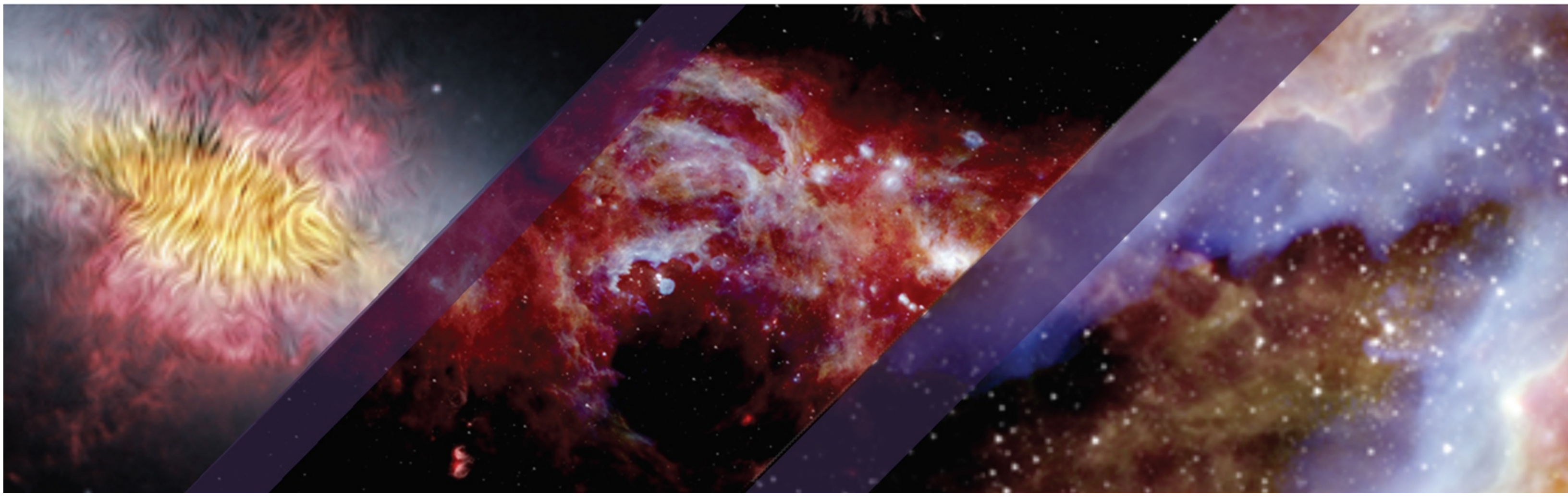

SOFIA Response to 5-Year Flagship Mission Review

September 30, 2020

SOFIA Response to 5-Year Flagship Mission Review

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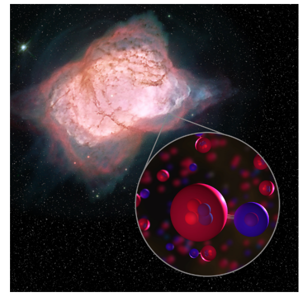


SOFIA found helium hydride, the first type of molecule to form in the early universe

The Stratospheric Observatory for Infrared Astronomy (SOFIA) is currently the only astronomical observatory in the world to provide access to the far-infrared and major swaths of the mid-infrared wavelength regions. With the advantage of large-scale mapping, high-resolution spectroscopy, and polarization measurements at wavelengths where the thermal signal is strongest, SOFIA will significantly extend the legacies of Herschel and Spitzer by making fundamental measurements related to star and planet formation, formation of pre-biotic molecules in the interstellar medium, the role of magnetic fields in the formation of galaxies and supermassive black holes in the local universe, and studying the water cycle and minerology of the Moon to support the Agency's Artemis mission. SOFIA science objectives address NASA's strategic goals described in Table 1.1.

SOFIA, a highly complex and versatile airborne astronomical platform, reached mature operations in its prime mission and transitioned from development and data acquisition to scientific discovery. In the extended phase, starting fall 2019, focus shifted to substantially increasing its scientific output and impact by raising the fraction of time spent on large coordinated community-driven observing programs; building a strong, diverse, multi-disciplinary science community; providing more observing opportunities in the Southern Hemisphere; increasing observing time during the Northern winter when conditions are optimal; and restructuring the Project to sustain operations within a lower annual budget.

This report provides the SOFIA Project's response to the Five-Year Flagship Mission Review (FMR) report that recommended a number of concrete suggestions to improve the scientific productivity and impact of SOFIA. The Project embraces these recommendations and fully addresses them in this response. Table 1.2 lists SOFIA's mission objectives and Table 1.3 describes the immediate and strategic initiatives as well as policy changes undertaken by the Project to substantially increase the publications and Hirsch (H)-index of the observatory by the next Senior Review, expected in 2022. This report also describes various studies and strategic planning activities undertaken by the Project following the FMR to address the individual recommendations and top-level advice. Key science metrics (Table 1.4) recommended by the FMR have been implemented and are being tracked by the Project.

The SOFIA Science and Mission Operations (SMO)[1] organization contributed to this response by conducting a strategic study focused on three themes: impact, productivity, and efficiency, each resulting in several initiatives. The impact-driven initiatives will maximize the relevance of SOFIA's results and ensure its legacy. The productivity-improvement initiatives will increase the rate of both observational data output and scientific publication. The efficiency-enhancing initiatives will optimize what the Project can do with the current staff, equipment, and flight rate to maximize discoveries per dollar. The SMO has made substantial progress in creating a science-driven culture and automating routine tasks, two principal FMR recommendations. The SMO is strongly engaging the astronomical community and initiating synergies with other observatories to increase SOFIA's influence in the fields of astrophysics and planetary sciences.

[1] The SMO is operated for NASA by the Universities Space Research Association (USRA).

Table 1.1 – SOFIA Science Objectives Address NASA Strategic Goals[a]

NASA Big Question and Strategic Goal	SOFIA Science Theme	Capabilities and Key Diagnostics
How did we get here? [b] Explore the origin and evolution of the galaxies, stars, and planets that make up our Universe[c]	Birth of Stars and Planets Establish the role of magnetic fields at sub-parsec scales by mapping Galactic star-forming regions' polarization in emission. Quantify the energetics of the interstellar medium that is the birthplace of stars and planets by measuring the dominant cooling lines, the radiative and stellar-wind feedback by stars, and the dynamics of the gas.	Far-Infrared (Far-IR) Polarimetry Far-IR Fine-Structure and Molecular Lines
Are we alone? [b] Building new worlds; planetary habitats; workings of solar systems[d]	Path to Life: Water, Organics, and Ices Compile an inventory of water and organics in protostars to understand chemical pathways from simple molecules to prebiotic species. Monitor temporal and spatial changes of planetary atmospheres in our Solar System as analogs to exoplanets. Provide water maps of key regions on the Moon.	Mid-IR H_2O Ices and Polycyclic Aromatic Hydrocarbons (PAHs) Mid-IR High-Resolution Spectral Surveys of Water and Organics Far-IR Molecular Lines
How does the Universe work? [b] Explore the origin and evolution of the galaxies, stars, and planets that make up our Universe[c]	Calibrating the Distant Universe Understand "single-pixel" (spatially unresolved) measurements of distant galaxies by investigating local analogs, specifically, by measuring far-IR lines and magnetic fields in local star-forming regions, the Galactic Center, and nearby galaxies.	Far-IR Fine-Structure Lines Far-IR Imaging and Polarimetry Mid-IR Imaging

a. NASA's Strategic Objective 1.1: "Understand The Sun, Earth, Solar System, and Universe," NASA Strategic Plan (2018)
b. NASA Astrophysics Roadmap (2013)
c. Science Mission Directorate Science Plan (2014)
d. Planetary Science Decadal Survey (2013-2022)

Table 1.2 – SOFIA Mission Objectives*

	Prioritized Mission Objectives for the Next 5 Years
1	Dedicate at least one-third to one-half of observing hours to Legacy programs
2	Maximize observing time in the Southern Hemisphere
3	Emphasize high-quality data collection; effort includes, but is not limited to: a. Maximizing observing in low water-vapor conditions b. Increasing observing opportunities during optimal observing months c. Conducting a robust proposal selection and technical evaluation process d. Prioritizing the collection of well-characterized, well-calibrated, large, homogeneous data sets
4	Pursue synergies with ground-based observatories and NASA missions via collaborative efforts and joint observing programs
5	Build a bigger and a scientifically diverse user community
6	Maintain the capability to upgrade and develop new instrumentation to support new discoveries or new astrophysics priorities

** SOFIA's prioritized mission objectives have been defined in response to the FMR; and, these objectives will be documented in the new Project Plan, which is under development for the extended mission.*

SOFIA Response to 5-Year Flagship Mission Review

The major initiatives and policy changes in Table 1.3 developed in response to the FMR report will collectively increase scientific output and the influence of SOFIA. Most of these initiatives have been executed. The remainder are scheduled for Science Observing Cycle (Cycle)-9. Initiative impact will be closely monitored; and, new initiatives will continue to be adopted to maintain and enhance SOFIA's productivity, scientific relevance, and community growth.

Table 1.3 – SOFIA Major Initiatives in 2019-2020

Science Selection, Implementation, and Delivery
Legacy programs will be a larger fraction of total observing time – 25% in Cycle-8 starting 2020; the goal is to increase this fraction in subsequent cycles – Introduction of pilot Legacy programs
Joint observatory proposals to broaden SOFIA's impact and user base – Cycle-9 call for proposals includes a joint observatory call
Reliable and consistent tracking of observing conditions using satellite data – Provides reliable and consistent water-vapor values – Will be used for flight planning and scheduling observations to optimize data quality
Observing proposals to stay alive over two cycles, beginning 2021 in Cycle-9 – Higher program completion rate, fewer instrument swaps, greater schedule flexibility
Change in policy for priority-2 programs to be completed once started – Boost program completion rate and publications
Implemented additional, more thorough technical review of the proposals – Ensure that selected observing proposals are feasible and publishable
Strategic use of director's discretionary time – Stronger community involvement, wider mission appeal (e.g., Moon water mapping)
Faster data delivery to the community – Deliver data in 15 workdays; reduced exclusive-use period to 6-months in Cycle-9

Observatory Operations
Extended Southern Hemisphere deployment in Cycle-9 (starting in 2021) with a combination of single long deployment plus a mini deployment – Increase observing opportunities in the Southern Hemisphere to 40 nights – Conducted evaluation of alternate Southern Hemisphere deployment sites to allow flexibility to execute mini-deployments when scientifically merited
Automated flight planning – Better agility to respond to delays/rescheduling due to weather or technical issues – Allows more accurate flight plans around restricted airspace
Cross-training staff and identifying on-call back-up mission operations staff to improve observatory efficiency
Reduced aircraft maintenance downtimes to once per year
Shorter (more frequent) flights in spring and fall months to optimize data quality
Implementation of new mission prep tool has significantly reduced pre-flight prep time

Table 1.3 – SOFIA Major Initiatives in 2019-2020 (continued)

PROJECT ORGANIZATION
~10% reduction in workforce in fall 2019 – Maintain staff for sustained 4 flights/week for weekend support, for observatory maintenance, and to conduct Southern Hemisphere deployments
Project reduced to two divisions: Science & Operations – Observatory systems, sustaining and development engineering dramatically downsized – Reduced management overhead; observatory configuration changes limited to mission-critical upgrades required to maintain current operations
SMO reorganization with primary focus on increasing science productivity and impact – More post-docs hired; faster data delivery to the community – Higher focus on community engagement to build impactful and ambitious Legacy programs, increase and broaden SOFIA's impact and user base, promote archival research

Table 1.4 presents key science metrics recommended by the FMR that have been implemented and are being tracked by the Project.

Table 1.4 – SOFIA Key Metrics and Goals

SCIENCE METRIC	GOAL
Publications per year:	> 75 (100)*
Scientific Impact Citation H-Index[2]:	> 30 (44)*
Oversubscription Rate[3]:	≥ 5
Data Processing and Archiving Time:	15 workdays
Completion Rate for High-Priority Programs[4]:	≥ 80%
Fraction of Completed High-Priority Programs Resulting in Publications[5]:	≥ 80%
High-Quality Observing Time: % research hours[6] at precipitable water vapor < 15 μm % on-sky efficiency[7] at precipitable water vapor < 15 μm	 ≥ 90% ≥ 90%

** stretch goals are in parentheses*

[2] The H-index, a cumulative impact metric, measures quantity with quality by comparing publications to citations.

[3] Oversubscription rate = observing time requested/observing time awarded.

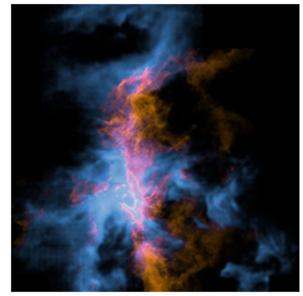
[4] High-Priority programs are ~75% of the total awarded programs and are labeled priority 1 (P1) and priority 2 (P2).

[5] Typically, there is a 2-year lag from data collection to publication.

[6] "Research hours" are defined as hours when the telescope door is open and observatory systems are ready to collect data.

[7] "On-sky efficiency" means the time that SOFIA is collecting data where atmospheric water-vapor content is low.

2. Updates Since the FMR Report



SOFIA measures the mechanical energy from stellar winds generated by infant stars

Since the year after the FMR panelists' report publication, mission status has been significantly influenced by the coronavirus pandemic 2019 (COVID-19), the High-Resolution Mid-infrarEd Spectrometer (HIRMES) science instrument cancellation, and NASA Science Mission Directorate (SMD) guidance.

2.1 COVID Impact

The COVID-19 pandemic suspended SOFIA operations, effective March 19, 2020.

Presented below are the high-level COVID-19 impacts on the SOFIA mission to date; this list does not account for potential future consequences.

- The loss of 45 total science opportunities from Palmdale, California, between March and August 2020.
- Additional loss of 28 science flights due to the cancellation of the Southern Hemisphere deployment, which also led to the loss of 2 community Legacy programs, German guaranteed-time programs, priority-1 and priority-2 U.S. guest-observer (GO) programs.
- SOFIA science metrics and goals described in this report are expected to be severely impacted by the COVID-19 shutdown of SOFIA operations.

The Project was allowed to prepare to return to flight under a "mission-critical" categorization by NASA HQ in June 2020. At the time of the preparation of this document, the Project is working towards getting the Observatory ready to return to operations after an extended period of downtime. The COVID-19 pandemic has significantly impacted the full implementation or progress of some of the initiatives and could delay their success or outcome.

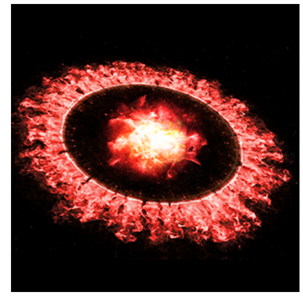
2.2 HIRMES Cancellation

The HIRMES science instrument (SI) development project was terminated by NASA SMD in April 2020 due to significant cost, technical, and schedule risks. NASA HQ has directed the Project to develop a roadmap to SOFIA's future science capabilities that will be submitted to NASA HQ at the end of fiscal-year 2020.

Mandatory telework orders have slowed the close-out of the HIRMES contract. The Project will continue to incur costs to support the HIRMES team until they are able to return to onsite work and resume the closeout activities.

2.3 SMD Guidance

Per HQ guidance, SOFIA restructured to achieve a sustainable operations model with a lower planning budget of $80M in fall 2019 compared to $85.2M. See Section 5.1 for more details. SOFIA is transitioning from a "program" to "project" under NASA SMD, Astrophysics Strategic Missions Program Office. The new Project Plan for SOFIA's extended mission is under development.



Dust survives obliteration in Supernova 1987A

3. Background

From February to May 2019, the NASA HQ-commissioned FMR panel evaluated the state of SOFIA and assessed the Observatory's plans for the next five years of operation. Table 3.1 presents the schedule of FMR and post-FMR activities conducted from November 2018 to March 2020.

Table 3.1 – FMR Schedule and Post-FMR Activities

Nov 19, 2018	Terms of Reference issued
Dec 19, 2018	Panel appointed
Feb - May 2019	Review conducted *Panel submits and receives responses to four separate RFI documents, panel interviews SOFIA staff at ARC site visit, 2 panelists fly on SOFIA*
Jun 7, 2019	Final FMR report shared with all stakeholders
Aug 12, 2019	NASA HQ public release of summary of FMR & SOMER reports *Astro 2020 Decadal Survey panel and APAC (Astrophysics Advisory Committee) receive publicly available FMR & SOMER recommendations/executive summaries from SMD*
Jan 24, 2020	Astro 2020 Decadal Survey panel receives responses to their RFI's about SOFIA's response to FMR & SOMER recommendations
Feb 28, 2020	APAC receives answers to RFI's about SOFIA's response to FMR & SOMER reports
Mar 6, 2020	APAC receives in-person presentation from SOFIA Project Scientist about responses to RFI's about FMR & SOMER

Section 3.3 describes the SOFIA Operations and Maintenance Efficiency Review (SOMER)
RFI's = Requests for Information
APAC = NASA Astrophysics Advisory Committee

3.1 FMR Report Recommendations

In June 2019, the panel published a report with ten recommendations to increase scientific productivity, scientific impact, and high-quality observing time and to improve the metrics for evaluating achievement in those areas. Their top-level recommendations called for "a paradigm shift in flight operations, substantial increase in flight hours at stratospheric altitudes, ambitious observing programs that have lasting archival legacy value, and aggressive pursuit of science synergies with ground-based observatories and other missions in NASA's astrophysics portfolio" (FMR Report Executive Summary, June 7, 2019).

All ten specific FMR recommendations have been evaluated by the SOFIA Project and are described in Section 6. The four top-level recommendations are presented in Section 5.

Table 3.2 – FMR Recommendations

TOP-LEVEL RECOMMENDATIONS

1	Devote a larger fraction of total observing time to Legacy programs
2	Aggressively pursue synergies with other missions/observatories
3	Maximize high-quality observing time
4	Increase research hours through flight operations initiatives

SOFIA reveals evidence that parts of the nebula formed separately to create the swan-like shape seen today

Table 3.2 – FMR Recommendations (continued)

	Ten Specific Recommendations
1	Nurture a science-driven culture within the mission
2	Embrace change in operational approaches
3	Emphasize completion of high-priority science programs
4	Emphasize the collection of high-quality data
5	Maximize observing time at stratospheric altitudes
6	Fly more Southern Hemisphere flights
7	Transfer data products into the archive quickly
8	Split aircraft operations from telescope/science operations
9	Invoke HIRMES cost and schedule control
10	Focus on current science operations rather than future science instrument development

3.2 Post-FMR: Project Studies and Strategic Planning

The responses to the individual recommendations in Section 6 are based on various studies and strategic planning exercises that were conducted after the release of the FMR report, the most significant of which are shown in Table 3.3.

