy attempts to load and initiate the ATS on the first ground contact each sunrise. Details of the mechanics of the SORCE ground autonomy design can be found in *Ground Autonomy for an Aging Spacecraft* by C. Labonde, prepared for the 2018 SpaceOps Conference [1]. The ATS is typically loaded within 4-5 minutes of sunrise in DO-OP mode although this number is highly dependent on ground contact scheduling and other ground autonomy load priorities. Within each ATS a state vector command and an associated NormalTargetSun command are sent approximately every 5-7 minutes. If the NormalTargetSun command is received with a valid state vector and ST measurements, the spacecraft will achieve Normal mode. Onboard the spacecraft, another TMON is looking for the spacecraft to achieve science attitude for 5 minutes before it takes the action of declaring victory and enabling all science collection RTSs so they can be initiated by the ATS. With this step, SORCE enters precision solar pointing and is configured to collect science.

Together the spacecraft's autonomous mode transitions and the ground's autonomously load capabilities result in a spacecraft that can promote from an unknown attitude in Safehold to precision science attitude collection in less than 20 minutes (on average). This efficient configuration leaves upwards of 30+ minutes for science collection each orbit day for the majority of SORCE orbits as shown in statistics collected in Fig. 2. Figure 2 shows statistics covering SORCE's transitions to normal mode collected after the initiation of DO-OP from March 2014 through May 2015, where T represents the time spent in normal mode each orbit. Achieving extensive time each orbit in Normal mode is critical to the success of DO-OP because many of the science collection sequences discussed in depth in the following section have minimum durations of 25 minutes. The variability of time spent in Normal mode is due to many factors including contact scheduling, orbit day duration changes as a function of beta angle, start tracker occultation's by the earth and occasional occultation of the ST during the maneuver to the initial science attitude.

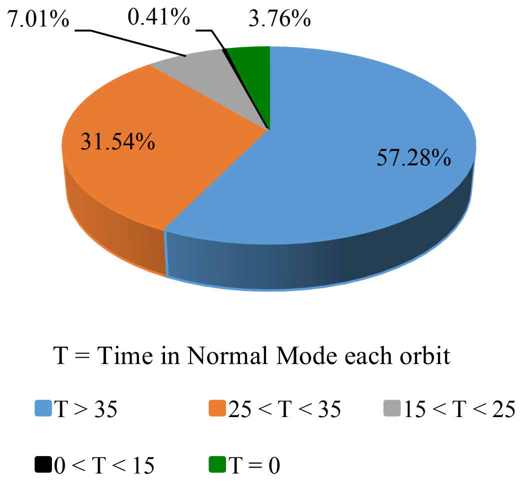

Fig. 2 Binned Time in Normal Mode as a Percentage of total orbits from March 2014 through May 2015.

B. Redesign of Science Collection and Planning

The SORCE science team worked closely with the mission flight director to streamline each instrument's essential observations required to achieve science requirements. A series of relatively timed sequences onboard the spacecraft were reserved for science operations. These onboard sequences were written to maximize the science return by interactively calling other RTSs to chain different science experiments together. The uncertainty of the length of time spent in science collection meant that each sequence of instrument commands would need to efficiently accomplish the required science. Ground planning software was also augmented with new scheduling rules that would ingest the daily ground contacts, assign priorities to each orbit day based on contact location and spacing, then prioritize science scheduling in the ATS. The ATS contains commands for each orbit to initiate the onboard spacecraft RTSs based on the desired science to be performed. The concept of prime science orbits was introduced to aid the ground software in selecting the optimal orbits to perform required science each day. The ground software tool will select up to four orbits per day to schedule special activities such as infrequent calibrations or high priority science observations. A prime science orbit is not necessarily the orbit with the most contact coverage, but can be an orbit with a ground contact where the onboard recorders can be dumped to send all stored data to the ground or high-quality TDRSS passes at the correct portion of orbit day. During development it was determined that there is a particular window during orbit day, when the spacecraft is most likely to have achieved normal mode and the instruments are most likely to be at their steady state operating temperate. Agreement on these rules took significant analysis by both the operations and the science team, but have yielded accurate and consistent measurements to continue the solar spectral irradiance (SSI) and total solar irradiance (TSI) climate records.

