Operations Challenges in a Dynamic Environment: A Three-Year Perspective of SAGE III

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***Abstract*—The Stratospheric Aerosol and Gas Experiment III on the International Space Station (SAGE III/ISS) was delivered to the International Space Station (ISS) on 23 February 2017. The SAGE III/ISS payload was robotically installed external to the ISS and began acquiring science measurements on 17 March 2017. The SAGE III/ISS instrument retrieves vertical profiles of atmospheric ozone, multi-wavelength aerosol extinctions, and other gaseous species.**

This paper will focus on the improvements made to the operations of the SAGE III/ISS payload. A key focus of the operations team following commissioning was to create robust tools that aid in the operations of the payload. A close collaboration with the SAGE III/ISS ground systems team allowed for the development of web-based tools to continuously monitor the health of the payload. The mission operations team also worked with the SAGE III/ISS science team to gain a better sense of how the instrument works to maximize the quality and quantity of the science data collected. Another unique aspect of the SAGE III/ISS payload, that will be discussed, is the challenges of operating a hosted payload on the ISS; an active platform that has frequent attitude maneuvers, dockings, and EVAs. This active environment increases the need for the SAGE III/ISS operations team command to the payload.

Through coordination and teamwork, SAGE III/ISS mission has developed an operations team, tool, and procedures that have successfully managed the payload around ISS activities and recovered from multiple instrument upsets. This has led the SAGE III/ISS payload to successfully surpass the acquisition metrics set forth prior to launch, allowing for the continued contribution to studying the atmospheric composition of the stratosphere and how it plays a role in Earth's climate.

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1. INTRODUCTION

The Stratospheric Aerosol and Gas Experiment III on the International Space Station (SAGE III/ISS) payload was launched in February 2017 as the latest instrument in the

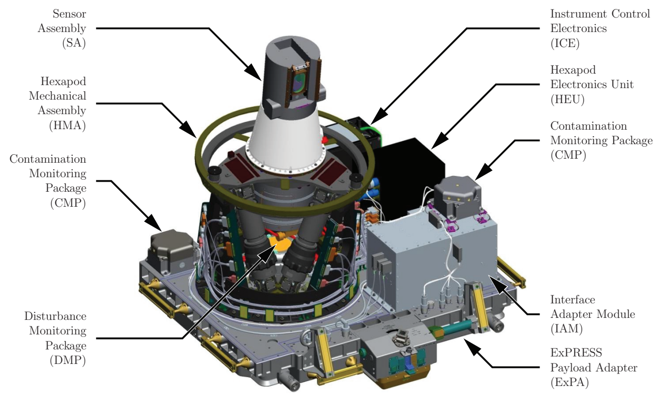

Figure 1. SAGE III/ISS Payload and Subsystems

SAGE family. SAGE III/ISS produces vertical profiles of atmospheric ozone, multi-wavelength aerosol extinctions, and other gaseous species by measuring the occultation of light that has passed through the atmosphere from the sun or moon as they rise and set. This method has been utilized for decades and has proven to be highly reliable through past instruments such SAGEII and SAGEIII/Meteor.

The payload is composed of several subsystems shown in Figure 1:

- The Interface Adapter Module (IAM) is the main flight computer and is responsible for managing all the other subsystems and the communications with the International Space Station (ISS).
- The Sensor Assembly (SA) is the telescope and spectrometer and Instrument Controller Electronics (ICE) is the control computer responsible for taking science measurements.
- The Contamination Monitoring Packages (CMPs) monitor contamination levels around the instrument so that the IAM can close the contamination window when detected contamination levels exceed thresholds established to help protect sensitive components in the telescope.
- The Disturbance Monitoring Package (DMP) monitors the vibration and motion at the payload site to potential account for them in the data product.
- The Hexapod Electronics Unit (HEU) and Hexapod Mechanical Assembly (HMA), collectively referred to as the hexapod, are responsible for pointing the SA.

With components that were built in house, such as the IAM and CMPs, and components, such as the HEU, provided from the ISS partner the European Space Agency, the SAGE III/ISS instrument was assembled and tested at the historical NASA Langley Research Center (LaRC) in Hampton Virginia. LaRC now serves as the base of operations for the various teams that work together to ensure the success of the SAGE III/ISS mission.

