A NASA History Office Report

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The Stratospheric Observatory for Infrared Astronomy

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Executive Summary

The Stratospheric Observatory for Infrared Astronomy (SOFIA) was an airborne observatory operated by NASA and the German Deutsches Zentrum für Luft- und Raumfahrt (DLR) from 2014 to 2022. SOFIA consisted of a reflective telescope mirror mounted on a heavily modified Boeing 747SP, a one-off design engineered with flexibility in mind. SOFIA blended advantages found in both ground- and satellite-based observation formats: unlike ground-based observatories, SOFIA could fly above much of Earth's atmospheric water vapor to better see celestial subjects; unlike satellite-based observatories perched in orbit, SOFIA existed as a crewed aircraft that could land every night for repairs and servicing. Scientific instruments could be swapped out, and cryogens, a category of substance designed to cool instruments collecting infrared light, could be replenished on board. Whereas satellite-based telescopes doing infrared observation were limited by the amount of cryogens they could carry into outer space, SOFIA's access to terrestrial resources enabled this work indefinitely. Over an eight-year period, SOFIA used infrared sensors to peer into dusty regions of the universe, producing new knowledge about star formation, the structure of our universe, and the chemical composition of celestial subjects.

Air-to-air views of SOFIA on a fly-by visit to Ames Research Center in January 2008. *(NASA ID: ACD08-0005-126/Carla Thomas)*

Despite its unique capabilities, SOFIA attracted a mixed reputation for good science with a hefty price tag. Though SOFIA entered development in 1996—and was expected to wrap modifications in 2001—the observatory would not reach full flight operations until 2014. The cost and schedule overruns sailed past the initial estimates, prompting difficult questions about sunken expenses and the long-term operating costs of a crewed 747 designed to fly over 100 nights per year. SOFIA's funding was canceled—and then reinstated—in 2005 and 2014, before its final conclusion in 2022. Despite spending roughly 18 years in development, the observatory operated for just 8 years out of an anticipated 20-year run.

This report contextualizes SOFIA in a broader history of airborne observation, situating its developmental delays and scientific victories against the backdrop of institutional changes at NASA over a roughly 30-year period. SOFIA was a hybridized facility combining cutting-edge astronomical research with precision flight operations, making it a remarkably complex platform to operate and an illustrative case study for those interested in the machinery of mission design. This report explores how SOFIA's scientific productivity was measured against its budget, while considering these elements in historical context.

SOFIA's crewed design introduced a decidedly human element to the mission. The roomy 747SP supported a large crew, hosting not just astronomers working with their instruments in real time, but a vibrant cohort of science educators from school districts around the country. SOFIA could also fly to the Southern Hemisphere during Northern Hemispheric summers, when nights were too short for optimized astronomical observation. These months-long deployments enabled the observation of astronomical objects unseeable from the north, and during deployments to New Zealand, Western Europe, and Latin America, SOFIA functioned as an ambassador for both international astronomy and NASA. In addition to enabling flexible forms of infrared science, the observatory cultivated sizable public interest in the places it traveled.

This report is intended to function as a primer for those within NASA seeking to quickly understand SOFIA's intricacies and how the observatory's development shaped its operational lifetime. Ideally, information on the collaborative efforts between the National Academy of Sciences, U.S. Congress, and NASA's Science Mission Directorate in developing SOFIA will be of use to those designing NASA's next generation of observatories. For those outside NASA, this report is intended to serve as a nonexhaustive guide to SOFIA's relevance to the history of science and technology. It is a case study with much to offer scholarly researchers, especially those interested in airborne laboratories, infrared astronomy, international science diplomacy, or the intersection of science and politics represented by federal budgets. SOFIA's development is resonant with several different turns in historical literature: scholarship on tensions between innovation and the maintenance of preexisting structures, literature on sustainability in astronomy, and the embeddedness of human culture within technological systems.

Introduction

What Was SOFIA?

On May 20, 1977, Anne Morrow Lindbergh christened a new Pan American passenger aircraft after her late husband, Charles Lindbergh. This particular Boeing 747 was a "Special Performance" model, a stubbier version of the standard Boeing 747, optimized for long-distance travel. The aircraft was dubbed the "Clipper Lindbergh" in an homage to the aviator's 1927 transatlantic flight from New York to Paris, situating the 747SP in a popular genealogy of aeronautic innovation.[1] The invocation of one of the 20th century's most famous experimental flights invoked a spirit of adventure, conjuring an earlier image of aviation as a conduit for exploration. The Clipper Lindbergh would fulfill this mandate, though not in the ways originally anticipated.[2]

The Boeing 747SP was designed to accommodate a joint request from Pan Am and Iran Air for a commercial passenger aircraft that could fly nonstop from New York to Tehran. Boeing was interested in the commercial market for ultra-long-range routes—which required faster cruising speeds and higher altitude—and in 1976 the company developed a shortened version of the 747 optimized for range at the expense of capacity. The market niche that prompted the aircraft's development, however, proved fleeting. Slowed by deteriorating diplomatic relationships in the Middle East, the subsequent skyrocket of global fuel prices, and competing aircraft, Boeing's enthusiasm for the 747SP evaporated by the mid-1980s. Despite being the longest-range airliner available until 1989, only 45 747SPs were ever manufactured. The final 747SP, a VIP model, was manufactured in 1987 for the United Arab Emirates to transport the government of Abu Dhabi. Pan American sold the fleet to United Airlines in 1986, and by the end of the 1990s, the bulk of the fleet had been retired to desert storage in Las Vegas.[3]

In 1997, after nearly 20 years of service as a passenger aircraft, the Clipper Lindbergh began a second life. In December 1996, NASA awarded a $484 million contract to the Universities Space Research Association, a nonprofit corporation composed of more than 80 universities. Their task was to develop and operate an airborne observatory large enough to expand infrared astronomy in the astrophysics community. Several experiments over the course of the 20th century proved the value of using airplanes to observe the cosmos from above the occluding water vapor of Earth's atmosphere.[4] The Stratospheric Observatory for Infrared

1 21441/306 Production List, 747SP, Airframe History: 21441. 21441/306–Production List—Boeing 747SP Website Photograph of "Clipper Lindbergh" *https://www.airliners.net/photo/Pan-American-World-Airways-Pan-Am/Boeing-747SP-21/788924*.

