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NASA's Management of the Stratospheric Observatory for Infrared Astronomy Program

September 14, 2020

Report No. IG-20-022

Office of Inspector General

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RESULTS IN BRIEF

NASA's Management of the Stratospheric Observatory for Infrared Astronomy Program

September 14, 2020 IG-20-022 (A-19-015-00)

WHY WE PERFORMED THIS AUDIT

The Stratospheric Observatory for Infrared Astronomy (SOFIA) is an airborne observatory housing a 106-inch telescope mounted onboard a Boeing 747SP that makes observations from between 38,000 and 45,000 feet, putting it above 99 percent of water vapor that interferes with ground-based infrared observations. The aircraft is operated out of NASA's Armstrong Flight Research Center in Palmdale, California, and is currently equipped with six interchangeable instruments that can be upgraded or replaced. SOFIA is used by astronomers to study astronomical objects and phenomena including star birth and death, formation of new solar systems, identification of complex molecules in space, nebulas and galaxies, and transient events like eclipses.

The SOFIA Program is a partnership between NASA—within the Science Mission Directorate's (SMD) Astrophysics portfolio—and the German Aerospace Center and operates in cooperation with the Universities Space Research Association (USRA) and German SOFIA Institute. NASA began development of SOFIA in 1991 and the Program achieved full operational capability in 2014, 13 years behind schedule with development costs over $1 billion (more than 300 percent over the initial cost estimate). Because SOFIA has experienced ongoing operational and technical challenges and has not met science output expectations, NASA has questioned whether its $83 million in annual operating costs could be put to better use. Likewise, the President's Budget Request has proposed terminating SOFIA on multiple occasions including most recently for fiscal year 2021. However, in the past Congress has continued to fund the Program.

In this audit, we evaluated NASA's management of the SOFIA Program's cost and technical performance to ensure maximum scientific return. Specifically, we assessed the Program's (1) delivery of reliable flight opportunities; (2) efficiency of research flights in maximizing the quantity and quality of data obtained from observations; (3) ability to meet established data processing time commitments and provide quality data; (4) expected technical capabilities, including development of next-generation instruments; and (5) overall operational effectiveness in maximizing science output. To complete this work, we interviewed SMD and SOFIA Program management; observed an operational flight; identified factors affecting Program scientific productivity; surveyed the science community; and reviewed operational requirements and goals, NASA's contract with USRA, SOFIA science instrument development, and NASA reports and studies on the SOFIA Program.

WHAT WE FOUND

Although responsible for several first-of-its-kind discoveries, SOFIA's 13-year development delay reduced the Program's ability to produce impactful science in a cost-effective manner, particularly when compared to the cost of and science produced by other infrared observatories that launched in the interim. Further, SOFIA has not fully utilized its unique capabilities to serve as an instrument test bed due to high instrument development costs, or to fly anytime anywhere because of a lack of instrument scheduling flexibility, the amount of time necessary to switch out instruments, and the prioritization of observations with greater scientific significance.

SOFIA also continues to experience operational and technical challenges related to flight operations, observation completion, data processing, USRA's award fees, and instrument development. While SOFIA was designed to fly 960 research (or observation) hours annually, it has yet to achieve this number of hours or dispatch the expected number of scheduled flights, resulting in much less science output than expected. While SOFIA typically has flown a 10-hour flight profile four times per week, an alternate schedule of 8-hour flights five times per week out of Palmdale from May to November appears to achieve more time in the stratosphere and therefore higher quality data. Further, although the Program's scientific productivity has improved in recent years, the resulting publications and citations are significantly below what is expected for a mission of SOFIA's budget and lower than comparable observatories. SOFIA's limited science output can be attributed to multiple factors including incomplete observation programs and issues with the timeliness and quality of data produced during an observation. In addition, performance ratings and award fees for USRA—which was awarded a contract in 2017 to manage SOFIA Program science operations—have been based on subjective judgments and were not adequately tied to primary science productivity metrics (publication and citation rates) that are standard across the astronomical community. The Program has also not developed any new instruments, only implemented one instrument upgrade, and SMD recently canceled the only new instrument in development due to cost concerns and technical challenges. Finally, SOFIA has not retired non-productive instruments in a timely manner.

The lack of clear and achievable performance expectations and lack of concurrence between SMD and SOFIA management on science output goals including publication and citation metrics has reduced productivity and threatens the Program's future viability. The Program is unlikely to achieve the community's expectation of 150 publications per year by 2022, or the Program's goal of 100 annual publications, as it only produced 33 publications in 2019 and the actions proposed to meet this goal fall short of the transformational changes required to address current operational and technical challenges. Further, the proposed actions are unlikely to mitigate SOFIA's lack of competitiveness because of the Program's poor efficiency on a science-per-dollar basis when compared to other observatories.

WHAT WE RECOMMENDED

To improve the Program's productivity, we recommended the Associate Administrator for SMD direct SOFIA Program management to: (1) implement quantifiable research hour requirements; (2) establish a requirement to maximize research hours in the stratosphere that considers implementing an 8-hour, five times per week flight profile whenever SOFIA operates from Palmdale between May and November; (3) establish observation program completion metrics, based on science value prioritization, to increase the probability observations result in publications; (4) develop and implement a process to increase the timeliness of delivering data to researchers; (5) establish science metrics, such as publications and citations per year, as criteria for the performance evaluation of the USRA contract award fee; (6) establish a requirement for new technology implementation; and (7) develop a process for tracking science instrument productivity and cost to maintain and establish an evaluation program to determine when an instrument should be retired. We also recommended the Associate Administrator for SMD and SOFIA Program management coordinate to: (8) reassess SOFIA's strategy and mission to identify and consider implementing alternative operational approaches and models to maximize SOFIA's capabilities within the Astrophysics portfolio and return on investment and (9) develop consensus between SMD and Program management and implement quantifiable operational and science output requirements.

We provided a draft of this report to NASA management, who concurred with all of our recommendations. We consider management's comments responsive; therefore, the recommendations are resolved and will be closed upon completion and verification of the proposed corrective actions.

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Acronyms

ALMA	Atacama Large Millimeter/submillimeter Array
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
EXES	Echelon-Cross-Echelle Spectrograph
FIFI-LS	Far-Infrared Field-Imaging Line Spectrometer
FMR	Flagship Mission Review
FORCAST	Faint Object Infrared Camera for the SOFIA Telescope
FPI+	Focal Plane Imager Plus
FY	fiscal year
GREAT	German Receiver for Astronomy at Terahertz Frequencies
HAWC+	High-resolution Airborne Wideband Camera + Polarimeter
HIRMES	High Resolution Mid-Infrared Spectrometer
JWST	James Webb Space Telescope
OIG	Office of Inspector General
PCA	Program Commitment Agreement
SMD	Science Mission Directorate
SOFIA	Stratospheric Observatory for Infrared Astronomy
SOMER	SOFIA Operations and Maintenance Efficiency Review
USRA	Universities Space Research Association

INTRODUCTION

The Stratospheric Observatory for Infrared Astronomy (SOFIA) is an airborne observatory—a Boeing 747SP aircraft modified to carry a 106-inch reflecting telescope—that makes observations from between 38,000 and 45,000 feet, putting it above 99 percent of water vapor that interferes with ground-based infrared observations.[1] NASA began development of SOFIA in 1991 and achieved full operational capability in 2014. At that point, SOFIA's development was 13 years behind schedule with total costs over $1 billion (more than 300 percent over the initial cost estimate). Since then, SOFIA has experienced ongoing operational and technical challenges. As a result, the President's Budget Request has proposed terminating SOFIA on multiple occasions but Congress has continued to fund the Program. Because SOFIA has not met operational or science output expectations, NASA has questioned whether its $83 million in annual operating costs could be put to better use. The fiscal year (FY) 2021 President's Budget Request again recommends terminating SOFIA in FY 2022.

We initiated this audit to evaluate how well NASA is managing the SOFIA Program's cost and technical performance to ensure maximum scientific return. Specifically, we assessed the Program's (1) delivery of reliable flight opportunities, including the efficiency of its observation time allocation process; (2) efficiency of research flights in maximizing the quantity and quality of data obtained from observations; (3) ability to meet established data processing time commitments and provide quality data; (4) expected technical capabilities, including development of next-generation instruments and retirement of instruments; and (5) overall operational effectiveness in maximizing science output. See Appendix A for details on the audit's scope and methodology.

SOFIA in Flight with Observatory Door Open

Source: NASA.

Background

NASA's science vision is to "understand the Sun and its effects on the solar system, the Earth, other planets and solar system bodies, the interplanetary environment, the space between stars in our galaxy (the interstellar medium), and the universe beyond."[2] To this end, the Agency develops, deploys, and operates ground-based, airborne, and space observatories. NASA developed SOFIA to produce scientific output comparable to the Agency's Great Observatories—the Hubble Space Telescope (Hubble), Compton Gamma Ray Observatory, Chandra X-ray Observatory (Chandra), and Spitzer Space Telescope

[1] The Boeing 747SP, or "special performance" model, is a modified version of the Boeing 747 jet airliner. It has a shortened fuselage (the central body portion of the aircraft that holds crew, passengers, and/or cargo) making it lighter, thus permitting longer range and increased speed relative to other 747 configurations.

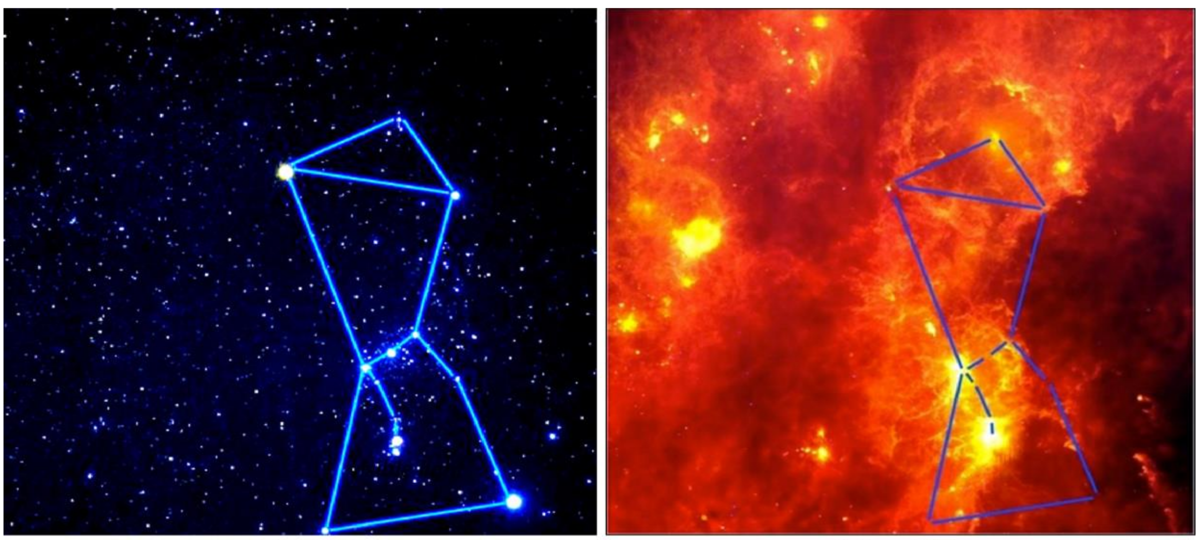
[2] NASA's Strategic Plan outlines its science vision through 2021 and beyond. See Strategic Objective 1.1, "Understand The Sun, Earth, Solar System, And Universe," in the *NASA Strategic Plan 2018* (February 12, 2018).

(Spitzer).[3] See Appendix B for information comparing SOFIA to Hubble, Chandra, Spitzer, and other observatories.

The case for "Great Observatory-class" science from SOFIA assumed a minimum 12-month overlap with Spitzer for complementary science observations and a minimum 1 year of operations prior to the launch of the Herschel Space Observatory (Herschel) mission.[4] NASA officials believed that 1 year of SOFIA operations would obtain sufficient results to benefit science planning for Herschel by identifying astronomical targets that Herschel could then study in greater detail. The Agency also intended for SOFIA to complement Hubble, Chandra, and the James Webb Space Telescope (JWST), as well as several major ground-based telescopes.[5]

Similar to Spitzer and Herschel, astronomers use SOFIA to study astronomical objects and phenomena in the infrared portion of the electromagnetic spectrum, including star birth and death, formation of new solar systems, identification of complex molecules in space, and nebulas and galaxies.[6] Using the Orion Constellation, Figure 1 demonstrates the difference between visible and infrared images.

Figure 1: Orion Constellation Seen in the Same Region—Visible and Infrared Light



visible light *infrared light*

Source: NASA.

[3] NASA's Great Observatories, a series of four space-borne observatories designed to conduct astronomical studies over many different wavelengths (visible, gamma rays, X-rays, and infrared), include Hubble (1990 to the present), Compton Gamma Ray Observatory (1991 to 2000), Chandra (1999 to the present), and Spitzer (2003 to 2020).

[4] Herschel was a space observatory built and operated by the European Space Agency.

[5] JWST is NASA's successor to Hubble and was planned to launch in March 2021. Due to impacts from the COVID-19 coronavirus pandemic and technical challenges, in July 2020 NASA announced JWST will be targeted for launch on October 31, 2021.

[6] Radiation is energy emitted in the form of waves (light) or particles (photons). Electromagnetic radiation comprises the spectrum of energy ranging from radio and microwaves; infrared, visible, and ultraviolet light; and x-rays and gamma rays. Because this radiation is associated with electric and magnetic fields that transfer energy as they travel through space, it is called the electromagnetic spectrum. Infrared is electromagnetic radiation at wavelengths longer than the red end of visible light and shorter than microwaves (roughly between 1 and 100 microns). Almost none of the infrared portion of the electromagnetic spectrum can reach the surface of the Earth, although some portions can be observed by high-altitude aircraft or telescopes on high mountaintops.

While some stars can be seen in the lower left portion of the visible light image (on the left), there are dense concentrations of dust throughout the rest of the field and radiant energy is blocked from passing through the region within the blue outline. However, the infrared light (right image) is able to travel through the dust and enable the imaging of newborn stars (in yellow), which otherwise would be hidden from view.