Table 3.3 – Post-FMR: Project Studies and Strategic Planning*

1	SOFIA Stratospheric Water-Vapor Analysis – June 2020 (Sections 6.4 and 6.5) *Assessed quality of observing conditions over past 6 years; conducted 11/19 -5/20*
2	SOFIA Deployment Options 2020 Assessment – April 2020 (Section 6.6) *Identified issues and constraints for 2020 Southern Hemisphere deployment*
3	Transforming SOFIA Into a Science-Driven Mission: A Strategic Plan – Jan 2020 *Strategic Plan from USRA in response to the FMR*
4	5x8 Flights Test Report – Jan 2020 *USRA evaluated cadence of five 8-hour flights per week during September 2019*

**For detailed assessment, please refer to supplementary material.*

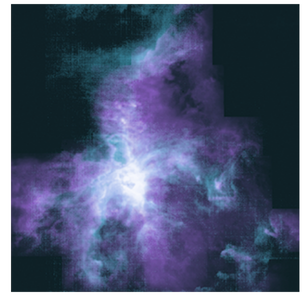
3.3 SOMER

The SOFIA Operations and Maintenance Efficiency Review (SOMER) was conducted prior to the FMR; and, NASA HQ briefed SOMER recommendations to the FMR panel. Two of the SOMER board members also served on the FMR board. In comparison, there was no science representation on the SOMER board, and there was no opportunity to provide science feedback to the SOMER panel for further adjustments. As a consequence, some suggestions for efficient aircraft operations were in conflict with optimal science productivity.

In those cases where the FMR recommendations for efficient aircraft operations were in conflict with optimal science productivity, SOFIA prioritized the science-enhancing initiatives. Most FMR panel deliberations and interactions focused on work conducted at the SOFIA Science Center and performed on behalf of NASA by the SMO. Only a limited portion of the FMR panel discussions were about efficient aircraft operations.

The Project's response to the SOMER report was submitted to NASA HQ on January 31, 2020.

4. SOFIA Observing Demand During the Prime Mission



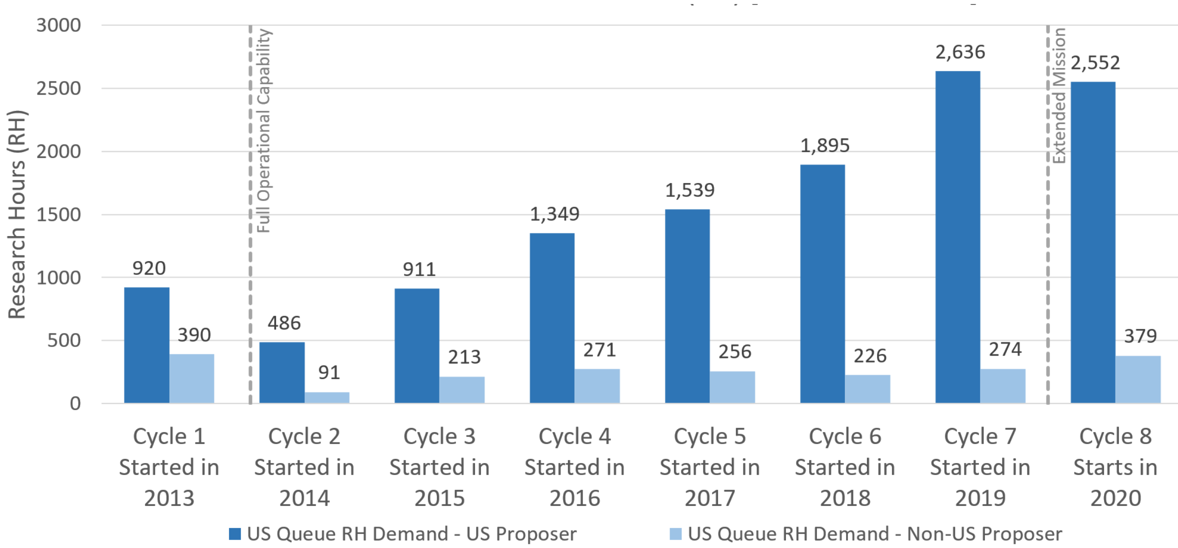
First signs of star birth caused by Orion's wind

This section presents the demand for research hours from the community and the observing opportunities offered by the Project from first observing cycle (in 2013), throughout the prime mission (2014-2019), and including planned observing opportunities in the extended mission (fall 2019).

4.1 SOFIA Research-Hour Demand

The SOFIA airborne observatory achieved full operational capability in February 2014, and demand for SOFIA observing time has consistently grown since (Figure 4.1). The U.S. queue for observing-time demand showed a significant increase (~37%) in the last two cycles, both from U.S. and non-U.S. institutions.

Figure 4.1 – Demand for SOFIA Research Hours (RH)

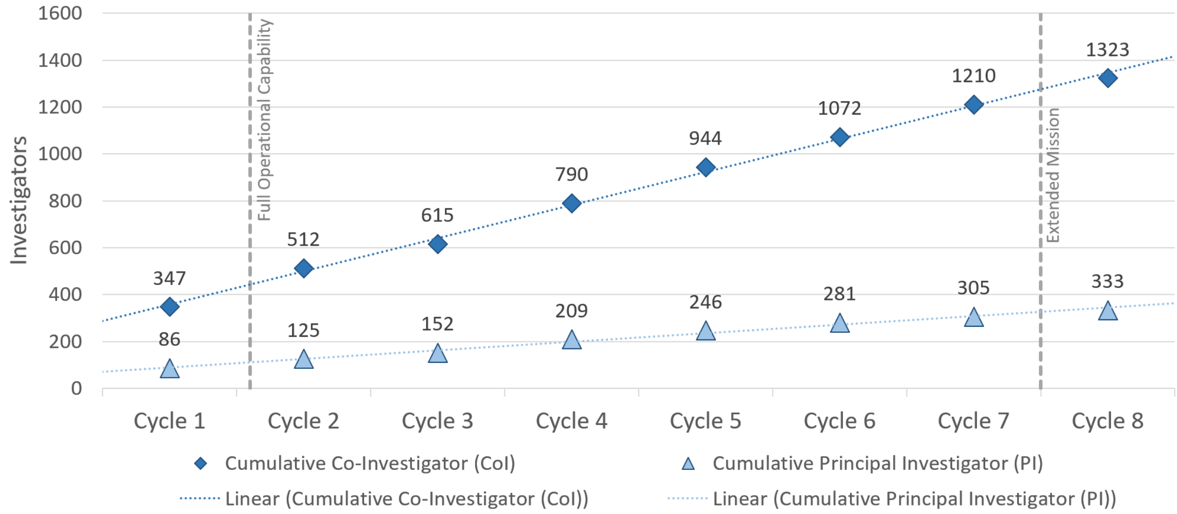


Note: Does not include German queue - Data provided by SMO

*RH include both GO and Legacy program hours

Observing time is in high demand with a >5 oversubscription rate, and more than 1200 unique co-investigators (Figure 4.2). SOFIA achieved the highest science program completion rate of ~65% in Cycle-6 and Cycle-7, flew the highest number of science flights (101), and completed the first Legacy program in Cycle-7 (post-FMR). To substantially increase science output and impact, SOFIA is now dedicating a larger fraction of time offered and awarded to Legacy programs (Section 5.3.1), aggressively pursuing synergies with NASA missions and observatories (Section 5.3.2), maximizing the collection of high-quality data by implementing/changing policies and procedures that impact data quality (Section 5.3.3), increasing research hours through flight operations initiatives (Section 5.3.5), and automating observatory operations to optimize efficiency and augment capability and flexibility (Section 6.2.1).

Figure 4.2 – Growth in SOFIA's User Community



4.2 Observing Opportunities Provided to the Community

Total observing opportunities and research hours provided to the science community by the Project have consistently increased since Cycle-1 in 2013 (Figure 4.3 and Figure 4.4). In the recently completed Cycle-7 in 2019, SOFIA flew 101 flights, the highest number of science flights to date. If not for COVID-19, SOFIA would have achieved 111 science flights in Cycle-7, using 81.4% dispatch rate (excluding weather losses).

Figure 4.3 – Research-Hour (RH) Plan vs. Actual Achieved

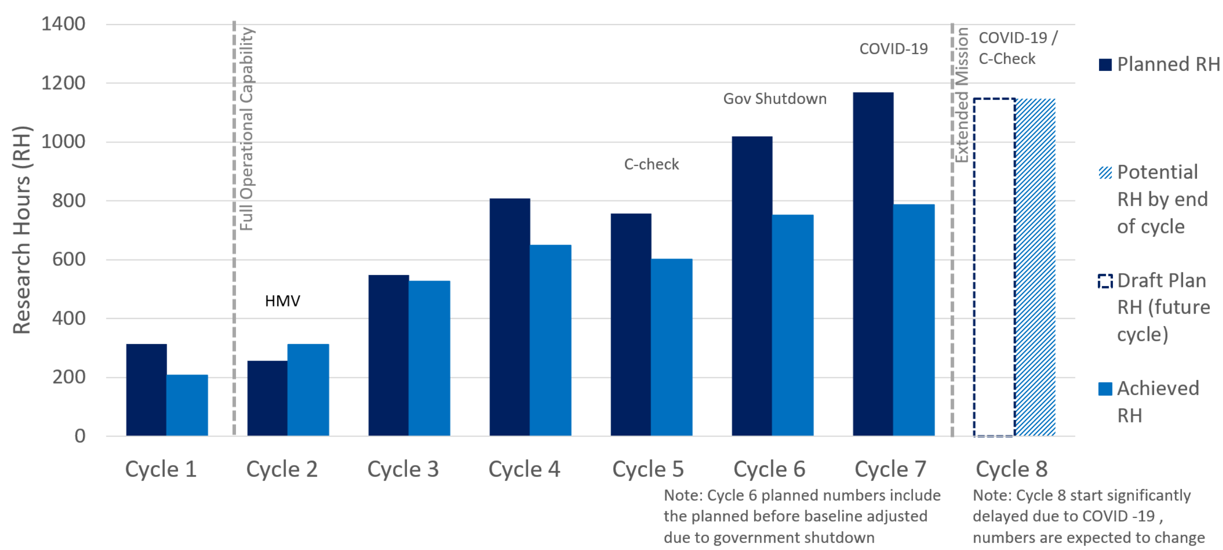


Figure 4.4 – Increasing Observing Opportunities for the Community

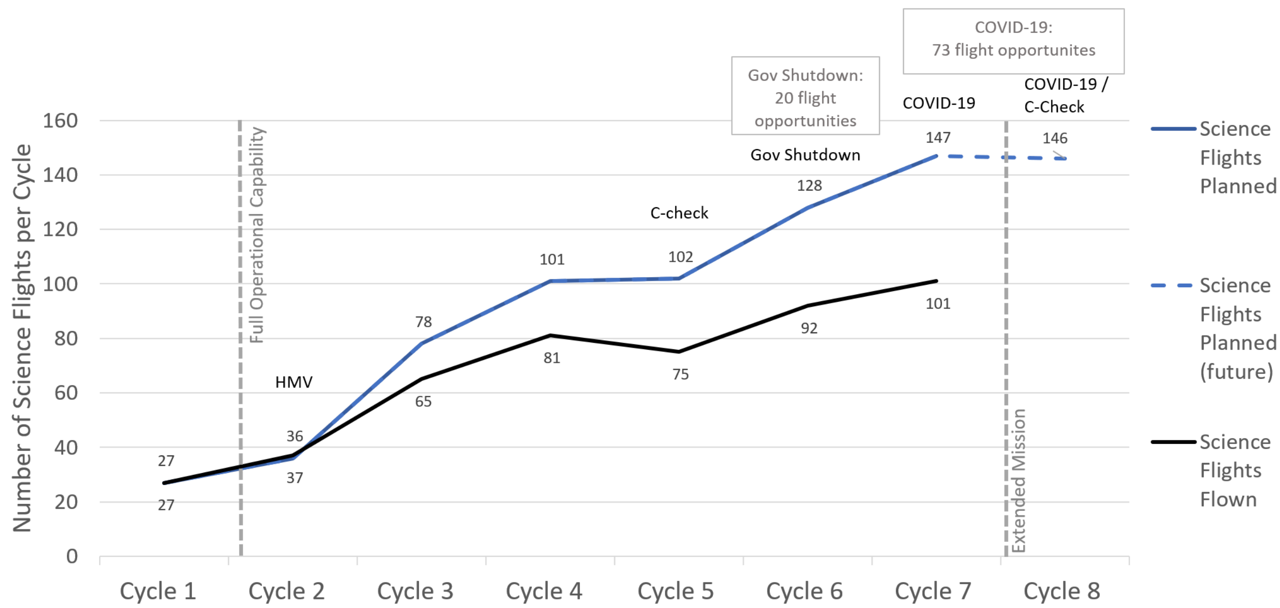
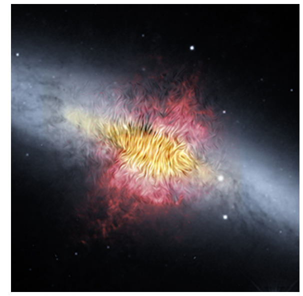


Figure 4.4 shows the number of flights that the Project originally planned (blue curve) in a given cycle and the number of flights achieved (black curve). The increase in divergence between the two curves starting Cycle-5 is caused primarily by two factors. First, starting in Cycle-6 (2018), the Project decided to add 25% contingency flights to increase the completion rate of high-priority programs, so more science flights were in the planning queue. For earlier cycles, three science flights-per-week were planned with a fourth contingency science flight to be executed only if one or more of the three planned flights were not flown. Beginning in Cycle-6, when the Project achieved a sustained 4-flight-per-week tempo, the contingency flights were redefined as actual planned flights with lower priority targets (filler programs). If one or more of the regular planned science flights were not flown, then the contingency flights would be used to observe lost priority-1 and priority-2 science programs. These changes have had a positive impact on the program completion rate (Appendix B, SOFIA Key Science Metrics, Table B.4). Second, events outside the Project's control—U.S. Government shutdowns, additional unplanned maintenance at the last C-check, and the COVID pandemic—reduced the total number of originally planned science flights in Cycles 5-7 (2017-2019) thus increased the gap between flights planned versus flights flown.

5. Response to the Top-Level FMR Recommendations



Weighing a galactic wind provides clues to the evolution of galaxies. The magnetic field detected by SOFIA, shown as streamlines, appears to follow the bipolar outflows (red) generated by the intense nuclear starburst.

This section presents the primary changes SOFIA is implementing (or considering) for the extended mission based on the FMR report. These changes are in direct response to the top-level recommendations by the FMR panel and include:

- Sustainable Operations
- Bold Initiatives
- Legacy Programs
- Synergies with Other Missions/Observatories
- Maximizing High-Quality Observing Time
- Increasing Research Hours Through Flight Operations Initiatives

5.1 Sustainable Operations Model for SOFIA

SOFIA entered its extended mission in fall 2019 (post-FMR), and the Project reorganized (per NASA HQ guidance) to achieve a sustainable operations model at an annual budget of $80M, below the historically appropriated $85.2M, and HQ put the $5.2M difference toward HIRMES development. Between 2017-2019 the Project had funds totaling up to $92M, which were above the appropriated $85.2M. The extra funding was realized primarily from fuel savings and a longer period of downtime in previous cycles. The Project used this additional funding to increase the staffing capacity (starting 2017) to accomplish sustained 4 flights/week operations compared to 3 flights/week and to fund HIRMES development.

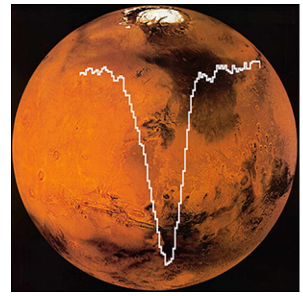
Sustainable operations were achieved in fall 2019 within $80M planning budget by:

- Roughly 10% reduction in non-science workforce while preserving the staffing capacity to operate four 10-hour flights per week (or five 8-hour flights per week in surge mode) plus weekend maintenance support
- Conducting annual Southern Hemisphere deployments with 24-flight minimum
- Maintaining the level of GO grant support
- Restructured to two divisions: (1) Science and (2) Operations (Section 6.8)
- Cutting observatory systems upgrades, sustainment and development engineering
    - Consolidated under operations
    - Reduced management overhead
    - No new spares; utilizing current inventory
    - Acceptance of operating with higher mission-assurance risk to allow SOFIA to fit within a smaller budget; risk related to the availability and reliability of SOFIA to collect science, as SOFIA system failures will take longer to troubleshoot and to fix with a smaller team.
    - SMO also underwent significant reorganization to invest more into science by cross training mission operations staff and automating routine tasks.

SOFIA Response to 5-Year Flagship Mission Review

To maintain the total amount of observing time operationally within the sustainable operations model, the Project has implemented the following initiatives.

- A single annual maintenance period
- Reducing the total number of instrument swaps within an observing cycle; to be implemented in Cycle-9 (2021) by going to 2-year observing cycle (i.e., proposals stay live over two observing cycles) for longer campaigns with a single instrument
- Reducing the time to swap instruments



SOFIA detects atomic oxygen in Martian atmosphere

5.2 Bold Initiatives in 2020-2021

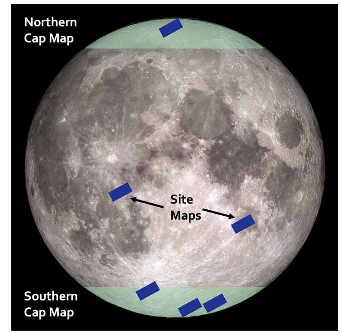
The Project is currently looking into further increasing the total number of flight/years by building a surge capacity to conduct longer Southern Hemisphere deployments and surge to 5 flights/week when scientifically merited. This will be a major change in SOFIA's operations model and will increase SOFIA's science return on investment. Funds above $80M (if appropriated) will be invested towards achieving such bold initiatives, all of which are listed in the Table 5.1.

Table 5.1– SOFIA Bold Initiatives in 2020-2021

1	Pursue large coordinated Legacy programs (coordinated with multiple observatories) using fewer, and the most productive, instruments. Approach significantly increases scientific impact while simplifying operations and data processing.
2	Grow the SOFIA community by building multi-disciplinary teams involved in large coordinated, multi-observatory programs.
3	Increase the total number of flights in the Southern Hemisphere to 50. This will be achieved with a combination of annual Southern Hemisphere deployment of 30 flights and two mini deployments of 10 flights each. This change will meet the community's demand by increasing the current Southern Hemisphere observing opportunities by ~50%.
4	Convert EXES[a] and GREAT[b] from PI[c]-operated to facility-operated science instruments (SI) to meet the community's demand and substantially increase the impact of these SIs.
5	Build the operational capacity to surge to five 10-hour flights per week.

a. EXES = Echelon-cross-Echelle Spectrograph
b. GREAT = German Receiver for Astronomy at Terahertz Frequencies
c. PI = Principal Investigator

5.3 Implementing Top-Level FMR Recommendations



Mapping water on the Moon, SOFIA pilot Legacy program; image shows locations of 6.1µm site maps on the lunar surface

"The mission would benefit greatly from…a substantial increase in flight hours at stratospheric altitudes, implementation of ambitious observing programs that have lasting archival legacy value, and aggressive pursuit of science synergies with ground-based observatories and other missions in NASA's astrophysics portfolio."

