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A Review of Science Ground Operations for the Stratospheric Observatory for Infrared Astronomy (SOFIA)

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The NASA Stratospheric Observatory for Infrared Astronomy (SOFIA) is a 2.5 m telescope in a modified Boeing 747SP aircraft that is flown at high altitude to do unique astronomy in the infrared. SOFIA is a singular integration of aircraft operations, telescope design, and science instrumentation that delivers observational opportunities outside the capability of any other facility. The science ground operations are the transition and integration point of the science, aircraft, and telescope. We present the ground operations themselves and the tools used to prepare for mission success. Specifically, we will discuss operations from science instrument delivery to aircraft operation and mission readiness. We will also provide a discussion of instrument life cycle including maintenance and repair, both before and after acceptance by the observatory as well as retirement. Included in that will be a description of the facilities and their development, an overview of the SOFIA telescope assembly simulator, our deployment capabilities, as well as an outlook to the future of novel science instrument support for SOFIA.

Keywords: Infrared astronomy, detectors, operations, airborne, NASA, ground support, facilities, deployment, receivers, instrumentation, mirror coating, telescope optics.

1. Science Ground Operations Overview

The Stratospheric Observatory for Infrared Astronomy (SOFIA), a joint project of NASA and the DLR, is 2.5 m telescope mounted in a Boeing 747-SP aircraft (Ennico *et al.*, 2018; Adams *et al.*, 2012). Science ground operations consist of science instrument (SI) maintenance, repair and preparation as well as telescope optics flight preparation and maintenance. SI operations cover all five instruments fielded on SOFIA (Smith *et al.*, 2014), both facility instruments and Principal Investigator (PI) instruments. Telescope optics work is in general limited to characterization, cleaning, and recoating of reflective optics. However, certain special projects are executed by science ground operations in support of improved telescope performance or to execute critical repairs (Waddell & David, 2016).

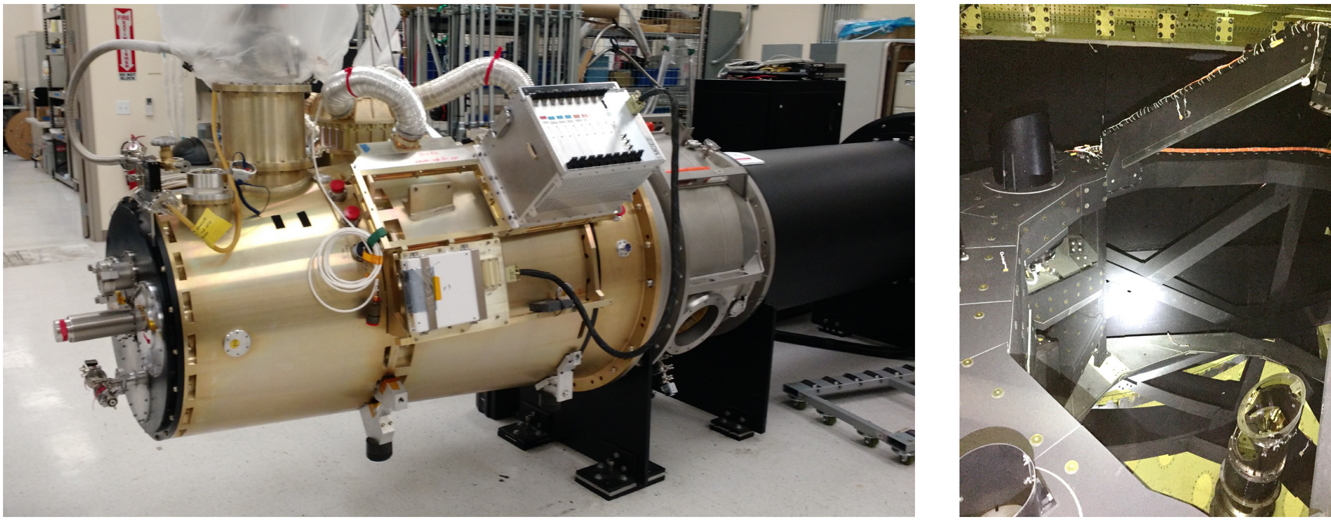

Fig. 1. (Left) The HAWC + SI mounted on the TAAS in the PIF for integrated testing. (Right) An image of the SOFIA telescope assembly taken during pre-flight inspection. Left, one sees the imagers. Right one can see the rear of the secondary and also the tertiary mirror. The primary is in the middle of the image. Images: Zaheer Ali (USRA).