SOFIA Program Overview

The SOFIA Program is a follow-on to NASA's Kuiper Airborne Observatory (Kuiper), and was designed with superior capabilities such as a larger telescope and more technologically advanced science instruments.[7] It resides within the NASA Science Mission Directorate's (SMD) Astrophysics Division portfolio and is managed by Ames Research Center (Ames). The Program is a partnership between NASA and the German Aerospace Center (DLR) and operates in cooperation with the Universities Space Research Association (USRA) and the German SOFIA Institute (Deutsches SOFIA Institut) at the University of Stuttgart.[8] The agreement provides DLR with 20 percent of the observatory's science utilization, managed by the German SOFIA Institute, in exchange for 20 percent of development and operating costs. As the primary contractor, USRA is responsible for all major aspects of the SOFIA Science Program, including conducting a solicitation and peer review of community-based observing proposals, selecting observation programs, and awarding observation time on SOFIA. USRA plans and executes observations, supports the researchers (those awarded the solicitations and observation hours), and processes all science data. The SOFIA aircraft is operated out of NASA's Armstrong Flight Research Center (Armstrong) in Palmdale, California.

Observatory Capabilities

As an airborne observatory, SOFIA leverages capabilities that are found in both ground and space observatories. Whereas the highest ground-based observatory sits at approximately 18,500 feet above sea level, SOFIA can make observations from the stratosphere at 38,000 to 45,000 feet, putting it above 99 percent of water vapor that interferes with ground-based infrared atmosphere observations.[9] In addition, the observatory's mobility allows researchers to observe from almost anywhere in the world and study transient events, such as a stellar occultation, that often take place over oceans where there are no telescopes.[10] Unlike most space missions, SOFIA can take advantage of emerging technologies because its scientific instruments can be upgraded or replaced and can be switched out depending on the planned observations.

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[7] Based at Ames Research Center, Kuiper was a modified Lockheed C-141A cargo transport fitted with a 36-inch telescope that operated from 1974 to 1995.

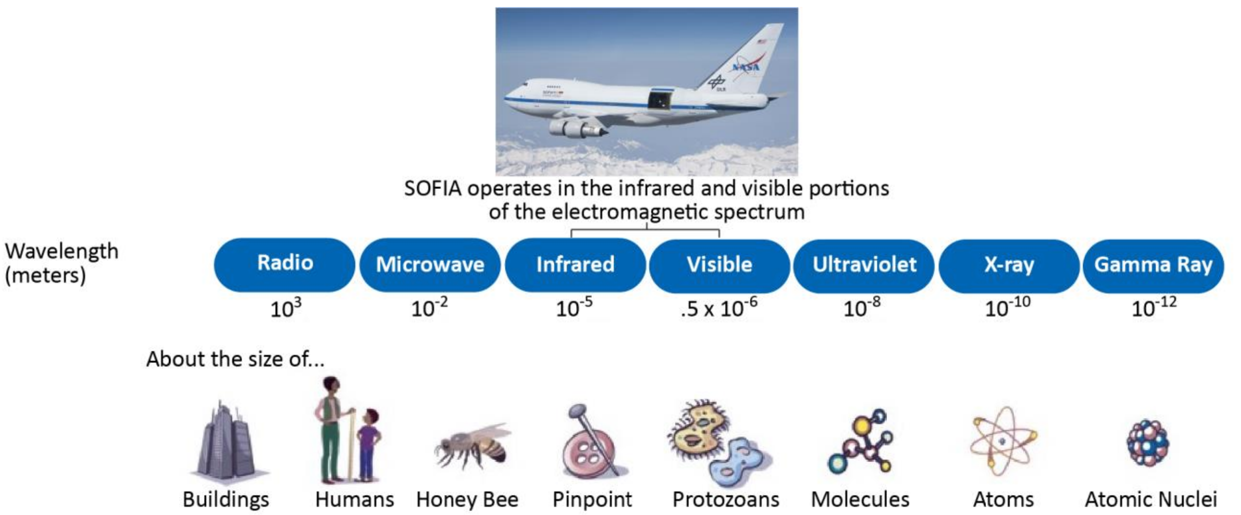
[8] DLR refers to Deutsches Zentrum für Luft- und Raumfahrt, the official name of the German Aerospace Center. USRA is an independent, non-profit research corporation that NASA first selected in 1996 to manage the entire SOFIA Program. In 2016 NASA recompeted the contract, and in 2017 selected USRA to manage SOFIA's science operations.

[9] The University of Tokyo Atacama Observatory located on the summit of Cerro Chajnantor in Chile at an altitude of 18,500 feet is the highest permanent astronomical observatory in the world. The stratosphere is one layer of the Earth's atmosphere. The troposphere is the first layer, which starts at the Earth's surface and is where nearly all water vapor or moisture is found and almost all weather occurs. The next layer is the stratosphere, which contains the ozone layer that absorbs and scatters solar ultraviolet radiation. That is followed by the mesosphere, thermosphere, ionosphere, and finally the exosphere, which is the upper limit of the atmosphere.

[10] An occultation occurs when one object is hidden by another object that passes between it and the observer.

The airborne observatory, which can fly three or more times per week for up to 10 hours each flight, is fitted with a 106-inch telescope mounted onboard a Boeing 747SP. The telescope is exposed to the night sky through a uniquely designed cavity door located at the rear of the aircraft. NASA designed SOFIA to study the universe in the infrared region of the electromagnetic spectrum and observe both infrared and visible wavelengths from 0.3 to 1,600 microns.[11] Figure 2 provides information on the electromagnetic spectrum and the wavelengths SOFIA can observe.

Figure 2: SOFIA Coverage in the Electromagnetic Spectrum



Source: NASA Office of Inspector General (OIG) presentation of Agency information.

Note: The infrared region of the electromagnetic spectrum is divided into near-, mid-, and far-infrared. Near-infrared light is closest to visible light and ranges from 0.78 to 3 microns, mid-infrared ranges from 3 to 50 microns, and far-infrared is closest to the microwave region and covers 50 to 1,000 microns.

SOFIA currently is outfitted with six instruments for observers' use (see Appendix C for further details):

- Echelon-Cross-Echelle Spectrograph (EXES): a mid-infrared high-resolution spectrograph to study molecular hydrogen, water vapor, and methane from sources such as molecular clouds, protoplanetary disks, and planetary atmospheres
- Far-Infrared Field-Imaging Line Spectrometer (FIFI-LS): an integral-field far-infrared spectrometer to study the formation of massive stars and the properties of the interstellar medium
- Faint Object Infrared Camera for the SOFIA Telescope (FORCAST): a dual-channel mid-infrared camera and spectrograph used to study celestial objects such as planets and star forming regions
- Focal Plane Imager Plus (FPI+): the standard tracking camera for the SOFIA telescope intended to be used as a fast frame-rate imaging photometer that can be used to observe stellar occultations and exoplanet transits[12]

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[11] A micron is a unit of length equal to 10^-6, or one millionth of a meter.

[12] An exoplanet transit is a planet outside of our solar system passing in front of its host star when observed from Earth.

- German Receiver for Astronomy at Terahertz Frequencies (GREAT): a modular dual-color heterodyne instrument to provide high resolution spectra and observe extended regions of the sky in the far-infrared
- High-resolution Airborne Wideband Camera + Polarimeter (HAWC+): a far-infrared camera and imaging polarimeter to study the early stages of star and planetary formation

Research Hour Requirements, Observation Cycles, and Selection of Observation Programs

SOFIA is designed to fly 960 research (or observation) hours annually and will typically achieve about 8 research hours in a 10-hour flight.[13] The Program plans its flights in cycles, defined as the flight plan covering a specified period of time, over a 1-year period. The flight plan determines the number of research hours available to the astronomical community. USRA solicits and selects the science research proposals from an annual call for proposals and awards them time as part of "observation programs" on SOFIA's calendar observation cycle. Table 1 provides the start and end dates of the eight observation cycles SOFIA has completed or is in the process of executing. SOFIA's observation programs are grouped by priority level—those deemed high-priority (Priority 1 and 2) and "filler" programs to be used as flight time permits (Priority 3).

Table 1: Observation Cycle Start and End Dates

	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Cycle 6	Cycle 7	Cycle 8
Start Date	4/11/13	2/17/14	3/1/15	2/1/16	2/4/17	5/19/18	4/27/19	4/25/20
End Date	2/4/14	2/28/15	1/31/16	2/3/17	1/2/18	4/26/19	3/12/20	4/23/21

Source: NASA OIG presentation of SOFIA Program data.

Note: Cycle 8 start and end dates will change due to COVID-19 coronavirus pandemic mitigation efforts.

SOFIA Program Timeline from Inception through the Start of Operations

NASA's science missions are heavily influenced by external stakeholders. The President and Congress provide direction through the annual budget and appropriation process while the science community—as represented by the National Academies of Sciences, Engineering, and Medicine (National Academies)—establishes mission priorities based on a broad consensus within various research disciplines in decadal surveys that align with five of SMD's six operational science divisions (Astrophysics, Biological and Physical Sciences, Earth Science, Heliophysics, and Planetary Science). In 1991, the National Research Council (the former name of the research arm of the National Academies) reviewed the field of ground- and space-based astronomy and astrophysics and recommended priorities

[13] Research hours are the amount of time the observatory is at an altitude where data can be collected with the cavity door open and all data collection systems in proper working order.

for the most important new initiatives of the 1990 to 2000 decade.[14] SOFIA was identified as the third-highest priority in the survey's moderate category with an estimated cost of $230 million over the decade.[15] The decadal survey highlighted the airborne observatory's importance in training instrument scientists, understanding physics in regions of high density and moderate temperature that characterize the primitive nebulae around newly formed stars, and its capability for diffraction-limited imaging and high-resolution spectroscopy at wavelengths inaccessible from the ground.[16]

As shown in Figure 3, NASA began SOFIA's formulation in 1991, initiated development in 1996, and the observatory reached full operational capability in 2014. SOFIA followed NASA's project life cycle, which is divided into two phases—Formulation and Implementation—that are further divided into Phases A through F.[17] The Formulation Phase includes Phases A (concept and technology development) and B (preliminary design and technology completion) during which project teams identify how their project supports NASA's strategic goals and develop technological and preliminary project designs. Once the Formulation Phase is confirmed, the project is approved for implementation. Divided into Phases C (final design and fabrication) through F (closeout), the Implementation Phase is where development and operation project plans are executed, and control systems are used to ensure they align with NASA's strategic goals. Phase D includes activities such as system assembly, integration, test, launch, and check out, and Phase E is characterized by operations and sustainment. After a project has been implemented, continuous evaluation of a project's status is conducted, including ongoing independent reviews and assessments.

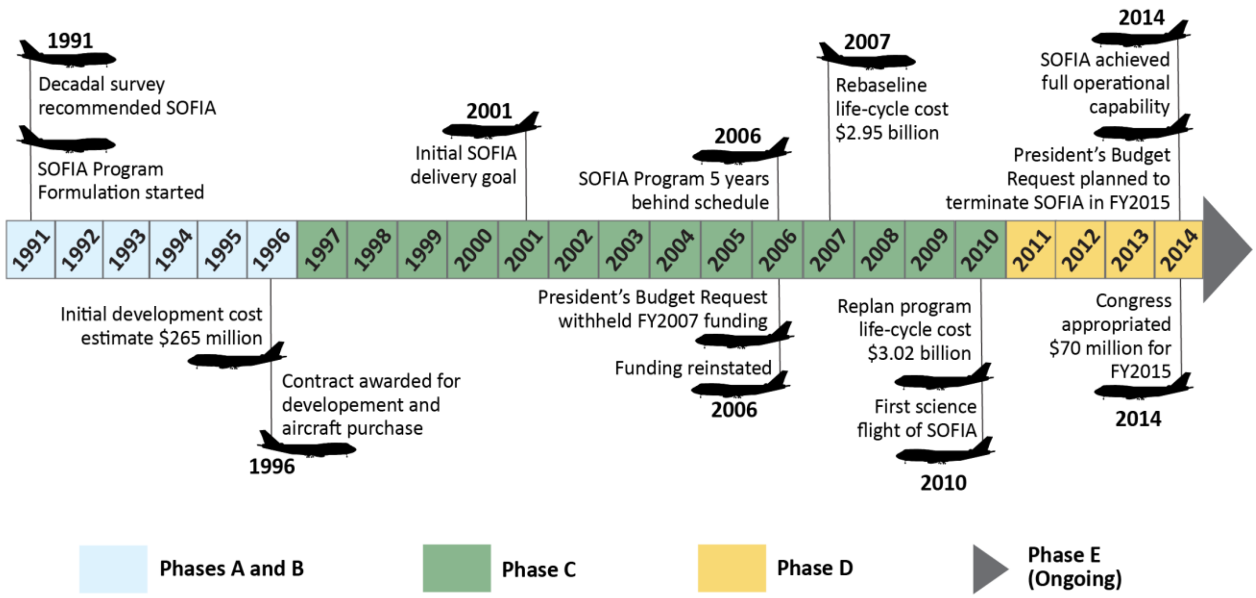
[14] National Research Council, *The Decade of Discovery in Astronomy and Astrophysics* (1991). The National Research Council was the research arm of the National Academy of Sciences. In July 2015, the institution became known as the National Academies of Sciences, Engineering, and Medicine.

[15] Moderate-sized programs are defined as programs that can be carried out relatively quickly in response to new scientific or technological developments, focusing research into the most rewarding areas and making possible greater participation by young astronomers.

[16] The resolution of an optical imaging system (such as a microscope, telescope, or camera) can be limited for most observations from Earth due to atmospheric conditions. Diffraction-limited imaging describes an optical system with resolution performance at its theoretical limit or ideal objective. Spectroscopy is the study of the interaction between matter and electromagnetic radiation.

[17] NASA Procedural Requirements 7120.5E, *NASA Space Flight Program and Project Management Requirements (Updated w/Change 18)* (August 14, 2012).

Figure 3: Timeline of SOFIA Program Notable Events and Activities



Source: NASA OIG presentation of Agency data.