— SOFIA FMR Panelist Report, June 7, 2019, page 2

5.3.1 Legacy Programs

The Project is fully committed to implementing ambitious "Legacy" programs, both community- and observatory-led, that will have long-lasting legacy value and will enhance SOFIA archival research. Legacy programs will be a larger fraction (more than one-third) of total observing time in accordance with the FMR panel recommendation. SOFIA selected two Legacy programs in Cycle-7 (April 2019 – April 2020); one of which mapped the central regions of the Milky Way in July 2019. This Legacy program was completed in a single observing series, and data were released immediately.

For Cycle-8 (selected November 2019, starting May 2020), the SMO selected 1 large Legacy program (~80 hours), and 4 pilot Legacies. Combined the 5 Legacy programs contribute ~25% of the total awarded time in Cycle-8. The use of pilot programs is newly established to test the efficacy of scientifically promising Legacy programs, by first awarding a small amount of the total requested time. The GO teams can demonstrate the feasibility and potential impact of their programs; and, if successful, the pilot programs are promoted to full Legacy programs in the subsequent years, thereby considerably increasing the fraction of total time devoted to Legacy programs. The pilot Legacy programs allow quick data access and have a positive impact on the publication rate.

5.3.2 Synergies with Other Observatories and NASA Missions

Since publication of the FMR report, the Project has collaborated with:

- The Volatiles Investigating Polar Exploration Rover (VIPER) mission
  - Project reached out to the VIPER mission and has implemented a pilot Legacy program to map water on the Moon covering polar regions and other key sites.
  - Follow-up observations will provide more information about how easily water might be accessed by future missions, such as the Artemis lunar exploration program.
- Space Telescope Science Institute (STScI)
  - Using Director's Discretionary Time (DDT), SOFIA SMO and STScI are collaborating on a SOFIA-Hubble demonstration project on Young Stellar Object outflows.
  - SOFIA Cycle-9 observing time (20 hrs.) earmarked to support JWST Early Release Science.
- Green Bank Observatory
  - Joint call for proposals negotiated to use Green Bank Telescope and SOFIA for Cycle-9.
- Atacama Large Millimeter/submillimeter Array (ALMA)
  - Under consideration, earmarking SOFIA observing time for synergistic ALMA observations.


SOFIA mid-infrared Legacy program survey of central regions of the Milky Way reveals features never seen before

5.3.3 High-Value Observing Time for the Community

The FMR report encouraged the Project to substantially increase high-value observing time available to the community. "High-value" was defined as time spent at altitudes > 40,000 feet, considered to be the stratosphere. The panelist report states "…the single greatest impediment to increasing science productivity is the limited amount of high-quality observing time available…" (FMR Report, June 7, 2019, p. 2).

In response, the Project conducted a study to first evaluate SOFIA's operational success at providing high-value observing time to the community. The study, described in Section 6.5, concluded that historically SOFIA has been collecting data in both 'very good' (< 15 microns precipitable water) and 'excellent' (< 10 microns precipitable) conditions for more than 90% of the time. Furthermore, the study revealed that water-vapor column values are a better measure than stratospheric altitude for determining the quality of observing conditions for conducting infrared astronomy. Therefore, zenith precipitable water vapor will be used to track observing quality in the extended mission.

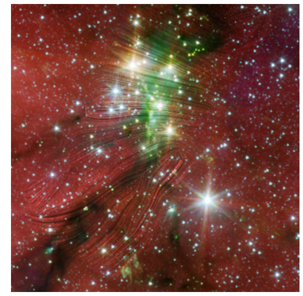
To increase high-value observing time, the Project will be spending more time in the Southern Hemisphere, particularly between May and October, when observing conditions from the Northern Hemisphere (Palmdale) are not ideal. This will be achieved by conducting "mini-deployments" (~8 flights) in addition to the annual (long) Southern Hemisphere deployment (June-August). The first mini-deployment is solicited in the Cycle-9 call for proposal. The Project is looking into building a capacity to surge to five 10-hour flights per week during the winter months from Palmdale, when observing conditions are excellent. Both of these initiatives will substantially increase the amount of high-value observing time for the science community.

5.3.4 SOFIA's Science Community

Even though not specifically called out in the FMR report, the mandate to significantly increase SOFIA's influence in the field of astrophysics and planetary sciences and to implement impactful Legacy programs requires a stronger, larger, multi-disciplinary SOFIA community base. In addition to efforts described in Sections 5.3.1 and 5.3.2, the Project will develop strategies to (1) expand and diversify SOFIA's scientific reach (e.g., Moon Legacy), (2) considerably grow HAWC+[8] user base to maximize the impact of this new capability, (3) increase the usage and visibility of SOFIA archival data, and build strategic partnerships or collaborations with other missions and observatories.

[8] HAWC+ = High-resolution Airborne Wideband Camera (SOFIA science instrument)

5.3.5 Flight Operations Initiatives

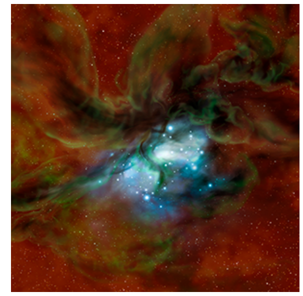


Composite image of the Serpens South Cluster. Magnetic fields observed by SOFIA are shown as streamlines over an image from the Spitzer Space Telescope.

The FMR panel supported the SOMER recommendation to pursue changes in flight operations with the goal of increasing the total number of annually planned flights, which directly impacts the total number of research hours offered to the science community. The Project is pursuing various operations initiatives to increase research hours and to improve data quality. Some examples are:

- Aircraft maintenance now will be performed annually, typically in late summer, compared to multiple maintenance periods as practiced in previous cycles. This initiative can potentially increase the total number of annually planned flights by 15 - 20% compared to the current baseline. Moreover, the gain in flight opportunities due to streamlining of aircraft maintenance that was typically scheduled in winter and spring also increases high-value observing opportunities, i.e., increases science flights scheduled at the time of the year when observing conditions are optimal (see Sections 6.4 and 6.5).
- Establishing alternate deployment sites to allow efficient execution of suitcase or mini ~10-flight deployments to the Southern Hemisphere. The Project has already identified alternate deployment sites and the site survey has been scheduled for fall 2020/winter 2021 to assess feasibility (see Section 6.6).
- Building a surge capacity to perform five 10-hour flights from Palmdale during the Northern Hemisphere winter to increase high-quality observing time. This initiative also will help reduce the total duration of the annual Southern Hemisphere deployment out of New Zealand, thus reducing stress on staff who are away from home for an extended period of time.

6. Response to the Ten Specific FMR Recommendations



SOFIA unravels the mysterious formation of star clusters

The FMR panelists gave concrete suggestions to improve SOFIA's science implementation, data quality, community engagement, and operational efficiencies. This section provides detailed responses to the ten FMR recommendations in the June 2019 FMR report. These responses incorporate the results from various studies and strategic planning activities undertaken by the Project over the past year to evaluate and address the FMR recommendations aimed at substantially increasing SOFIA's scientific productivity and impact before the next Senior Review, expected in 2022. Collectively, the changes and initiatives described here will improve SOFIA's scientific output and return on investment, while also being fully responsive to the science community. The success of these initiatives will be regularly assessed, adjusted, and improved to continue to increase and diversify SOFIA's scientific reach.

6.1 Science-Driven Culture

FMR Recommendation #1: Nurture a Science-Driven Culture within the Mission

To transform the culture within the SMO, organizational initiatives/changes have been implemented at three interrelated levels—science leadership, staff development, and community engagement. Additionally, all processes and procedures have been reviewed with the aim of increasing scientific output, increasing scientific impact, ensuring high-quality data collection, and maintaining efficient science and mission operations.

SMO leadership now emphasizes the importance of staff research. In fall of 2019, the SMO added two new senior-level positions: 1) Associate Director for Research and 2) Senior Science Advisor. These positions have been filled by veteran astronomers to increase efforts related to research and science community outreach and to assist with the hiring and mentoring of post-doctoral researchers and undergraduate interns. The Senior Science Advisor maintains the SOFIA science story productions that are incorporated into the SOFIA newsletters and may become public outreach stories. The SMO initiated monthly scientists' all-hands meetings to:

- Achieve higher engagement and better communication.
- Ensure the observatory's vision and goals (near- and long-term) are communicated to the research staff and community.
- Explore new ideas on topics related to scientific productivity and community building.

In spring 2020, the SMO hired a new Director who believes that staff research is integral to the success of the SOFIA mission. Scientifically productive staff provide technical solutions to improve data calibration, professional evaluation of data quality and process improvements that shorten the time between data collection and publication. As a new initiative, annual performance appraisal of research staff includes an evaluation of research. The Associate Director for Research has been assigned to provide an independent evaluation of science

SOFIA helps answer the question: Is the magnetic field dragging the material toward the super massive cluster of ~1,000 stars in the large Magellanic cloud?

research productivity by the research staff, most of whom work under the Associate Director for Science Operations. This new evaluation process will set and maintain an expectation of science research productivity of SMO scientists. The support by both Associate Directors for staff research includes a monitoring of staff research time to ensure that staff will get their time to pursue research.

SMO staff has grown to increase the overall research productivity of the organization and its connectivity to the astronomical community.

- Two new instrument scientists, one hired, and one being recruited so that individual staff scientists can increase their research time above their 20% research-time allocation.
- Assigned at least two, and typically three instrument scientists per instrument to reduce workload and allow instrument scientists to use their research time more effectively.
- Three new postdocs focused exclusively on SOFIA were added to staff making a total of six postdocs. Under consideration, to hire more postdocs.
- Mentoring of staff and postdocs will support their research, foster collaborations, enhance science productivity and impact.
- Under consideration, graduate students and interns will be hired to collaborate on staff's research and to participate in outreach efforts to increase productivity, diversity and community engagement. Project will provide support for hiring NASA interns for this effort.

SMO's new processes and policies to improve science community development and culture:

- Proposal selection and evaluation processes now focus on choosing and implementing projects that are most likely to obtain the highest data quality and to be completed in at most two years
- Larger fraction of time (25%) offered and awarded to Legacy programs in Cycle-8
- More aggressive and strategic use of DDT (e.g. in Cycle-7, Betelgeuse and in Cycle-8 mapping water on the Moon observing campaigns)
- Collaborating with NASA missions and ground-based observatories
- Implemented an additional, more thorough technical review of the proposals to ensure that all scheduled observations are not only feasible but are appropriately designed to produce publishable results
- Publication record of guest observers will be weighted more heavily during selection.
- SMO Director can approve observations deemed high-risk/ high-reward and can even increase the requested observing time to maximize the probability of mission success
- Changed the policy for priority-2 observing programs
  - Priority-2 projects, once started, will be completed (effective fall 2019)
  - Will boost program completion rate and publications
- Observing programs to stay alive over two cycles, beginning in 2021 with cycle-9
  - Longer campaigns with a single SI
  - Faster publication if projects can be finished in a single observing series
  - Greater scheduling flexibility
  - Higher program completion rate
  - Fewer instrument swaps will provide more observing opportunities
  - Higher-quality data

SOFIA Response to 5-Year Flagship Mission Review

- Change in data archiving procedure ensures faster data delivery (Section 6.7)
- Publication record of SOFIA's GOs will be an important factor in future selection process (starting Cycle-9)
- Reduced the exclusive use period for GO proposals to 6 months. Further reduction to 3 months is under consideration. Making data public faster could lead to faster publications. But, more importantly, this policy can potentially enhance SOFIA's archival research. Data from Legacy programs become public immediately once archived.

SOFIA reveals the complex nature of a "simple" star formation tracer

6.2 Change in Operational Approaches

FMR Recommendation #2:

Embrace Change in Operational Approaches/Simplify Operations

NASA and the SMO have implemented operational changes and/or provided clarification in areas referenced in the FMR panelists' recommendation #2.

6.2.1 SMO Efficiencies: Automation and Cross-Training

Cross-training allows schedule optimization and increased flexibility by limiting lost flights, minimizing staffing levels, and providing stress relief. Automation relieves staff of tedious busy-work, saves time, and prevents human errors. The SMO has automated tasks across all observatory functions—flight planning, in-flight operations, science instrument operations, and ground support (see Appendix C for complete list).

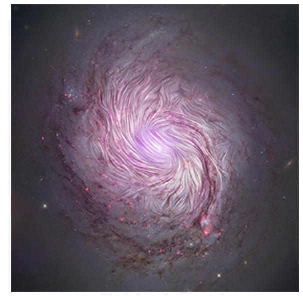
Select examples are:

- Automated creation of data package that is transferred onto the aircraft prior to every flight in order for the on-board Flight Executor to run.
- Automated submission of a flight plan. The tool archives the weather used to generate the flight plan, generates the flight-plan package and uploads or partially uploads to several different places on the SOFIA network.
- Auto-generation all the flight series/flight plan content displayed on SOFIA public website to reduce time needed to update a typical flight series from several hours to ~5 minutes.
- Auto-production of the web-page display of various metrics (e.g., the number of proposals and hours of GO programs executed per science flight series).
- Automated the updates to flight-plan for weather forecast at 36 and 12 hours prior to flight. The tool retrieves the most recent weather forecast data and modifies the original flight plan to satisfy constraints (e.g., instrument-specific telescope elevation range, avoidance of restricted flight areas, arrival leg duration, and total flight duration).

MUSPOT (Mission Unified SOFIA Proposal and Observation Tool) was the first step toward reducing the size of the mission operations flight crew (from 5 to 4). This newly implemented software tool automates and standardizes the observation review and preparation by the telescope operators. MUSPOT has provided additional relief of repetitive tasks by the telescope and instrument operators by reducing their pre-flight preparation time from hours to minutes and by increasing in-flight observation awareness. MUSPOT synergizes unique observatory software (proposal and observing planning tools, USPOT/DCS) with observatory industry standard tools (SkyServer/Aladin).

SOFIA Response to 5-Year Flagship Mission Review

The first step toward reducing the size of the mission operations flight crew was interrupted due the COVID-19 pandemic. Cross-training of Telescope Operators (TO) and Science Instrument Operators (SIO), collectively Mission Operations Specialists, to work either position was targeted for completion prior to this year's New Zealand deployment. Remote training has continued, however, in-flight hands-on training between the two functional positions (TO and SIO) is pending and must resume prior to any second-chair mission director (MD2) training. Once science flights resume on a regular basis and the final step of cross-training the Mission Operations Specialists is complete, then MD2 skills training will begin.



SOFIA shows magnetic field alignment over an entire galaxy.

TO/SIO Cross-Trained as MD2 is the second step toward reducing the size of the mission operations flight crew (from 4 to 3). This initiative will proceed hand-in-hand with automation of many of the mission director's tasks. Not only will these automation/cross-training efforts further reduce the stress of mission directors and increase the robustness of mission operations flight crew scheduling, cross-training also provides a knowledgeable pool of potential new first-chair mission directors (MD1), which will shorten the extensive training and certification times.

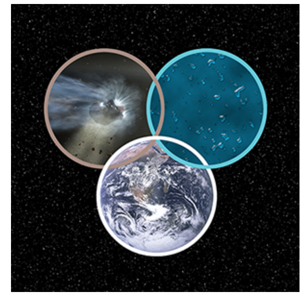
6.2.2 Communication Channels Upgrade on the Aircraft

The Project researched options to install an upgraded high-bandwidth internet on the aircraft because current communication channels are too slow to perform some activities that could enhance observatory efficiency. Below are the preliminary findings of a cost-benefit analysis of either upgrading to another satellite communications system or using a cellphone tower-based internet service provider (ISP). See **Appendix A** for details on requirements for remote observing. The Project intends to conduct a detailed cost-benefit analysis and a market survey to provide recommendations by December 2021.

- An upgraded satellite communications system requires significant investment and downtime.
- A cellphone communications system is available within budget and allows SOFIA to achieve more robust access to the plane from the ground, perform stronger real-time community engagement, share data with GOs, and send real-time and post-observation information to personnel on the ground.
- A cellphone communications system will not provide the internet bandwidth to enable remote observing capabilities or to impact staffing levels or workload. Efficiencies that reduce on-aircraft staffing requirements and workload have been achieved through automation and cross-training (**Section 6.2.1**).

The SOFIA aircraft has a single satellite phone in place with a maximum connection speed of 432 kilobits per second (kbps). Light internet browsing and emailing can be done at 432 kbps, but more bandwidth-intensive functions such as video conferencing or driving high-rate data displays require higher bandwidth (500 to 1,500 kbps). The current satellite-based system has high latency rates that make remote observing inefficient. Connection speed is driven by number of satellites available, thus science flights approaching the polar regions of both hemispheres experience lower connection speed due to fewer available satellites. The satellite-based system is billed according to the amount of data being transferred through the system; therefore, bandwidth-intensive functions will increase the cost.

SOFIA Response to 5-Year Flagship Mission Review


SOFIA observations fuel debate about the origin of the Earth's oceans

Upgrading to higher-bandwidth satellite communications requires modification of the aircraft antenna system, which involves significant engineering support and design reviews. This level of effort is not feasible due to recent cuts to the sustaining engineering workforce to fit within a smaller budget; and, observatory configuration changes are typically limited to mission-critical upgrades to maintain current operations. The one-time cost is expected to be $2,000,000, with monthly costs of $6000 that could be higher depending on the usage. However, this system upgrade could increase transmission speeds by 6.5 times the current data rates and would cover all Northern Hemisphere flights. Additional, design assessments will be required to determine exact transmission speeds.

SOFIA's upgrade to tower-based cellphone communications over the Continental U.S. and parts of Canada also requires time and effort to integrate and install the necessary infrastructure; but, the advantages of using this cellphone system are increased download speed by almost 3 times (up to 1.2 mbps) compared to the current satellite-based system and significantly reduced usage cost. However, upload speed remains relatively the same as the satellite-based system. Cellphone data plans are purchased via monthly subscription for unlimited data usage; and, the cellphone system increases performance of bandwidth-intensive functions. The one-time cost for up to 1.2 mbps at commercial-flight-cruise altitude is estimated at $200,000, and monthly costs are relatively lower compared to the satellite-based upgrade. The data rate degrades with altitude; and, since SOFIA often flies higher than commercial airlines, the data rate may be impacted. This system will not function at all over the Pacific Ocean, which covers a significant portion (40-50%) of SOFIA's flight paths.

6.2.3 Evaluating Productivity of Science Instruments and Observing Modes

The streamlining of science instrument (SI) and observing modes will be addressed as part of the instrument roadmap development exercise that will conclude on September 30, 2020. The Project will define a process for tracking SI productivity and cost to maintain and establish an evaluation program to determine when an instrument or observing mode should be retired. In the Cycle-9 call, the instruments for Southern Hemisphere deployment were specified (for the first time) as GREAT, HAWC+ (for the long deployments) and FIFI-LS[9] (for the mini-deployment). This approach will both simplify the choices for the observer and capitalize on the most productive instruments for SOFIA.

6.2.4 Reduction in the Number of Instrument Changes

The SMO will increase the available science flight opportunities by reducing the total number of instrument swaps within an observing cycle. This practice will be implemented in Cycle-9 (beginning 2021) that will schedule observations over two observing cycles (~2 years) to allow for longer campaigns with single instrument. Additionally, planning is underway to reduce the instrument-swap time from 3 days to 2 days for all facility-class SIs.