Two key facilities, both located in Palmdale at SOFIA's operations center, enable successful ground operations: the SOFIA Science Labs (SSL) and the SOFIA Mirror Coating Facility (MCF). The SSL consist of five SI labs, an optics lab, capable of becoming a Class 100 (ISO 5) clean room, an electronics shop, and the Pre-Flight Integration Facility (PIF). The latter is the home of the Telescope Assembly Alignment Simulator (TAAS) (Fig. 1) which is used for characterization, testing, and preparation of SIs (Thompson *et al.*, 2012). The MCF functionally comprises of a mirror stripping and a mirror coating room, with additional support areas; it is intended and tooled to coat the SOFIA primary mirror (PM). This capability was originally part of the faculties at NASA Ames Research Center (Colditz *et al.*, 2014), where the original coating was applied to the PM, but now the MCF resides at the operations center in Palmdale.

1.1. *SOFIA SI ground operations*

SOFIA SI ground operations for SIs have been integrated to the observatory functions on a basic three SI phase concept: one SI is being prepared for mission flights, another is installed on SOFIA and executing missions, and a third is in post mission flight series testing or maintenance. Due to the number of SIs we now have, there is a fourth, out-of-phase state an SI may be in, that of repair or upgrade. SI preparation includes standard systems checks at room temperature, intermediate, and operational temperatures. The methods for preparation are mature and standardized, reflecting the maturity of the observatory operations and providing a consistent way of ensuring that SIs are ready for the mission.

Within the SSL and the PIF there is a variety of maintenance, measurement, and test equipment. Of that, the TAAS is a unique and critical tool for SI preparation, allowing instruments to test modifications and optimizations, as well as observation processes, when combined with the Software Integration Lab (SIL) which is a simulation system that allows testing of SI software. SIs mount to the TAAS as they would to the telescope in the aircraft. While the TAAS does not have elevation change capability like the telescope, it does have several light sources that allow bore sight calibration and end-to-end instrument testing (Colditz *et al.*, 2014). The processes executed during these tests are recorded in procedures and refer to a master work flow document called the *SI Traveler*. All activities done to or with the SI are therein captured and therefore traceable. During this period of preparation, any changes that need to be made to the SI control software are also implemented, allowing end-to-end testing prior to aircraft installation (Klein *et al.*, 2014). Once testing is complete, the SI is secured and prepared for installation onto the aircraft.

As SOFIA is unique among observatories, so is the act of installing a SI onto SOFIA's telescope. As has been described by the SI development teams in various papers (Herter *et al.*, 2012; Heyminck *et al.*, 2012; Mainzer *et al.*, 2003), the SIs differ significantly in form factor and concept of operations;

however, the interface to the telescope is tightly controlled. Therefore, installation is standardized to electronic racks, instrument, and ancillary equipment installation such as the up GREAT cryocooler compressors. As SOFIA is an aircraft, tight coordination with the SOFIA Aircraft Maintenance team is required for everything, from bringing the SI through the aircraft door, to over what parts of the main deck floor the SI may be moved. Once the SI is installed, certain alignments of SI internal systems to the telescope may be necessary. Additionally, line operations, where the observatory operates on the ground outside to test SI integration and readiness, may be required. The (up)GREAT SI, for example, requires a radio alignment and beam finding to be executed. To do this, we install the SI and verify basic functionality, then, the secondary mirror is covered, and a cold source is introduced to find the beam (Heyminck *et al.*, 2012). With the SI ready for the mission, routine maintenance such as cryogen fills and pre-flight checks of hardware continue on the aircraft for the flight series; included in that are activities such as executing the adiabatic demagnetization cycle for the HAWC + SI and preparing the up/4GREAT SI for power transfers. During the flight series, mission crew members create reports that lead to actions once the SI has come off the aircraft.

At the completion of a flight series, the SI is removed from the aircraft, typically with another one directly succeeding it on SOFIA; occasionally for aircraft maintenance periods SOFIA is left without an SI installed. As is typical for SIs, there is often a list of actions to be performed post observation series. Filters may be changed to prepare for the targets in the next flight series, hygroscopic IR windows may have reached their lifetime and need to be replaced, or there may be some discrepancy that needs to be addressed. For facility owned SIs, the SOFIA Science Maintenance and Engineering team (M&E) will execute all repairs, scheduled configuration changes, and maintenance. All SIs are configuration controlled and the exact configuration of the SI is known prior to installation on SOFIA (Temi *et al.*, 2014).