2 The aircraft's first flight was April 25, 1977. It was delivered to Pan Am on May 6, 1977. In 1986, it was purchased and renamed by United Airlines, where it remained in service as a passenger aircraft until 1995.

3 A little more than a quarter of the remaining 747SPs survived for use as luxury VIP or business jets. This would be a lifeline for SOFIA in the 2010s, when engineers at NASA Armstrong needed to source extra engines in order to cobble together a supply chain of spare parts. Guy Norris and Mark Wagner, *Boeing 747: Design and Development Since 1969* (Osceola, WI: Motorbooks International, 1997), *http://archive.org/details/boeing747designd00norr*, pp. 74–75.

4 This report will focus on eclipse chasing in the 1920s and 1930s, Galileo, astronomical observations made on board NASA's Lear Jet Observatory, the NASA Ames U-2R, and the Kuiper Airborne Observatory as direct precursors to SOFIA.

Astronomy, or SOFIA, was to be the largest one. Consequently, the 747SP's long-range endurance and high-altitude capabilities made it an ideal choice for flights that needed to stay in the air as long as possible to maximize observation time. The plan was to mount a 2.5-meter telescope inside a cavity on board the former Clipper Lindbergh.

By the time of the repurposed passenger aircraft's first flight as SOFIA in 2009, an airplane commemorating a historic turn in global aviation had transformed into a hallmark of astronomy's exploration of the infrared spectrum. SOFIA flew a total of 921 times between May 2010 and September 2022.[5] Just like any ground-based telescope, SOFIA was an observational *facility,* capable of hosting a range of different scientific instruments and observational programs. Unlike traditional observatories, however, SOFIA could fly into the stratosphere above 98 percent of Earth's atmospheric water vapor. This above-atmosphere advantage primed it for observation of the infrared portion of the electromagnetic spectrum, which is blocked for ground-based observatories by Earth's atmospheric moisture content.

SOFIA's engineering offered infrared astronomers a figurative and literal middle ground between space-based and ground-based astronomical observation. Unlike space-based observatories, which require human extravehicular activities (EVAs) to make serious alterations, SOFIA landed after every 10-hour flight, allowing hardware repairs and instrumentation swaps to be conducted on the ground between observations. The telescope was mounted behind a large door on the port side of the aircraft, which opened during observation. Its effective observation diameter of 2.5 meters (or 100 inches) was the same size as that of the Hubble Space Telescope's mirror. SOFIA's flights were all crewed, meaning instrumentation had human operators in physical proximity while in the air. Because of its geographic flexibility, SOFIA could fly to the Southern Hemisphere during northern summers. International deployments to places like Chile and New Zealand, coupled with SOFIA's ability to fly local science educators, helped cultivate positive relationships with communities abroad. In cities like Christchurch, SOFIA took on a celebrity status, as did the astronomers and flight crew on board. In Western Europe, SOFIA's partnership with the German DLR was celebrated as a triumph of the international scientific community.

Overview of Content

Airborne astronomical observatories are rare, and SOFIA was an order of magnitude more sensitive than its most immediate predecessor. This report takes a chronological approach, making SOFIA's development more legible by placing it in a broader history. **Section I**, "Precursors in Airborne Observation," contextualizes SOFIA's structural idiosyncrasies in a wider history of aviation. This section outlines the utility of aircraft as tools for astronomy, tracing how advancements in aeronautics shaped by the midcentury geopolitical conflicts helped enable new forms of airborne science. What began as a tool for better seeing lunar eclipse shadows in the 1930s was fully embraced by NASA in the 1960s as a tool for early infrared observation.

Section II, "The Kuiper Airborne Observatory and the Decade of Infrared," follows NASA's attempts to scale up early attempts at airborne infrared observation. The Kuiper Airborne Observatory (KAO) represented an important expansion of the capabilities demonstrated by earlier airborne observatories. When the National Academy of Sciences proclaimed the 1990s as "The Decade of Infrared," KAO's funding was redirected to a newer, bigger platform that would eventually become SOFIA and inaugurate a new era of infrared observation. KAO was SOFIA's most immediate genealogical predecessor, and the new observatory's design drew heavily on input from astronomers who worked on KAO. Taken together, Sections I and

5 First light was May 26, 2010, though the project start date is listed as 2014 on the NASA Science SOFIA website. *https://science.nasa.gov/mission/sofia/*.

II illustrate the experimental nature of airborne astronomical observation, the format's development and use within NASA, and its unique advantages for infrared observation. Later attempts to quantify SOFIA's scientific productivity struggled with the fact that there are very few observatories with which to compare it—situating SOFIA in a family of airborne observatories operated within NASA offers a more suitable backdrop with which to evaluate its strengths and weaknesses. This section also details the beginning of collaborations with the German space agency.

Section III, "The Development of SOFIA," examines the extensive hardware modifications needed to transform a passenger aircraft into a flying observatory. Rather than develop SOFIA in-house, NASA awarded the contract to the University Space Research Associates (USRA) in 1996. USRA, a consortium of research universities, hired several subcontractors to perform the necessary modifications while the German DLR developed SOFIA's telescope. The hardware modifications—and the managerial apparatus developed to implement them—proved more complicated than anticipated, and after several years-long delays, project management was transferred back to NASA. In 2005, the SOFIA Project Office was relocated to Dryden Flight Research Center (renamed Armstrong Flight Research Center in 2014), while responsibility for science operations remained at Ames Research Center (Ames). In 2014, the SOFIA Project Office moved back to Ames while flight operations remained at Armstrong, requiring continued coordination between the two centers. This section chronicles the Phase C delays that stretched SOFIA's achievement of full-flight operation status from its initial anticipated delivery date of 2001 more than a decade to 2014.