As part of the new concept of science operations, the instruments need to be powered on and configured for science each orbit. In DO-OP, many of the spacecraft's loads, including the MU, are powered on at sunrise after the solar array current has reached 20 Amps and the APE 'day' table is applied. The APE is unable to send commands directly to the instruments, but the MU is capable of sending instrument commands. A new method of powering on the MU and instruments was devised to work around these design constraints. The APE is able to send a power switch command to the MU directly and this command was incorporated into the APE day table resulting in the MU being powered autonomously when solar array current exceeds 20 Amps. Then, an update to the MU FSW designed, tested and loaded that would sequentially power on the instruments. The MU FSW update incorporated the default sequences for each instrument to complete the instrument's science configuration. With this design and implementation each instrument is autonomously powered and made ready for science. In consideration of the fragility of the power system, the instrument turn-ons were staggered over a five-minute interval to better ensure the solar array current is near maximum before increasing the loads on the spacecraft bus. The coordinated power-up sequence also helped to avoid large transients in the system which prevented unintended consequences such as computer resets. Within five minutes of sunrise all instruments are powered on, configured for science and waiting for commands from the ATS to initiate science collection sequences.

C. Establishing New Methods of Communication

As a new way of collecting science was coming together, the attention of the ops team turned to how to collect the science data on the ground. SORCE is certified to communicate with two of the NASA Near Earth Network (NEN) of ground network (GN) stations located in Wallops, Virginia and Santiago, Chile. After the July 2013 power anomaly, with each sunset, valuable science data is wiped from the SORCE virtual recorders when the OBC is powered off. Thus, in order to retrieve the science for a given orbit the ground contact to dump recorders has to be scheduled late enough in the orbit day so that the science collection was complete, but with margin to dump the recorder multiple times before sunset. Given these restrictive scheduling rules and limited visibilities of the two certified ground station locations, SORCE can expect to schedule to approximately 60 GN contacts per month out of 450 orbits. Rather than accept that science would be limited to ~13 percent of the year, the SORCE operations team began to work through alternative options using the TDRSS, also commonly referred to as the Satellite Network (SN). SORCE was originally designed to communicate with the SN for redundancy during launch and critical operations. Until 2013, SORCE had used the SN command and telemetry link for health and safety checks or during emergency/critical operations and the data downlinked was limited to 4 kbps. With the help of the Orbital ATK engineering support team, the flight operations team determined it was possible to increase the bandwidth twofold to 8 kbps forging a path for the spacecraft to send science data down via the real-time SN link. In conjunction with this change, it was necessary to fine-tune the telemetry filter tables on the spacecraft to maintain the visibility into engineering housekeeping data