1.2. *Telescope optics flight preparation and inspection*

Prior to and post each flight, the entire telescope is inspected for mission readiness. The M&E team enters the telescope cavity, in the aft section of the aircraft, and checks the state of all optics and telescope hardware. Similarly, in the cabin side of the aircraft the portion of the telescope that attaches to the SI and all mechanisms for vibration isolation, balancing, and movement are inspected. Furthermore, in the hold of SOFIA, below the main deck where cargo would ordinarily be, telescope bearing oil systems reside and their state is inspected as well. For each flight, all systems must be in specific operation ranges before the telescope is brought into operation. These checks are a subset of the master checklist that will certify the aircraft for flight and therefore mission readiness. Any discrepancies must be resolved prior to flying the mission.

1.3. *Mirror coating operations and other telescope maintenance and activities*

The MCF is certified for readiness to coat the SOFIA optic multiple times a year by coating of witness samples. The samples are of the same material and polish as the mirror and are loaded across what would be an arc of the PM providing characterization of the coating as it would be if a mirror recoating were executed. Were that to occur, the mirror would be removed from the aircraft and placed on the mirror cart, as shown below in Fig. 2, with a mirror surrogate mounted. The cart would be rotated such that the optical surface could be accessed. Wet chemical metal etchants would then be used to strip the mirror of the Al coating. After cleaning of chemical residue, inspection, and another cleaning, this time of debris, the mirror would be ready to be taken over to the coating chamber for deposition of the reflective layer of Al.

Fig. 2. Within the stripping room, shown here is the PM cart. The door to the right leads to the coating room. Not seen here is a complete wet chemistry bench. Image: Gregory Perryman (USRA).

Critical non-flight preparatory inspections are also routinely done on the telescope. The Deutsches SOFIA Institut (DSI) team, a contractor of DLR, is tasked with maintenance and optimization of all telescope systems excepting optical components. M&E carries out inspections on the mirrors, including emissivity and reflectivity tests. These tests determine what cleaning and eventually replacement or recoating activities will be done. The PM cleaning is done *in situ*, without removal, using a mild detergent solution. Combined with the relative lack of exposure of the SOFIA PM to hazards, the *in situ* mirror cleaning process has been so successful that the SOFIA PM is still using its original coating (Fig. 3).

The secondary mirror must be removed to be cleaned; this has been done once. The tertiary has also been cleaned *in situ*. Other optics related maintenance activities include inspection, maintenance, and repair of special insulation in the telescope cavity and materials compatibility testing for the mirror surface. This includes the development of highly absorptive black coatings that are compatible with the conditions of a telescope assembly exposed to 45,000 ft altitude (Waddell & David, 2016). That development was complicated by the fact that many chemicals not typically seen at observatories need to be used to maintain the aircraft.

Additionally, special tasks have been carried out by M&E in support of critical SOFIA needs. In August of 2011, during a routine inspection of temperature and pressure sensors mounted on the non-optical side of SOFIA's 2.5 m (100-inch) PM, technicians noticed that about one dozen of more than 110 aluminum sensor wire tie-down tabs had detached. When the sensor tabs separated from the back surface, the adhesive used to attach the sensors took some of the mirror material with it. Each blemish was smaller than a postage stamp. The SOFIA USRA M&E along with the DSI team developed a method to, *in situ*, remove the aluminum tabs and grind and polish out the cracks, to keep them from continuing to expand. M&E team members, along with Science team members have also conducted studies on stray light issues on SOFIA (Logsdon *et al.*, 2016; Waddell *et al.*, 2016). Multiple sources have been identified over the last several years of operations and both coating and baffles have been developed to counteract those effects. Special coating was developed to cover fasteners that were causing diffuse reflection, and baffles have been installed and tested that dramatically reduce specular reflection of thermal light from the SOFIA engines off of the PM Assembly Spider Arms (Baxter *et al.*, 2013; Waddell *et al.*, 2016).