2. UTILITIES

Successful operations require powerful tools in order to maintain the health and safety of the instrument. These utilities assist in the day-to-day operations and provide quality of life improvements. Either commercial off the shelf or custom made solutions, they improve analysis, automate tasks, and reduce chances of human error.

Operations Website

In order to minimize downtime from anomalies, the operations team needs to be able to respond quickly and have the tools available to determine the root cause. One of the most useful is the SAGE III/ISS operations website, which was developed by the ground systems team in collaboration with operations. The operations website features standard operational plots, reports, and access to the SAGE III/ISS database. The website gives operators the ability to quickly see the status of the instrument and subsystems, limit violations, and important software messages which are received in near real time from the instrument. The operators can easily access any of the data since the start of the mission, investigate anomalies, and construct health trends.

ISS monitors critical limits and notifies the operations team when a limit violation occurs; the website also monitors an expanded list of limits and can notify the operations team as well. This automatic notification and easy access to telemetry allows the operations team to quickly respond to anomalies. The large operations team further allows for diagnostics and coordination with ISS to be simultaneous, allowing Single Event Upsets (SEUs) to be resolved in hours instead of days.

Custom Tools

Leveraging existing technology and software and combining it with Python, the operations team has created several tools that are central to the planning and analysis of events. Using AGI's Systems Tool Kit (STK) automated by Python, the operations team is able to predict all of the expected events for a given time range and generate routine command files to load to the instrument. These tools are also used in event analysis, by combining the simulation capabilities in STK with event data the operations team is able to generate simulated movies that show the event from the perspective of the instrument. The ability to simulate exactly what happened during an event is beneficial for event diagnostics.

3. DEVELOPING OPERATIONS

The SAGE III/ISS operations, science, and ground systems teams are all conveniently located at NASA Langley Research center. This close proximity has been beneficial to the SAGE III/ISS project. Shortly after commissioning, half of the operations team left and new operators had to be brought on. It was helpful that the operations team could utilize the knowledge and experience of the science and ground systems teams while the new operators were being trained. The training also gives the new operators a chance to experience all facets of the payload to help determine what they are passionate about so that they are motivated and engaged.

To assist with operators knowledge and understanding of the ISS environment and to improve their ability to trend data the development of the operators technical skills has become a higher priority for the team. Operators are strongly encouraged to attend conferences such as PyCon or SciPy to improve their programming knowledge. The operations team members all have the opportunity to attend the Payload Operations Integration Working Group (POIWG) in Huntsville Alabama, which is a conference that brings together the Payload Operation Integration Center (POIC) staff and payload operators, so that every member of the SAGE III/ISS team have the opportunity to interact with members of POIC and learn from other payloads hosted on ISS.

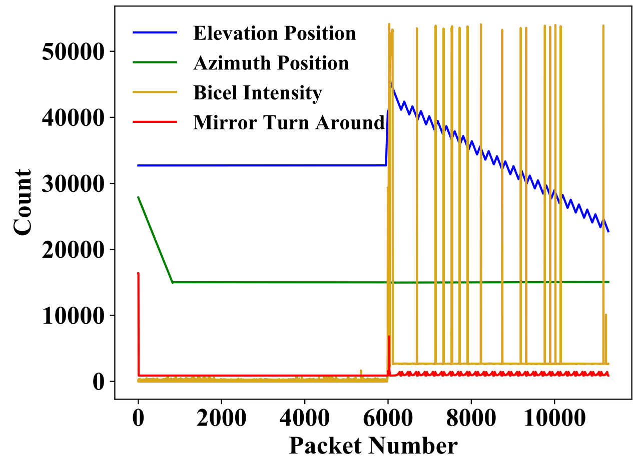

Figure 2. SAGE III/ISS Moonset Event with EMI Impulses

Data Trending

As operations became more routine, the operations team started to delve more into detailed trending of the instrument, investigating smaller anomalies, and developing optimizations. One of the first things that the operations team honed in on was looking at the science events that failed occasionally and classifying them. While investigating these failed events operators discovered that small anomalies were occurring which caused events to fail. These anomalies were not immediately discovered because they occurred very rarely and would usually affect only a single event at a time.