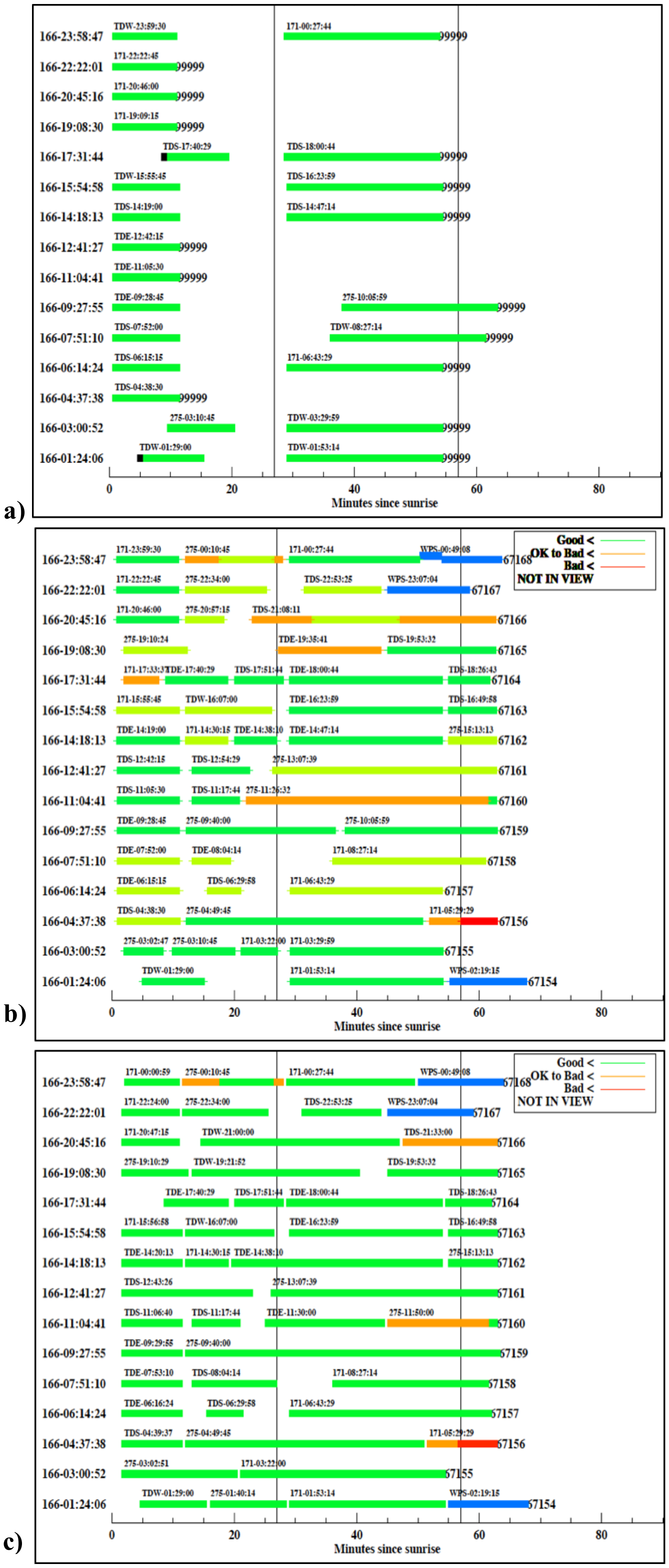

Fig. 3 a) Safety contacts scheduled at the beginning of the scheduling process (Execution – 3 weeks). b) Schedule results after applying released TDRSS time (Execution-1week). c) Schedule after optimization just prior to execution.

while allocating a significant portion of the real-time downlink to science packets. This resourceful adaptation of existing capabilities made each orbit a possible science orbit.

The FOT worked closely with the White Sands Ground Communication Scheduling team to redefine the way SORCE used the SN. In order to maximize SN contact time without incurring prohibitive expense or impacting other missions, SORCE began to take advantage of the weekly release of unscheduled time on the SN in order to fill in as much of orbit day as possible. The evolution of the contact schedule for a given day as it passes through the scheduling process is shown in Fig. 3. The color markings for each contact refer to the predicted geometry between SORCE and the TDRSS spacecraft. Analysis has shown that the quality of the data downlink changes relative to the angle between the two spacecraft so the SORCE scheduling team has developed tools to predict and take into account this angle when selecting a contact. Green contacts should have no dropped data, orange contacts could have some degraded data quality, and red contacts are expected to have intermittent data drop outs. The blue color coding on Figure 3 refers to a scheduled GN contact. Recent analysis shows that in the three years of DO-OP mode, 73 percent of SORCE's orbit day has been covered with a green contact, indicating excellent data downlink opportunities for high quality science.

Scheduling is a time-intensive, detailed task that is entirely handled by a team of trained student operators at LASP. From start to finish, scheduling SORCE SN contacts is a 4-week process involving the selection of contacts to meet minimum healthy and safety requirements, resource conflict resolution with other missions, filling in the schedule with unused time and finally, optimizing the requests to have long-duration, high-quality contact with good geometry relative to the SORCE spacecraft.

D. Repurposing Onboard Fault Protection

One of the most critical and complicated pieces of redesign necessary to make DO-OP successful, involved reconfiguring the onboard fault protection to work with the spacecraft's new expected states. The shift in philosophy towards automation both on the ground and the spacecraft was driven by necessity, but steered SORCE operations into new territory. The most significant effort went into designing a sequencing of autonomous events to detect the version of APE FSW running onboard the spacecraft at sunrise and update the FSW to the most recent version if necessary. This sequence is known to the operations team as ‘Boot to Bank 2’ (B2b2), referencing the storage location of the most recent FSW version on the APE computer. This fault protection sequence is interspersed with the nominal OBC boot sequence where every sunrise different checks and waypoints have been added to confirm the state of the FSW before progressing in the spacecraft configuration. The spacecraft is continuously monitoring the APE FSW version both at sunrise and throughout orbit day. If at any time, the spacecraft detects the need to correct the APE FSW, a sequence of RTSs on the OBC will prepare the spacecraft to autonomously load APE FSW in a safe manner. Due to the fact that the spacecraft relies on APE FSW8.0 to safely configure the spacecraft to survive each eclipse, ensuring this software is correct is of the utmost importance and is prioritized above all other autonomous operations.