While the Program's initial development cost was estimated at $265 million, actual costs totaled $1.1 billion through 2014—more than 300 percent over the initial estimate. Additionally, NASA spent more than 17 years developing SOFIA—13 years longer than originally planned. These significant cost overruns and schedule delays during development resulted in a rebaseline and replan, a major program reorganization, geographic relocations of flight operations, and multiple budget revisions.

By 2006, the SOFIA Program had been in development for 10 years and was nearly 5 years behind schedule. In February 2006, the FY 2007 President's Budget Request eliminated SOFIA funding as a result of ongoing cost growth due to technical and schedule issues but NASA indicated it was conducting an internal review about the Program's future. The Agency concluded there was no scientific or technical reason to cancel the Program and instead significantly reorganized its management structure. NASA assumed control of observatory development from USRA; assigned responsibility for science operations to Ames; and assigned responsibility for platform development, aircraft maintenance, quality assurance oversight, and systems engineering to Armstrong.

NASA also rebaselined the SOFIA Program in July 2007, revising expected costs and establishing a total life-cycle cost estimate of $2.95 billion—$955 million for formulation and development and $2 billion for 20 years of operations. At that time, the Agency estimated the observatory would reach full operational capability in December 2013. In March 2009, we reported that SOFIA Program management had not completed actions required to address long-term servicing needs of the aircraft, failed to obtain an independent cost estimate, and lacked an effective process to evaluate the Program's cost efficiency in meeting schedule milestones.[18]

[18] NASA Office of Inspector General (OIG), *Final Memorandum on Audit of the Stratospheric Observatory for Infrared Astronomy (SOFIA) Program Management Effectiveness* (IG-09-013, March 27, 2009). The Program subsequently implemented our four recommendations for corrective action.

Because of subsequent delays related to the cavity door system, in October 2010 NASA again increased development cost estimates for the Program to $1.1 billion and delayed full operational capability to December 2014. The Standing Review Board for the 2010 replan highlighted an erosion of the altitude capabilities of the SOFIA aircraft due to the repositioning of the telescope, noting it may lead to compromises in the scientific performance of the system.[19] Moreover, the Board did not believe the goal of full operational capability was a meaningful metric and stated the goal was driving the Program to meet quantity of flights rather than good quality science data. SOFIA incorporated initial operational capability as a milestone and started commissioning instruments and flying science flights in 2010.[20]

In February 2014, the Administration attempted to terminate the Program again by significantly reducing SOFIA's budget to $12.3 million in the FY 2015 President's Budget Request, citing its high cost and the Agency's need to attract an additional financial partner. However, Congress continued to support the Program and appropriated $70 million that year.

We issued a second audit report in July 2014 that found the Agency needed to ensure a consistent infusion of new technology, revise the methodology for calculating researcher funding, reevaluate the number of research hours SOFIA can fly per year, and implement periodic assessments on the cost efficiency of SOFIA's science return.[21]

SOFIA Program Status 2015 through 2020

In 2015, NASA modified SOFIA's Technical Performance Commitment by adding a prime mission duration of 5 years (from the end of FY 2014 during which SOFIA entered Phase E and achieved full operational capability, to September 30, 2019), but did not change the Program's 20-year operations capability requirement.[22] The 5-year prime mission change appears to correlate with NASA's intention, as we recommended in 2014, to periodically assess the cost efficiency of SOFIA's science return.[23] At the end of a prime mission, NASA assesses the science performance, management, and proposed future science program of its missions to decide whether an extension is warranted, a process usually conducted through a Senior Review.[24] The Senior Review process is designed to assess and prioritize the scientific merits of NASA's operating missions. The actions that can result from a Senior Review

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[19] The Standing Review Board is an independent advisory board chartered to assess programs and projects at specific points in their life cycle and to provide the program, the Decision Authority, and other senior management with a credible, objective assessment of how the program is progressing relative to Agency criteria and expectations.

[20] Initial operational capability is a point in time during development when a system can meet the minimum operational capabilities for a researcher's stated need, whereas full operational capability is when the system is delivered to a researcher and they have the ability to fully employ and maintain it to meet operational needs.

[21] NASA OIG, *SOFIA: NASA's Stratospheric Observatory for Infrared Astronomy* (IG-14-022, July 9, 2014). The Program subsequently implemented our 10 recommendations for corrective action.

[22] The Technical Performance Commitment, part of the Program Commitment Agreement, summarizes technical performance requirements, identifies baselines and thresholds needed to achieve program objectives, and demonstrates traceability to Agency strategic goals and outcomes and Agency requirements.

[23] IG-14-022.

[24] The Senior Review practice was codified in the NASA Transition Authorization Act of 2005: "The Administrator shall carry out biennial reviews within each of the Science divisions to assess the cost and benefits of extending the date of the termination of data collection for those missions that have exceeded their planned mission lifetime." The NASA Authorization Act of 2017 modified the review period to 3 years. Historically, members of the Senior Review Subcommittee have been affiliated with academic institutions, museums, and research centers.

include allowing a mission to pass from its prime phase into extended operations, maintaining the status quo, or significantly restructuring or terminating the mission.[25] However, in each year SMD has planned a Senior Review for astrophysics missions since 2015, Congress has prohibited SOFIA's inclusion in the process.[26]

In July 2016, NASA and DLR extended their Memorandum of Understanding for DLR to continue receiving 20 percent of SOFIA observation time in exchange for providing telescope assembly and support and funding the German share of the total costs of operating SOFIA on a long-term, continuing basis, in cooperation with NASA. Another extension of the Memorandum of Understanding is due in December 2020.

Also, in March 2017, NASA awarded USRA an 18-year cost-reimbursement contract (includes a 5-year base with six 2-year options and a 1-year option for close-out) with a value up to $513.8 million.[27] The contract includes performance incentives that reward USRA for cost control, cost reduction, schedule performance, technical performance, science engagement and return, and small business subcontracting.

SOFIA completed its 5-year prime mission on September 30, 2019, after which NASA was required by law to conduct a Senior Review of the Program. However, Congress prohibited NASA from including SOFIA in the 2019 Senior Review.[28] In response, the Agency conducted two alternative reviews of SOFIA: (1) the SOFIA Operations and Maintenance Efficiency Review (SOMER) to ensure SOFIA was operationally efficient and effective in planning and executing its science program and (2) the SOFIA Five-Year Flagship Mission Review (FMR) to ensure the Program was and will remain scientifically productive and relevant. The SOMER was completed in April 2019 and concluded that fundamental changes in the management and operational models and workforce construct were necessary to significantly improve flight-hour production and/or reduce program operations and maintenance costs. The FMR was completed in June 2019 and concluded that a new vision and transformative change were needed to strengthen SOFIA's role as a general-purpose flagship-class observatory that takes full advantage of its observational capabilities. In response to the SOMER and FMR, the Program submitted an implementation plan to SMD in January 2020.

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[25] Each mission that participates in a Senior Review submits a proposal outlining how its science investigations will benefit the Astrophysics Division's research objectives over the next several years. The criteria for this evaluation are: the mission's scientific merit, such as unique capabilities and relevance to stated NASA research objectives; promise of future impact and productivity; progress made toward achieving previous recommendations; impact of past scientific results as evidenced by publications and citations; broad accessibility and usability of data; spacecraft and instrument health and safety; observatory stewardship in terms of maximizing the scientific return while minimizing the ongoing costs; plans to prepare for the future by providing the training, mentoring, and leadership opportunities that will expand the skills of its staff, as well as foster the next generation of mission leaders; and the effectiveness of communications and communications plans, including communication with the science community and general public.

[26] H. Rep. No. 115-704, *Commerce, Justice, Science, and Related Agencies Appropriations Bill, 2019* (May 24, 2018). However, Congress initially inserted language indicating that NASA should not include SOFIA in a Senior Review in H. Rep. No. 114-130, *Commerce, Justice, Science, and Related Agencies Appropriations Bill, 2016* (2015). Senior Reviews were held in 2016 and 2019.

[27] Cost-reimbursement types of contracts provide for payment of allowable incurred costs, to the extent prescribed in the contract.

[28] H. Rep. No. 115-704.

The FY 2021 President's Budget Request again proposed terminating SOFIA by reducing the Program's annual budget from approximately $85 million to $12 million to cover storage and disposition of inventory, citing its science productivity and cost effectiveness relative to other large science missions. In March 2020, SOFIA observation flights were suspended because of the COVID-19 coronavirus pandemic, but SOFIA science center operations continued via teleconferencing. In June 2020, NASA announced plans to resume SOFIA flights in July 2020.

SOFIA Has Not Fully Achieved Its Potential

Although responsible for several first-of-its-kind discoveries, SOFIA's 13-year development delay has reduced the Program's ability to produce impactful science in a cost-effective manner. Further, SOFIA has not fully utilized its unique capabilities to serve as an instrument test bed to reduce the risk for future space mission detectors and to fly anytime, anywhere as planned to capture transient events such as comets, eclipses, and other moving targets. As a result, SOFIA's value to the astronomical community has been reduced.

SOFIA Contributions to Science

Despite its many challenges, SOFIA has made significant technical and scientific achievements. For example, the development of the HAWC+ instrument allows the observatory to measure magnetic field structure at wavelengths at or near the peak of the thermal dust emission, a capability unique to SOFIA. Additionally, other scientific achievements include:

- *Feedback in the Orion Bubble*. SOFIA discovered in the Orion Bubble that a massive star transfers more energy into the gas surrounding the star via its stellar wind rather than its starlight as had previously been surmised.
- *Discovery of Helium Hydride*. The helium hydride ion is thought to be the first molecule ever formed in the universe, yet it had not previously been detected. SOFIA discovered a spectral line from helium hydride for the first time and confirmed its existence.
- *Magnetic Field in M82*. In the M82 galaxy (also known as the Cigar galaxy), SOFIA discovered that the magnetic field direction was perpendicular rather than parallel to the plane of the galaxy. Such a perpendicular orientation had never been seen before and is most likely the result of a vast "superwind" blowing out of the poles in the galaxy due to an intense burst of star formation in its nucleus.

Development Delays Caused SOFIA's Expected Operating Environment to Change

When the observatory was initially designated a high-priority in the 1991 Decadal Survey, the National Research Council described SOFIA as a cost-effective mission with costs estimated at $230 million for the decade.[29] SOFIA's first science flight was projected to take place in 1998, and assuming an operating lifetime of 20 years, the mission would end in 2018. In actuality, SOFIA's development costs rose to $1.1 billion and the first science flight did not occur until 2010.[30]

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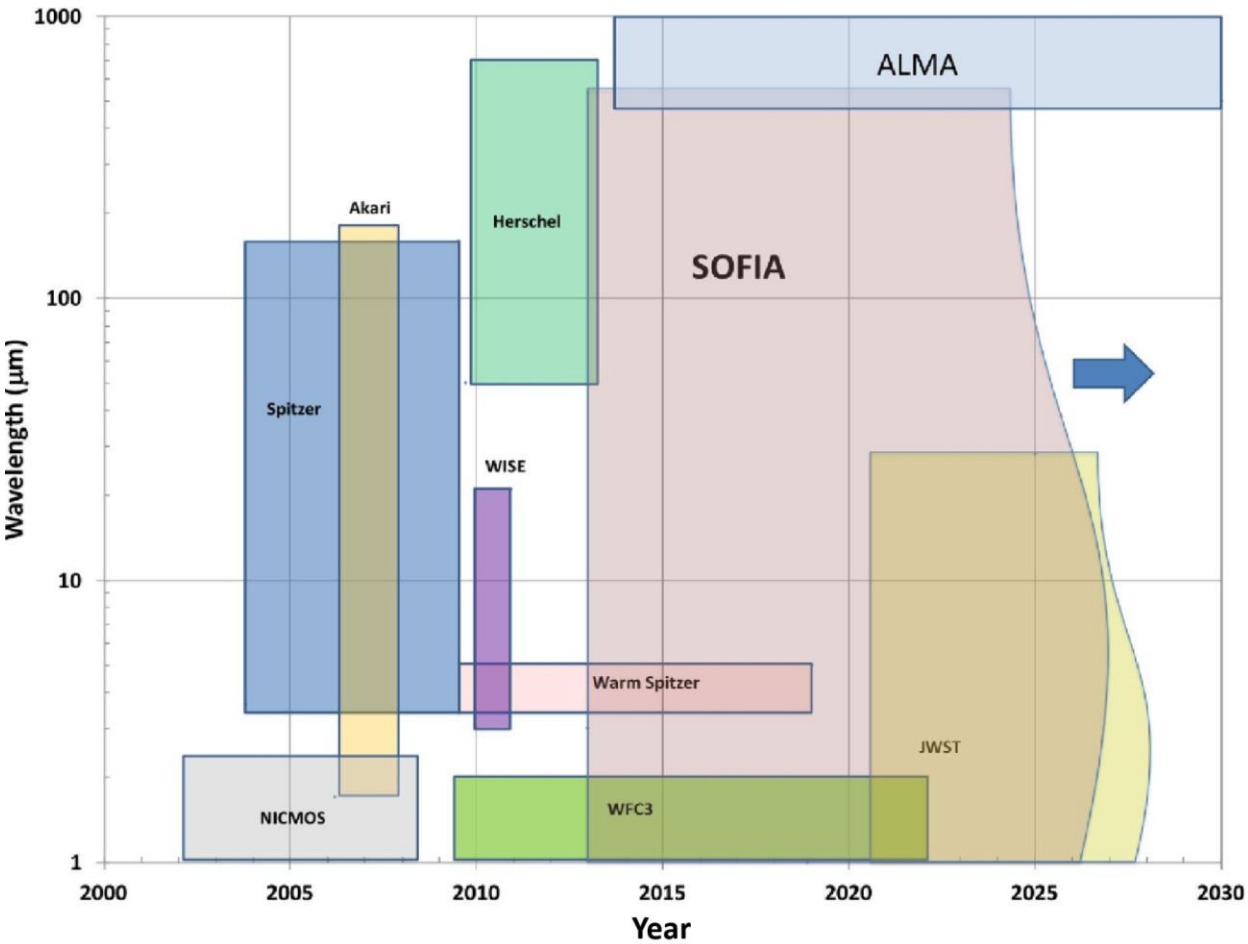
[29] NASA initially estimated the Program's development cost at $265 million.

[30] SOFIA started flying science missions as part of its development activities prior to entering its operations phase.