One of these small anomalies was found while investigating several moonset events which were all terminated early, seemingly without any event criteria being met. One thing that all of these events had in common was an unusual impulse pattern in the bicell intensity data, which is a measure of the light intensity within a small area around the center of the instruments field of view, as shown in the yellow line in Figure 2. Each of these impulses occurred for a single data point and one of the impulses fell below the low light threshold which caused the event to terminate. Upon reviewing other science events it was found that these impulses occurred frequently in lunar events but rarely caused the science events to end prematurely, and it never occurred in solar events. It was determined that these impulses were caused by electromagnetic interference in the hardware that measures general light intensity for lunar events. It was first suspected that the electromagnetic interference was caused by something on the ISS, however reviewing pre-launch data showed that the impulse signal was affecting the hardware during ground testing and was likely originating from something within the instrument itself.

The operations team implemented changes to prevent the behavior from terminating events early, but the investigation into this behavior as well as others emphasized the importance of deep data analysis and the operations and science teams working together to greatly increase data trending and develop new tools to assist with and automate the work.

Trending Automation

The SAGE III/ISS operations and science teams decided to invest in developing artificial intelligence (AI) tools to automate data trending and analysis as well as perform tasks that are simply not feasible for a human to do. One of the initial tasks for the AI was to trend all 8000+ data parameters to learn how each parameter is correlated to the others. Using several years of data the AI was able to learn how various data parameters trend over time and perform predictive analysis to show how data may look several years into the future which has been used to track component degradation and give an idea of when degradation could begin to affect the instruments operation. The AI is also able to perform anomaly detection beyond what is possible with simple parameter limits, and can even be used to warn operators about possible anomalies before they happen.

Another tool was developed to assist subject matter experts (SMEs) in annual trending review. This tool automated the data trending and plotting and was incorporated it into a user friendly Jupyter notebook which provided the SMEs with an interactive tool for trending reviews. This did not replace in-depth data analysis but acts as easy to use tool to monitor the general health of the instrument and a jumping off point for the deeper data analysis for specific parameters that require further analysis.

Pandemic Operations

The spread of the COVID-19 virus presented a new challenge to everyone around the world. As countries began locking down in an attempt to slow the spread of the virus and not overwhelm their medical facilities many people began working remotely from home. The SAGE III/ISS operations team can monitoring and trending the health of the instrument remotely but many of the critical tasks must be performed on center at LaRC. Because it was deemed mission essential, a small number of the operations team was granted limited access to center while it was locked down. This allowed the operations team to perform the necessary commanding to allow the SAGE III/ISS instrument to continue operating and collecting science data.

To minimize the amount of time that personnel were on center and reduce the amount of commanding required, changes were made to normal operations while still ensuring the safety of the instrument. Prior to COVID-19, operators would verify that all of the data was from the previous day was in the database as gaps occasionally occur. Rather than perform these down-links every day, the process was changed to recover gaps only once a week since the memory in the IAM holds almost a week of data. It was also decided that a small amount of non-science event data loss would be acceptable to further reduce the need for operators to be on center. Another change that was made involved how operators handled attitude maneuvers. Attitude maneuvers originally required operators to time-tag a mode change to Safe mode before the maneuver and come in afterwords to command the instrument back into Normal mode to resume science taking activities. This approach was used because the timing of the maneuver can sometimes shift the day prior.

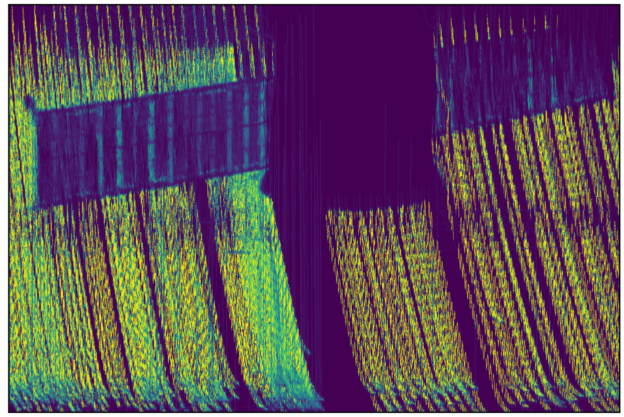

Figure 3. Image of the Progress Capsule

To allow for less on-site work, time-tags to just disable and enable science taking within a generous time around the maneuver are loaded instead.