In addition to the design of B2b2, many of the existing TMONs were adapted to perform new functions for autonomy. The TMON table consists of 128 individual monitor points, each with its own telemetry reference, threshold, persistence and response RTS. With the invention of DO-OP, there was the need to use onboard fault protection to autonomously trigger events on the spacecraft as part of nominal science operations. Examples of this include the description of spacecraft mode transitions described in Section IIA above and the use of a TMON to enable science RTSs once the spacecraft detects the proper configuration described in Section IIB. Another set of TMONs were created for DO-OP that would initially trigger once the spacecraft exited Safehold and would continue to trigger subsequent tiers of TMONs at a set cadence. This group of TMONs acts as a sophisticated timer to track how long the spacecraft has been in OBC-control. To compliment this set of timer TMONs, ground autonomy was designed to check the TMONs state and with knowledge of each orbit time until sunset it can detect if the spacecraft will safely return to APE-controlled Safehold prior to Sunset. This creative use of onboard fault protection resources to generate information for new ground fault protection is an excellent example of how spacecraft resources were carefully crafted to make DO-OP successful.

III. Autonomy in Action

In February 2014, the culmination of the work described above was loaded to the SORCE spacecraft as OBC FSW9.0. A total of 92 of 128 onboard RTSs (73 percent) were modified during the DO-OP design demonstrating the breadth of changes necessary to implement this new ops concept. On February 24, 2014 SORCE booted to OBC FSW9.0 and on this day began a new phase of science operations, DO-OP.

In DO-OP, the SORCE spacecraft is powered down to its most basic, safe state with all non-essential loads off to survive eclipse. The observatory is configured to spin at ~0.5 degrees per second to maintain its pointing within 45 degrees of the Sun vector. When the coarse sun sensors detect that the spacecraft has exited eclipse, it declares sunrise, powers on the RWAs and magnetic torque bars, points towards the Sun and zeros out spacecraft body rates by transferring momentum from the spacecraft into reaction wheels. Once the solar array current has been above 20 amps for more than 60 seconds the spacecraft to autonomously builds itself back up to an operational state through the boot sequence of the main computer. During the boot process, the computer runs through a series of checks to validate the observatory state of health and is designed to detect and correct a number of problems. If a serious problem is detected the observatory will remain in safe-hold mode for that orbit day. If no problems are detected the system autonomously commands from safe-hold mode to contingency mode. Minimal ground intervention is required to load an absolutely timed sequence of commands to promote from contingency to normal science mode and to initiate science activities. This sequence of turning on at sunrise, loading a stored command sequence to execute during orbit day, and turning off again at sunset occurs fifteen times per day.

In May 2014, DO-OP had been in operations for three months with careful observation and the FOT was ready to make small changes to improve performance. In some cases, the original DO-OP design was handcuffed so that the FOT could observe autonomy was working as expected before releasing its full capabilities. A new OBC FSW10.0 was deployed in June 2014 that enabled the B2b2 sequence, allowed fully autonomous mode transitions, and defaulted to the new 8k downlink rate for TDRSS. Additional capabilities were included in OBC10.0 software update to allow the operations team to autonomously apply patches to the main computers flight software every sunrise rather than loading and burning the entire software image. This patch table functionality has offered increased flexibly to the operations team at LASP to make changes to the spacecraft’s onboard autonomy to address health and safety or science concerns The patch table is applied each sunrise at boot and will autonomously load the updated products. To date, two patches have been applied in January 2017 to respond to the changing performance of the SORCE spacecraft.

In June 2015, a second update to DO-OP was deployed. In addition to improving on the science data collected each orbit and how efficiently the spacecraft achieved Normal mode, this software also allowed the operations team to save additional power by turning the reaction wheels off in eclipse.