Members of the astronomical community we spoke to describe this major delay as problematic for two reasons. First, Herschel launched in 2009 and conducted important infrared science observations, some of which SOFIA could have performed. Figure 4 depicts the approximate observing wavelength capabilities and operational timeframes of SOFIA, Herschel, and several other infrared observatories. Note the significant overlap in the wavelength observation capability of SOFIA and Herschel between 60 and 600 microns. As a result, SOFIA subsequently played a supplementary role in producing data for some of Herschel's science. In addition, Herschel performed its mission for less than one-third of the cost, approximately $51,000 per observation hour, versus SOFIA's approximately $172,000 per hour.[31]

Figure 4: Wavelength Capabilities of Infrared Observatories



Source: Harold W. Yorke, Erick T. Young, and Eric E. Becklin, *SOFIA in the era of JWST* (July 6, 2018).

Note: µm is the symbol for micrometer, also commonly known as a micron. Akari is Akari satellite, ALMA is Atacama Large Millimeter/submillimeter Array, NICMOS is Near Infrared Camera and Multi-Object Spectrometer (instrument aboard Hubble), Warm Spitzer is Spitzer's warm mission, WFC3 is Wide Field Camera 3 (imager aboard Hubble), and WISE is Wide-field Infrared Survey Explorer.

[31] As of April 2013, Herschel accumulated 27,300 lifetime observation hours with a life-cycle cost of $1.4 billion, or about $51,000 per hour. Comparatively, SOFIA had actual and planned life-cycle hours of approximately 17,553 with a life-cycle cost of $3 billion to NASA, or $172,000 per hour.

Second, SMD officials believe that while SOFIA was viewed as state-of-the-art when it was first formulated, its sensitivity has been far exceeded in some wavelengths by those of the Atacama Large Millimeter/submillimeter Array (ALMA), which became operational in 2011, and JWST, targeted for launch on October 31, 2021. By current standards, SOFIA lacks sensitivity due to its "warm" telescope.[32] Specifically, because SOFIA's telescope does not have a cryocooler like JWST, its observations are limited to our own and nearby galaxies. Observatories like ALMA and JWST have sensitivities 100 to 1,000 times greater than the capabilities available 15 years ago when SOFIA was developed.

Emerging balloon-borne observatory technologies also threaten SOFIA's scientific value. SMD officials noted that balloon-borne technology has significantly advanced in recent years and can compete with SOFIA in providing comparable science in some of the same wavelengths at a much lower cost. In recent years, balloon-borne observatories have increased their weight capacities, observation altitudes, and total flight time. Additionally, because these observatories fly autonomously, safety risks to pilots and passengers are nonexistent. Further, they have significantly lower development costs. Table 2 details several balloon-borne observatories NASA is currently developing that will operate within SOFIA's wavelength capability.

[32] Sensitivity is a measure of the minimum signal that a telescope can distinguish above the random background noise. The more sensitive a telescope, the more light it can gather from faint objects and the better able it is to study and image more distant objects. Everything that has heat—including the atmosphere, telescopes, and infrared detectors themselves—emits infrared light. Infrared telescopes and detectors need to be kept cool enough in order to not radiate infrared light, thus creating additional random background noise and hindering their ability to detect faint infrared sources in the universe.

Table 2: Balloon-borne Observatory Missions with Instrument Wavelengths Comparable to SOFIA

Mission	Responsible Entities/Partners	Objective and Target	Wavelength	Observation Hours	Development Cost (millions)
ASTHROS[a]	• NASA • Johns Hopkins University • Arizona State University	**Objective:** Understand how galaxies evolve, and map hydrogen in protoplanetary discs and star formation **Target:** Milky Way and its magnetic fields in star-forming regions, Large Magellanic Cloud, and star formation in galaxies	112, 122, and 205 microns	Up to 504 hours (21 days)	$8.3
BLAST[b]	• NASA • National Institute of Standards and Technology • University of Pennsylvania • Arizona State University • Northwestern University • National Radio Astronomy Observatory	**Objective:** Survey the origins of stars and planets, including systems similar to our own solar system **Target:** Cosmic microwave background radiation and magnetic fields in the Milky Way's star-forming regions	250, 350, and 500 microns	Up to 840 hours (35 days)	$2.6
GUSTO[c]	• NASA • University of Arizona • Massachusetts Institute of Technology	**Objective:** Study all phases of the stellar life cycle, from the formulation of molecular clouds, through star birth and evolution, and to the formation of gas clouds and reinitiation of the cycle **Target:** Milky Way, Large Magellanic Cloud, and star formation in galaxies	158 and 205 microns	1,800 hours (75 days)	$40
STARFIRE[d]	• NASA • University of Pennsylvania • California Institute of Technology • Arizona State University	**Objective:** Study cosmic star formation history **Target:** Star formation in galaxies	240 to 420 microns	Up to 672 hours (28 days)	$7.7

Source: NASA.

[a] ASTHROS is Astrophysics Stratospheric Telescope for High Spectral Resolution Observations at Submillimeter-wavelengths.
[b] BLAST is Balloon-borne Large-Aperture Submillimeter Telescope.
[c] GUSTO is Galactic/Extragalactic ULDB Spectroscopic Terahertz Observatory.
[d] STARFIRE is Spectroscopic Terahertz Airborne Receiver for Far-InfraRed Exploration.

SOFIA Has Not Fully Realized All of Its Capabilities

As an airborne observatory that returns to base after every flight, one of SOFIA's key advantages over space-based observatories is that it could be used as a test bed for new instrument technologies (including detectors) that would reduce the risk of instrument failure on future space missions. The 1991 Decadal Survey states SOFIA would be an excellent facility for the rapid development of advanced instrumentation and a natural evolutionary replacement for Kuiper, SOFIA's predecessor. Kuiper developed over 50 instruments in its 21-year operational life compared with the 8 SOFIA has developed as of June 2020. This mission objective has not met expectations because of stricter safety requirements imposed by the Federal Aviation Administration and NASA. These requirements were not in place for Kuiper. SMD management told us that more stringent airworthiness requirements, such as instrument crash survivability, in addition to the increased complexity of SOFIA instruments, resulted in instrument development costs that rival space missions and prevented SOFIA from becoming a test bed for assessing new instrument technology.

Furthermore, SMD officials and SOFIA researchers we spoke to do not believe SOFIA has delivered on its planned capability to fly anytime, anywhere to conduct science. They note that a lack of instrument scheduling flexibility and the amount of time necessary to switch out instruments makes it difficult to observe targets of opportunity. For example, observing transient targets, such as a supernova, occultation, and eclipse, may require a particular instrument and for SOFIA to be at a particular location on the globe, which at times has been difficult to schedule.[33] Program officials stated that they have considered these types of observation proposals a lesser priority because they were generally of lower science value when compared to other observations.

Additionally, researchers report that the unknown timing of instrument availability for an upcoming observation cycle limits their ability to select appropriate astronomical targets—especially moving targets—during the proposal process. Specifically, the instrument schedule is established based on demand after all proposals are submitted.

SOFIA's equipment logistics and heavy reliance on human operators to execute observations relative to that of space observatories has led to limitations on the amount and quality of science that can be conducted. This is particularly evident in its limited deployments to New Zealand. Flights from New Zealand are in high demand from researchers due to interest in astronomical targets that may only be viewed from the southern hemisphere. Compared to the flights from Palmdale, those from New Zealand yield higher data quality and require 24 percent fewer observation hours to produce a publication due to lower atmospheric water vapor in that region. Additionally, SMD officials stated that the Program has been reluctant to schedule flights around the winter holiday months, which coincides with the time of year when atmospheric conditions are the most favorable to return high quality data for flights originating from Palmdale. Program officials stated they plan to fly more during the winter months in future cycles.

Program officials have acknowledged the superior observing conditions of flights originating from New Zealand and in 2019 proposed a new mission objective during SOFIA's FMR to increase southern hemisphere flights to a minimum of 411 research hours annually. While the FMR panel did not present specific goals, they concurred that SOFIA should fly more southern hemisphere flights and

[33] A supernova is a powerful and luminous explosion of a star and is the largest explosion that takes place in space.

recommended considering an additional southern latitude location to conduct flight operations. Since the FMR, SOFIA has reduced its goal significantly. In fact, through the three upcoming observation cycles the number of projected New Zealand flights will provide 224 research hours for Cycle 8 and 280 for Cycles 9 and 10.[34] Through the most recent observation cycle (which ended in March 2020), the highest number of southern hemisphere research hours SOFIA achieved in a year was 200 hours. Achieving 411 annual research hours would require a significant increase in southern hemisphere deployments relative to duration, frequency, or both. However, it is not clear that SOFIA is capable of such increased deployments. Program officials noted the difficulties the current deployment schedule placed on staff being away from home and family for an extended period of time as well as the expense of such deployments.[35]

[34] The Program canceled the Cycle 8 deployment to New Zealand due to the COVID-19 coronavirus pandemic. Consequently, in July 2020 the Program stated they plan to offer 320 research hours in Cycle 9.

[35] In FY 2020, SOFIA spent approximately $3 million for contractor support during flight operations away from Palmdale.

Operational and Technical Challenges Resulted in Reduced Science Productivity and Research Capability

After 6 years of full operation, SOFIA continues to experience technical and execution challenges with its flight operations, observation completion, data processing, and instrument development. As a result, SOFIA has been unable to achieve science productivity levels commensurate with its costs and stakeholder expectations. These ongoing challenges, if unaddressed, will limit the Program's ability to achieve its current goals and its ability to maintain a significant role in the current observatory landscape.

SOFIA Has Not Achieved Research Hour Expectations

SOFIA has not yet achieved the 960 annual research hours it was designed to provide the astrophysics community as noted in the 2010 Program Commitment Agreement (PCA) established from the 2010 replan, resulting in less science output than expected.[36] In the 2015 PCA, SMD removed the 960-hour requirement by Cycle 5 and gave the Program the discretion to establish the amount of planned research hours for each cycle. They also established an 80 percent completion rate goal for the Program's planned research hours. Table 3 provides the research hours the Program baselined each cycle and the research hours actually accomplished. The Program did not plan to achieve a research hour level consistent with SOFIA design objectives at the estimated costs established in the Program's 2010 rebaseline until Cycle 7. Moreover, they have yet to actually achieve even that level of productivity. As Table 3 illustrates, SOFIA has generally achieved the 80 percent requirement from the 2015 PCA. However, while the number of research hours the Program completes annually continues to increase, the Program has fallen almost 900 hours short of the research hour goals through Cycle 7.[37] As a result of the reduced productivity, as Table 3 shows, beginning with Cycle 5 NASA has paid more per actual research hour completed than estimated at the 2010 replan.

[36] The PCA identifies broad program objectives, the program's relationship to Mission Directorate goals, program overview and authority, technical performance requirements, schedule and cost commitments, acquisition strategy, high-risk areas, internal and external agreements, required reviews, and expected outcomes.

[37] Cycle 7 was impacted by the COVID-19 coronavirus pandemic, unplanned maintenance, and weather-related cancellations.

Table 3: Research Hours by Cycle

	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Cycle 6	Cycle 7	Cycle 8
	4/11/13-2/4/14	2/17/14-2/28/15	3/1/15-1/31/16	2/1/16-2/3/17	2/4/17-1/2/18	5/19/18-4/26/19	4/27/19-3/12/20	4/25/2020-4/23/2021
Baselined Research Hours	313	256.3	548	808	758	860	1,169	928
Actual Research Hours	207.5	313	527.3	646.9	601.7	751.1	786.3	TBD
Percentage of Hours Achieved	66%	122%	96%	80%	79%	87%	67%	TBD
Estimated Cost Per Research Hour at Replan	N/A	N/A	N/A	N/A	$81,615	$122,109	$78,255	TBD
Actual Cost Per Research Hour Completed	N/A	N/A	N/A	N/A	$130,214	$156,071	$95,542	TBD

Source: NASA OIG analysis and/or presentation of SOFIA Program data.

Note: Cycle 8 start and end dates will change due to COVID-19 coronavirus pandemic mitigation efforts. For Cycles 1 through 4, SOFIA did not have an annual research hour expectation and therefore, an estimated cost per research hour at replan could not be determined for those periods of time.

A key reason for SOFIA's reduced research hours is that it does not meet expectations for achieving the scheduled number of flights. Specifically, the aircraft has not met the Program's stated dispatch rate goal of 90 percent (flights planned divided by the flights actually conducted) since beginning operations in 2014.[38] SOFIA Program management calculates the dispatch rate using a rebaselined flight schedule to reflect operational decisions, such as extending the cycle and rescheduling flights when aircraft maintenance takes longer than expected. However, our calculation of SOFIA's dispatch rate measures the actual flights achieved against the baseline flight schedule for each cycle. In our opinion, this approach more accurately reflects the observatory's dispatch rate. Table 4 shows the Program's dispatch rate goal, the Program's calculated rate, and the Office of Inspector General's calculation of the actual dispatch rate. The average dispatch rate for Cycles 2 through 6 is 72 percent, based on our calculation, 18 percent lower than the Program's 90 percent goal. We found that unscheduled maintenance is the primary reason SOFIA is unable to achieve its scheduled flight goals.

[38] In January 2020, the Program proposed to reduce the dispatch rate goal to 80 percent.

Table 4: SOFIA Flight Dispatch Rate (February 2014 to March 2020)

Cycle Number	Flight Dispatch Rate Goal	SOFIA Program Calculation of Flight Dispatch Rate	NASA OIG Recalculation of Flight Dispatch Rate
2	90%	93%	64%
3	90	88	79
4	90	79	82
5	90	64	66
6	90	87	68
7	90	TBD	TBD

Source: NASA OIG analysis of SOFIA Program data.

Note: Cycle 1 was accomplished prior to SOFIA becoming fully operational and therefore not included in this table.

SOFIA does not factor its actual performance in achieving scheduled flights when establishing its baseline research hours. Consequently, the Program overstated the achievable research hours available for each cycle in the annual call for proposals in some cycles. SOFIA is likely selecting too many proposals based on an overly optimistic dispatch rate, which results in an inability to complete observation programs. Incomplete observations negatively impact the researcher's ability to publish their results, affecting SOFIA's science output performance.