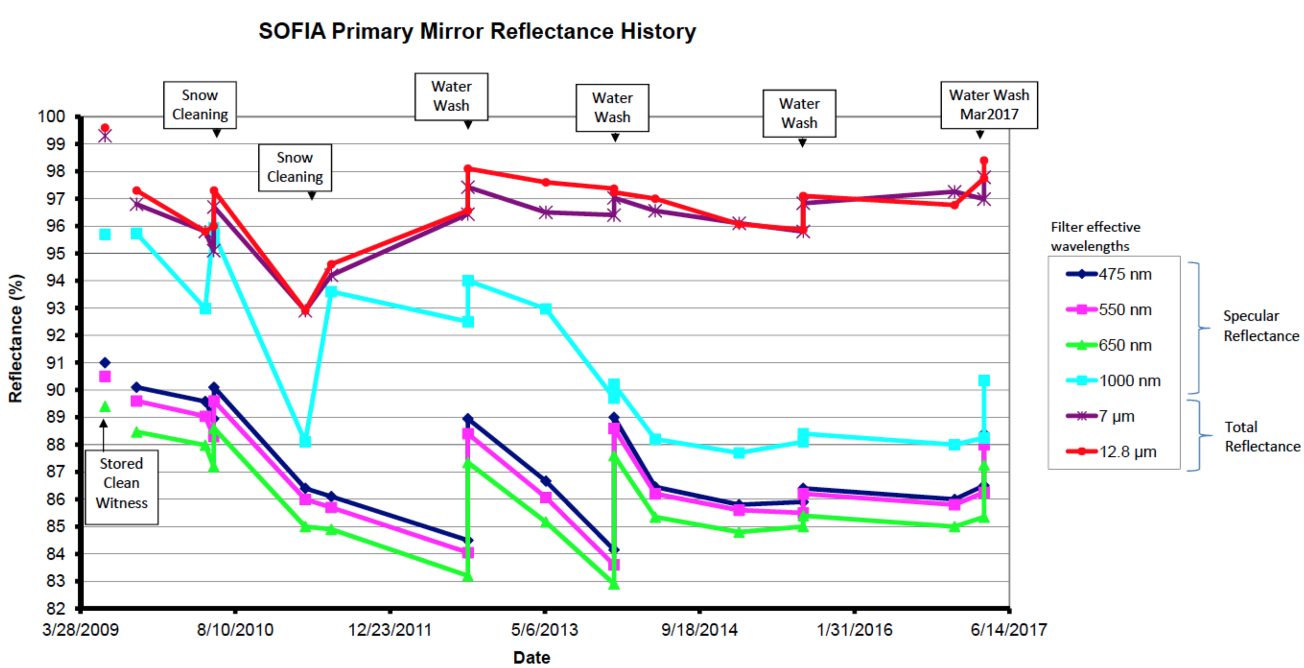

Fig. 3. The PM has been cleaned several times since the original coating. In the IR one sees that the reflectance is excellent and that the *in situ* water wash leads to improved performance each time it is carried out. Chart: Jeff Holman (Ames Research Center).

2. Facilities and Capabilities

2.1. *SOFIA science labs*

The SOFIA Science Labs house all operational phases of an SI life cycle. SIs either have their own lab assigned to them or share a lab, as dictated by their size and amount of ancillary equipment. The labs have separate access control as well as independent temperature control. Multiple power types are available as well as GPS and Ethernet. Ceiling height and air exchanges are designed to allow cryogen and basic chemical operations. The electronics shop has ESD certifications and the capability to fabricate cables and harness to NASA flight standards. A wide range of measurement and test equipment is available. The optics lab can become a class 100 k area at need. A flow bench, flow cabinets, and vacuum oven are also available therein.

In the PIF, the TAAS allows SIs to prepare for installation. The flange to which the SIs mount is vacuum capable and allows testing of the SI pressure boundary. The remainder of the TAAS may be purged with N2 gas resulting in a 0.01% or less water vapor in the optical path; this simulates the low water vapor conditions of in-flight observations and allows calibration and characterization that would otherwise be blocked by ambient water vapor on the ground. Three light sources: the focused chopped light source, a small chopped hot plate, and a large chopped hot plate allow for a variety of tests, ranging from single pixel interrogation and beam scanning to testing pupil viewing modes (Colditz, 2017; Thompson *et al.*, 2012).

In 2016, we have also added the capability of providing two cryo-cooler compressors for SI use. Currently, the capability is only present in the GREAT SI lab in support of up/4GREAT. However, the system is built modularly and can be expanded as needed. With the third generation SI HIRMES scheduled to fly in 2019, an expansion of the cryo-cooler capability is planned to be implemented in late 2018 (Smith, 2017, 2018). Given the general push of technology and the increasing scarcity of liquid helium, it is likely that the facility will need to support increasing mechanical cooling systems in the future (Farrah *et al.*, 2017).