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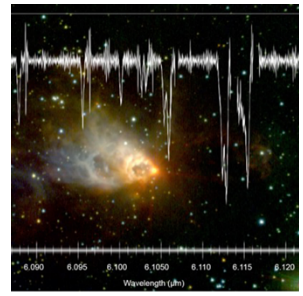
[9] FIFI-LS = Field-Imaging Far-Infrared Line Spectrometer



SOFIA pinpoints water vapor in a young star

6.2.5 Software Upgrades

The Project is streamlining and clarifying the software upgrade process as described below.

For science mission-critical software development tasks, the deployment schedule will be driven by the required-by date for supporting the science observations. This may require software deployment inside the one-year deployment schedule that is driven by once-a-year maintenance downtime. New observation modes to support new SIs will be driven by the commissioning schedule and will not be managed under the once-a-year software deployment schedule until the new SI has been accepted as a facility-class SI.

There is no software development freeze. Development tasks required to sustain and maintain the mission systems and facility-class SIs will continue on a coordinated schedule. Non-mission-critical flight systems and SI software development will be deploying software updates once a year, so all developers can coordinate changes and fixes to ensure interfaces are preserved. In addition, the Project reduces the number of reviews and integration testing required to deploy software that is not time-critical, which reduces the number of integration downtimes to once a year on the aircraft. By reducing the number of integration downtimes in the extended mission, more science flights can be conducted. Ground systems software (DCS and SI Data Pipeline) will continue to release and deploy software as required and will not be managed to the once-a-year deployment schedule.

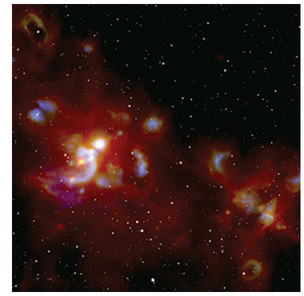
6.3 High-Priority Science

FMR Recommendation #3: Emphasize Completion of High-Priority Science Programs

SOFIA raised the completion rate of high-priority science programs by changing the way science flights are scheduled and planned. The observatory achieved highest program completion rates of 65% and 68% in Cycle-6 and Cycle-7 respectively, for high-priority science programs completed in the same cycle. This higher program completion rate was a direct result of a new priority scheme put in place starting Cycle-6. This scheme divides selected proposals in primarily three categories: priority 1 (P1), priority 2 (P2) and priority 3 (P3 or "filler"). P1 and P2 combined make up roughly 75% of the selected proposals.

In early cycles, only three science flights/week were planned with a fourth contingency science flight to be executed only if one or more of the three planned flights were not flown. Beginning in Cycle-6, the "contingency" flights were redefined as actual "planned" flights with either lower priority targets (filler programs) or lost P1/P2 targets. With the new scheduling methodology, four science flights are planned and scheduled per week with 25% of flights planned as lower P3 flights or lost P1/P2 flights. Thus, more targets are needed for planning purposes. The net result of this change has been 1) a higher completion rate of P1 and P2 programs, 2) increased observing opportunities, and 3) more P3 programs have been started, giving Principal Investigators (PIs) some data that could be used to strengthen subsequent proposals.

To further improve the science program completion rate, the SMO is putting much greater emphasis on selecting proposals that are more likely to be completed. The SMO also will



SOFIA detects cosmic fireworks of massive star formation

opt to preemptively cancel programs that, based on the data collected so far, and in spite of a favorable initial outlook, have no prospect of meeting their scientific goals. After the proposal time allocation committee (TAC) scientific grades are available, the SMO has implemented an additional, more thorough technical review of the proposals to ensure that all scheduled observations are not only feasible but also appropriately designed to produce publishable results. The SMO Director will specifically evaluate and approve observations deemed high-risk/high-reward and can even increase the requested observing time to maximize the probability of mission success. These changes have been implemented in Cycle-8 and are expected to improve the program completion rate to ~80%.

Addtionally, starting Cycle-9, all accepted SOFIA observing proposals will stay alive for two cycles (Cycle-9 & Cycle-10) while continuing to solicit an annual call for proposals for each cycle. This will allow observations to be scheduled over two cycles and will provide the flexibility to conduct longer observing campaigns with a single instrument, which in turn will increase the feasibility of completing higher-priority programs within the same observing series.

6.4 High-Quality Data

FMR Recommendation #4: Emphasize the Collection of High-Quality Data

The Project is implementing several initiatives to ensure highest quality data are provided to the science community. Data with high signal-to-noise can increase discovery space and increase scientific productivity by enhancing archival research. As FMR pointed out, poor quality data can drain resources and make post-processing more complex, time consuming and cause delay in data delivery.

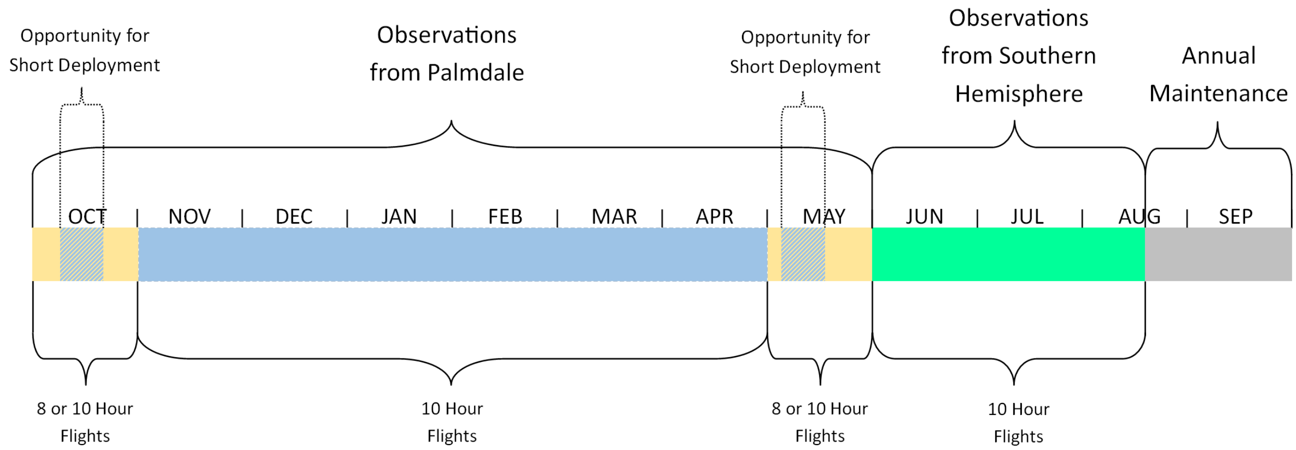
Data quality on SOFIA depends on various factors:

1. Maximizing observing time in low water-vapor conditions
2. Selection of observing programs
3. Planning and scheduling of observing programs
4. Execution of observing programs

Maximizing High-quality Observing Time in Low Water-Vapor Conditions

To measure and track observing conditions on SOFIA, the Project led a detailed study using the NASA GEOS weather database to determine whether operationally SOFIA can provide high-quality observing conditions for conducting infrared astronomy. This study showed that NASA GEOS is an excellent database to reliably measure zenith precipitable water vapor (PWV) in micrometers along SOFIA's flight path. The water-vapor data for all SOFIA flights since 2014 show that operationally SOFIA has provided "very good" observing conditions (< 15μm) for more than 90% of the observed research hours. The Project will continue to optimize observing schedule based on this study to increase the percentage of "excellent" observing conditions (< 10μm), which currently comprise 76% of the observed research hours since 2014 for Northern Hemisphere flights. More details are provided in Section 6.5 and the complete study is provided as supplementary material. Based on study findings, Figure 6.1 presents the ideal SOFIA observing schedule.

Figure 6.1 – Ideal Observing Schedule: Maximizing Science Return and Data Quality



Selection of Observing Programs

Selection of science programs based on their observing conditions needs is under consideration. This is standard practice by ground-based observatories. For example, it is well known to ALMA users that if their proposals require observing at high frequencies then their chances of getting data will be only 5-10%, because very dry observing conditions are required to accomplish observations in those high-frequency bands. Similarly, for SOFIA, selection of observations that require extremely dry conditions must be considered carefully, especially if they require long integration time to achieve high signal-to-noise, which could put them at high risk of incompletion and poor data quality. Awareness about water-vapor variations with altitude and seasons to the SOFIA users can be beneficial, so that they can consider this as a factor while planning their observing proposals.

Planning and Scheduling of Observing Programs

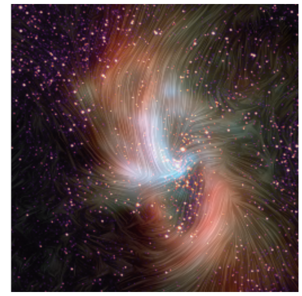
To ensure high data-quality, SMO is considering a modification to proposal scheduling software to allocate telescope time based on the deployment site, the time of year, and the latitude. This optimization process would allow SOFIA to allocate only the time necessary to achieve the required signal-to-noise for each project, rather than a fixed-time allocation based on standard conditions. The SMO also is evaluating using monthly average observing conditions based on the water-vapor study as one of the parameters in their flight planning and scheduling tools.

Execution of Observing Programs

With the automation of flight planning tools, the response time to changes in flight planning before the mission has greatly reduced. Flight plans on SOFIA are adjusted based on 36-hour and 12-hour weather update before the mission. So far these adjustments are made to correct for wind directions. Incorporating changes in water vapor due to bad weather could further avoid collection of poor-quality data. The water-vapor study from NASA GEOS has found that 36-hour weather forecast is very accurate and can be reliably used to adjust flight plans. The Project will provide all the necessary tools developed as a result of this study to the SMO to be able to generate weather maps needed 36 hours before the mission to adjust flight plans to ensure optimal observing conditions for high-priority science programs.

SOFIA Response to 5-Year Flagship Mission Review

The SMO is developing a metric for data-quality, which may be different for each instrument. Such a metric will allow the Project to assess where further improvements or investments are needed.



SOFIA shows magnetic fields may be keeping Milky Way's black hole quiet

6.5 High-Value Observing Time

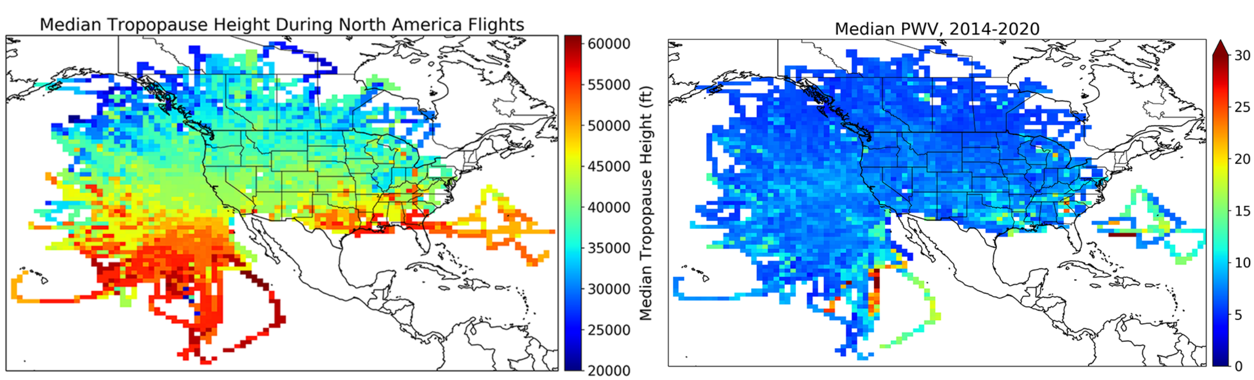
FMR Recommendation #5:
Maximize Observing Time at Stratospheric Altitudes

The Project strongly embraces the FMR and SOMER top-level recommendations to prioritize and maximize high-value, high-quality observing time on SOFIA. The FMR also endorsed the SOMER recommendation #4 to reduce the flight profiles to shorter 8-hour flights to increase the percentage of aircraft time at high-value altitudes. The FMR and SOMER panels assumed that stratospheric altitudes are typically > 40,000 feet.

In response, the SOFIA Project led a stratospheric hours and water-vapor study using satellite data from NASA GEOS to determine a reliable and consistent method of measuring and tracking high-value observing time on SOFIA. The major findings and conclusions of the study revealed that operationally SOFIA is providing optimal observing conditions to the science community for conducting high-quality infrared astronomical observations. The study showed that the zenith water vapor is a more appropriate metric for measuring and tracking high-value observing time on SOFIA compared to the time spent in stratospheric altitudes. The Project briefed the results of this study to NASA HQ on June 26, 2020, and recommended slightly revised metrics based on zenith water vapor (Table 1.4). The full briefing is provided in the "SOFIA Stratospheric Water-Vapor Analysis Study," June 2020.

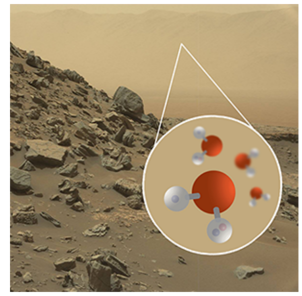
Figure 6.2 compares stratospheric heights with zenith water vapor based on SOFIA's actual flight paths for all North American flights from 2014 to 2020. Zenith water vapor is low even when SOFIA is not in the stratosphere. Regardless of flight altitude, SOFIA historical data shows that 93% of the time the Observatory is collecting data in "very good" water-vapor conditions (<15 microns).

Figure 6.2 - Stratospheric Heights vs. Zenith Water Vapor: All North American SOFIA Flights



- *PWV = Precipitable Water Vapor*
- *Tropopause = boundary between troposphere and stratosphere*
- *Maps are based on SOFIA's actual flight paths for the research hours portion of the flights; maps do not include data between June and August when SOFIA is observing in the Southern Hemisphere*

Major Findings:



SOFIA's observations bring scientists closer to understanding just how much liquid water Mars once had

Zenith precipitable water vapor (PWV) is the right metric for measuring and tracking observing conditions

- Observing conditions are found to be "very good" (i.e., low water vapor < 15 precipitable microns), and "excellent" (water vapor < 10 microns), even when SOFIA is technically not in the stratosphere
- For all North American SOFIA flights since 2014, SOFIA spent 76% of the research hours in "excellent" conditions (< 10 microns) and 93% in "very good" conditions (< 15 microns)
- For all New Zealand flights since 2014, SOFIA spent 91% of the time observing in "excellent" conditions (< 10 microns) and 99% in "very good" conditions (< 15 microns)

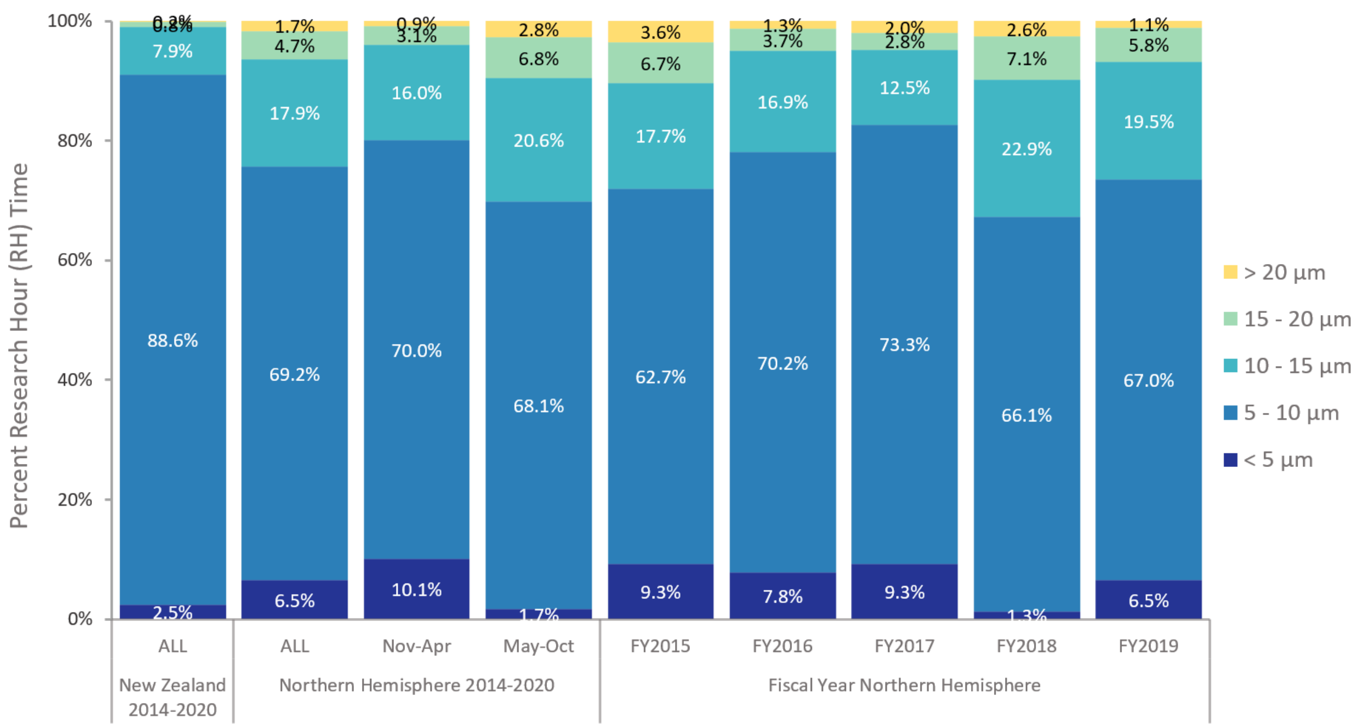
Figure 6.3 shows the zenith precipitable water vapor from satellites at all SOFIA flight levels based on data available from the NASA GEOS weather database.

Observing conditions are categorized as:

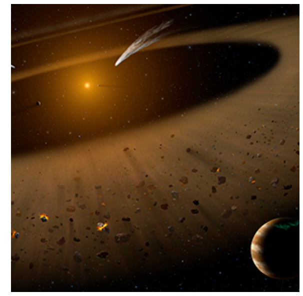
- Excellent: < 10 µm
- Very good: 10 - 15 µm
- Acceptable*: 15 - 20 µm

highly dependent on wavelength, SI, and specific science observation

Figure 6.3 – Zenith PWV from Satellites (All Flight Levels)



- *May-Oct data are skewed towards lower PWV, because SOFIA typically does not conduct operations between June – August from Palmdale.*
- *During June, July & August, "very good" water-vapor conditions occur less frequently, and shorter flights are recommended.*
- *Research hours are defined as hours when the telescope door is open and observatory systems are operational and ready to collect data.*


SOFIA confirms nearby planetary system is similar to our own

Stratospheric altitude (SA) is not well-correlated with zenith PWV

- SA varies significantly during the flight
- SA depends strongly on weather and location; SOFIA may not be in the stratosphere even at altitudes > 40,000 feet due to these factors
- Stratosphere in New Zealand can be as low as 34,000 feet
- The adoption of this metric will overly constrain SOFIA operations

Water-vapor data clearly shows seasonal variations

- Observing conditions are significantly better during North American late fall to early spring compared to between late spring to early fall
- During June-August—when observing conditions are poor in North America—SOFIA goes to the Southern Hemisphere to fly and does not conduct operations from Palmdale

Transitional altitude is the altitude where the PWV drops to a "very good" level

The water-vapor study finds that the transitional altitude begins at 38,000 feet for North American operations, where the chances of "excellent" observing conditions increase by a factor ~2 between 38K and 39K (using data from all North American SOFIA flights since 2014). This factor is even higher >3 between May-October.