SOFIA Is Not Optimizing Research Time in the Stratosphere

SOFIA was designed to fly in the stratosphere above 99 percent of the water vapor that negatively impacts far-infrared astronomy. Accordingly, the altitude and time spent in the stratosphere is a key factor in the quantity and quality of observation data obtained during each flight. Also, the altitude of the stratosphere varies by location on the globe and time of year affecting the efficiency of the flight's profile in producing research time in the stratosphere.

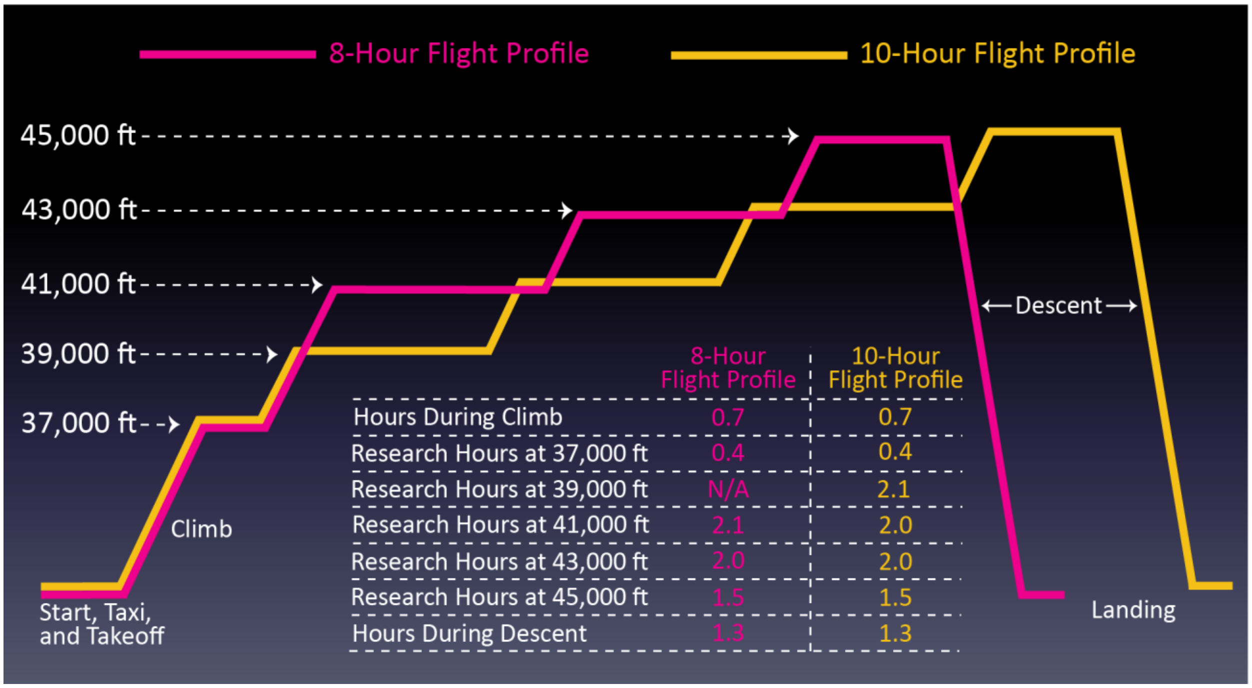
Since reaching full operational capability in early 2014, SOFIA has flown a 10-hour flight profile (the time from takeoff to landing) typically four times per week. However, some SMD management officials and members of the FMR and SOMER recommend an 8-hour flight profile because it is more efficient at achieving flight time in the stratosphere. Program officials agreed that an 8-hour profile flown five times per week can be more efficient and comparable resource-wise depending on the location and time of the year.[39]

Specifically, while a 10-hour profile provides more total flight time than an 8-hour profile, it does not always provide more time in the stratosphere due to stratospheric altitude variation and the weight of the additional fuel needed to achieve the extra flight time. The additional weight increases the time needed for SOFIA to burn off fuel to become light enough to reach higher altitudes, and therefore reduces the amount of time in the stratosphere to a level comparable to an 8-hour flight profile during

[39] The Program is in the process of developing a more nuanced scheduling approach based on historical water vapor content data rather than strictly altitude.

the months of May through November when the stratosphere begins above 39,000 feet.[40] The 10-hour profile requires SOFIA to spend 2.1 hours at 39,000 feet, at an altitude below the stratosphere, to burn off fuel. This is the primary difference between the two profiles as shown in Figure 5. In general, 8-hour flights, five times per week achieves more time in the stratosphere than 10-hour flights, four times per week during these months, an additional 3.5 to 6 hours per week, depending on the month.

Figure 5: SOFIA 8-Hour and 10-Hour Flight Profiles



	8-Hour Flight Profile	10-Hour Flight Profile
Hours During Climb	0.7	0.7
Research Hours at 37,000 ft	0.4	0.4
Research Hours at 39,000 ft	N/A	2.1
Research Hours at 41,000 ft	2.1	2.0
Research Hours at 43,000 ft	2.0	2.0
Research Hours at 45,000 ft	1.5	1.5
Hours During Descent	1.3	1.3

Source: NASA OIG presentation of SOFIA Program information.

Note: Feet (ft).

Through Cycle 6, SOFIA has completed 375 science flights achieving 2,139 of 2,893 planned stratospheric research hours (74 percent). Research flight time in the stratosphere is important because data collected below the stratosphere is typically not of the highest quality due to water vapor levels. For example, during a test flight a supernova remnant was observed both in and below the stratosphere but the data collected from below the stratosphere did not have sufficient brightness to be useful to the researcher.[41]

The FMR panel believes that performing observations in the stratosphere is the single most important thing SOFIA can do to increase its scientific return. Further, an FMR representative believes that poor data quality has been one of the major limitations to SOFIA's productivity and will continue to result in fewer publications. An observatory's long-term productivity is affected in part by its ability to attract the astronomical community to its data archives with high quality data and compelling observations.[42]

[40] For the months of July, August, and September, the stratosphere is above 45,000 feet for flights originating from Palmdale and neither flight profile reaches the stratosphere.

[41] A supernova remnant is the structure resulting from the explosion of a star in a supernova.

[42] Observatories produce publications via both the researcher executing the observation and the astronomical community accessing the observatories' data archives.

To this point, after 10 years of data collection SOFIA data archives have produced 8 publications—5 percent of SOFIA's total publications. For comparison, Hubble had 9 publications from its archive the first year of operations. Further, after 10 years of data collection, Hubble had 877 of its 2,867 publications (31 percent) derived from its archive.

In response to recommendations from the SOMER and FMR, the Program incorporated 36, 8-hour flights into the planned Cycle 8 schedule during a 9-week period that was scheduled to begin in April and run through June 2020.[43] The 8-hour flights are scheduled to be flown four times per week, with 1 week of five flights and 1 week of three flights. By scheduling fewer than five flights per week the Program is not optimizing the potential amount of research hours above the stratosphere. Additionally, the Program did not schedule any flights during October because of planned maintenance and did not schedule any 8-hour flights during November. An 8-hour flight profile five times per week, when SOFIA is flying out of Palmdale from May through November, appears to be the more productive option for obtaining high quality data.

SOFIA Is Not Meeting Science Productivity Expectations

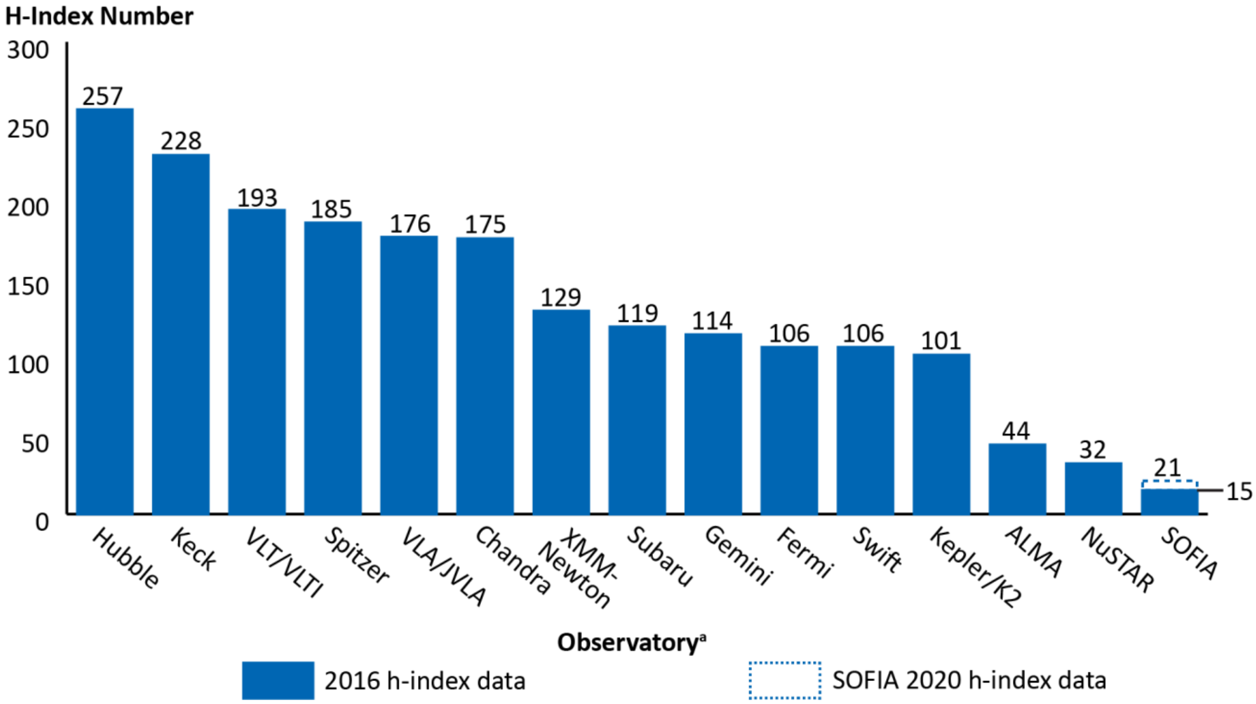
According to SMD management, SOFIA has not met the expectation of delivering "Great Observatory-class" science. While its scientific productivity has improved in recent years, its performance in producing publications and citations is significantly below what is expected for a mission of SOFIA's budget in its 7th year of operations. Specifically, SOFIA's h-index—an accepted standard intended to measure simultaneously the quality and quantity of scientific output—is significantly lower compared with other observatories.[44] A study by the Space Telescope Science Institute compared 2016 h-index values across 15 different ground- and space-based observatories and found that SOFIA's h-index value of 15 was at the bottom of all those observatories by a significant margin.[45] Although SOFIA's h-index value improved to 21 in 2020, it still trails all the other observatories (see Figure 6).

[43] The schedule for Cycle 8 will be revised due to impacts from the Agency's COVID-19 coronavirus pandemic response and Program managers stated they will consider the feasibility of adding additional 8-hour flights to the schedule.

[44] The h-index is calculated using publications and citations. A lower h-index number signifies a lesser quality and/or lesser quantity of science output.

[45] Jenny Novacescu, Space Telescope Science Institute, *Comparative h- and m-indices for Fifteen Ground- and Space-Based Observatories* (March 15, 2017).

Figure 6: H-Index for Ground and Space Observatories



Source: NASA OIG presentation of Space Telescope Science Institute information and SOFIA Program data.

Note: The data in this figure is from 2016, including SOFIA's h-index of 15. Its h-index rose to 21 in 2020, 6 years after SOFIA reached full operational capability and 8 years after the first scientific paper was published. The graph represents NuSTAR's h-index 4 years after the first scientific publication and ALMA's h-index 5 years after the first scientific publication. Like SOFIA, Kepler/K2's h-index represents 8 years since the first scientific paper was published.

[a] Keck is W.M. Keck Observatory, VLT/VLTI is Very Large Telescope/VLT Interferometer, VLA/JVLA is Karl G. Jansky Very Large Array, XMM-Newton is X-ray Multi-Mirror Mission, Subaru is Subaru Telescope, Gemini is Gemini Observatory, Fermi is Fermi Gamma-ray Space Telescope, Swift is Swift Gamma-Ray Burst Mission, Kepler/K2 are the Kepler and K2 Missions, and NuSTAR is Nuclear Spectroscopic Telescope Array.

Incomplete Observation Programs Limit Science Output

SOFIA defines an observation program as complete after at least 80 percent of its awarded observation time has been performed. The FMR recommended the completion of at least 80 percent of high-priority programs because it improves the likelihood the observation will result in a publication. Our analysis of data from April 2013 to February 2017 found that completed observation programs were over two times more likely to produce a publication than incomplete programs.[46] Additionally, according to SMD and SOFIA program officials, publications resulting from incomplete programs are less likely to be impactful since they are reporting only partial results.

[46] Based on publication data through Cycle 4, to allow for 2 years to publish after cycle completion: 45 out of 99 complete observation programs produced at least one publication (45 percent), whereas only 34 out of 160 incomplete observation programs produced at least one publication (21 percent).

A SOFIA observation program may not be completed or may not start at all due to various reasons, including canceled flights because of aircraft maintenance issues, or an inability to schedule flights when astronomical targets are available. For Cycles 1 through 6, SOFIA completed between 36 and 63 percent of the high-priority observation programs selected.[47] Additionally, during those same cycles 20 percent of high-priority programs were never started. Both of these factors contributed to SOFIA's publication rate of about 34 percent for high-priority programs selected in the first four observation cycles.[48]

The Program has taken steps to increase observation program completion rates by carrying over incomplete programs from one cycle to the next and selecting proposals more likely to be completed. The incomplete programs carried over from one cycle to the next are allocated additional observation time. The Program implemented a final technical review starting in Cycle 8 to ensure selection of proposals more likely to be completed. While these are both positive steps, carrying over incomplete programs will limit the number of available observation hours for new programs in future cycles. In addition, the SOFIA Program has not been tracking the reasons for incomplete observations on a program-by-program basis. As a result, the Program lacks the information necessary to identify the root causes of incomplete observation programs and take additional steps to increase completion rates.