The delays that characterized SOFIA's development phase had devastating consequences for the observatory, eating away at resources earmarked for an ambitious infrared astronomy program. Despite having been designed to operate for a full 20 years, SOFIA was concluded in 2022 after performing 8 years of science observation. **Section IV**, "Eight Years of Project Science," begins with the onset of SOFIA's full flight operational status in 2014 and traces the eight years of project science the observatory completed before its final cancellation in 2022. This section focuses on the close collaborations between astronomers in the SOFIA Project Office at Ames and the flight operations team at Armstrong that enabled the observatory's science missions. Because the 747SP was no longer being constructed by Boeing or serviced by major commercial airlines, maintaining SOFIA required the improvisation of a supply chain sourced from other retired aircraft. Section IV also details SOFIA's major scientific discoveries, its international deployments, and use as both an educational outreach and diplomacy tool.

The decision to finally end SOFIA was prompted by the National Academy of Sciences' 2021 Decadal Survey, which concluded that SOFIA was not productive enough to warrant its nearly $84 million yearly operating budget. The Academy's recommendation, made at the behest of some of the most prominent astronomers in the field, prompted NASA's Science Mission Directorate to cancel SOFIA's triennial review, bringing the mission to an abrupt end. **Section V**, "Conclusion of SOFIA," narrates the arguments surrounding this decision in the broader context of the observatory's attempts at optimization.

SOFIA's termination raises many interesting questions about how scientific research is quantified in a zero-sum system characterized by limited resources. The Academy's assessment pointed to the fact that SOFIA prompted far fewer scientific papers than the Hubble, Chandra, or Spitzer space telescopes, and that its high operating budget could be redistributed among other, newer, NASA projects. Proponents of SOFIA claimed that these comparisons were fundamentally incommensurate—because SOFIA was an airborne observatory, it had roughly 8–9 hours of astronomical observation per flight several times per week, compared to the 24-hour observation cycles of space-based telescopes. Counterarguments maintained that the simple tabulation of scientific publications was too narrow a metric of productivity and that SOFIA's other strengths—serviceability, instrument flexibility, public engagement, and outreach—were rendered illegible in this equation.

This project report is composed of material drawn from publications and archival sources related to the development and operation of SOFIA. It intends to function as a primer for scholars and policymakers interested in the observatory's history. The document places SOFIA in a broader context of airborne astronomical observation, tracing the mission's development phase, flight testing, and operations through its conclusion in 2022. The materials collected in this document are supplemented with oral interviews from a range of former affiliates. While the report is not exhaustive, it serves as a topographical overview of major milestones and setbacks in SOFIA's history.

SECTION I

Precursors in Airborne Observation, 1923–63

SOFIA is significant in both the history of aircraft development and astronomical observation, two fields deeply influenced by the global geopolitical conflicts of the 20th century. Beginning in the 1920s, early aerial excursions sponsored by National Geographic were driven by civilian interest in eclipse-chasing for scientific purposes. These flights were branded as scientific expeditions, echoing the spirit of 19th-century exploration. Over the following decades, military demands dramatically reshaped aircraft design. World War II led to the development of larger planes capable of flying at higher altitudes. The onset of the Cold War spurred advancements in surveillance satellites and spy planes, improving cameras, sensors, and other detection technologies, which later enhanced astronomical observation capabilities.

Early Airborne Observation

Airborne astronomy was a straightforward idea, attempted almost as soon technology capable of doing it was developed. The first flight of an airplane occurred in 1903, with the first attempt at airborne observation occurring just 20 years later. Attempts to better see celestial phenomena from the air began in the 1920s, when astronomers guessed that the cloud-free observation offered by airplanes would provide novel astronomical insights. The first attempt at airborne astronomy was undertaken on September 10, 1923, when the U.S. Navy deployed a fleet of 16 aircraft to measure the centerline of a solar eclipse from the anticipated path of totality.[6] The flight was largely unsuccessful from a measurement standpoint but generated significant interest from the press and public.

Early airborne astronomy focused almost exclusively on solar eclipse observation, using shadows to correct astronomical almanacs and maps. A more successful flight than the 1923 expedition was organized in 1930 by the Naval Observatory, when an Akeley motion picture camera was mounted on a Vought O2U-1 and used to record the eclipse's shadow on film and confirm its predicted path for corrections to lunar almanacs.[7] In-flight eclipse observation was attempted again in 1932 by the Army Air Corps and the National Geographic Society. The 1932 flight took off with three cameras—a long focal-length camera for photographing the Sun's corona and a medium and short focal-length camera to record the shadow caused by the eclipse—as well as an electroscope for the measurement of cosmic rays.

6 Wendy Whiting Dolci, "Milestones in Airborne Astronomy—From the 1920s to the Present," American Institute of Aeronautics and Astronautics, no. 975609 (1997).