Additionally, the Science Operation Center Software Integration Lab (SOC-SIL) located almost immediately above the labs in Palmdale gives the SI teams the opportunity to simulate the aircraft experience in software. The SOC-SIL is operated and maintained by the SOFIA Science Information Technology group (IT). This capability allows the SI teams to perform dry runs of their software and hardware against simulated aircraft systems while also being on the TAAS and putting light on the sensor, to ensure that their SI will integrate with the aircraft platform. Observation modes, AORs, and flight plans can all be tested against the SIL with the assistance of the mission operations team (telescope operators, mission directors, flight planners). Furthermore, SOFIA Science IT has provided bidirectional in all permutations between the labs, the aircraft, remote sites, and the SIL.

Fig. 4. (Left) FIFI-LS cooling down in its lab; the labs can be reconfigured and repurposed easily to accommodate different work. (Right) A view of the TAAS and other equipment from a corner of the PIR; in the center column of power drops is also the connectivity to the aircraft and SOC-SIL. Images: Zaheer Ali (USRA).

Fig. 5. From the left to the right: the mirror coating chamber, the chamber lid stand, and under the tarp, a mirror weight load surrogate. Also of note are the large bay doors and the overhead crane. A HEPA vent diffuser can also be seen above. Image: Gregory Perryman (USRA).

2.2. *The mirror coating facility*

The mirror coating room is shown in Fig. 5. The coating chamber is 4.3 m in diameter and 4.9 m in height. It is a filament ring based physical vapor deposition system using the evaporation of pure Al to coat the mirror to 150 nm thickness with a 5–10% variation in reflectivity across the coated surface. The chamber is a dual vacuum zone system with the PM seated near the vertical center facing downward. An Ar plasma cleaning is executed *in situ*, prior to coating. Internal pressure and residual gas are monitored to ensure optimal film properties. The system is semi-automated, with specific operations being governed and interlocked through a control system, but action being dictated by the operators. Currently, the MCF is only tooled to accommodate the SOFIA PM. However, with additional development, it could be used for different size optics with different metals.

3. SI Lifecycle

3.1. *SI development and preparation for delivery*

SOFIA has a robust program for development of new SIs. During development and build of the SIs, the SI scientist and the SI engineer, at times, travel to the development institution to be trained on the instrument function, operation, and science capability. As the instrument gets closer to completion and delivery, science M&E team becomes involved in process development as well as planning of shipment and immediate post-delivery activities. During this time the facility is also made ready; in the case of HIRMES, we will be adding additional cryo-cooler capability. IT and software needs are also considered with requirements from the SI development team driving any addition of capability.

3.2. *Integration, commissioning, and acceptance*

Once delivery criteria are satisfied and a pre-shipment review is passed, the new SI arrives at the operations center. Depending on the distance, and needs of the SI, it may ship in pieces as did the GREAT SI or it may arrive whole, and even at cryogenic temperature, as did HAWC+. At this point, many test and V&V activities are executed. In the lab electrical systems are checked, power draw is verified, and then the SI is set up for testing. Some SIs have used the TAAS extensively, as has been described elsewhere in this paper, other SIs have specific test stands or built-in systems to allow end-to-end testing. At this time, software integration is also carried out using the SOC-SIL and the

Hardware-In-the-Loop (HIL) lab, each of which can simulate interaction of the SI with the telescope and mission control systems.

After readiness criteria have been met and a pre-installation review is passed, the SI is installed on the aircraft. This final stage of integration encompasses all aspects of the observatory. Line operations, open door testing at night using optical targets, may be executed, depending on the needs of the SI and the observatory. At this time, observing modes, astronomical observatory requests (AORs), and observational systems are tested. Additionally before flight, an electromagnetic interference test is conducted to verify that the aircraft will not interfere with the SI and vice versa. Commissioning then begins and is a combination of verification of SI performance on-sky as well as general operational capabilities (Adams *et al.*, 2012; Colditz, 2017; Risacher *et al.*, 2016; Smith *et al.*, 2014).