Weather forecast

The study concluded that the 36-hour water-vapor/weather forecast from NASA GEOS is very accurate and can be used to update the science observing legs in the flight plans 36 hours before the mission to ensure optimal data quality.

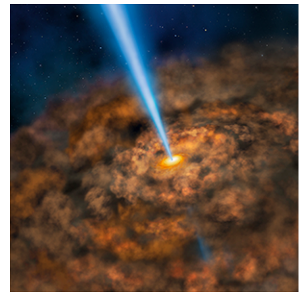
Next steps to improve "excellent" observing conditions from the Northern Hemisphere and how best to use the water-vapor study findings to improve SOFIA data quality:

Project will:

- Use NASA GEOS 36-hour water-vapor forecast to fine tune or change flight/observing plans to preserve the quality of observations.
- Monitor the following metrics (revised FMR panelists' recommendation):
  - Research hours at zenith precipitable water vapor (PWV) < 15 microns
  - On-sky efficiency at zenith precipitable water vapor (PWV) < 15 microns
- Increase observing opportunities in (Palmdale) Northern winter by scheduling a single maintenance period in late summer/early fall.
- Expand observing time in Southern Hemisphere during the summer. The Project has planned significantly more Southern opportunities beginning in Cycle-9.

SMO will (under consideration):

- Customize flight lengths (between 8 and 10 hours) especially during summer, early fall and late spring to ensure highest priority science programs have optimal observing conditions.
- Similar to ground-based observatories, use observing conditions as a key parameter (necessary for optimal data quality) when scheduling/planning observations.
- Evaluate how observing conditions can be incorporated into the time estimator for the SOFIA users and flag type of observations that would require very low water vapor (< 5 microns) for a significant duration to achieve sufficiently high data-quality.
- Develop a metric for assessing data quality for each SOFIA instrument.



SOFIA finds cool dust around energetic active black holes

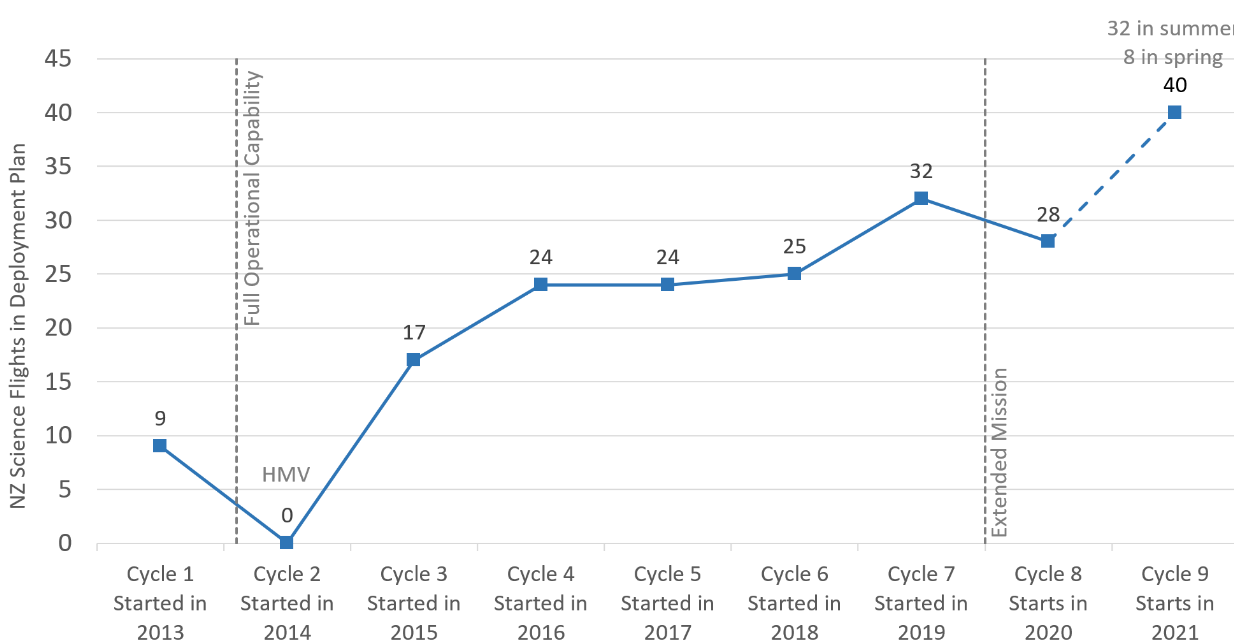
6.6 Fly More Southern Hemisphere Flights

FMR Recommendation #6: Fly More Southern Hemisphere Flights

The SOFIA Project is working towards increasing Southern Hemisphere observing time to take advantage of excellent observing conditions during the Austral Winter when observing conditions in Palmdale are not ideal. Additionally, Southern Hemisphere targets, such as the inner galaxy and Magellanic Clouds, have high demand from the science community. Various operations strategies are under consideration or planned to achieve more Southern Hemisphere flights, including implementation of different flight cadences, rain-mitigation plans, and a cost-benefit analysis to investigate alternative operational bases.

SOFIA's primary operations base is in Palmdale, California. Operations typically move to Christchurch, New Zealand, in the austral winter (Northern summer) when the Project conducts its annual long deployment. The strategic deployment to the Southern Hemisphere positions SOFIA to maximize science productivity, impact and data quality. During the planning and scheduling process for each observing cycle, the Project has managed to consistently increase observing opportunities in the Southern Hemisphere since achieving full operational capability in 2014 (Figure 6.4), with the highest number of planned flights in Cycle-7. Starting in Cycle-9[10] in 2021, the Project offers an additional mini-deployment to the Southern Hemisphere, which will increase the total number of panned flights to 40. A mini-deployment at a different time of the year will allow the Project also to schedule a new instrument in the Southern Hemisphere.

Figure 6.4 – New Zealand Science Flights in Deployment Plan



[10] The Project canceled the Cycle-8 deployment to New Zealand due to the COVID-19 pandemic. Consequently, in July 2020, the Project has extended the length of Cycle-9 to 15 months, and that includes two long deployments and one mini deployment to New Zealand totaling 72 flights (576 research hours) in the Southern Hemisphere.

SOFIA Response to 5-Year Flagship Mission Review

SOFIA data reveals magnetic fields in the Orion nebula

SOFIA has healthy proposal pressure for both Northern and Southern Hemisphere skies and receives high-quality, high-impact proposals for both hemispheres. Operationally, the Project experiences excellent observing conditions (>90% of the time) in both hemispheres, but the optimal observing conditions are at different times of the year. For Palmdale, ideal observing conditions are from November to April, and reasonably good conditions are found in October and May. For New Zealand, ideal observing is from May to September. During this optimal observing time in the Southern Hemisphere, for flights based out of Christchurch, SOFIA has implemented a new strategy to partially mitigate persistent winter weather issues in Christchurch, by providing alternate flight plans to enable divert landing sites in Australia, allowing flights to take off when all divert landing sites in New Zealand are forecasting rain at landing.
Increasing observing opportunities in the Southern Hemisphere requires a new operations strategy to package more science flights over a total shorter duration. Because of increased stress on staff who spend the entire summer months away from home, the Project is looking at ways to reduce the overall time spent in New Zealand without compromising the total number of observing opportunities. Thus, in Cycle-8 the Project planned for a new compressed observing tempo of 4 flights, followed by 2 days off, compared to the typical observing cadence of 4 flights, followed by 3 days off.

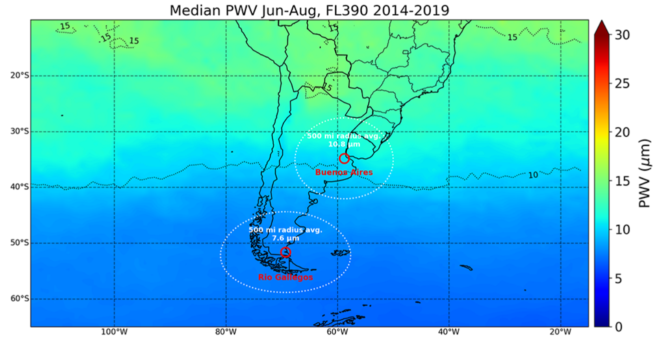
Exploring Alternate Deployment Sites

The SOFIA Project conducted an evaluation of basing site alternatives in the Southern Hemisphere, plus Alaska and Hawaii. Twenty-five sites in six countries/territories were assessed for suitability from a scientific and operational perspective. To optimize scientific productivity, the Project identified suitable sites in the range of 35 to 50 degrees south latitude. Operational factors evaluated included aircraft range, availability of divert sites, ground support availability, airfield/airport characteristics, weather, geography, logistics, and accommodations.

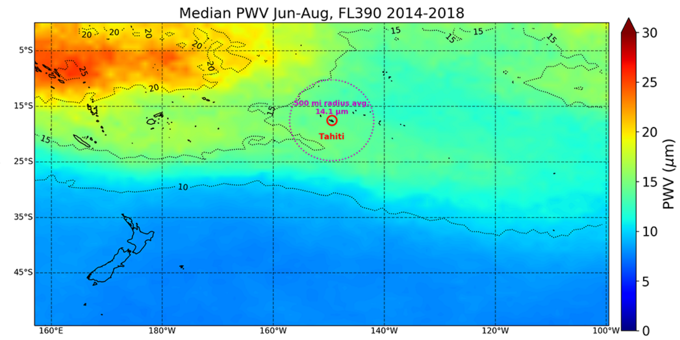
Five to seven suitable basing alternatives were identified, some within non-stop range of Palmdale. Among the top candidates were Rio Gallegos and Buenos Aires, Argentina, and Tahiti, French Polynesia. Site surveys and a cost analysis will be required to confirm basing site feasibility. The Project also assessed potential issues and constraints for simply returning to New Zealand on multiple occasions during the year. Alternate deployment sites will give SOFIA the flexibility to conduct mini deployments when science requires it, as geo-political situation changes (e.g., COVID-19 pandemic), and when Palmdale nights are short, and atmospheric water vapor is high.

Water-vapor analysis using NASA GEOS weather information will assist in flight planning, and the Project will produce observing-quality maps for any deployment site (see example PWV maps for Argentina and Tahiti, Figure 6.5).

Figure 6.5 – Sample Observing-Quality Maps for Two Potential Deployment Sites



Argentina



Tahiti

6.7 Quickly Transfer Data to the Archive

FMR Recommendation #7: Transfer Data Products into the Archive Quickly

The Project is committed to quickly providing data into the hands of observers. The goal is to have >70% flux-calibrated level-3 data archived within 15 working days. The data sent to the archive is science-ready, which means cosmetically cleaned and flux-calibrated. The SMO has taken the following steps to accelerate data processing.

- Change in policy to archive data for each accepted observing program as they are completed, rather than waiting for 100% of the data to be analyzed from the (flight) series.
- If level-3 data are not archived within 15 working days, observers are notified of the delay and the plan for getting it done.
- In the event of significant anticipated data processing delays, observers are offered an opportunity for a preliminary view of their data.
- GOs will be sent a survey questionnaire two months after being notified of new data product availability, in order to engage them in quality assessment and to obtain their feedback on SMO services.
- SMO is converting the data processing tools from their native languages to Python; two facility instruments are already complete. Public release of the data processing tools (initial release planned by the end of 2020) will allow the community to review details of how their data were processed.

The SOFIA science data archive fully transitioned to the Infrared Science Archive [11](IRSA) effective March 31, 2020. This transition greatly enhances SOFIA's archival research by allowing the community to more easily combine SOFIA data with other missions such as Herschel, Spitzer, and Infrared Space Telescope (ISO). By the end of 2020, IRSA features will include:

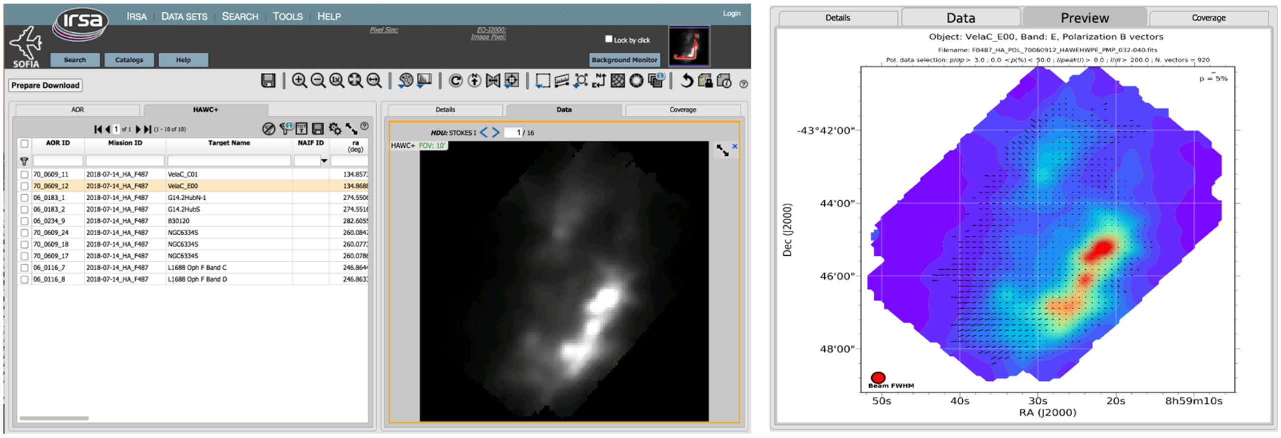
- Enhanced data visualization (Figure 6.6) to support exploration and quick-look analysis
- Data discovery feature that places SOFIA data alongside other infrared mission data sets
- Links to SOFIA publications to increase visibility and citations

[11] IRSA located at the Infrared Analysis and Processing Center (IPAC) https://irsa.ipac.caltech.edu/applications/sofia

Figure 6.6 – IRSA SOFIA Archive Page
Enhancing Data Visualization by Adding Polarization Vectors

Original HAWC+ IRSA Results Page

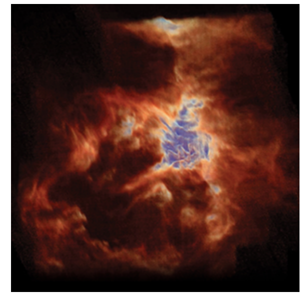
New HAWC+ IRSA Results Page



IRSA makes SOFIA data searchable using a well-known and standardized graphical user interface and places SOFIA data in a context that encourages and aids multi-mission research in infrared astronomy, including virtual observatory standardization to aid multi-wavelength research in across the electromagnetic spectrum. Figure 6.7 below is a screenshot of the IRSA/SOFIA interface, showing how GOs and archival researchers can readily search for SOFIA data with a standard interface.

Figure 6.7 – IRSA-SOFIA Website

⋆ *First release of SOFIA data on IRSA went public in March 2019*



SOFIA 3D Data Cube of Orion's Dragon

6.8 Split Aircraft and Science Operations

FMR Recommendation #8:
Split Aircraft Operations from Telescope and Science Operations

This FMR recommendation was adopted from the SOMER report and relates to aircraft operations and maintenance. The SOMER recommended breaking up the integrated model of the observatory and managing aircraft operations through an independent entity, such as the NASA Airborne Science Program (ASP).

Addressing SOMER Aircraft Operations Recommendation

The implementation of the SOMER recommendation to manage aircraft operations through an independent entity was explored in depth in discussions with ASP but did not yield an operational solution compatible with the highly modified and integrated nature of the observatory. The SOFIA aircraft is highly modified and permanently integrated with the telescope/observatory systems such that it is most efficient to manage them together. It was determined that the SOMER-recommended approach of splitting the aircraft from the observatory systems would not improve either the observatory's operational efficiency or scientific productivity nor would it realize cost savings. SOFIA is an astronomical observatory that flies, incorporating telescope control and data networks as an integral part of the aircraft system. The maintenance, operations and cost of mission systems (i.e., observatory systems) that allow SOFIA to take scientific data could not be fully addressed by ASP due to highly complex and integrated nature of this observatory. The Project currently uses the same staff to maintain and operate both the aircraft and observatory mission systems. Thus, separating the observatory's integrated functions into "only aircraft" and "only science," without adequately addressing the breakdown of the intermediate "mission systems," would increase inefficiencies and the cost.

Restructured SOFIA Organization

In alignment with the core intent of this FMR/SOMER recommendation, the Project has streamlined aircraft operations by:

- Significantly reduce the observatory systems budget to bolster science operations
- Restructuring the overall organization to minimize complexity and to achieve sustainable operations model within an $80M budget.

NASA project management implemented changes in the SOFIA organizational structure to minimize complexity and to reduce management overhead costs. Post FMR, the Project has executed a 10% reduction in workforce in non-science SMO work areas with acceptance of operating at a higher risk:

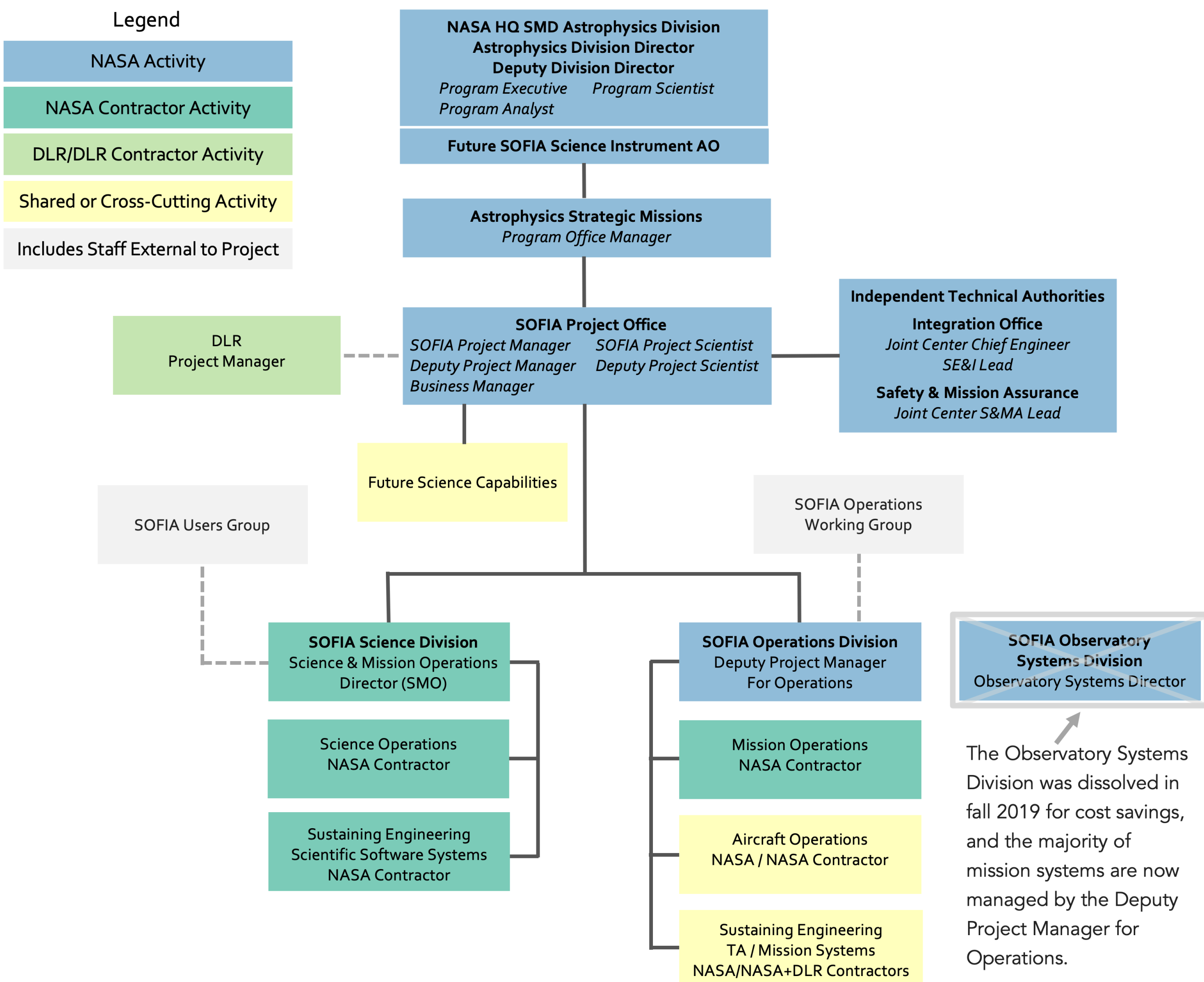
- Aircraft operations were streamlined by reducing the Operations Division civil-servant management structure, the aircraft operations contractor workforce, and the aircraft equipment and maintenance costs.
    - The NASA Operations Director position (civil-servant) was eliminated, and now the SOFIA Operations Division is managed by the NASA Deputy Project Manager for Operations.