7 Observations were made on the Honey Lake expedition of 1930. Ibid., p. 2.

The Army Air Corps arranged the aerial photography of the 1932 eclipse for the National Geographic Society, prompting questions about the military applications of airborne eclipse observation with what was soon dubbed a "flying laboratory." The flight offered insights into how propellor settings and carburetor adjustments offered more altitude, oxygen equipment necessary to keep pilots conscious, and cameras that provided better insulation against low temperatures.[8] The photographs were taken at an altitude of 27,000 feet, an altitude difficult for both the aircraft and the pilots sitting in exposed cockpits blasted by freezing air. The pilots used oxygen masks to counter high-altitude disorientation but still needed to write instructions for crucial procedures down in big letters on the controls themselves. Captain Albert Stevens, who was part of the original 1923 expedition, manipulated the cameras at the back of the aircraft and communicated flight directions to the pilot audibly in loud yips—one yip meant a left turn, while two indicated a right.[9]

In-air eclipse observations improved throughout the 1940s and, like most advancements in aeronautics during the period, were shaped by wartime technological advancements made in the wake of World War II. In May 1948, observers on board a Boeing B-29 Superfortress were able to comfortably observe an eclipse obscured from ground observers by bad weather.[10] The four-engine B-29 was designed for high-altitude flight, although its initial purpose was strategic bombing, and it far exceeded the cost of the entire Manhattan Project in its development.[11]

The Transition from Propellor to Jet Aircraft

The shift from propellor to jet aircraft prompted by the aeronautic advancements of World War II drove the maturation of airborne astronomical observation into the 1960s. As tensions with the Soviet Union increased after the onset of the Cold War, the U.S. military focused extensively on observation technologies that could be deployed from high altitudes on satellites or spy planes.[12] In 1958, Congress dissolved the National Advisory Committee for Aeronautics and transferred its assets to the newly formed National Aeronautics and Space Administration (NASA). The formation of NASA combined older aeronautic prowess with scientific resources, offering a powerful new institutional vantage point from which to pursue airborne astronomy.

In the early 1960s, eclipse observation was still seen as airborne astronomy's most obvious application, though developments in infrared detection and the commercial availability of jet aircraft opened new possibilities for the format.[13] The first use of jet aircraft for high-altitude astronomical observation at Ames occurred in 1963, when the National Geographic Society and Douglas Aircraft Company leased a DC-8 aircraft from Delta Airlines to observe the July 20 eclipse with a 6-inch-diameter optical telescope.[14] The four-engine DC-8 used for the project was roomy enough to accommodate 55 scientists operating

8 "Questions naturally arose whether flights incident to the eclipse possessed any military value whatever. They did prove to be of value, for we learned things about propellor settings and carburetor adjustments that gave us more altitude, about oxygen equipment that gave us stronger pipelines, about cameras that gave us better insulation against low temperatures." Albert W. Stevens, "Photographing the Eclipse of 1932 from the Air," *National Geographic* (November 1932): 581–586.

9 Dolci, "Milestones in Airborne Astronomy," p. 2.

10 Ibid., p. 3.

11 "The program ultimately cost $3 billion dollars, versus $2 billion for the Manhattan Project that developed the nuclear bomb." "B-29 Superfortress, U.S. Heavy Bomber," *The Pacific War Online Encyclopedia*, *http://www.pwencycl.kgbudge.com/B/-/B-29_Superfortress.htm*.

12 Peter W. Merlin, *Unlimited Horizons: Design and Development of the U-2*, NASA Aeronautics Book Series (Washington DC: NASA, 2015), p. V.

13 In 1961, Frank Low developed the Gallium-doped Germanium bolometer detector, extending the range of observable spectrum to much longer wavelengths. The bolometer could be used to measure radiant energy from stars as infrared radiation. Dolci, "Milestones in Airborne Astronomy—From the 1920s to the Present," p. 3.

14 Frank Low, "Airborne Infrared Astronomy: The Early Days," in *Airborne Astronomy Symposium: A Symposium Commemorating the Tenth Anniversary of the KAO*, NASA Conference Publication 2353, NASA-CP-2353 198500095 (NASA Airborne Astronomy Symposium, NASA Ames Research Center, 1984), *https://ntrs.nasa.gov/api/citations/19850009539/downloads/19850009539.pdf*, p. 1.

25 experiments and powerful enough to hoist a 700-pound spectrograph that replaced half of the plane's passenger seats. The spectrograph, used to record a narrow band of the Sun's corona, was mounted on the 6-inch telescope. Because the DC-8 could move across Earth quickly, "chasing" the lunar shadow at high altitudes, it stretched the time of totality for those on board to 142 seconds from 100 seconds for observers on the ground.[15]

From Eclipse Observation to Infrared

Galileo

The success of the 1963 flight of the four-engine DC-8 and its high-altitude solar eclipse observations prompted immediate interest in the astronomical community.[16] Dr. Michel Bader of Ames had directed one of the science teams aboard the DC-8, and petitioned NASA to purchase a high-flying jet for use as an airborne science platform. The Convair 990 selected for service was dubbed "Galileo" in 1965, after an Italian astronomer on board remarked that he could see the moons of Jupiter that Galileo first observed with a 17th-century telescope.[17]

Like the airborne observatories before it, Galileo was used for eclipse observation, but its most significant findings came from its use in infrared spectroscopy. Dr. Gerard Kuiper, at that time the Director of the Lunar and Planetary Lab at the University of Arizona, obtained a set of near-infrared spectra of Venus that indicated that the planet's thick atmosphere was, surprisingly, not made from water. Galileo's scientific instruments helped analyze Venus's composition, which was eventually determined to be made primarily of carbon dioxide. The aircraft's infrared sensors were also capable of measuring Earth's atmospheric temperatures, as well as the types of gases that absorb infrared radiation, allowing for more sophisticated comparisons of the Venusian climate with our own. The findings were made despite the aircraft's thick quartz windows through which the instruments made their observations.[18]

Galileo operated until April 12, 1973, when it collided with a Navy aircraft near Moffett Field in California, killing all 11 on board the airborne observatory.[19] Though a second Convair 990—dubbed Galileo II—was used for some astronomical observation, the need for an airborne observatory with an open-port telescope became increasingly clear.[20]

The Learjet Observatory

Gerard Kuiper's discovery on board Galileo underscored the utility of airborne infrared observation, and by 1966 it was apparent that an open-port telescope was needed to extend the wavelength coverage beyond the spectral limit of ground-based observation.[21] In 1968, a 12-inch open-port reflecting telescope was installed in a passenger window on board a Learjet.[22] Capable of flying between 45,000 and 50,000 feet, the

15 Dolci, "Milestones in Airborne Astronomy," p. 4.

16 Low, "Airborne Infrared Astronomy," p. 1.

17 Professor Guglielmo Righini, who was on board with scientists from a range of different countries. Dolci, "Milestones in Airborne Astronomy," p. 5.