During commissioning, the SI development team trains both the SOFIA science team and the science operations team on operations and maintenance of the SI. This is also the time during which any discrepancies or incomplete items with the SI are resolved. On the second generation SI HAWC+, we found that ground performance was as expected; however, upon initial flight, it was discovered that neither the SI could maintain a temperature sufficiently low for operation of the detectors, nor could it maintain temperature long enough to last an entire flight. It was quickly understood that this was due to acoustic coupling from the telescope into the SI. The SI development team, with assistance from external experts and the science M&E team was able to resolve this issue. SI disassembly, modification, and testing were all carried out at the SOFIA operations center in the SOFIA Science Labs. Once such issues are resolved, an acceptance process is carried out. This is the formal hand over from the development team to the SOFIA Science Mission Operations team to operate and maintain the SI for the remainder of its lifetime. At this time, the SI enters standard operations, becoming part of the nominal three-phase cycle for instruments operating in the observatory. On occasion, an upgrade or optimization may be carried out such as that done recently for FIFI-LS with a new set of filters and modifications to the holders.

3.3. *Retirement and repurposing*

As per the capabilities and from technology advancements it becomes necessary to retire SIs whose cost to support is greater than their scientific relevance. The SOFIA call for proposals informs the science community that an SI is being offered for the last time and will not be offered in the future. If there is no sufficient reason put forward to retain that SI, SOFIA science informs M&E to retire the instrument. Currently, we have retired only HIPO and FLITECAM. HIPO, being a PI class instrument was returned to PI Ted Dunham at Lowell observatory, and any observatory hardware was returned. FLITECAM, is in the process of being repurposed. Certain components have become spares for other SIs, the filters will be preserved for possible use by other SIs or the SOFIA Focal Plane Imager, and other systems will be used for training or preserved against possible use by SI developers (Pfüller *et al.*, 2016).

4. Ground Operations on Deployment

Deployments represent a unique capability of SOFIA as an airborne observatory. The mobility of our operations allows us to take advantage of better observing conditions and view parts of the sky unavailable from our home base. Also, the airborne capability allows us to execute observations where no other observatory possibly could, such as occultations observed far out over the ocean. When SOFIA deploys, it is not only the aircraft and those who operate systems in flight who travel, but also the support structure in personnel and equipment for both the aircraft and SI. This represents a nontrivial and crucial portion of the deployment which enables the use of multiple SIs in one deployment and the ability to maintain and repair the SIs, telescope, and aircraft.

4.1. *Deployments to the southern hemisphere operations center — Christchurch, NZ*

SOFIA science ground operations on deployment to Christchurch are intended to copy operations at the Science Operations Center in Palmdale (Savage *et al.*, 2015). In executing four deployments we have taken all three phases of SI ground operations capability, in equipment, cleanliness, and ability to execute operations. Previously, all equipment was shipped from our operations center in Palmdale to our Southern Hemisphere operations center in Christchurch. However, in 2016 we indefinitely stationed significant amounts of equipment there and in 2017 we also added the capability to prepare cryo-cooled SIs by modifying the facility to provide power and routing for cryo-cooler systems. Additionally, supply chains exist for all consumables, including cryogens, gases, and chemicals. Multiple SI swap operations have been executed during a single deployment as well as an open SI repair.

4.2. *Suitcase deployments*

As targets of opportunity may present themselves anywhere in the world, SOFIA has the capability to be deployed for a short duration to carry out specific observations. This was demonstrated in October of 2017 when SOFIA deployed for a week to Daytona, Florida from the Palmdale, California operations center to observe an occultation of Triton. Due to the track of this occultation being over water in the Atlantic, only SOFIA was capable of observing it. This was similar to the Pluto occultation which was observed over the Pacific in 2015 with a science flight departing from Christchurch (Leppik *et al.*, 2018). That flight not only supported the New Horizons fly-by of Pluto, but helped calibrate previous occultations of Pluto due to SOFIA observing the central flash (Pasachoff *et al.*, 2017; Person, 2016). The Daytona suitcase deployment was a success with SOFIA observing the central flash of Triton's occultation (Risacher *et al.*, 2016).

5. Looking Forward

SOFIA science ground operations are now mature with standardized practices, an experienced staff, and a suite of facilities and equipment able to accomplish the mission. However, as SOFIA continues to innovate in instruments and operations, with SIs such as HIRMES on the horizon and new targets of opportunity coming up, our operations will continue to evolve. In the short term, we are working on optimizations and efficiencies with current facility SIs, trying to cut down preparation time and cost while at the same time increasing reliability. Over a longer term, we plan to upgrade the facility to be able to support later generation SIs which will likely have new requirements as well as find ways to repurpose retired SIs to be able to support the SOFIA mission.

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