SOFIA Observation Data Delivery Is Untimely

SOFIA continues to experience challenges processing observation data in a timely manner, an issue we noted in 2014.[49] The data produced during an observation is stored on hard drives aboard the aircraft and then subsequently transferred to Ames for processing and calibration. Generally, data needs to be processed and calibrated to the Level 3 category to be useful to researchers.[50] Level 3 data delivery requirements to the science community and researchers vary by the type of instrument, facility, or principal investigator, and range from 21 to 84 calendar days (the number of days starts from the date of observation and ends upon delivery).[51] As Figure 7 illustrates, except for EXES in Cycle 7, SOFIA did not meet data delivery requirements for any instrument during Cycles 6 and 7, with delivery times ranging from 35 to 124 days and 10 to 194 days, respectively.[52] According to Program officials, the delays resulted from the large number of operating modes for various instruments and corresponding number of calibration methodologies, problematic data due to poor instrument performance, and an insufficient number of staff to process the data. For example, a degradation of the FORCAST instrument's optics starting in Cycle 6 resulted in poor background subtraction and other inherent limitations that could not be addressed by the subsequent data refinement process.

[47] SOFIA did not have a completion goal until the March 2020 Strategic Plan, which set a goal of 90 percent. The FMR stated the goal should be 80 percent.

[48] Cycles 5 and 6 are not included in the calculation of this rate because publications may still be produced based on a 2-year publication cycle.

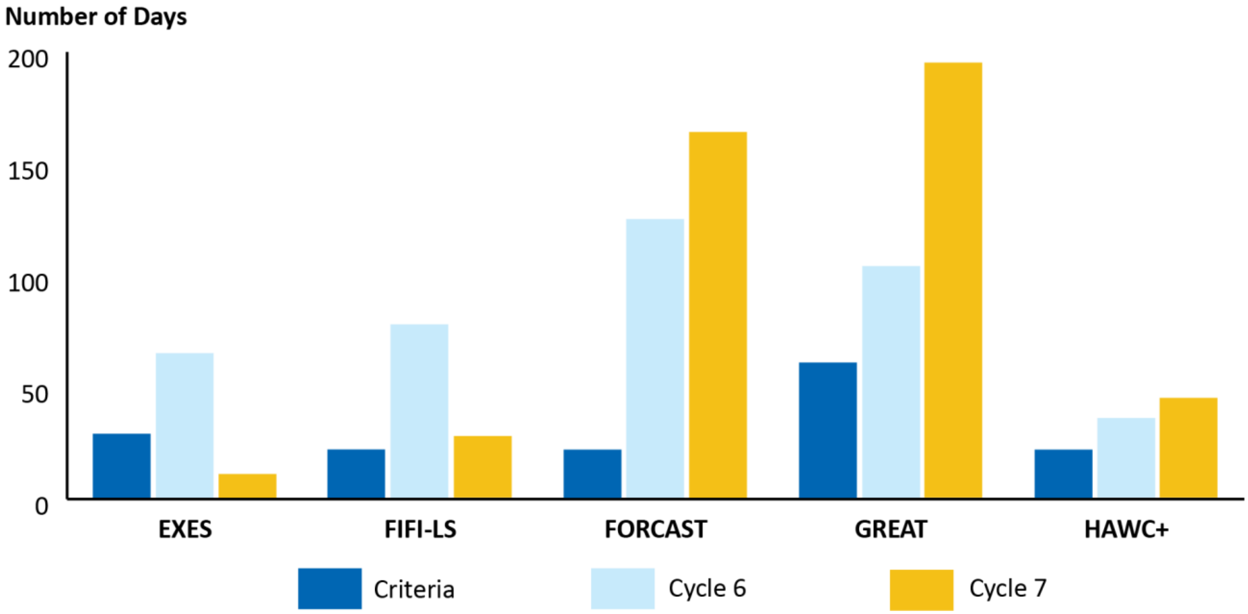
[49] IG-14-022.

[50] Observation data is divided into three levels and categorized as Level 1, 2, or 3. Level 1 is raw data provided by SOFIA instruments that has been converted to a standard format. Level 2 is data that has been corrected for instrument artifacts (e.g., bad pixels are removed). Level 3 is data that has been calibrated and made available to the science community in the SOFIA data archive.

[51] Facility instruments are designed, developed, and operated by a NASA Center or designee and their data reduction and delivery are managed by USRA. Principal investigator instruments are designed and developed by individual researchers or organizations other than NASA, and their data reduction is managed by the principal investigator and published on SOFIA's Science Center website.

[52] As of April 2020, Cycle 7 observations were still being executed.

Figure 7: Level 3 Data Release by Science Instrument for Observation Cycles 6 and 7



Source: NASA OIG presentation of SOFIA Program data.

Note: Criteria refers to the number of days Level 3 data is required to be released to researchers after observation. Cycles 6 and 7 data refer to the number of days it actually took to release that data.

The timeliness and quality of the data delivered to researchers directly impacts their interest and ability to publish papers based on that data. Some researchers we surveyed indicated their frustration at the consistently late delivery of data, which caused them to lose interest in the observation.[53] Researchers also noted that subpar quality data impedes meaningful conclusions and in one instance caused the retraction of a paper. Both scenarios result in reduced science productivity for SOFIA.

A significant contributing factor to SOFIA's data delivery challenges is its Water Vapor Monitor, which has not functioned at a level that can support reliable data processing. Although SOFIA is able to fly in the stratosphere above 99 percent of water vapor in the Earth's atmosphere the aircraft does not always fly in the stratosphere. Even when it does, there is sufficient residual water vapor in the stratosphere to have a noticeable effect on most far-infrared observations. The Water Vapor Monitor is intended to measure residual water vapor continuously during flight to support accurate calibration of observation data.

Because the Water Vapor Monitor is an outdated design that cannot provide reliable data, it has not worked properly and the Program had to develop various workarounds to obtain the measurements necessary to properly calibrate observation data. This included developing and integrating an internal water vapor measurement capability for some instruments; relying on meteorology reports; and as in the case with FIFI-LS, the instrument scientists performing water vapor measurements as they execute their observations. These workarounds add time and effort to the data calibration process and often

[53] We surveyed a judgmental sample of 225 SOFIA researchers, of which 26 responded (a response rate of 11.6 percent). The sample includes all researchers who were not Program staff and the survey inquired about program completion, scheduling, data, instruments, and SOFIA viability.

burden the instrument scientists with additional tasks during the observation. The Program continues to work on resolving the issues with the Water Vapor Monitor but does not appear optimistic.

In our survey, we queried researchers to determine if they had any concerns with the timely delivery of data from their observations. Thirteen of the 26 who responded expressed concerns about the timely delivery of data, specifically with the FIFI-LS and FORCAST instruments. They noted that the lack of an effective data reduction and refinement process significantly impacted FIFI-LS science productivity. Additionally, 6 researchers expressed frustration with not receiving data on time from FORCAST, with one waiting up to 7 months for the data. Three researchers also reported that the lack of timely data will likely discourage them from proposing to use SOFIA in the future. Additionally, one researcher of FIFI-LS stated he was unable to work on his observation data for 8 months because he needed water vapor data to make necessary corrections. Another researcher who was able to get the data privately ahead of a 9-month data release delay stated that if he had waited for the official data it is highly likely he would have moved on to another project and not published a paper using SOFIA data.

USRA Award Fee Not Tied to Science Productivity

NASA awarded a follow-on, cost-reimbursement contract with an award fee element to USRA in 2017 to manage the Program's science operations. The contract has the potential to run through 2035 and is valued up to $513.8 million, including a maximum of $24.9 million in award fees. The award amount is used to provide motivation for excellence in achieving cost, schedule, technical performance, and desired program outcomes. However, NASA has not adequately assessed science productivity when determining the contractor's annual award fee. Specifically, the contractor's performance ratings have been based primarily on subjective judgements and were not adequately tied to the primary science productivity metrics—publication and citation rates—that are standard across the astronomical community.

USRA's award fee, which was worth up to $1.3 million for FY 2019, is based on the following criteria: cost control, cost reduction, schedule performance, technical performance, science engagement and return, and small business subcontracting. The science engagement and return category, which includes publications and citations, was weighted at 18 percent during FY 2018. Therefore, the vast majority of the award fee determination (82 percent) was based on the contractor's performance in categories that were not directly related to science outcomes. NASA recognized this weighting was too low and subsequently increased the percentage of the award fee determined by the science engagement and return category to 28 percent for FY 2019 and then 50 percent for FY 2020. Allocating a greater portion of the award fee to science outcomes increases the importance of using objective measurements and standard observatory metrics to support the ratings and could be a positive step in ensuring greater accountability for contract performance.

USRA received favorable performance ratings of "very good" in FYs 2018 and 2019 for the science engagement and return category.[54] This category includes publication and citation rates—the most important observatory metrics—but those ratings are generally not supported by objective measurement or quantitative metrics. For example, the FY 2018 performance report noted that SOFIA's publication production rate was low but improving. Further, the FY 2019 report noted that two individual publications were well received and the contractor was doing a very good job tracking and

[54] Federal Acquisition Regulation 16.401 establishes five rating categories within a 100-point system: Excellent (100–91), Very Good (90–76), Good (75–51), Satisfactory (50), and Unsatisfactory (49 and below).

presenting publications at monthly reviews, but also noted an urgent need to dramatically increase research paper production. There is no mention of the actual number of publications or citations produced in either of the performance years. Instead the performance reports cite metrics not tied to outcomes—such as the oversubscription rate—in the evaluations.[55] The oversubscription rate is designed to measure the astronomical community's interest in using SOFIA. While this metric has been trending up, it can be misleading. For example, from Cycle 7 to Cycle 8 the metric increased from 4.8 to 6.6 (an increase of 27 percent) not just from prospective researchers requesting more observation hours, but also by SOFIA offering less hours. Specifically, the increase was mainly due to 21 percent fewer observation hours available than the previous cycle. Moreover, when examining the total number of proposals submitted during the same time period, we found only a 3 percent increase from Cycle 7 (190 proposals) to Cycle 8 (196 proposals).

Taking a quantitative approach to measuring publications as part of the performance rating would ensure stronger accountability for results. SOFIA management reported that in FY 2020, and going forward, they plan to place a greater emphasis on the achievement of publications and citations when evaluating the contractor's performance. While this should improve the effectiveness of the award fee evaluation process, the level of success will depend greatly on whether they establish goals that can be tied to objective, quantitative ratings criteria.

Lack of New Technology Development and Instrument Updates

In 2014, we reported that the ability to update SOFIA's technical capabilities is one of the Program's primary advantages and an important justification for its relatively high operating cost.[56] The astronomical community has identified introduction of new technology as the most important factor in ensuring SOFIA's long-term relevance and success. At that time, the research community expressed that new technology should be introduced into SOFIA's instrument suite approximately every 2 years. This has not occurred and as of May 2020 there were no new instruments in development.

Since our 2014 report, SMD has not introduced new technology at a rate commensurate with researcher community expectations, has not developed any new instruments, and only implemented one upgrade, HAWC+ in 2016.[57] Additionally, SMD canceled development of its latest science instrument, the High Resolution Mid-Infrared Spectrometer (HIRMES), which was considered by some SMD and Program officials to be crucial for SOFIA's future in producing high-value science.[58] HIRMES started development in September 2016 for delivery in December 2018 with an estimated cost of $17 million. However, a lack of maturity in HIRMES' critical technology resulted in five replans, significant projected cost growth

[55] The oversubscription rate is calculated by dividing the number of observation hours that prospective researchers request during the annual call for proposals by the number of observation hours available. For example, if prospective researchers request 200 hours of observation time and only 100 hours are available, the oversubscription rate is 2.

[56] IG-14-022.

[57] HAWC+ is a second-generation instrument. While HAWC, its predecessor, was developed and intended to be part of SOFIA's original suite of instruments, it was never commissioned.

[58] HIRMES was intended to observe protoplanetary disks; detect water vapor; and study young stellar objects, the solar system, and nearby galaxies through high spectral resolving power, unprecedented sensitivity, low resolution spectroscopy, and high spectral mapping speed that either matches or surpasses the capabilities of Herschel, Spitzer, and JWST.

of $55.6 million, delivery delays of almost 4 years, and de-scoping in capability. Due to these factors, SMD terminated HIRMES development in April 2020.

SMD and the Program's inability to properly manage the development of HIRMES and deliver the final product will significantly impact SOFIA's science productivity. Specifically, the Program will have to restart the process of formulating and developing a new technology. In our opinion, the elimination of this new cutting-edge technology expected by the user community will also reduce their interest in SOFIA. Moreover, the Program expected HIRMES to increase its science productivity, which would have been beneficial during SOFIA's 2022 Senior Review. Further, the $32 million spent developing HIRMES before its cancellation instead could have been spent on needed upgrades to existing instruments that would have also improved SOFIA's science productivity.

SOFIA researchers and Program officials agree that upgrades to existing instruments could increase observation efficiency and help mitigate SOFIA's lack of observation time by enabling instruments to map larger areas of the sky during the same amount of observation time. For example, a proposed technical improvement to FIFI-LS's capability could increase its efficiency by 160 percent by adding an additional observation mode. Increased scientific observations and archival data could lead to higher near-term publication and citation rates. Another potential upgrade which could improve productivity exists with the HAWC+ instrument. HAWC+ was designed with four detector arrays, but only three were installed and one is not fully functional. Two new detectors could be installed for $4 million, which could double the instrument's capacity and reduce the research time to obtain the same amount of data or obtain additional data in the same amount of research time.

We also found that SOFIA's science instrument disposition procedures do not ensure non-productive instruments are retired in a timely manner, nor does the Program track the cost of maintaining its suite of instruments to be able to assess whether Program funds are being used efficiently. For example, the First Light Infrared Test Experiment Camera or FLITECAM—an infrared camera and spectrometer—only produced two papers yet it was maintained and active for 5 years from 2013 to 2018. In comparison, GREAT produced 33 papers during the same period. Maintaining non-productive instruments in an operationally ready state requires resources that could be put to better use, such as the development of new instruments or maintenance of more productive instruments.

SOFIA Lacks Clear and Achievable Science Output Performance Requirements

The absence of clear and achievable performance expectations and lack of concurrence between SMD and SOFIA management on science output expectations and goals has reduced productivity and threatens the Program's future viability. SMD established performance requirements focused on Program operations such as research flight hours per year, and consequently does not hold the SOFIA Program accountable for science productivity output such as publication and citation metrics.