18 Low, "Airborne Infrared Astronomy," p. 3.

19 VPNAVY, "United States Navy Patrol Squadrons VP-47 Memorial Page," *https://www.vpnavy.org/vp47mem_20nov2000.html* (accessed June 6, 2024).

20 Low, "Airborne Infrared Astronomy," p. 3.

21 Ibid., p. 4.

22 For much of the 1960s, this aircraft was known as the "Lear Jet," a name that changed to "Learjet" after subsequent company mergers. For more on this transition, see the historical note accompanying the Lear Jet Corporation collection, Series V of the William P.

aircraft's telescope revealed new sources of infrared, peering into previously occluded realms. Astronomers made the first measurements of the "internal energies of Jupiter and Saturn, far-infrared observations of the great nebula Orion, studies of star formation regions and the bright IR [infrared] sources at the center of the Milky Way galaxy."[23] Ed Erickson and Jim Pollock followed up on Kuiper's initial observations of the Venusian atmosphere, deducing that the clouds of our neighboring planet were composed of sulfuric acid.[24]

NASA Ames U-2 Aircraft

In the early 1970s, Ames operated a modified U-2R variant of the U-2 spy plane.[25] The aircraft could fly at over 70,000 feet, making it a useful tool for the collection of atmospheric data. The Lockheed U-2, developed by Lockheed Corporation in the 1950s, was originally used for Cold War surveillance and intelligence gathering, equipped with sophisticated cameras and sensors for aerial photography.[26] As such, the former national security asset was well-equipped to monitor land use, vegetation, and incipient natural disasters; the California Department of Water Resources used the aircraft's photographic capabilities to measure water levels on the West Coast.[27] The Ames U-2 also contributed to several Earth science missions, studying clouds, aerosols, and the greenhouse effect.[28]

Delivered by the U.S. Air Force in June 1971, the Ames U-2 aircraft was used for research at high altitudes, enabling the discovery of dipole distribution of the cosmic microwave background radiation. Follow-on facilities like NASA's Cosmic Background Explorer and the Wilkinson Microwave Anisotropy Probe were inspired by the U-2 aircraft's findings.[29]

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and Moya Olsen Lear Papers at the Museum of Flight: *https://archives.museumofflight.org/agents/corporate_entities/1696?utm_source=chatgpt.com* (accessed June 16, 2025).

23 Dolci, "Milestones in Airborne Astronomy," p. 8.

24 Mark V. Vorobets, Maurice A. Valdez, and Aphisong C. Sangbouasy, "Interview with Ed Erickson—NASA," November 5, 2019, *https://www.nasa.gov/general/interview-with-ed-erickson/* (accessed June 16, 2025).

25 NASA was first involved in the history of the U-2 spy plane in May 1960, when the CIA attempted to pass off Gary Powers's downed U-2 aircraft over Soviet airspace as a NASA weather reconnaissance plane. See Peter W. Merlin, *Unlimited Horizons: Design and Development of the U-2* (Washington, DC: NASA SP-2014-620, 2015).

26 Ibid., pp. 81–82.

27 Ibid., p. 186.

28 Ibid., pp. 185–187.

29 Edwin F. Erickson and Allan W. Meyer, "NASA's Kuiper Airborne Observatory, 1971–1995: An Operations Retrospective with a View to SOFIA" (Washington, DC: NASA SP-2013-216025, 2013), p. 5.

SECTION II

The Kuiper Airborne Observatory and the Decade of Infrared

KAO

The successful expansion of airborne astronomy onto jet aircraft encouraged the development of a 36-inch telescope a full three times larger—and an order of magnitude more sensitive—than that of the Learjet Observatory. The proposal was advocated by Michel Bader and Robert Cameron, who had both been involved with the July 1963 DC-8 eclipse observation.[30] The plans and specifications for this new observatory were drafted in 1967 and finalized in 1970, with development of the telescope undertaken by Fecker Systems of Owens, Illinois, and the modification of a Lockheed C-141 "Star-Lifter" undertaken by Lockheed Aircraft Systems in Ontario, California.

The C-141's full transformation into the Kuiper Airborne Observatory took roughly four years: the aircraft was procured from Lockheed in January 1970, with science flights commencing by July 1974.[31] In 1972, assembly of the Cassegrain telescope was moved to Ames and completed locally with both civil service and contractor personnel.[32] Gerard Kuiper, whose initial observations on Galileo helped underscore the utility of airborne observation, died in December 1973, just a few months prior to the C-141A's first operations, while on vacation in Mexico City.[33] In an homage to Kuiper's initial discoveries, the new facility was posthumously dubbed the Kuiper Airborne Observatory (KAO).[34]

From 1974 to 1995, KAO made several landmark discoveries in the field of infrared astronomy across more than 1,400 flights and over 10,000 hours of research time.[35] In 1977, KAO discovered rings around Uranus. In 1986, the observatory analyzed the chemical composition of Halley's Comet, providing insights into the makeup of early solar system materials. In 1988, the observatory was the first to detect an atmosphere around Pluto. It also contributed foundational knowledge to the process of star formation, interstellar molecules and astrochemistry, and the spatial relationships between gas and dust at the center of the Milky Way galaxy.[36]

30 Dolci, "Milestones in Airborne Astronomy," p. 4.
31 Erickson and Meyer, "NASA's Kuiper Airborne Observatory, 1971–1995," p. 9.
32 Ibid.
33 "Historical Background," Gerard P. Kuiper Papers, University of Arizona Libraries, *https://lib.arizona.edu/special-collections/collections/gerard-p-kuiper-papers* (accessed July 18, 2024).
34 Nans Kunz, "The Making of SOFIA: The Stratospheric Observatory for Infrared Astronomy, 1985 to 2016" (Hampton, VA: NASA Langley Research Center, SP-2016-09-100), 2016), p. 11.
35 Erickson and Meyer, "NASA's Kuiper Airborne Observatory, 1971–1995," p. 11.
36 Ibid., p. 10.