The operators had to change how work is conducted in the design, test, and simulation lab. It was deemed that the lab space was too small to allow for appropriate social distancing and was restricted to only allowing a single person to be in the lab at a given time. This posed a problem to testing upcoming code changes. The solution was to set up a web camera that whoever was in the lab could use and allow all necessary parties, such as quality assurance, engineers, or other operators observe the activity. This allows most activities to proceed with only a small delay however activities that require multiple people, such as moving large pieces of hardware, have been put on hold.

4. ISS Challenges

There are many aspects to ISS that directly affected the design of the payload and how SAGE III/ISS operations were set up. Being a hosted payload on a platform as active as the ISS, requires many operational activities to be planned around those of ISS, either to preserve the health and safety of the payload or per agreements with ISS. Examples of the more routine activities are performing mode changes for attitude maneuvers, closing the contamination window for dockings, or even powering off for Extra Vehicular Activities (EVAs). While these are scheduled in advance, there have been times when real-time decisions are made to which the operation team needs to respond. The POIC staff at Marshall Space Flight Center (MSFC) try to be as accommodating as possible, ultimately however SAGE III/ISS is along for the ride as our needs are secondary to the needs of the crew and the ISS as a whole.

Blockage

It was known early on that the structure and docked vehicles would interfere with the acquisition of events by blocking the instrument's line-of-sight. It was estimated pre-launch that up to 15.2 percent of events could be blocked but after operating for three years blockage has only affected 7.8 percent and is still the primary reason for failed events. Since blockage occurs at fixed locations relative to the SAGE III/ISS instrument, it is possible to render an image of the obstruction shown in Figure 3, using the light intensity reported from blocked events over several months.

Power Failure

Operating an instrument on a manned platform does have its benefits. On September 21, 2019 SAGE III/ISS experienced an abrupt loss of operational power. The POIC informed us that a power relay to had failed open and after determining there was no significant risk commanded the relay closed allowing the SAGE III/ISS team to restore power the instrument. Two days later the same relay failed open again at which point the POIC informed us that the relay would need to be replaced. Fortunately the auxiliary power to the survival heaters was still available to preserve the sensitive electronics. A power failure such as this would normally end a mission but being on ISS means that maintenance can be performed and after 28 days replaced the relay and restored operational power to SAGE III/ISS. While confident that the instrument had made it through this unscathed, the operations team methodically powered up each subsystem individually to make sure everything performed as expected.

Over the course of the power failure communications between ISS, POIC, and the affected payloads became vital to relay information and updates. SAGE III/ISS teams were able to participate in meetings to discuss the impacts of the power failure, the investigation into what caused the it, and the planning for what would be done to fix the problem. ISS and POIC made sure that payloads we given all available information and had open lines of communication to express their needs during the anomaly.

Communication with POIC

During anomalies the operations team is in communication with POIC to inform them of the instrument status, potential risks, and recovery steps. A unique situation arose on March 5, 2020 in which members of the operations team noticed that telemetry from the SAGE III/ISS payload had not been updated in several hours but the ground systems that monitor telemetry did not notify anyone, in fact the ground systems were reporting that everything was nominal. This was not a necessarily a failure of our ground systems but was in fact an anomaly on the instrument which occurred in such a way that a single packet of telemetry was being sent repeatedly. When this was noticed the operations team contacted POIC to ask if the telemetry that they monitor was also stale to determine if the problem was in the instrument itself or within the ground systems. At first POIC informed operators that their telemetry was not stale and that the SAGE III/ISS instrument was in a nominal state, however through further communications with POIC it was determined that despite their systems showing that telemetry packets were received the telemetry was in fact not being updated. Without any insight into the SAGE III/ISS payload operators were forced to request POIC to power off the instrument while discussing how to proceed with powering the instrument back on and verifying the health and safety.