A. Performance in DO-OP

In DO-OP mode, the spacecraft performance has been very reliable. Analysis after the first year of operations in this new mode showed the spacecraft reaching Normal mode on 96 percent of all orbits. An additional statistic is that 89 percent of all orbits over the first year collected science for over 25 minutes (the minimum required science duration). An interesting, an unexpected, side effect of DO-OP has been increased stability of the battery as measured by the minimum bus voltage, see Fig. 4. The rate of degradation of the battery slowed after DO-OP was deployed in 2014, but it is difficult to attribute this change directly DO-OP. A small, but significant increase in minimum bus voltage was seen after the June 2015 OBC FSW 11.0 update to DO-OP . This change saved enough power to increase the end of discharge voltage by 0.06V, which is the equivalent of 12 months of battery degradation, effectively extending the life of the mission. Now entering the fourth year of DO-OP, SORCE continues collecting science data every orbit despite the battery challenges.

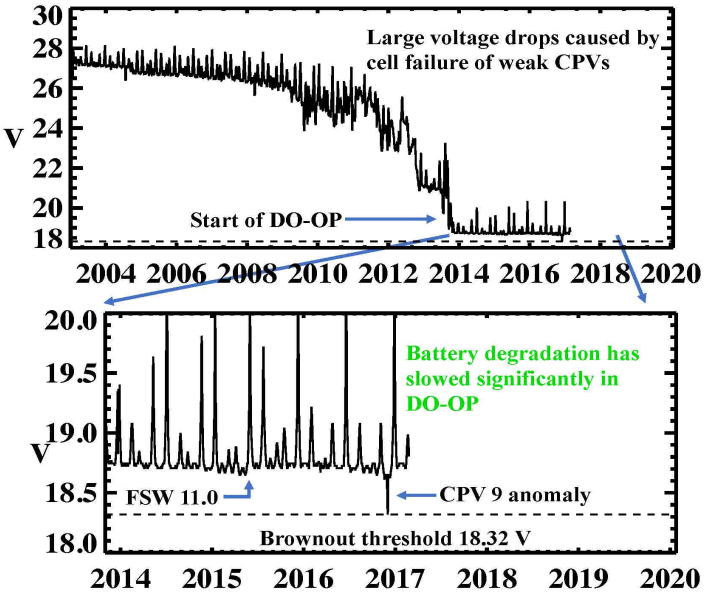

Fig. 4 Battery performance in DO-OP mode and impact of OBC11.0 (RWAs off in eclipse).

IV. Conclusion

The recent experience of the SORCE flight operations team offers an excellent example of innovative engineering using limited resources. The goal of this paper is to extend to the space operations community the lessons learned during this critical redesign in order to aid other missions facing equally daunting challenges. The end result is a mission extended well beyond its designed life continuing to return important data to the science community to extend the climate record.

Appendix A

Acronym List

APE = Attitude Power and Electronics
ATS = Absolutely Timed Command Sequence
B2b2 = Boot to Bank 2
CEU = Central Electronics Unit
CPV = Common Pressure Vessel
CSS = Coarse Sun Sensor
DO-OP = Daylight-Only Operations
FOT = Flight Ops Team
FSW = Flight Software
GN = Ground Communications Network
LASP = Laboratory for Atmospheric and Space Physics
MU = Instrument Microprocessor Unit
OBC = Onboard Computer
RTS = Relatively Timed Command Sequence
RWA = Reaction Wheel Assembly
SIM = Spectral Irradiance Monitor
SN = Satellite Communications Network
SOLSTICE = Solar Stellar Irradiance Comparison Experiment
SORCE = Solar Radiation and Climate Experiment
SSI = Solar Spectral Irradiance
ST = Star Tracker
TDRSS = Tracking and Data Relay Satellite System
TIM = Total Irradiance Monitor
TMON = Telemetry Monitor
TSI = Total Solar Irradiance
XPS = XUV Photometer System

Acknowledgments

This paper highlights many of the larger challenges the flight operations team confronted during the development of SORCE DO-OP, but some of the most substantial work occurred in the fringes driving minor details to conclusion. From our student operators who spend enormous resources optimizing TDRSS scheduling to maximize SORCE science, to the flight ops teams who are on revision 120 (and counting) of our ground autonomy scripts, the flight operations team continues to learn and adapt to our dynamic spacecraft. The continuation of this mission is made possible by the hard-working members of the SORCE team, which extends beyond the operations cadre to include the Orbital-ATK engineering and system teams, the dedicated SORCE scientists, the White Sands Ground Scheduling Group, and the technical management team at NASA Goddard. All should be proud of their contribution to help SORCE continue its important mission.

References

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