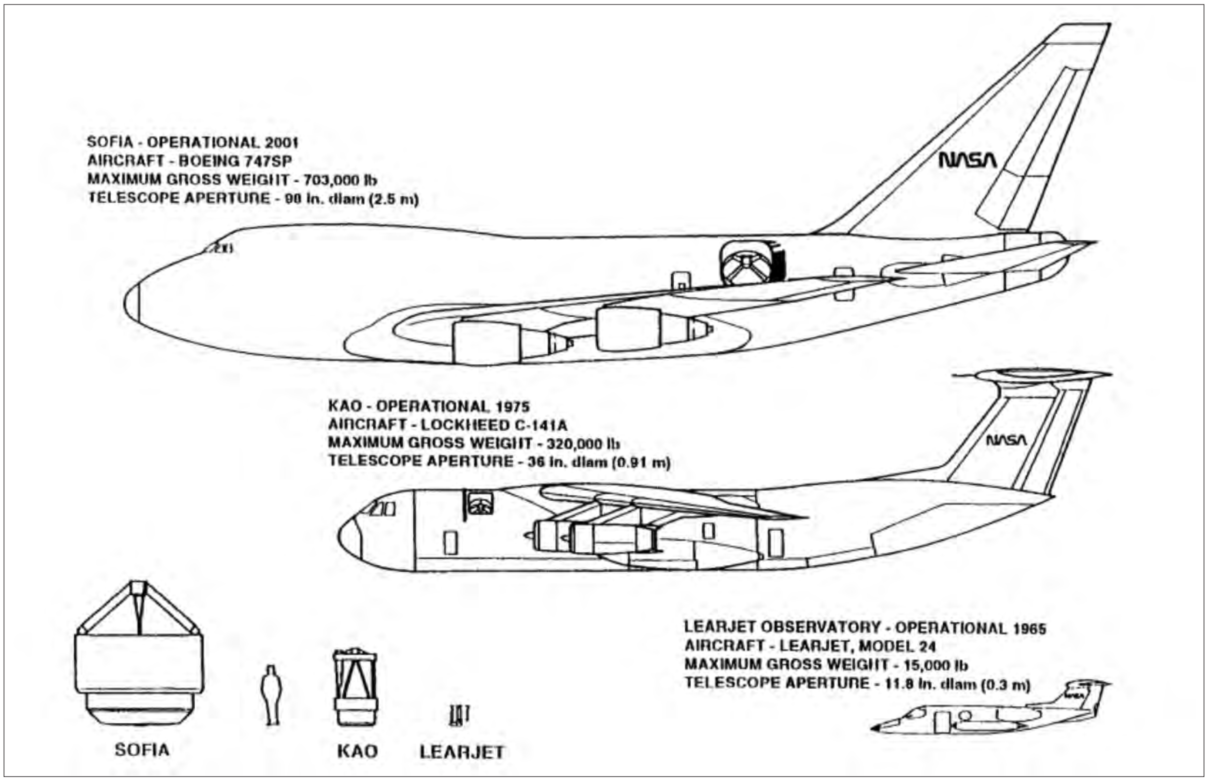
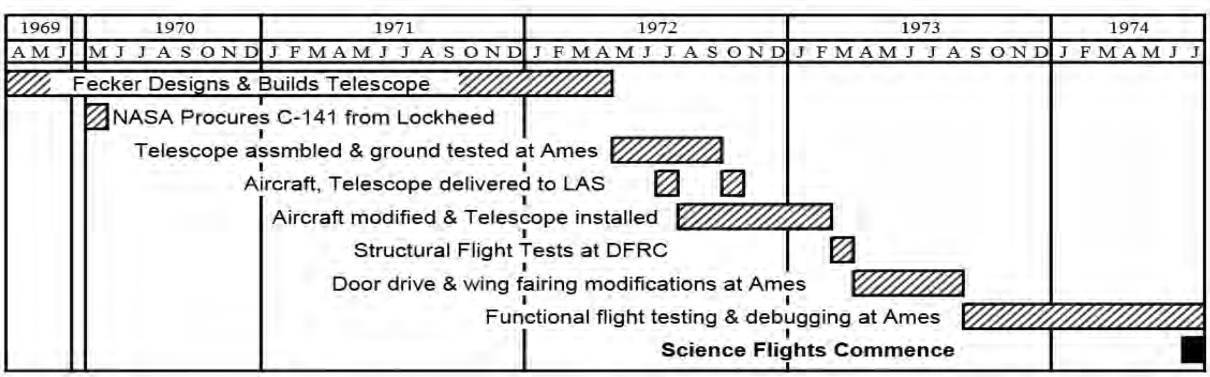


Illustration showing the relative sizes of airborne observatories and their telescopes. *("Industry Briefing" delivered by C. Wiltsee in 1995. Stratospheric Observatory for Infrared Astronomy (SOFIA) Project Collection, Collection Number ARC24.12)*