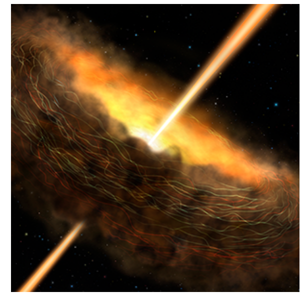
SOFIA Response to 5-Year Flagship Mission Review

- The Observatory Systems Division was dissolved.
  - NASA Observatory Systems Director position (civil-servant) was eliminated.
  - Observatory mission systems are managed by the NASA Deputy Project Manager for Operations.
  - Development and maintenance of SI software, SI data pipeline, and ground mission systems are managed by SMO Director, USRA.
  - Some sustainability engineering tasks (civil-servant and contractor) were eliminated.
- Project management and administrative tasks were reduced by cutting back on some mission support positions.

SMO staffing levels have been maintained and bolstered in some areas to increase scientific productivity and impact. Originally, the SOFIA Project operated with three divisions: Science, Operations, and Observatory Systems. Beginning in fall of 2019, the Project now has only two divisions: Science and Operations (Figure 6.8). The streamlining to just two divisions reduced management overhead costs and minimized complexity.

Figure 6.8 - SOFIA Project Modified Organizational Structure as of Fall 2019





SOFIA reveals that magnetic fields may be feeding active black holes.

The Deputy Project Manager for Operations integrates operations activities across all Project areas to ensure the observatory and its support teams execute the mission. The Deputy Project Manager for Operations oversees operations at AFRC Bldg. 703 and on deployment, including aircraft, instruments, telescope assembly, cavity door, mission controls and communications system, laboratories, maintenance/sustaining engineering, mirror washing/coating, and deployment logistics.

The Science Division is managed by the SMO Director. The SMO Director interfaces with the astronomical community to maximize the observatory's scientific output and impact. The SMO Director administers the U.S. program of SOFIA scientific usage, including observing proposal solicitation, review, time and data analysis grant awards, as well as integrating the observation scheduling of both U.S. and German programs. Scientific observatory software and facility-science-instrument software systems, the data processing pipeline, and data archive are managed by the SMO Director.

6.9 Invoke HIRMES Cost and Schedule Control

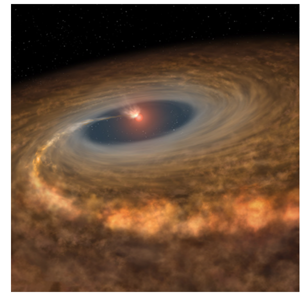
FMR Recommendation #9: Invoke HIRMES Cost and Schedule Control

The HIRMES development was terminated by NASA SMD on April 1, 2020, citing significant technical, cost and schedule risks. NASA SMD also was concerned that continuing to fund HIRMES would have impacted important SOFIA activities and would have limited the Project's ability to increase SOFIA's scientific return.

The maturation of HIRMES detector technology remains valuable for future astrophysics needs, for both SOFIA and other future mission needs. A proposal was requested by NASA SMD from the HIRMES team at GSFC for technology maturation funding beginning in FY 2021. This proposal, if accepted, will be funded using funding external to the SOFIA program as part of the astrophysics strategic technology program.

Additionally, following the direction from NASA SMD to provide a roadmap for future SOFIA instrument development, to be delivered by the start of FY2021, the Project has started to evaluate the options to provide enhanced instrument capabilities for SOFIA. These include, but are not limited to, a restart of HIRMES at the appropriate time, a call for new instrument proposals, and/or upgrading existing instruments with state-of-the-art detectors. The Project has requested the SMO to lead this activity by collecting community's input in preparing a roadmap for future SOFIA instrumentation and capabilities. The SMO is holding multiple community workshops to collect input from the science community and provide recommendations to the Project. The final roadmap is expected to be submitted to the NASA Astrophysics Division by the end of September 2020.

6.10 Focus on Current Science



SOFIA captures first stochastic accretion event in a high-mass protostar

FMR Recommendation #10: Focus on Current Science Operations rather than Future Instrument Development

At the time of the release of the FMR report, HIRMES was still under development. This recommendation assumed that the Project would introduce new science capabilities from HIRMES by 2021. The SOFIA Project initially embraced this recommendation and in the near-term decided to primarily focus on significantly enhancing its scientific productivity and impact by prioritizing acquisition of high-quality science data with the current suite of instruments, while pursuing the completion of the HIRMES instrument development in parallel. The development of new science instruments is one of SOFIA's strongest features, and in the long run, the observatory plans to develop new cutting-edge instrumentation and upgrades to existing instruments based on community input. By developing and deploying the newest technology, the SOFIA observatory will remain fresh and vibrant, with the flexibility to adjust to new science discoveries, new science priorities, and guaranteeing continued robust interest from the science community.

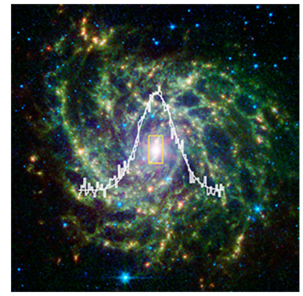
However, with the termination of HIRMES, the Project no longer has a new science capability on the near-term horizon. As noted in Section 6.9 above, the Project is developing a roadmap for future instrumentation. The options include, but are not limited to, a restart of HIRMES at the appropriate time, a call for new instrument proposals, and/or upgrading existing instruments. This direction will be pursued without losing focus on the primary goal of increasing the scientific output of the observatory by maximizing the potential of the current suite of instruments, especially HAWC+ and GREAT, which are in high demand from the science community.

The Project also is considering offering fewer instruments in future calls for proposals starting with the few most scientifically productive instruments. Limiting the number of instruments offered per observing cycle has the following advantages:

- Leads naturally to larger Legacy observation programs
- Increases archive research: an archive of large, homogeneous data sets will likely enhance archival research and increase publications.
- Cuts down on the number of days used for instrument changes; longer single instrument campaigns
- Leads to a lower level of instrument support labor

In the Cycle-9 call, this approach has been applied to the Southern Hemisphere long deployment by offering the two most productive instruments rather than offering all instruments.

Appendix A:
Broadband Connectivity on SOFIA



SOFIA data assists in understanding star formation in the nucleus of Galaxy IC 342

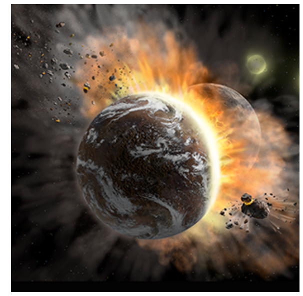
Broadband access on SOFIA will enable better connection between the on-board crew and the ground. Some of the benefits will be:

- Possible personnel efficiencies in operations,
- Some science shift staff may be placed "on-call" instead of flying,
- Smoother and more efficient operations,
- Quicker access to necessary expertise when troubleshooting.

To maximize possible gains by remotely participating in science and mission operations, the following three key metrics for broadband connectivity are necessary:
Speed: the observatory will need greater than 1 Gigabit per second (Gbps) data rate;
System Reliability: 95%+ reliability of the network system;
Maximum Downtime: with no more than five-minute outages because anything less will likely result in lost science

A.1 Broadband Access on the Ground at Home Base

This capability has been demonstrated for some line operations. Routine access would enable remote science instrument and mission director/telescope operator user interface and procedural debugging while SOFIA is on the ground. Science center staff who remain at their base (NASA Ames) could participate in line and hangar operations without having to travel. There are frequent high-stress situations on the ground before takeoff for science flights when systems are not behaving as expected. On-call ground crew could participate in debugging. This capability is a benefit for crew stress reduction, it may help save a flight, and success of line operations will be improved. Day of flight activities involve loading files onboard for usage during the flights; those activities will benefit from dedicated access before aircraft access before door-closing (compared to present procedure of walking the files from ground computers on board, which is a 5-10-minute walk.) Day of flight audio access during pre-takeoff activities would be a benefit as well, so that ground crew could listen to MADS communications and assist with issues that arise, including impact of late takeoff or configuration of science systems or user interfaces. Debugging pre-takeoff systems would benefit from a connection to the plane that shows the mission director user interface console and potentially the telescope assembly monitoring systems. Operations will still require on-board participation, so no significant SMO cost savings from current operating procedures is predicted, though the program may save a flight per year.



SOFIA helps build a more complete picture of what happens when exoplanets collide

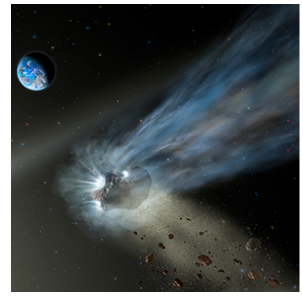
A.2. Broadband Access in Flight

Ground resources including the Data Cycle System and public databases, which are routinely used from the office, are inaccessible during flight. Mission and science operations crew would benefit from ability to access DCS to clarify observing parameters, to find related information from DCS entries not foreseen as required during preflight preparation (e.g. content of another proposal/observing plan on the same target or observing mode). They will also benefit from access to email for critical late updates. Ground-based decision support can be provided in near-real-time, e.g. when the flight plan must be diverted around a storm and priorities for the replan are made. (The mission director is in charge of such decisions, with instrument scientist providing scientific decisions; the Project would provide on-call support for them.) At present, such access must be obtained through satellite call, which is not routinely available. This capability requires a reasonably robust and moderate data rate. The Project learned that NASA is considering the INMARSAT 8-200 kbps service, which may be adequate for this function as long as it is not relied upon for critical activities and no large data files (or video or audio) are required. While no direct cost savings can be quantified, this access will contribute to the reduction in size of both mission and science operations stress and eventually onboard staffing levels when combined with other initiatives.

A.3. Integration of Ground Crew into Flight Operations

With sufficiently high reliability and data rate, broadband internet access can allow ground crew to perform roles currently performed by onboard crew. This would result in significant savings by reducing travel (from Ames to Armstrong for science crew, and from California to New Zealand for mission operations and science crew) and reducing duty-day and crew rest (though a full study of the new duty day and crew rest for this scenario has not yet been made). Many ground-based 29 observatories have evolved into remote operations, as automation technologies and broadband access have improved. The requirements are near-100% reliable access and a high data rate of order 1 Gbps. (The data rate requirement is only an estimate.) Remote observing requires live mirroring of user interfaces, audiovisual contact with onboard crew (e.g. skype video, or minimally text chat combined with audio), and data transfer.

Quick look data processing support can be provided from the science center (as opposed to onboard, as currently is done for HAWC+ and FIFI-LS facility-class science instruments), if data files can be transferred to the ground and results uploaded sufficiently rapidly. The Project estimated the required bandwidth for HAWC+ as 1 GB per file involving 10 minutes of observation, or 6 GB/hr., which corresponds to 13 mbps broadband. The ground staff would receive the data, run through the pipeline, and send back an assessment and summarized result (like a jpg image). The requirement for an audiovisual link (using the skype requirements as an example) is 512 kbps; for two such connections (mission operations, science operations), the requirement is 1 mbps. A critical requirement is 100% reliability. Loss of connection for 10 minutes can be enough to ruin a scientific observation on SOFIA, because the flight legs are generally of order an hour long and they are efficiently filled with observing. Lower-criticality functions like data



SOFIA's observations of a comet's first passage through the Solar System

processing could remain on the ground with lower consequence, though the science operations crew would end up flying relatively blind, making observations as planned but without feedback as to progress on data quality. The minimal cost-savings estimate is that only less-critical activities remain on the ground; the Project estimates the savings of order six trips from Ames to Armstrong. A full cost savings estimate from this level of broadband access requires more detailed evaluation.

A.4. Increased Participation of Guest Observers in Flights

Guest observers are invited to participate in the flights for which their observations are performed. SMO typically invites two observers per flight. Reports from observers about such participation has been overwhelmingly positive. The Project can increase participation by allowing observers who do not travel and fly on SOFIA to get near-real-time updates during their flight legs. The minimal version would require a moderate-reliability, constant connection at a data rate sufficient for text and occasional jpg image transfer; a 10 kbps connection should suffice. Improved access would be via an audiovisual connection and using the skype requirements as an example would require 500-1500 kbps.

Appendix B: SOFIA Key Science Metrics

This Appendix B summarizes SOFIA's key science metrics (Table B.1), as well as other performance indicators routinely tracked by the Project.

Table B.1 – SOFIA Key Metrics and Goals

Science Metric	Goal
Publications per year:	> 75 (100)*
Scientific Impact Citation H-Index[12]:	> 30 (44)*
Oversubscription Rate[13]:	≥ 5
Data Processing and Archiving Time:	15 workdays
Completion Rate for High-Priority Programs[14]:	≥ 80%
Fraction of Completed High-Priority Programs Resulting in Publications[15]:	≥ 80%
High-Quality Observing Time: % research hours[16] at precipitable water vapor < 15 μm % on-sky efficiency[17] at precipitable water vapor < 15 μm	 ≥ 90% ≥ 90%

** stretch goals are in parentheses*

[12] The H-index, a cumulative impact metric, measures quantity with quality by comparing publications to citations.

[13] Oversubscription rate = observing time requested/observing time awarded.

[14] High-Priority programs are ~75% of the total awarded programs and are labeled priority 1 (P1) and priority 2 (P2).

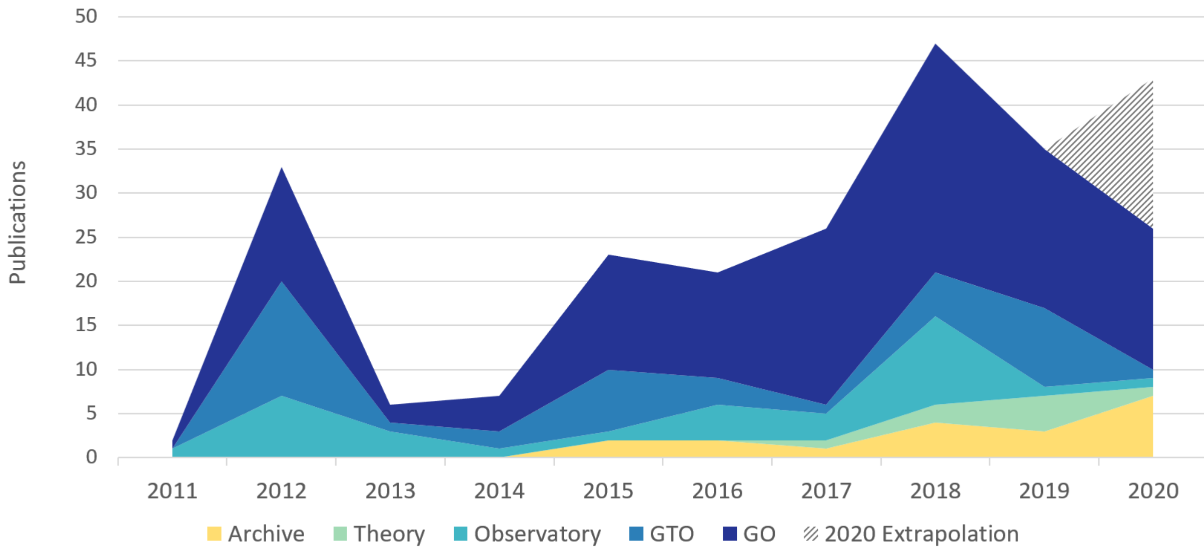
[15] Typically, there is a 2-year lag from data collection to publication.

[16] "Research hours" are defined as hours when the telescope door is open and observatory systems are ready to collect data.

[17] "On-sky efficiency" means the time that SOFIA is collecting data where atmospheric water-vapor content is low.

The number of peer-reviewed papers based on SOFIA data are presented below by year (Figure B.1). The 'Archive' and 'Theory' categories contribute to SOFIA's archival publications, where 'GO and GTO' categories contributes towards science publications. The 'Observatory' publications are related to upgrades and new instrument capabilities.

Figure B.1 - Scientific Publications by Calendar Year

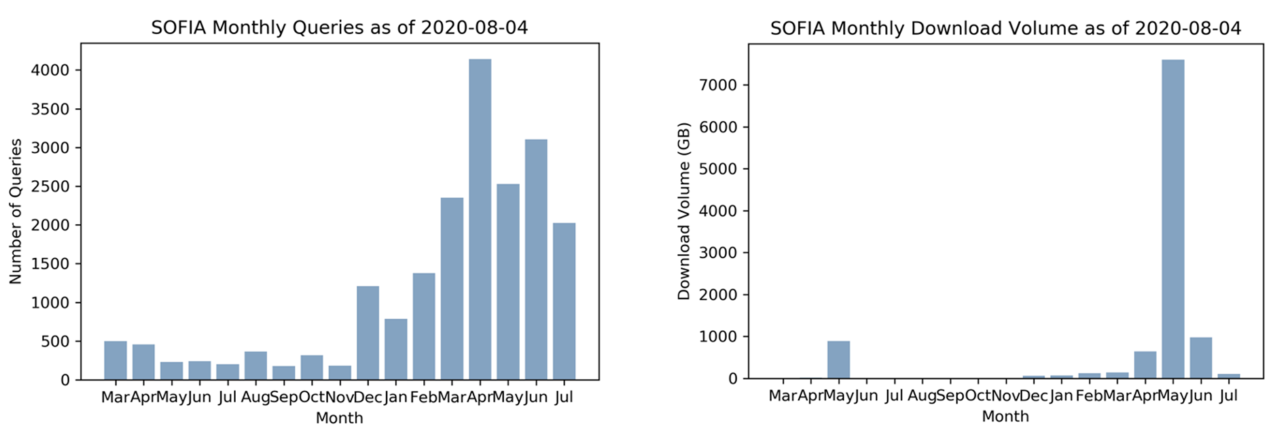


Type	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
GO	1	13	2	4	13	12	20	26	18	16
GTO	0	13	1	2	7	3	1	5	9	1
Observatory	1	7	3	1	1	4	3	10	1	1
Theory	0	0	0	0	0	0	1	2	4	1
Archive	0	0	0	0	2	2	1	4	3	7
Total	2	33	6	7	23	21	26	47	35	26 [43]

Guest Observer (GO) = awarded observing time through a competed, peer-reviewed proposal process.
Guaranteed Time Observation (GTO) = allocated to instrument development teams as reward for developing SIs

The Infrared Science Archive (IRSA) SOFIA usage statistics (Figure B.2) are tracked and reported monthly.