Following this anomaly the operations and ground systems teams were able to implement additional methods of monitoring the incoming telemetry to alert operators if there was ever a recurrence of this anomaly, but it was through communications with POIC that operators were quickly able to determine that there was anomaly with the instrument itself and power cycle the instrument to regain insight and control of the instrument.

Communications with POIC is crucial to the smooth operation of SAGE III/ISS for commanding and real-time information regarding ISS activities, attitude changes, potential debris avoidance maneuvers, and more. POIC is also able to clearly inform the operators team when they require specific commanding for the SAGE III/ISS instrument when ISS needs to divert electrical power to support the crew during periods of lower power availability, or to cease all movement of the instrument to ensure crew safety when they are near SAGE III/ISS.

5. Design Challenges

During operations, sometimes needs change and aspects of the system might be utilized differently than originally intended. As circumstances evolve, the benefits and short comings of decisions made during the payloads design become apparent. Software can be updated and fixed but hardware limitations require changes in operations and how data is analyzed.

Contamination

Two contamination monitoring packages (CMP) were added to the SAGE III/ISS instrument to monitor contamination that falls onto the instrument which could have a negative impact on science data products. The CMPs provide information to the IAM which uses an internal Fault Detection, Isolation, and Recovery (FDIR) system to protect the instrument from spikes in contamination that fall on the instrument. The two CMPs contain 8 quartz crystal sensors in total which are exposed to the environment and additional crystals which are isolated and protected from any contamination. As contamination mass accumulations on the exposed crystals the fundamental frequency of the crystal changes, this is compared to fundamental frequency of the isolated crystal to produce a beat frequency between the two crystal. The beat frequency can be used to determine the amount of mass deposited on the exposed crystal over time [1].

Pre-launch it was believed that the contamination environment around ISS would be fairly low due to restrictions placed on modules and visiting vehicles limiting the amount of acceptable contaminant outgassing. This was mainly an assumption as there were not any active contamination sensors on ISS to provide real data on the contamination environment and the outgassing of new modules and visiting vehicles. Not too long after SAGE III/ISS was installed and powered on it was found that the contamination environment of ISS was vastly different to what was expected, elevating the CMP to a very high visibility subsystem with high interest from other groups such as Boeing Space Environments who utilized the CMP data to perform more analysis on the ISS environment and vehicle outgassing.

This interest in the CMP data has presented a challenge for the operations team, requiring the operators to invest a significant amount of time to understanding every facet of the CMPs and the measurement they take. While the CMPs were designed and tested for operation before launch, time constraints and the fact that the CMPs were a secondary subsystem meant that the design and testing was less rigorous compared to other mission essential subsystems. For example, the sensors in the CMPs were recessed into the housing under the assumption that it would help protect them from damage and, in the case of one sensor, modify the field of view. Though seemingly benign, this changes the molecular conductance of the sensor and can cause sensors to report different contamination levels even when exposed to the same