Timeline of KAO's development, which was much speedier than SOFIA's even when adjusted for KAO's smaller scale. *(Edwin F. Erickson and Allan W. Meyer, "NASA's Kuiper Airborne Observatory, 1971–1995: An Operations Retrospective with a View to SOFIA," NASA/SP-2013-216025, 2013. Figure 7, p. 9)*

Interior of the Kuiper Airborne Observatory's (KAO) Mission Director's Console. Photograph dated February 11, 1985. *(NASA ID: AC85-0110-002/Tom Trower)*

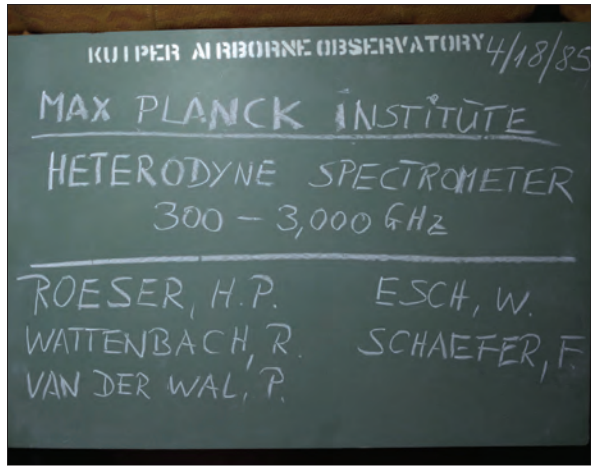


Photo of instrument plaque Planck Institute Heterodyne Spectrometer used by Hans-Peter Röser onboard Kuiper in the mid-1980s. *(NASA ID: ARC-1985-AC85-0402-1)*

Cutaway illustration of the telescope and mission control areas from 1988. BMFT stands for the German Bundesministerium für Forschung und Technologie, or the Federal Ministry for Research and Technology. The BMFT was a central player in the development of the German space program from the 1970s through the early 1990s. *(NASA ID: AC88-0371-2)*

The KAO also laid the groundwork for the German-U.S. collaborations that would enable SOFIA. By the early 1980s, there was growing scientific interest from German research institutes on infrared astronomy. In 1983, the companies Dornier and Zeiss conducted a study on a German airborne infrared telescope called ASTROPLANE on behalf of the DFVLR (German Aerospace Research and Testing Institute). While ASTROPLANE never materialized, German scientists Hans-Peter Röser and Reinhard Genzel, a future Nobel Laureate, were allowed to conduct observations onboard KAO using their own instruments. Röser and Genzel were not expected to contribute financially to KAO's development or operations costs. When discussions turned to the development of a newer, larger airborne astronomical platform, formal cooperation between Germany and the United States was front of mind. In June 1985, the Council of West German Observatories recommended that BMFT (then the Federal Ministry of Research and Technology) participate in SOFIA.[37]

The Decade of Infrared Astronomy

In 1972, just as NASA was nearing completion of the observatory that would become the Kuiper Airborne Observatory, the Astronomy Survey Committee to the National Academy of Sciences recommended that NASA undertake design studies for a very large stratospheric telescope.[38] A new, larger airborne observatory that could build on the legacies of Learjet and KAO was an immediately attractive option. By the mid-1980s, after a full decade of successful KAO operations, preliminary engineering studies at Ames identified the Stratospheric Observatory for Infrared Astronomy as a next-generation facility.[39] This new observatory was to build on NASA's history of airborne observation and function as a complement to the SIRTF (Space Infrared Telescope Facility, before the name change to Spitzer) telescope being developed. It was a model that would be flexible, expanding beyond the hyper-specific observational capacities of balloons floating above the stratosphere.[40]

The Kuiper Airborne Observatory was not concluded because it was obsolete, but because its operating budget was re-allocated to the development of a new airborne observatory that would improve the quality of infrared astronomy just by virtue of its larger size.[41] KAO was largely understood as a scientifically productive facility, with $10 million of up-front development costs (roughly $66.1 million in 2024 dollars, adjusted for inflation) and a $13 million operating budget by 1995 ($37.3 million in 2024 dollars).[42] It was also able to run with a small team. Though the organization of staff involved changed over the observatory's lifespan, KAO's operations were carried out by 26 civil servants and 31 contractors, coordinated by the Airborne Astronomy Branch at NASA Ames.[43] The Ames Flight Operations Directorate was responsible for aircraft maintenance, though structural flight tests were conducted at Dryden Flight Research Center in 1973.[44]

37 Alois Himmes, "SOFIA—eine gemeinsame Idee der USA und Deutschlands," in *SOFIA: Mission infrarotes Universum,* ed. Alfred Krabbe, Dörte Mehlert, and Jürgen Wolf (Stuttgart: Universität Stuttgart, Institut für Raumfahrsysteme, 2025), *https://doi.org/10.18419/OPUS-15639,* pp. 21–22.

38 Erickson and Meyer, "NASA's Kuiper Airborne Observatory, 1971–1995," p. 54.

39 "ARC SOFIA Preliminary Feasibility Study" (NASA Ames Research Center, December 1984), Stratospheric Observatory for Infrared Astronomy (SOFIA) Project Collection, Collection Number ARC24.12, NASA Ames Research Center Archives, p. 6.

40 Ibid.

41 Kunz, "The Making of SOFIA," p. 12.

42 Inflation adjustments based on a 3.7 percent annual U.S. inflation increase since 1970. Erickson and Meyer, "NASA's Kuiper Airborne Observatory, 1971–1995."

43 Ibid., p. 34.

44 See Figure 7 in Erickson and Meyer, "NASA's Kuiper Airborne Observatory, 1971–1995," p. 9.

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TABLE 1. Changes from KAO to SOFIA: Conditions for "Best" and "Worst" Cases.

Major impacts appear in heavy boxes.