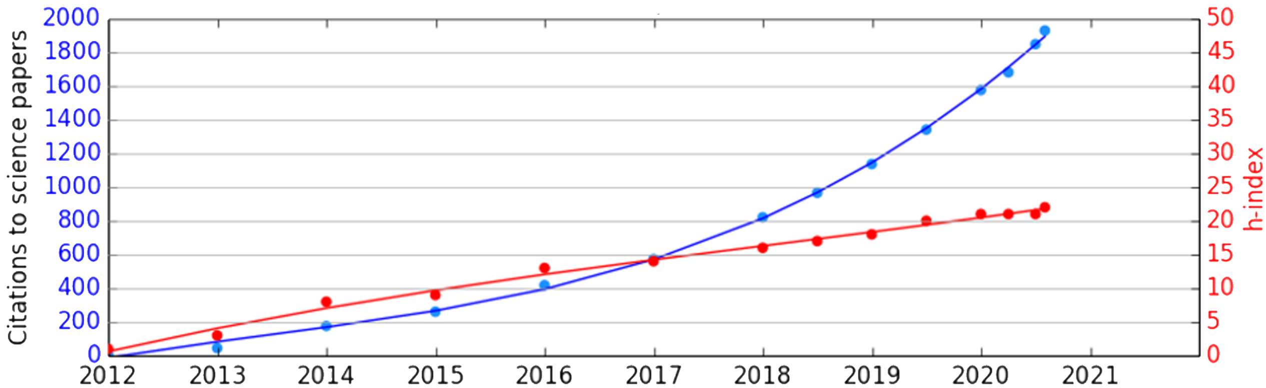
Figure B.2 – IRSA - SOFIA Usage Statistics



B.2 Scientific Impact Metrics

Figure B.3 presents SOFIA scientific impact metrics. The Hirsch (H)-index is a metric for evaluating the cumulative impact of the Observatory's output and performance; the value of the H-index measures quantity with quality by comparing publications to citations. The H-index is not sensitive to number of observing hours and the size of the community when comparing different observatories or missions.

Figure B.3 – Scientific Impact Metrics



Type	1/1/12	1/1/13	1/1/14	1/1/15	1/1/16	1/1/17	1/1/18	1/1/19	1/1/20	3/30/20	6/30/20	7/31/20
Citations	8	45	176	261	418	573	821	1137	1574	1681	1848	1929
H-index	1	3	8	9	13	14	16	18	21	21	21	22

B.3 Observatory's Oversubscription

The SOFIA airborne observatory achieved full operational capability in February 2014, and demand for SOFIA observing time has been consistently growing. Observing time is in high demand with a >5.0 oversubscription rate.

See Figures B.4 to B.7 below for the numbers of hours requested and the number of hours approved, as well the number of proposals submitted and the number approved, for each cycle. The numbers are broken out in terms of U.S. and non-U.S. principal investigators.

Figure B.4 – Number of Submitted Proposals (P1, P2, Legacy) [U.S. QUEUE ONLY]

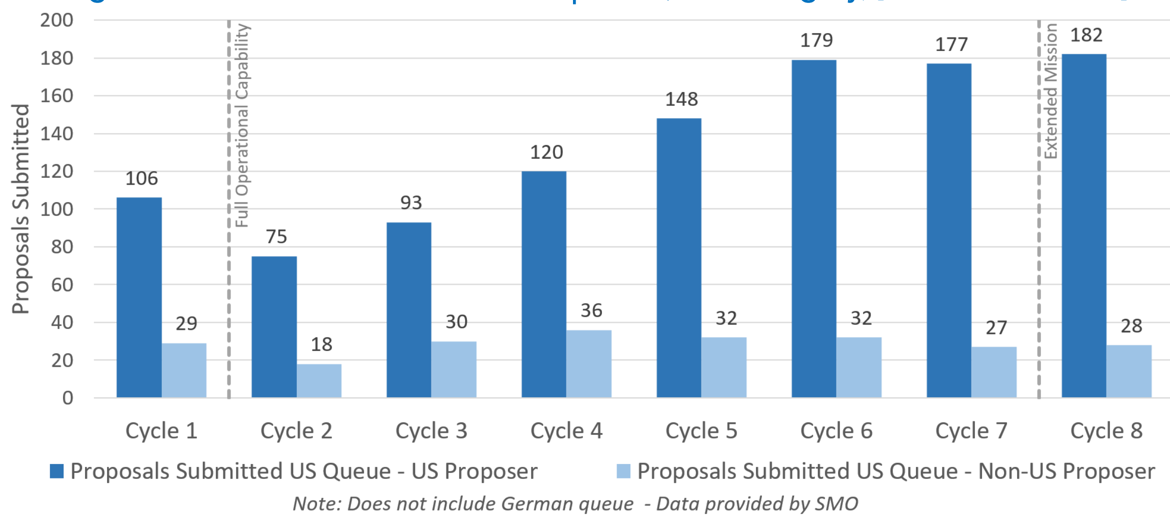


Figure B.5 – Number of Approved Proposals (P1, P2, Legacy) [U.S. QUEUE ONLY]

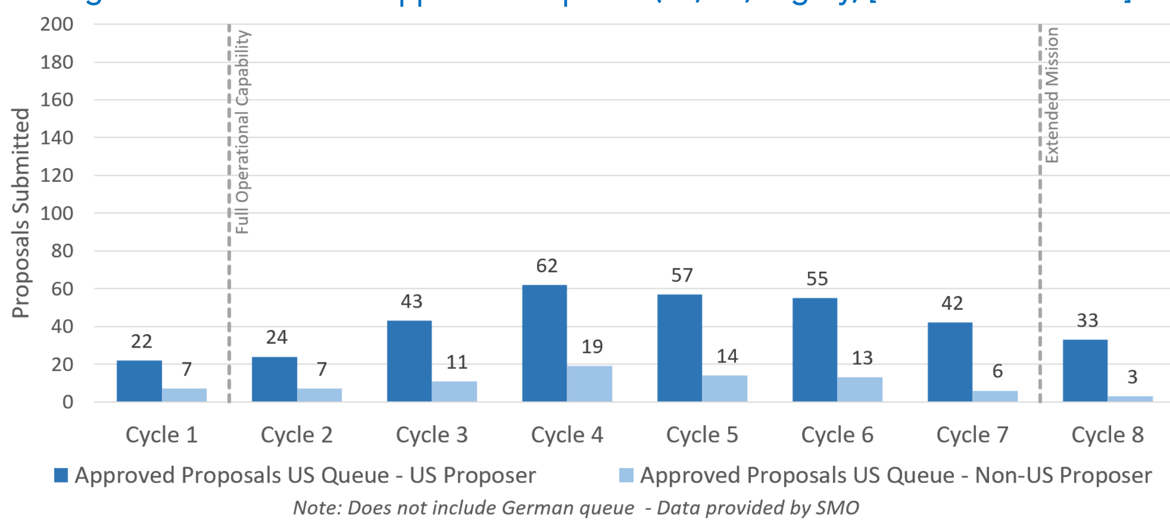


Figure B.6 – Hours Requested (P1, P2, Legacy) [U.S. QUEUE ONLY]

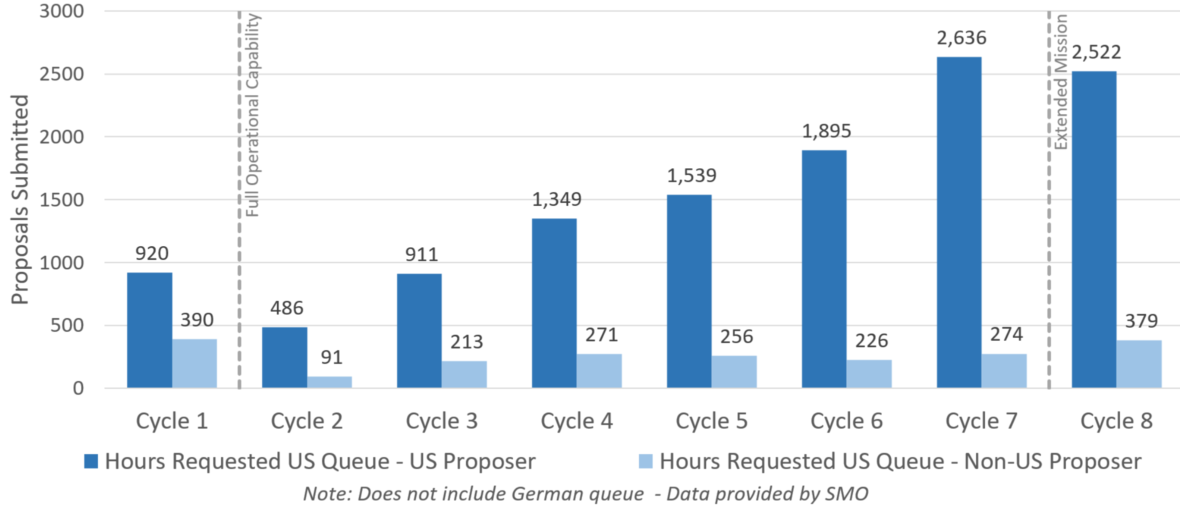
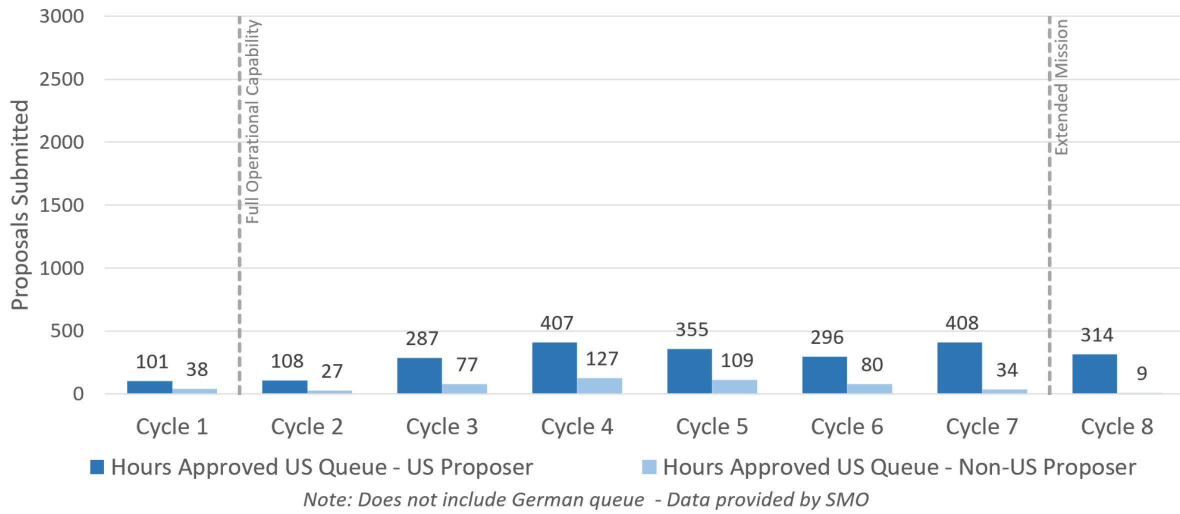


Figure B.7 – Hours Approved (P1, P2, Legacy) [U.S. QUEUE ONLY]



B.4 Principal Investigators and Co-Investigators

SOFIA is consistently adding users and has more than 1200 unique principal investigators (Figure B.8 and Figure B.9).

Figure B.8 – Growth in SOFIA's User Community

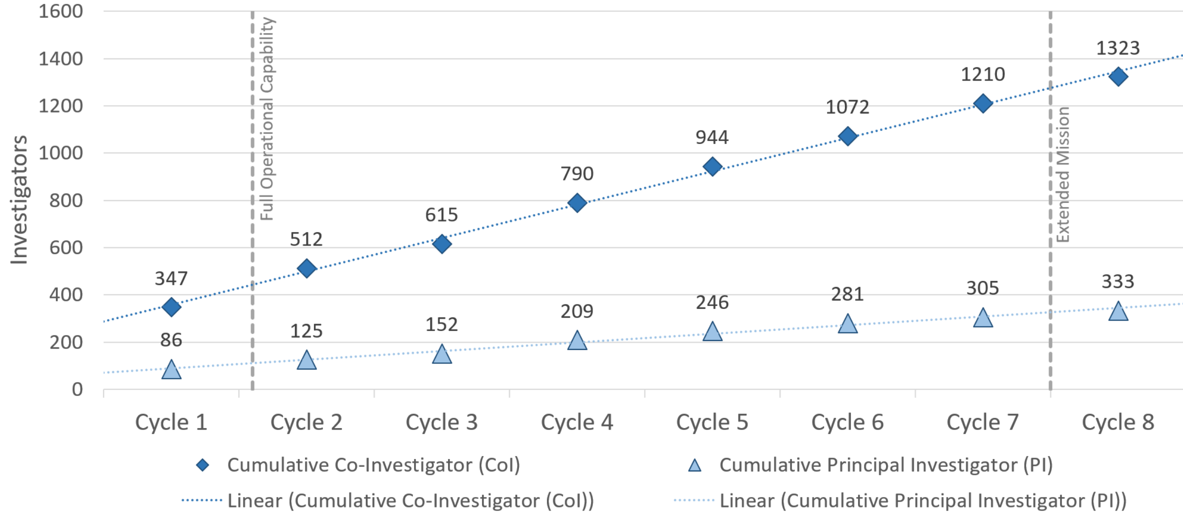
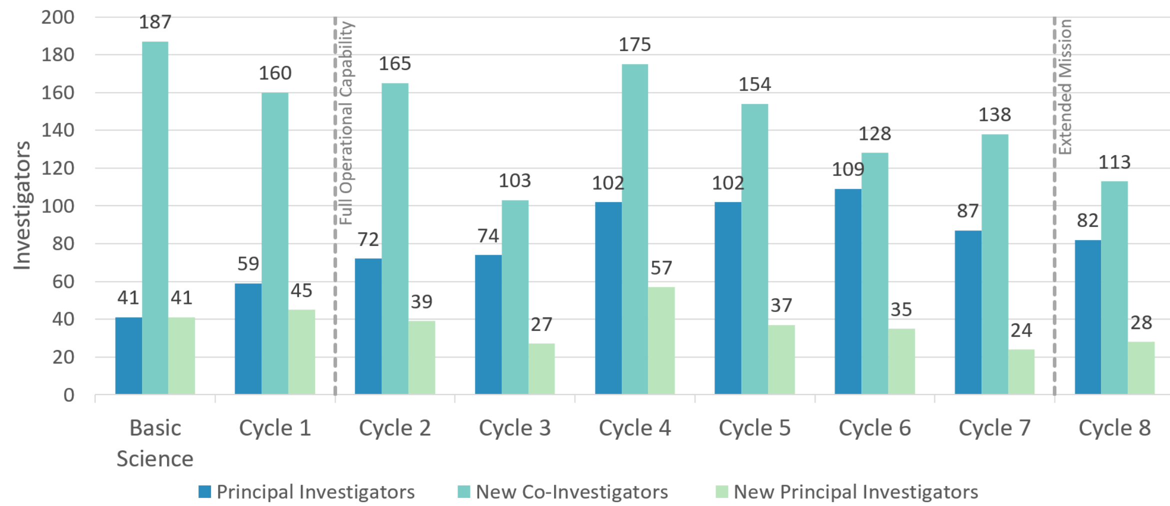


Figure B.9 – SOFIA User Community Trend



B.5 Data Processing and Archiving Time-Scale

Table B.2 presents the data delivery to SOFIA users, showing the percentage of calibrated level-3 data archived within 15 working days; the Project's goal is to have >70% calibrated level-3 data archived within 15 working days. The data sent to the archive is science-ready, which means cosmetically cleaned and flux-calibrated. This is equivalent to a higher level data product for many space observatories.

Table B.2 – Percent Calibrated Data Archived within 15 Working Days

SOFIA Instruments	Data Calibrated and archived within 15 working days	Data Calibrated and archived within 55 working days
FORCAST	35%	59%
GREAT	0%	47%
FIFI-LS	30%	50%
EXES	14%	71%
HAWC+	40%	60%
Total	20%	52%

** GREAT and EXES are principal-investigator (PI)-class science instruments, which are operated and maintained by the builder of the instrument and not by SOFIA SMO scientists*

B.6 Latency: Time between Data Acquisition and Publication

Table B.3 below shows the average and median lag time between initial and final data taking to publications. Comparing Cycle-4 to previous cycles, there is some indication that the "lag time" between data collection and publications is getting shorter. However, the Project will need more statistics to confirm the shorter lag time. For Cycle-5 (finished in April 2018) and Cycle-6 (finished in April 2019) publications are still coming in, and it will take another year for the Project to evaluate if this "lag time" is getting shorter. Cycle-7 (ended April 2020) and Cycle-8 (start date TBD due to COVID-19) are not shown. Reduction in the exclusive-use period from 12 months to 6 months starting in Cycle-9 is expected to reduce this lag time.

Table B.3 - Average and Median Time between First Data Collection and Publication

Cycle	Average Time First Data Taking to Publication (Months)	Average Time Last Data Taking to Publication (Months)	Median Time First Data Taking to Publication (Months)	Median Time Last Data Taking to Publication (Months)
1	34	32	28	26
2	34	28	30	22
3	33	28	33	29
4	29	23	30	23
5	31	20	22	19

**Table presented in 02/2020 in response to Astro 2020 Decadal Survey request for information.*

B.7 Program Completion Rate

Table B.4 presents the fraction of high-priority guest-observer programs that were completed for each observing cycle. Cycles 6 and 7 show an increased completion rate due to the 3-tier priority system introduced in Cycle 6.