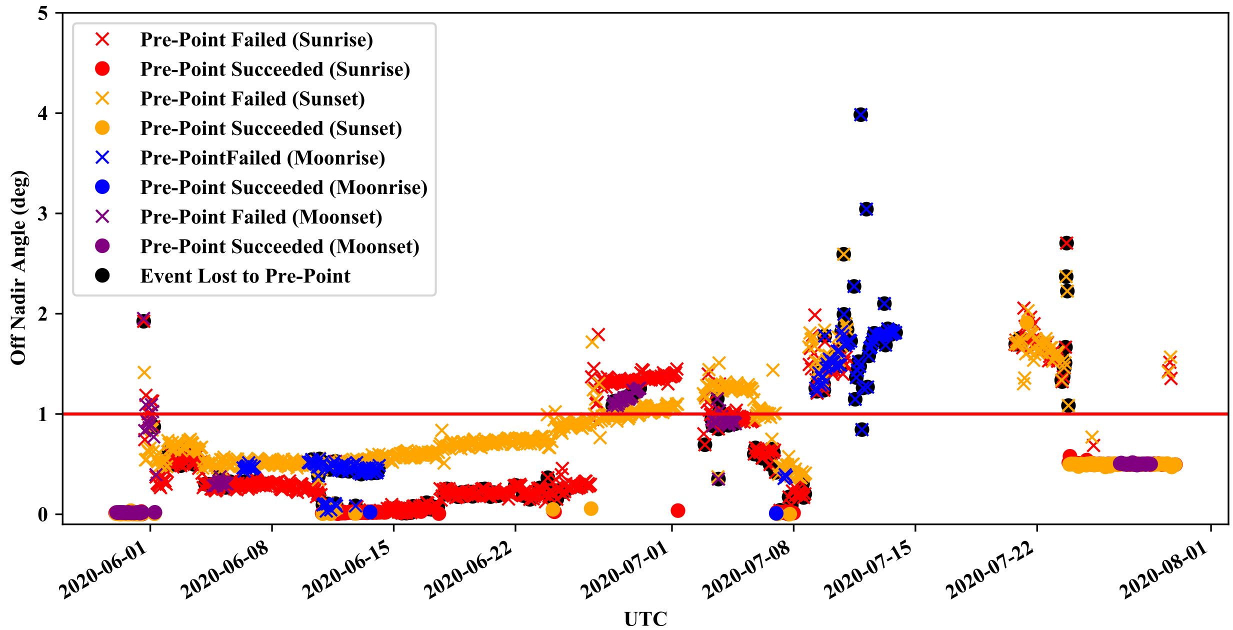

Figure 4. Hexapod Pointing Error

molecular flux.

Pointing Problems

In order to obtain accurate profiles, the instrument needs to scan vertically through the atmosphere and which is achieved by orienting the SA within one degree of nadir per the projects requirement. However the attitude of ISS varies continuously about a nominal orientation over the course of an orbit. The nominal attitude also changes depending on which vehicles are docked at each of the docking ports of the ISS. The ISS will also adjust its yaw to improve power generation. The hexapod was included as part of the payload to account for these dynamic changes and pre-point the instrument nadir. Designed to have a range-of-motion of eight degrees, the hexapod corrects for the pitch and roll of the ISS and the SA scan head rotating to correct for yaw and track the sun or moon during events, SAGE III/ISS can take accurate measurements.

While SAGE III/ISS was going through integration and testing, ISS was planning for the addition of a new module, the Multipurpose Laboratory Module (MLM), which was expected to change the nominal pitch of ISS by approximately seven degrees. This would potentially impact the amount of science events that the SAGE III/ISS would be able to successfully acquire because the hexapod is only able to correct for up to eight degrees. The solution was to insert a static wedge to bias the hexapod by seven degrees and counteract the effect of MLM. SAGE III/ISS launched with the seven degree wedge and, as of October 2020, MLM has yet to be installed. Since the wedge angle is less than the hexapod's range of motion, the hexapod is able to compensate for the wedge and successfully point the instrument. Without MLM operators must wait for ISS to be flying in certain orientations in order to perform some calibration activities, but otherwise the lack of MLM has not caused many difficulties for nominal operations. That is, until the SpaceX crew vehicle started to dock at station.

On May 31, 2020, the SpaceX Crew Dragon docked at the ISS causing a change in the pitch by over a degree in the same direction as the wedge. As a result the operations team started to receive notifications that events were not able to pre-point and were unable to acquire the sun or moon. The reason for this is in how the communication between the subsystems was set up. When the IAM commands an event to start the hexapod adjusted the orientation of the SA to correct for the pitch and roll of ISS's attitude. The hexapod then passes the information needed to correct for ISS's yaw to the SA, however when the hexapod is commanded to move beyond its range-of-motion it rejects the move command and does not return the yaw that needs to be compensated to the SA. In some cases the SA was not oriented too far off from nadir and the target was still within the field-of-view of the SA which allowed the target to still be acquired and tracked during the event.

The operations team devised a solution to allow the hexapod to pre-point while still meeting requirements. Using offset quaternions in one of the control tables, the hexapod was set to point the instrument half-of-a-degree from nadir. After this change on July 23, 2020, SAGE III/ISS began acquiring events again with a more controlled off-nadir nadir angle as shown in Figure 4.