Lack of Science Requirements and Performance Metrics Has Reduced SOFIA's Science Productivity

In the absence of specific science requirements and objectives, SOFIA has focused primarily on operations and left SMD management without criteria for properly monitoring and assessing the Program's science achievements or mission success. In an effort to give SOFIA more mission flexibility, SMD did not establish detailed science requirements or objectives in its official Program Plan or PCA, which is atypical for an SMD mission.[59] As a result, it is difficult for NASA to hold the SOFIA Program accountable for poor levels of science productivity, particularly when compared to other large science missions. SOFIA and SMD management acknowledged the lack of a science-driven mission focus for the SOFIA Program. This was also a key finding in the FMR panel's evaluation of SOFIA in 2019.

SMD missions, such as Hubble, JWST, and Spitzer, have detailed Level 1 science requirements—the mission's fundamental and basic set of requirements and specific science goals—that directly relate to the science themes for their respective mission. These missions pose science questions and define the specific objectives and requirements necessary to answer those questions. For example, NASA's Nancy Grace Roman Space Telescope—formally known as the Wide Field Infrared Survey Telescope—currently scheduled to launch in the mid-2020s is expected to answer specific questions regarding exoplanets, such as, *what is the frequency of habitable worlds* and *what determines their habitability*. The mission then defines a series of highly detailed objectives and requirements the observatory must achieve in order to answer those questions. The detailed objectives and requirements include completing the statistical census of planetary systems in the galaxy; measuring the frequency, mass, and separation distribution of outer habitable zone planets; and detecting at least 150 Earth-mass planets. Detailed objectives and science requirements serve as criteria that allows SMD and program management to evaluate mission success.

[59] The Program Plan is an agreement among the program manager, Center Director, and Mission Directorate Associate Administrator that provides program goals and objectives, stakeholders, baselines, and control plans. The most recent signed version was in 2014.

In contrast, SOFIA's Program Plan and PCA identifies general science themes that will be studied, such as the birth of stars in our galaxy, planet formation in nearby solar systems, interstellar cloud physics, protoplanetary discs, and the origin and evolution of biogenic atoms. However, there are no specific science questions posed within these themes, objectives or requirements that define how SOFIA will answer those questions, or activities that SOFIA can be measured or tracked against. As a result, there are no clear measures of mission success.

According to SMD and SOFIA management, the absence of detailed science requirements and objectives for SOFIA was a reflection of the "better, faster, cheaper" management mantra of NASA at the time the project initially was under development. The goal was to give SOFIA maximum flexibility in executing science operations because officials believed that if the technical and operational requirements were achieved the science would naturally follow. SMD granted this flexibility despite early indications that SOFIA's science achievements may be less than envisioned due to its long development delays.

More importantly, SMD has not established formal science performance metrics for the Program going forward. In 2014, a science review of SOFIA determined SMD's Astrophysics Division and SOFIA must work together to produce a set of metrics concentrated on scientific productivity.[60] In June 2019, SMD management noted the need for SMD and SOFIA to develop a common understanding of the metrics and goals necessary to align with FMR's recommendations; however, as of June 2020 SMD had yet to establish science metrics or associated goals for the Program.

Goals and Improvements Proposed by SOFIA Are Insufficient to Achieve Performance Expectations

The FMR panel that evaluated SOFIA in 2019 concluded drastic improvements to SOFIA's scientific productivity were needed for the Program to meet the expectations of the astronomical community for a mission of SOFIA's size and cost. Specifically, the panel reported SOFIA is a flagship mission in terms of cost and complexity but does not routinely deliver flagship quality data products or science. The panel further concluded that a minimum of 150 annual publications along with doubling the h-index value would likely be necessary to pass NASA's 2022 Senior Review. SMD officials concurred that the performance expectations outlined in the FMR were valid and would need to be achieved for SOFIA to meet the community's expectations moving forward. Members of the panel noted that SOFIA likely would not have passed NASA's 2019 Senior Review had Congress not intervened to have it excluded.

To achieve FMR expectations SOFIA needs to more than quadruple the highest number of publications it has ever produced in a year (see Table 5). One of the primary drivers behind the issuance of publications is available research hours, and the highest number of annual research hours SOFIA has achieved to date is 786.3. Based on the current rate of publication, SOFIA would need to fly approximately 2,760 annual research hours to complete enough observation programs to reach the 150-publication threshold. This is more than three times the highest research hour total SOFIA has been able to achieve in a year and almost three times the number of research hours SOFIA could fly in a year based on its 960-hour design capability.

[60] The SOFIA Science Assessment Review Panel delivered a report on July 11, 2014, that evaluated SOFIA's science case.

Table 5: Number of SOFIA Publications Produced Annually, 2013 to 2019

2013	2014	2015	2016	2017	2018	2019
3	6	22	17	23	36	33

Source: NASA OIG presentation of SOFIA Program data.

The FMR recommended more than doubling SOFIA's h-index value from 21 to 44 by 2022, in 2 years; however, this appears unachievable as the Program has yet to double its h-index value from 2016, which was 13 (see Table 6).[61] Further, the current plan does not include this metric, since the science productivity goals the Program has proposed do not specifically address increasing the h-index. Compounding this, the decision in April 2020 to cancel HIRMES development means that no new instruments will be commissioned before 2022. HIRMES was considered by some SMD and Program officials to be crucial for SOFIA's future in producing high-value science and serving as the major instrument for producing research publications. The introduction of a new instrument could have potentially partially mitigated the lack of achievement of the FMR's science productivity goals.

Table 6: SOFIA H-Index Value, 2013 to 2020

2013	2014	2015	2016	2017	2018	2019	2020
3	8	9	13	15	19	20	21

Source: NASA OIG presentation of SOFIA Program data.

Note: The 2016 h-index of 13 was provided by the SOFIA Program and was their value as of January 1, 2016. The SOFIA 2016 h-index of 15 provided in Figure 6 by the Space Telescope Science Institute included additional data through the end of the year.

In response to the SOMER and FMR reviews, SOFIA proposed increased science productivity goals but to a degree less than FMR expectations. In March 2020, SOFIA released a strategic plan that reported a goal of at least 100 publications per year by 2022 versus the 150 recommended by the FMR, 33 percent less. To achieve this goal, SOFIA has implemented a number of operational changes that we believe will yield incremental improvements, but ultimately fall short of the transformational changes advocated by the FMR panel. For example, as we previously discussed, SOFIA plans to implement an 8-hour flight profile to increase the efficiency of acquiring high quality data in the stratosphere and improve the percentage of observation programs completed by carrying over incomplete programs to the next cycle. In addition, SOFIA managers told us that USRA is more rigorously vetting and eliminating program proposals that may not result in publishable data or cannot be completed. The Program is also factoring in a proposed researcher's publishing track-record to increase the likelihood that observations performed result in publications. The FMR also recommended SOFIA allocate at least one-third of total observation time to legacy science programs, which are larger observation programs with well-defined goals that are expected to lead to significant advances in their fields of study and develop joint observations with other observatories. Towards that end, SOFIA is devoting increased observation time to community-led legacy science programs and is in the process of discussing the possibility of joint observations with other observatories, both of which can increase the impact and value of SOFIA's science. While the Program's changes may improve its performance, given SOFIA's operational and technical challenges and the cycle time needed to produce a publication, the 100-publication goal by 2022 appears to be unachievable.

[61] To achieve an h-index of 44, SOFIA's 44th most cited publication needs to have been cited 44 times.

Additionally, incremental improvements are not what the FMR called for or believed was necessary to achieve the community's expectations. The FMR's recommendations were based on the assumption that SOFIA would enter NASA's Senior Review process in 2022 and identified paths forward to make SOFIA more scientifically productive leading up to the review. The Senior Review process is designed to assess the scientific merits of NASA's operating missions against one another in order to prioritize missions. The actions that can result from a Senior Review include allowing a mission to pass from its prime phase to extended operations, maintaining the status quo, or significantly restructuring or terminating the mission.

SOFIA is unlikely to meet the performance expectations of the astronomical community because of its poor efficiency compared to other observatories when evaluated using the most common definition of science per dollar.[62] A 2012 operational review noted one of the biggest risks to the Program after achieving full operational capability would be the lack of broad support from the community on a science-per-dollar basis, as the small number of observation hours available for such an expensive mission was unavoidable due to SOFIA's high operating costs. For example, Spitzer, an infrared satellite observatory, had lower development and operating costs than SOFIA but has produced 8,840 publications and 398,939 citations. ALMA, a ground-based observatory with similar development and operating costs, became operational a year after SOFIA's first science flight. While ALMA experiences similar observational limitations such as bad weather and atmospheric water vapor, it has produced a total of 1,814 publications (430 in 2019) and 33,050 citations. Additionally, 1,773 proposals were received for ALMA's most recent observation cycle despite the fact that ALMA does not provide any grant funding to its researchers, which demonstrates a very large researcher base interested in the observatory. In comparison, SOFIA has produced a total of 172 publications (33 produced in 2019), 1,574 citations, and received 229 proposals for its most recent observation cycle. (See Table 7 for a comparison of the observatories.) In sum, we do not believe the Program's proposed actions are sufficient to mitigate SOFIA's lack of competitiveness on a science-per-dollar basis compared to other missions and observatories.

Table 7: Observatory Publications and Citations

Observatory	Publications	Citations
ALMA[a]	1,814	33,050
Spitzer[b]	8,840	398,939
SOFIA[c]	172	1,574

Source: NASA OIG analysis of observatory data.

[a] The publication totals for ALMA are from 2011 through March 2020; the citation totals are from 2011 through July 2019.
[b] The publication totals for Spitzer are from 2004 through March 2020; the citation totals are from 2004 through September 2019.
[c] The publication and citation totals for SOFIA are through the end of 2019.

[62] Science per dollar refers to return on investment, or the amount of science produced by a mission measured by outcomes such as publications and citations per dollar spent on a mission.

CONCLUSION

SOFIA has not met operational or science productivity expectations, which has caused stakeholders to question whether the $83 million spent annually on the Program can be put to better use. SOFIA has experienced multiple challenges including a 13-year development delay that resulted in a diminished role in the observatory landscape; not meeting expectations to serve as a test bed for instruments and observing targets of opportunity; insufficient research hours in the stratosphere; incomplete observation programs; delayed data processing; problems developing instruments; insufficient science productivity and output; and lack of clear and achievable science goals and metrics. While the Program has made efforts to increase the number of research hours, percentage of observation programs completed, and number of publications produced by modifying their operational strategy and establishing science productivity goals, we believe these efforts will fall short of NASA and science community expectations.

Further, while the Program has set ambitious productivity goals, these goals appear to be unachievable given the Program's past performance and ongoing operational and technical challenges. Moreover, these goals do not meet stakeholder expectations. To meet the expectations of the Agency and the astronomical community, SOFIA and SMD management need to reconsider the platform's role within the current landscape of observatories and emerging technologies—specifically taking into consideration its return on investment from a science productivity perspective—if it is to continue as part of the Agency's Astrophysics Division portfolio.

Recommendations, Management's Response, and Our Evaluation

To improve the Program's productivity, we recommended the Associate Administrator for Science Mission Directorate direct SOFIA Program management to:

1. Implement quantifiable research hour requirements.
2. Establish a requirement for the Program to maximize research hours in the stratosphere that considers implementing an 8-hour, five times per week flight profile whenever SOFIA operates from Palmdale between May and November.
3. Establish observation program completion metrics, based on science value prioritization, to increase the probability observations result in publications.
4. Develop and implement a process to increase the timeliness of delivering data to researchers.
5. Establish science metrics, such as publications and citations per year, as criteria for the performance evaluation of the USRA contract award fee.
6. Establish a requirement for new technology implementation given the cancellation of HIRMES.
7. Develop a process for tracking science instrument productivity and cost to maintain and establish an evaluation program to determine when an instrument should be retired.

We recommended the Associate Administrator for Science Mission Directorate and SOFIA Program management coordinate to:

8. Reassess SOFIA's strategy and mission to identify and consider implementing alternative operational approaches and models to maximize SOFIA's capabilities within the Astrophysics portfolio and return on investment.
9. Develop consensus between SMD officials and Program management and implement quantifiable operational and science output requirements.

We provided a draft of this report to NASA management, who concurred with all of our recommendations. We consider management's comments responsive; therefore, the recommendations are resolved and will be closed upon completion and verification of the proposed corrective actions.

Management's comments are reproduced in Appendix D. Technical comments provided by management and revisions to address them have been incorporated as appropriate.

Major contributors to this report include Raymond Tolomeo, Science and Aeronautics Research Director; Gerardo Saucedo, Project Manager; Monique Brewer; Tai Leathers; Jiang Yun Lu; Andrew McGuire; and Lauren Suls.

If you have questions or wish to comment on the quality or usefulness of this report, contact Laurence Hawkins, Audit Operations and Quality Assurance Director, at 202-358-1543 or laurence.b.hawkins@nasa.gov.

Paul K. Martin
Inspector General

APPENDIX A: SCOPE AND METHODOLOGY

We performed this audit from July 2019 through August 2020 in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objective. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objective.

Our audit objective was to evaluate NASA's management of the SOFIA Program's cost and technical performance to ensure maximum scientific return. The scope of this audit included the Program's flight execution performance, observation data quality and data processing, science instrument development, and overall operational effectiveness in maximizing science output. We performed work at NASA Headquarters, Ames, and Armstrong. We conducted interviews across multiple levels of SOFIA Program and SMD management at Headquarters and each Center, and observed an operational science flight to gain an understanding of Program practices and status. We reviewed Program operational requirements and goals and compared those to its operating statistics, such as dispatch rates, research hours per cycle, and data processing timeframe. We also evaluated science productivity by paper published by individual instrument. We identified factors that affect Program scientific productivity and surveyed 225 science community members to assess their interest in the observatory and identify operational concerns. In addition, we reviewed NASA contract NNA17BF53C to determine contractual requirements for USRA operations and evaluated the award fee process. Specifically, we identified the criteria for determining the award fee amount and analyzed the performance reports used to support the ratings and award fee totals awarded to the contractor. We also reviewed current science instrument development and its impact to SOFIA Program capability. Finally, we obtained and reviewed copies of the April 2019 SOMER and June 2019 FMR reports.