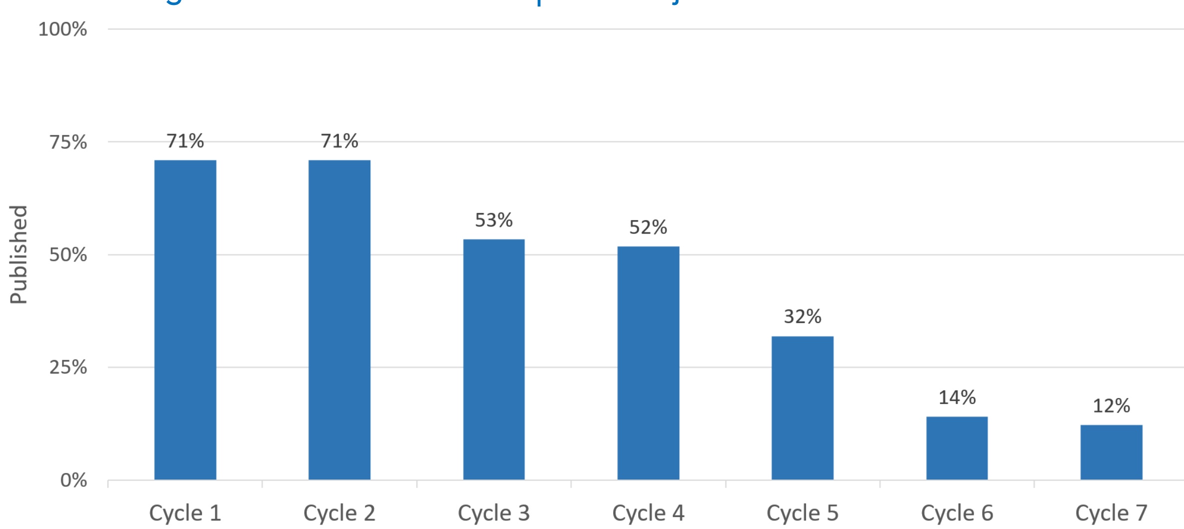
Table B.4 – Fraction of High-Priority Programs Completed

	Cycle 1 Started in 2013	Cycle 2 Started in 2014	Cycle 3 Started in 2015	Cycle 4 Started in 2016	Cycle 5 Started in 2017	Cycle 6 Started in 2018	Cycle 7 Started in 2019
fraction of high-priority programs completed (total completed / total selected)	56%	69%	32%	40%	38%	63%	68%
fraction of high-priority programs completed (total completed / total started)	63%	73%	37%	54%	47%	69%	83%

B.8 Fraction of Completed Programs Resulting in Publications

Figure B.10 below presents the fraction of completed high-priority observing programs that resulted in published papers. The Cycle-6 and Cycle-7 fractions are relatively lower due to the typical ~2-year time lag between observations and publication.

Figure B.10 – Fraction of Completed Projects that Have Been Published



Computation:

Number of programs in a cycle that are:

- P1 or P2 (or "must do" or "should do" categories for earlier cycles) and published divided by the sum total of programs in a cycle that are:
  - P1 or P2 (or "must do" or "should do" for earlier cycles), and
  - Received at least 80% of their awarded observing time OR were published, and are not "ongoing" as part of a preproposal that was awarded time in a later cycle

Table B.5 below presents statistics related to the completion of SOFIA high-priority programs.

Table B.5 - Publication of High-Priority Programs

	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Cycle 6	Cycle 7
Fraction of started high-priority proposals with at least 1 paper	71%	53%	52%	32%	14%	12%

Notes: High-priority programs reported here include both priority-1 and priority-2 programs that comprise of ~75% of the total awarded time.

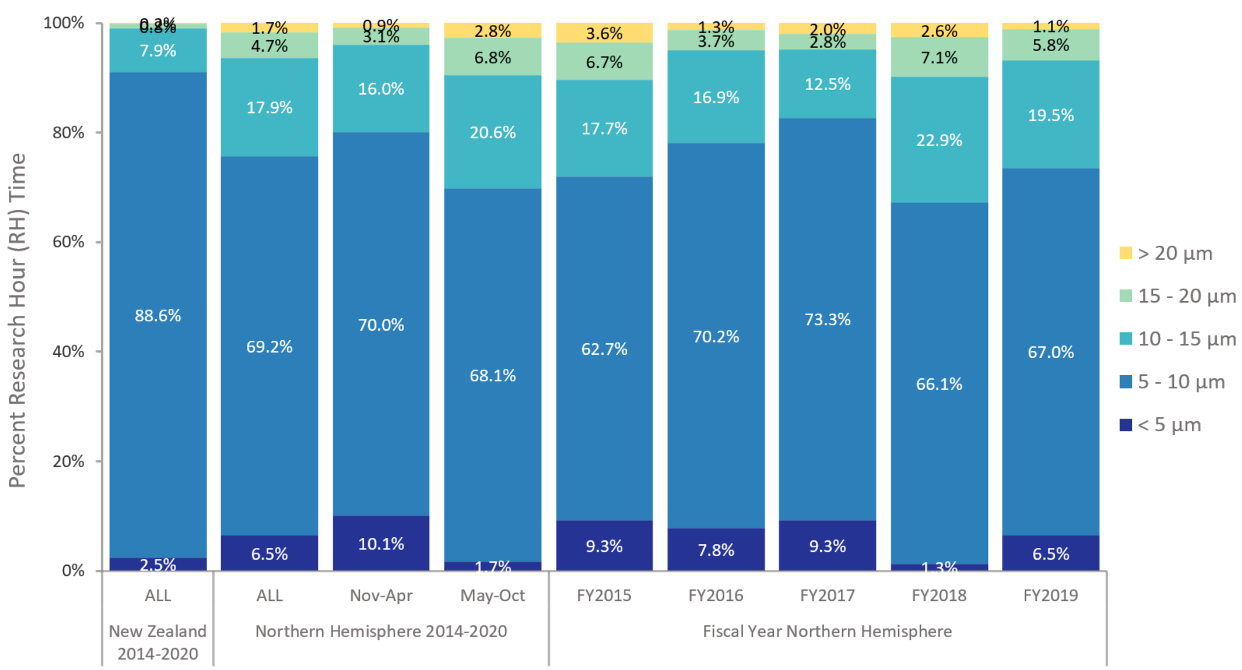
B.9 High-Quality Observing Time

Figure B.11 shows the zenith precipitable water vapor from satellites at all SOFIA flight levels based on data available from the NASA GEOS weather database. The zenith precipitable water wapor statistics for all SOFIA flights show observing conditions.

Observing conditions are categorized as:

- Excellent: < 10 µm
- Very good: 10 - 15 µm
- Acceptable: 15 - 20 µm
  (highly dependent on wavelength, SI, and specific science observation)

Figure B.11 – Zenith PWV from Satellites (All Flight Levels)



* *May-Oct data are skewed because SOFIA typically does not conduct operations between June – August from Palmdale.*
* *During June, July & August, "very good" water-vapor conditions occur less frequently, and shorter flights are recommended.*
* *Research hours are defined as hours when the telescope door is open and observatory systems are operational and ready to collect data.*

B.10 Instrument Productivity and Impact

Table B.6 below presents science papers by year for each instrument (as of 03/06/2020).

Table B.6 - Science Papers / Year

	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
FORCAST	8	2	4	7	8	10	8.5	8	0	55.5
GREAT	19	0	2	12	7	11	11.5	11	0	73.5
FLITECAM *	0	0	0	1	0.5	0.5	0	0	0.5	2.5
HIPO *	0	1	0	1	0	0.5	0	0	0.5	3
EXES	0	0	0	1	1	1	7	6	0	16
FIFI-LS	0	0	0	0	0.5	0	5	2	0	7.5
HAWC+	0	0	0	0	0	0	4	5	1	10
Total	27	3	6	22	17	23	36	32	2	168

** High-speed Imaging Photometer for Occultation (HIPO) and First Light Infrared Test Experiment CAMera (FLITECAM) science instruments have been decommissioned*

Note: Full Operational capability in February 2014

Note: The fractions imply joint instrument papers

Table B.7 below presents the number of citations of refereed papers by science instrument (as of 03/06/2020).

Table B.7 - Number of Citations of Refereed Papers by Science Instrument

SI	#Papers	#Cites
GREAT	73.75	805
FORCAST	55	602.75
FIFI-LS	7.75	50.75
EXES	16	46
HAWC+	10	36
HIPO	2.6	26.9
FLITECAM	2.5	20
FPI+	0.4	0.6
Total	168	1588

Appendix C: Post-FMR Automation Efficiencies on SOFIA

The SOFIA Project has implemented automation across all observatory functions—flight planning, in-flight operations, science instrument (SI) operations, and ground support in response to the Five-Year Flagship Mission Review (FMR) report recommendation to automate tasks that would reduce cost, staff stress, and demonstrate commitment to the future.

Some software automation efforts that have been completed between June 2019-July 2020, since the FMR report was published, are presented below.

Short-Term Scheduler (STS) Software

The Short-Term Scheduler (STS) is the software that auto-generates flight plans (with auto-selected setup target and calibration). This is the system for which the Project has accomplished the most automation:

- Automated the 36hr and 12hr weather updates – apply weather and "repair" flight plan as necessary. Typically takes a flight planner between ½ hr and 2 hrs to do this work.
- Automated the creation of the "overlay" package needed for on board Flight Executor software – tool downloads gigabytes of data, error checks, sends out email if some of the data is missing, packages it, checks it into the data repository and sends out an email. Mission Operations staff then retrieves the package and installs on the aircraft. Saves time, prevents errors by avoiding hand copying / storing.
- Automated the generation of the flight plan package needed for a flight.
- Automated the generation of project documentation - needed once per flight series, a Word document that includes text detailing the Science Observation Plan for the series and a tabular representation of each flight in the series.
- Automated the generation of the flight series / flight plan content displayed on the SOFIA public website. Further enhancement to overlay flight plans on Google map has started.
- Automated the creation of a RA/Dec plot of observations durations and priorities. This can be done for all targets in an entire cycle, per instrument, per priority, for all data, for only planned data, only flown data etc. These plots were previously generated by hand.
- Enhancements to existing automation:
    - Greatly enhanced Special Use (restricted) Airspace areas; extended to polygons, easy to update via Google earth, configurable prohibited zone that varies by location.
    - Continued improvements to the auto generated Confluence Flight Series / Flight Plan pages (content is now automatically pushed to Confluence without user interaction, added flight plan check output link, indicate primary vs. contingency flights, add Instrument Operator information, populate planned research hours, add the ability to automatically display a plot of all flights in the flight series on the flight series page.
    - Enhanced auto generated comments added to Flight Plan legs that are more accurate and uniform than user generated comments. Flight leg comments are now automatically generated by the STS, providing a summary of the overall object observing time in all flights for each leg, as well as information about the Sun elevation. Planners reported that manually commenting legs by hand takes about 30

minutes per flight, so 4 hours of work for an 8-flight flight series. In addition, the auto generated comments avoids potential mistakes that could happen when calculated and added manually.

Cycle Scheduler (CS) - for Cycle planning

Software that lays out entire cycle of observations including instrument and target schedule

- Now runs multiple CS instances simultaneously
- Enhanced reporting:
  - Enhanced "lego" (or schedule) display
    - Displays density of targets in the schedule spreadsheet
    - Quick visual to indicate how "full" a scheduling cell is
  - New calibrator visibility report to alert cycles planners of a potential lack of calibrators for certain series
  - New duplicate report that automatically detects resubmitted proposals to aide in cycle planning

Workstation Subsystem Graphical User Interface (GUI)

On-aircraft user interface used by Telescope Operators (TOs) and Mission Directors (MDs) to control the Observatory.

- Greatly enhanced scripting capability with ability to load target position files, run Astrometry.Net to correct pointing and search Starcat (onboard star catalog database) for targets via script. The goal is to autmomate TO target acquisition.
- Updated user interface to support solo TO.
- Provide the ability to "offset" a position. From a given position and an offset, the TO may easily create a new position, offset from the original by a known amount without having to do the math by hand entering data using personal tools.
- Enhanced Auto Logging Utility that automatically comments significant events
  - Doubled the number of automatically logged comments
  - Mission Directors and Telescope Operators no longer need to report certain temperatures, altitude/altitude changes, Science Instrument mode, telescope assembly state information in their comment files as this content is now auto generated.
- Prototype version of a new metrics tool will:
  - Ease Mission Director/Telescope Operator need to manually mark various events
  - Generate one of the important metrics input files that is currently created post process and often requiring manual work in flight.

Facility Science Instrument Software

On aircraft software run on the Facility Science Instruments (FSI) to control Observatory and the instrument.

- Help set up / update FSI virtual hosts for telescope/instrument operator cross-training Initiative.

FIFI-LS

- Implemented On-The-Fly scan mode in the control software. This mode is expected to result in observing efficiency gains.
- FITS header updated to support infrared science archive where SOFIA data are archived
  - Added NAIF ID to headers
  - Greatly simplifies how IRSA serves out solar-system observations

FORCAST

FITS header updates to support non-sidereal slit observations – saves hours of "very labor-intensive manual" reduction per FITS file during data processing.

HAWC+

Upgraded HAWC+ control software to support telescope/instrument operator cross training initiative:

- Improved the user interface.
- FITS header update to support IRSA: added NAIF ID to headers – greatly simplifies how IRSA serves out solar-system observations
- Automated observing scripts that now send all commands to change telescope elevation rather than stopping, handing control to the telescope operator to change elevation, and then passing control back.
- Automated instrument setup from the observation Astronomical Observing Request (AOR) filter setting. Using these settings as input, code automatically sets filter, pupils, biases and sends the correct mode to the observatory software. This upgrade improves efficiency and makes the instrument easier to operate.

Telescope Assembly Simulator

- A high-fidelity simulator of the real Telescope Assembly that includes simulation of optical guide cameras
- Simplifies mission planning
- Enhancements to simulated images to render simulated images that are closer to those seen in flight to support MOPS mission planning, prevent surprises during flight
  - Simulate scattered moonlight
  - Simulate twilight sky background
  - Simulate the wavelength dependence of FPI focus
  - Model atmospheric extinction
  - Enhancements to existing ghost modeling
- Provided GUI to support configuration of telescope assembly simulator camera controller options (previous controls were obscure)

Data Cycle System

- MUSpot – integrated USPOT/Aladin in a new software tool that automates and standardizes observation review and preparation work done by telescope operators and greatly reduces the their pre-flight preparation time.

SOFIA Response to 5-Year Flagship Mission Review

- Added automation to support proposal time allocation committee (TAC) lead approval process: Automated the phase 1 proposal review notes upload and notification email generation /distribution.
- Automatically assign TAC panels based on proposal category.
- Improved "Observation Block" time accounting to simplify the technical review process for the Instrument Scientists.
- Automated calculation of average altitude for science leg.

Data Processing Systems (pipeline software)

- Successfully ported two of the pipelines (FIFI-LS and FORCAST) from IDL to python
- Conversion of the HAWC+ CRUSH pipeline from Java to Python is ongoing
- Refactored all Python pipeline code into a single namespace package which supports code sharing and reuse and is a prerequisite for public release.
- Transitioned to a cloud-based development environment, for support of Continuous Integration development processes.
- Continuous Integration for automated pipeline testing in the DPS development environment implemented for all pipeline repositories.
- New on-the-fly scan mode implemented in FIFI-LS. This mode is expected to result in observing efficiency gains.
- Developed semi-automated tools to transfer data to the IRSA archive.

Metrics

- Automated generation of two of the required tables on metrics confluence page:
    - Number of Proposals executed per science flight series
    - Hours executed for GO projects per flight series
- Started automation of Observatory operational metrics
- Started automation of SOFIA paper / citation count / H-index metrics

Appendix D – Acronyms and Abbreviations

747SP	Boeing 747 Special Performance
ALMA	Atacama Large Millimeter/submillimeter Array
AO	Announcement of Opportunity
AOR	Astronomical Observing Request
APAC	Astrophysics Advisory Committee
ARC	Ames Research Center
ASMPO	Astrophysics Strategic Missions Program Office
ASP	Airborne Science Program
Astro	Astrophysics Division
C-Check	Extended Aircraft Maintenance (performed as defined by the manufacturer)
CDRL	Contract Deliverable
COVID-19	Coronavirus Disease 2019
CS	Cycle Scheduler
CY	Calendar Year
DCS	Data Cycle System
DDT	Director's Discretionary Time
DLR	Deutsches Zentrum fur Luft- und Raumfahrt e.V. (DLR), German Aerospace Center
DPS	Data Processing System (pipelining)
DSI	Deutsches SOFIA Institut
EXES	Echelon-cross-Echelle Spectrograph
FIFI-LS	Field-Imaging Far-Infrared Line Spectrometer
FITS	Flexible Image Transport System
FLITECAM	First Light Infrared Test Experiment CAMera
FMR	Flagship Mission Review
FP	Flight Plan / Flight Planner
FPI	Focal Plan Imager
FSI	Facility-class Science Instrument
FORCAST	Faint Object InfraRed CAmera for the SOFIA Telescope
FPI+	Focal Plane Imager Upgrade
FSI	Facility-class Science Instrument
FY	Fiscal Year
Gbps	Gigabit per second
GBT	Green Bank Observatory
GEOS	Goddard Earth Observing System
GO	Guest Observer
Gov	Government
GREAT	German Receiver for Astronomy at Terahertz Frequencies
GSFC	Goddard Space Flight Center
GTO	Guaranteed Time Observation
H-index	Hirsch Index
H_2O	Water
HAWC+	High-resolution Airborne Wideband Camera Upgrade
HIPO	High-speed Imaging Photometer for Occultation
HIRMES	High-Resolution Mid-infrarEd Spectrometer

HMV	Heavy Maintenance Visit
HQ	Headquarters
ID	Identification
IDL	Interactive Data Language
IO	Instrument Operator
IR	Infrared
IRSA	NASA/IPAC Infrared Science Archive
ISO	Infrared Space Telescope
ISP	Internet Service Provider
JWST	James Webb Space Telescope
K	Thousand
kbps	kilobits per second
M	Million
MADS	Mission Audio Distribution System
mbps	megabits per second
MD	Mission Director
MD1	First-Chair Mission Director
MD2	Second-Chair Mission Director
MOPS	Science Mission Operations
MUSPOT	Mission Unified SOFIA Proposal and Observation Tool
NAIF ID	NASA Navigation and Ancillary Information Facility Identification
NASA	National Aeronautics and Space Administration
NH	Northern Hemisphere
NZ	New Zealand
OC	Observing Cycle
P1	Priority 1
P2	Priority 2
P3	Priority 3
PI	Principal Investigator
Post-doc	Post-Doctoral Researcher
PSI	PI-class Science Instrument
PWV	Precipitable Water Vapor
RA	Right Ascension
RFI	Request For Information
RH	Research Hours
S5YFMR	SOFIA 5-Year Flagship Mission Review
SH	Southern Hemisphere
SI	Science Instrument
SIL	Systems Integration Laboratory
SMD	Science Mission Directorate
SOFIA	Stratospheric Observatory For Infrared Astronomy
SOMER	SOFIA Operations & Maintenance Efficiency Review
SMO	SOFIA Science and Mission Operations
STS	Short-Term Scheduler
STScI	Space Telescope Science Institute
SVN	Apache Subversion (a software versioning and revision control system)

TA	Telescope Assembly
TAC	Time Allocation Committee
TBD	To Be Determined
TO	Telescope Operator
UI	User Interface
U.S.	United States (of America)
USPOT	Unified SOFIA Proposal and Observation Tool
USRA	Universities Space Research Association
VIPER	Volatiles Investigating Polar Exploration Rover
μm	Micrometer