6. Lessons Learned

Lesson One: The SAGE III/ISS has benefited from close interaction and communication between operations, science, and ground system teams. This gives everyone the opportunity to share knowledge and learn from each other while building experience that can be utilized to resolve anomalies. This interaction helps keep team members engaged and allows them to find what they are passionate about within the mission. Enabling team members to take on tasks that they are passionate about has lead to a higher quality of work being done. The passion and drive that team members are able to develop has been vital in replacing former operators when they have moved on to other missions and to build the highly competent team that SAGE III/ISS has today.

Lesson Two: It is important to trend and visualize data to understand anomalies no matter how insignificant it might seem. The smallest pattern might just help pinpoint the problem. Time also needs to be invested in developing the tools to perform the analysis. Once in place, automated data trending tools frees up the operators time that would have been spent just trending the data so that they can develop solutions.

Lesson Three: It is important to consider how things might be used in the future and design them with flexibility. When circumstances change, the flexibility will allow operators to adapt and support the change in the most efficient and beneficial way. Building an operations team that is able to adapt to changes quickly is vital for an instrument on a dynamic platform such as ISS. Operators need to be able to assess the current state of things and determine what needs to be done to ensure the safety of the instrument as ISS activity plans may change with little warning. This flexibility has also made the transition to teleworking, because of COVID-19, significantly easier and is a credit to the team that they maintained operational excellence during these times.

7. CONCLUSIONS

Throughout the three-year prime mission, SAGE III/ISS has seen many of challenges: from changes in the team members, flight anomalies both internal and external to the payload, and even a pandemic. At each turn, hard work and collaboration among the operations, science, and ground systems teams have contributed to swift anomaly resolution and enables the SAGE III/ISS team to successful operate the instrument. By utilizing tools to improve operator efficiency and increase accuracy of data analysis, the operations team can ensure the longevity and accuracy of SAGE III/ISS. The SAGE III/ISS project has developed a highly competent team and dedication over the past three years has paid off as SAGE III/ISS has been recommended for extended operations.

ACKNOWLEDGMENTS

We would like to thank the ground systems and science teams and the rest of the operations team for all of their hard work and commitment to making the SAGE III/ISS project a success.

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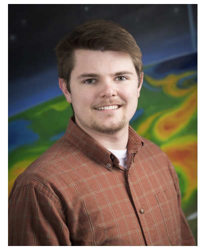
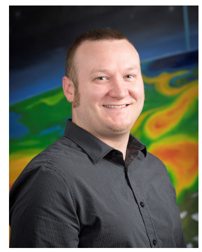
BIOGRAPHY



Andrew Peterson *completed two undergraduate degrees from Virginia Tech in 2016; one in Electrical Engineering and the other in Computer Engineering. He then completed his graduate degree in Electrical Engineering a year later, also at Virginia Tech. Shortly after he was hired as an operations engineer for SAGE III/ISS. In 2018, he became the Deputy Mission Operations Manager for SAGE III/ISS and has been in that role since.*



Samuel Porter *became a Payload Operations Engineer with SAGE III in 2017 after completing his education. He attended Bridgewater College where he did research into induction accelerators and earned a Bachelor of Science degree in applied physics. He then attended Christopher Newport University and earned a Master of Science degree in applied physics and computer science. He conducted research on space weather for his master's thesis to find a coupling function between events that occur in Earth's magnetosphere in response to solar wind drivers, specifically Steady Magnetospheric Convection events. The coupling function will serve to identify, with greater accuracy, when Earth's magnetosphere is in a state of Steady Magnetospheric Convection.*

Jamie Nehrir *graduated from Montana State University in 2009 with a Master's degree in electrical engineering with an emphasis in remote sensing/optics and started working at NASA Langley in 2011. She began working on SAGE III as a test engineer for the Instrument Assembly (telescope/detector portion of SAGE) in preparation for integration into the flight payload. She became the lead test engineer during the final phase of integration and testing of the SAGE III payload. This included operating and validating the functionality of the payload through environmental testing. Once the payload launched, Jamie transitioned to the Mission Operations team as a payload operations engineer. As the Mission Operations Manager, she strives to maintain the excellent health of the payload and continue to collect high-fidelity science data.*