Assessment of Data Reliability

We used computer-processed data to perform this audit, and that data was used to materially support findings, conclusions, and recommendations. In order to assess the quality and reliability of the data, we compared the information with other available supporting documents, corroborating it with program documents and input from various program officials. From these efforts, we believe the information we obtained is sufficiently reliable for this report.

Review of Internal Controls

We reviewed and evaluated the internal controls associated with NASA's management of the SOFIA Program and its operations. We noted concerns as discussed in the report. Our recommendations, if implemented, should address the concerns.

Prior Coverage

During the last 6 years, the NASA Office of Inspector General and Government Accountability Office have issued three reports of significant relevance to the subject of this report. Unrestricted reports can be accessed at https://oig.nasa.gov/audits/auditReports.html and https://www.gao.gov, respectively.

NASA Office of Inspector General

SOFIA: NASA's Stratospheric Observatory for Infrared Astronomy (IG-14-022, July 9, 2014)

Government Accountability Office

NASA: Assessments of Major Projects (GAO-16-309SP, March 30, 2016)

NASA: Assessments of Major Projects (GAO-17-303SP, May 16, 2017)

Appendix B: Comparison of SOFIA with Other Ground and Space Observatories

Table 8 compares SOFIA's organizational partners, status, type of observatory, objective, target, wavelength coverage, and total mission observation hours with other ground and space observatories.

Table 8: Comparison of SOFIA with Other Ground and Space Observatories

Mission[a]	Organization(s)[b]	Description	Wavelength Coverage	Total Mission Observation Hours
ALMA[c]	• European Space Agency • National Science Foundation • National Institutes of Natural Sciences (Japan)	**Status:** In operation **Type:** Ground **Objective:** Study light from some of the coldest objects in the universe **Target:** Molecular gas and dust of the universe, stars, planetary systems, galaxies, and life itself	320 to 8,600 microns	51,830
Chandra	NASA	**Status:** In operation **Type:** Space **Objective:** Understand the structure and evolution of the universe through the detection of X-ray emission from very hot regions **Target:** Exploded stars, clusters of galaxies, and matter around black holes	0.00012 to 0.012 microns	136,302
Gemini	• National Science Foundation • NRC (Canada) • CONICYT (Chile) • MINCyT (Argentina) • MCTIC (Brazil) • KASI (Korea)	**Status:** In operation **Type:** Ground **Objective:** Advance our knowledge of the universe by providing the international Gemini community with forefront access to the entire sky **Target:** Extrasolar planets, exoplanets, solar system, stars, galaxies, and distant quasars	0.9 to 5 microns	119,860
Herschel	• NASA • European Space Agency	**Status:** Completed **Type:** Space **Objective:** Unveil a face of the early universe that was previously hidden **Target:** Stars, atmospheres, galaxies, comets, and planets	55 to 672 microns	27,300

Mission[a]	Organization(s)[b]	Description	Wavelength Coverage	Total Mission Observation Hours
Hubble	NASA	**Status:** In operation **Type:** Space **Objective:** Study the universe with a clear view free from the blurring and absorbing effects of the atmosphere **Target:** Distant stars, galaxies, and planets in our solar system	0.1 to 2.5 microns	202,530
JWST	• NASA • European Space Agency • Canadian Space Agency	**Status:** In development **Type:** Space **Objective:** Study every phase in the history of our universe **Target:** Galaxies and luminous objects formed after the Big Bang, stars, protoplanetary systems, planets, and our solar system	0.6 to 28 microns	35,000
Keck I and II	• NASA • University of Hawaii • University of California • California Institute of Technology • California Association for Research in Astronomy	**Status:** In operation **Type:** Ground **Objective:** Advance the frontiers of astronomy **Target:** Exoplanets as well as celestial objects in our solar system, galaxy, and beyond	0.19 to 25 microns	170,226
Spitzer	NASA	**Status:** Completed **Type:** Space **Objective:** Study the early universe in infrared light **Target:** Comets, stars, exoplanets, stellar nurseries, planetary systems, and distant galaxies	3.6 to 160 microns	96,745
SOFIA	• NASA • German Aerospace Center	**Status:** In operation **Type:** Airborne **Objective:** Study the solar system and beyond in ways that are not possible with ground-based telescopes **Target:** Stars, new solar systems, complex molecules, celestial objects in our solar system, magnetic fields, black holes, and galaxies	0.3 to 1,600 microns	17,553

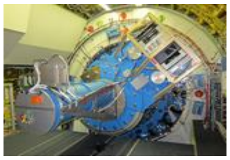
Source: Various.

[a] ALMA is Atacama Large Millimeter/submillimeter Array, Gemini is Gemini Observatory, Herschel is Herschel Space Observatory, JWST is James Webb Space Telescope, and Keck I and II are Keck I and II Telescopes.
[b] NRC is National Research Council of Canada; CONICYT is Comisión Nacional de Investigación Científica y Tecnológica; MINCyT is Ministerio de Ciencia, Tecnología e Innovación; MCTIC is Ministério da Ciência, Tecnolgia, Inovação e Comunicações; and KASI is Korea Astronomy and Space Institute.
[c] New receivers with wavelengths, from 6,000 to 8,500 microns and 3,300 to 4,500 microns, are in process of implementation.

Appendix C: SOFIA Science Instrument Suite

Table 9 shows SOFIA's science instrument suite including the class of the instrument, cycle it was first offered, developing institution, type of instrument, and its wavelength coverage.

Table 9: SOFIA Science Instrument Suite

Science Instrument Name and Acronym	Class	Cycle First Offered	Developing Institution	Instrument Type	Wavelength Coverage
Echelon-Cross-Echelle Spectrograph (EXES) 	Principal Investigator	Cycle 3	University of California, Davis	Echelon Spectrograph	4.5 to 28.3 microns
Far-Infrared Field-Imaging Line Spectrometer (FIFI-LS) 	Facility	Cycle 3	University of Stuttgart (Germany)	Imaging Spectrometer	51 to 200 microns
Faint Object Infrared Camera for the SOFIA Telescope (FORCAST) 	Facility	Cycle 1	Cornell University	Mid-/Far-Infrared Camera	5 to 40 microns
Focal Plane Imager Plus (FPI+) 	Facility	Cycle 4	Deutsches SOFIA Institut (Germany)	Optical Photometer	0.36 to 1.1 microns
German Receiver for Astronomy at Terahertz Frequencies (GREAT) 	Principal Investigator	Cycle 1	Max Planck Institute, Bonn (Germany)	Infrared Heterodyne Spectrometer	60 to 200 microns
High-resolution Airborne Wideband Camera + Polarimeter (HAWC+) 	Facility	Cycle 5	Jet Propulsion Laboratory	Far-Infrared Bolometer Camera and Polarimeter	50 to 240 microns

Source: SOFIA Program.

APPENDIX D: MANAGEMENT'S COMMENTS

National Aeronautics and Space Administration

Headquarters
Washington, DC 20546-0001

Reply to Attn of: Science Mission Directorate

TO: Assistant Inspector General for Audits

FROM: Associate Administrator for Science Mission Directorate

SUBJECT: Agency Response to OIG Draft Report, "NASA's Management of the Stratospheric Observatory for Infrared Astronomy Program (A-19-015-00)

NASA appreciates the opportunity to review and comment on the Office of Inspector General (OIG) draft report entitled, "NASA's Management of the Stratospheric Observatory for Infrared Astronomy Program" (A-19-015-00) dated August 6, 2020.

In the draft report, the OIG evaluated NASA's management of the SOFIA Project's cost and technical performance to ensure maximum scientific return. Specifically, they assessed the Project's (1) delivery of reliable flight opportunities; (2) efficiency of research flights in maximizing the quantity and quality of data obtained from observations; (3) ability to meet established data processing time commitments and provide quality data; (4) expected technical capabilities, including development of next-generation instruments; and (5) overall operational effectiveness in maximizing science output. In the draft report, the OIG makes nine recommendations to the Associate Administrator for the Science Mission Directorate (AA/SMD) designed to improve the Program's productivity.

There have been a number of changes implemented by the SOFIA Project since the OIG collected their data for this audit. These changes were initiated by the Project, and many were in response to the findings of the SOFIA Five Year Flagship Mission and SOFIA Operations and Maintenance Efficiency Reviews. These changes have already addressed many of the recommendations included in this OIG Report; they are called out in the SMD responses to the OIG draft report recommendations.

Specifically, the OIG recommends the following:

Recommendation 1: Implement quantifiable research hour requirements.

Management's Response: Concur. As SOFIA enters its extended mission operations phase and transitions from a Program to a Project, the SOFIA Project and SMD are developing a new SOFIA Project Plan. This requirement will be included in the new

SOFIA Project Plan. The Project Plan will be established on or before September 30, 2020.

Estimated Completion Date: September 30, 2020

Recommendation 2: Establish a requirement for the Program to maximize research hours in the stratosphere that considers implementing an 8-hour, five times per week flight profile whenever SOFIA operates from Palmdale between May and November.

Management's Response: Concur. Water vapor is the key parameter impacting the quality of science observations in the infrared. The Project recently developed a method to reliably, consistently, and accurately measure and track water vapor on SOFIA flights using satellite observations from the NASA Global Earth Observing System (GEOS) database. This method also provides accurate forecasts of water vapor that can be efficiently used to adjust flight plans 36 hours before the mission to optimize science data quality and maximize time in low water vapor conditions. This method also provides information on seasonal changes in observing conditions/water vapor that will be used to plan and schedule science observing proposals with specific instruments to optimize data quality and maximize time in the stratosphere or in low water vapor conditions. A requirement for using this method to plan science flights has been established, as has a metric for tracking it. The requirement and metric will be included in the new SOFIA Project Plan. The Project Plan will be established on or before September 30, 2020.

The Project will consider using 5x8 flights when SOFIA operates from Palmdale during late Spring and early Fall. This consideration will be driven by science observing proposal requirements with the goal of maximizing science and data quality.

Estimated Completion Date: September 30, 2020

Recommendation 3: Establish observation program completion metrics, based on science value prioritization, to increase the probability observations result in publications.

Management's Response: Concur. The Project has already begun tracking this metric and it will be included in the new SOFIA Project Plan. NASA has already included tracking this metric as a part of the contract of SOFIA's prime contractor, Universities Space Research Association (USRA). The Project Plan will be established on or before September 30, 2020.

Estimated Completion Date: September 30, 2020

Recommendation 4: Develop and implement a process to increase the timeliness of delivering data to researchers.

Management's Response: Concur. The process of timely data delivery to SOFIA was reviewed by the prime contractor after the 2019 Flagship Mission Review. Various policy changes and initiatives have already been implemented to ensure timely delivery of data to the researchers. A metric has been established, and this metric will be included in the new SOFIA Project Plan. The Project Plan will be established on or before September 30, 2020.

Estimated Completion Date: September 30, 2020

Recommendation 5: Establish science metrics, such as publications and citations per year, as criteria for the performance evaluation of the USRA contract award fee.

Management's Response: Concur. The USRA award fee plan was changed in FY 2020 to substantially increase the weighting of the Science Engagement, Productivity and Impact category from 28% to 50%. The evaluation criteria include substantive increases in: science publications, archival publications, citations, use of SOFIA results by the community, and vigorous and impactful outreach efforts.

Estimated Completion Date: Complete

Recommendation 6: Establish a requirement for new technology implementation given the cancellation of HIRMES.

Management's Response: Concur. Upon the termination of HIRMES on April 1, 2020, SMD directed the SOFIA project to evaluate the options to provide enhanced instrument capabilities for SOFIA with a due date for a plan of September 30, 2020. Options to consider included, but were 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 SOFIA project is on track to deliver a SOFIA Instrumentation Roadmap to SMD by September 30, 2020.

Estimated Completion Date: September 30, 2020

Recommendation 7: Develop a process for tracking science instrument productivity and cost to maintain and establish an evaluation program to determine when an instrument should be retired.

Management's Response: Concur. Upon the termination of HIRMES on April 1, 2020, NASA directed the SOFIA project to evaluate the options to provide enhanced instrument capabilities for SOFIA with a due date for a plan of September 30, 2020. Included in this plan will be the process for tracking existing science instrument productivity and cost to maintain, and this plan will establish an evaluation program to determine when an instrument should be retired. The SOFIA project is on track to deliver a SOFIA Instrumentation Roadmap by September 30, 2020.

Estimated Completion Date: September 30, 2020

The OIG also recommend the Associate Administrator for Science Mission Directorate and SOFIA Program management coordinate to:

Recommendation 8: Reassess SOFIA's strategy and mission to identify and consider implementing alternative operational approaches and models to maximize SOFIA's capabilities within the Astrophysics portfolio and return on investment.

Management's Response: Concur. The results of trade studies such as surge deployments to the Southern Hemisphere and deployments to alternative sites that have been completed to date will be included in the new SOFIA Project Plan. The Project Plan will be established on or before September 30, 2020. In addition, there will be an annual assessment of Project decisions on staffing and operations, as well as on science priority observational support and the Return on Investment (ROI), as part of NASA's annual Planning, Programming, Budgeting, and Execution (PPBE) process.

Estimated Completion Date: September 30, 2020

Recommendation 9: Develop consensus between SMD officials and Program management and implement quantifiable operational and science output requirements.

Management's Response: Concur. As SOFIA enters its extended mission operations phase and transitions from a Program to a Project, the SOFIA Project and SMD are developing a new SOFIA Project Plan. The quantifiable operational and science output requirements will be included in the new SOFIA Project Plan. The Project Plan will be established on or before September 30, 2020.

Estimated Completion Date: September 30, 2020

We have reviewed the draft report and did not identify information that should not be publicly released.

Once again, thank you for the opportunity to review and comment on the subject draft report. If you have any questions or require additional information regarding this response, please contact Mr. Peter Meister on (202) 358-1557.

Thomas Zurbuchen
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Thomas H. Zurbuchen, Ph.D.
Associate Administrator
Science Mission Directorate

APPENDIX E: REPORT DISTRIBUTION

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(Assignment No. A-19-015-00)