Item	KAO	SOFIA	Change %
Observation Flights/year	80	160	+100
Support Flights/year	20	<40	+100
Down Days per year	265	<165	-40
Down Days / Observation Flight	~3:1	<1:1	-67
Focal Plane Instruments / Flight	1	1*	~0
Maximum Viewing Targets / Flight	10 dim~ 100 bright	10 dim~ 200 bright	+100
Maximum Mission Crew	4 to 5	2 to 3	-25 to -50
Mission Crew Trainees (as required)	~2	~2	+0
P.I. Teams / Flight (maximum, including host & guest teams, plus instruments for background tests)	2	2 to 3	0 to+50
P.I. Team Members (including supporting technicians)	4 to 6	6 to 15	0 to +275
P.I. Racks	1 to 2	4 to 5	+100 to 250
Outreach/Educators with Docent	3	6	+100
Media Guests (incl. foreign observers)	2	4	+100
Engineering Development Personnel	2	2	0
Cargo Doors to the Main Cabin	1	0	-100
Other Seats Vacant or removed During normative observation flight	0	12 to 18	∞
Total Personnel During Science Operations	18	~26 to 30	+44 to +77

* SOFIA Level I Requirements mandate not precluding use of more than one instrument on a SOFIA Flight.

Changes from KAO to SOFIA, May 1996. This chart illustrates the scale of ambitious changes anticipated in the leveling up from KAO to SOFIA. *(Stratospheric Observatory for Infrared Astronomy [SOFIA] Project Collection, Collection Number ARC24.12)*

Plans for the transition from KAO to SOFIA were characterized by ambitious expectations, including doubled annual observation flights and a 40 percent reduction in grounded days per year. Several KAO users made up the SOFIA Study Office (SSO), first inaugurated at Ames in 1985. This included Dr. Ed Erickson, who served as the facility scientist for the KAO and was subsequently asked to step in as lead study scientist for SOFIA.[45] The formation of the SSO occurred just before the January 1986 Challenger accident, resulting in increased scrutiny of SOFIA's design plans just as funding from NASA Headquarters began increasing. Despite the shifting climate, Erickson organized the SOFIA Technology Workshop at Ames in 1986 to bring interested contractors together to brainstorm the different telescope configurations and aircraft modifications that might be possible. Seven German participants attended, and, following the workshop, SOFIA Phase A studies began both at Ames and in Germany.[46] The SSO also arranged a contract with the Boeing Military Airplane Company (BMAC) to explore the feasibility of 747 modifications for an open-port 3.1-meter telescope. BMAC was interested in how the open port might be used for intercontinental ballistic missile interception for President Ronald Reagan's Strategic Defense Initiative, also known as the "Star Wars" program.[47] BMAC's initial estimate of $250 million dwarfed the SSO's budget of $25 million, ultimately bringing the telescope size down to 2.5 meters.

By the 1990s, interest in SOFIA was amplified by broader excitement about infrared observation. Dubbed the "Decade of Infrared" by the National Academy of Sciences, this portion of the electromagnetic spectrum was seen as crucial to many of the period's biggest astronomical questions.[48] The turn toward infrared observation was facilitated by technological developments made the decade prior—the 1980s saw tremendous improvements in solid-state detector chips sensitive to infrared radiation and the demonstration of long-duration containment of superfluid liquid helium in space.[49] Many of the advancements that improved infrared detection in the 1980s stemmed from the declassification of military and surveillance detectors used for the detection of Soviet missiles in space over the course of the Cold War.[50] After the collapse of the Berlin Wall in 1989 and the subsequent weakening of the Soviet Union's government, the Pentagon was more willing to release information on the classified infrared detectors previously used on Air Force surveillance satellites.[51]

The designation of the 1990s as the "Decade of Infrared Astronomy" came formally in 1991, with the National Academy of Sciences' publication of its decadal survey on astronomy and astrophysics.[52] The Academy's surveys on this topic had been published once a decade since 1964, convening preeminent astronomers and research scientists around the prioritization of the questions anticipated in the coming years. The Academy's decadal surveys functioned as a totem of community consensus and often helped set the research agenda for large agencies like NASA.[53] This became an increasingly important dynamic in the

45 Kunz, "The Making of SOFIA," p. 64.

46 Ibid., p. 65.

47 Ibid.

48 Frederick C. Gillett and James R. Houck, "The Decade of Infrared Astronomy," *Physics Today* 44, no. 4 (April 1, 1991): 32–37, *https://doi.org/10.1063/1.881285*.

49 Ibid.

50 W. Patrick McCray, *Giant Telescopes: Astronomical Ambition and the Promise of Technology* (Cambridge, MA: Harvard University Press, 2004), p. 198.

51 Ibid.

52 National Academy of Sciences, Astronomy and Astrophysics Survey Committee, *The Decade of Discovery in Astronomy and Astrophysics* (Washington, DC: National Academy Press, 1991), *https://doi.org/10.17226/1634* (accessed June 16, 2025).

53 "Astronomy and Astrophysics Panel Report" National Academy of Sciences, January 1, 1991, NTRS Accession number 91N33019, *https://ntrs.nasa.gov/api/citations/19910023705/downloads/19910023705.pdf* (accessed June 16, 2025).

1990s, as the bulk of funding for astronomical research shifted from NSF grants to direct support from the U.S. space program, turning NASA into an increasingly important patron of astronomical research.[54]

Enthusiasm in the scientific community was high in the 1990s for an airborne observatory to integrate infrared sensors that were not available the decade prior.[55] The 1991 survey *The Decade of Discovery in Astronomy and Astrophysics* emphasized infrared observation as the proving ground for questions central to the foundations of astrophysics. If adequately supported, these spectral observations promised new insights into the formation of galaxies, stars, and planets, and they could plausibly illuminate the origin of quasars and active galactic nuclei.[56]

The committee made concrete recommendations; in addition to the development of the Space Infrared Telescope Facility (later known as the Spitzer Space Telescope), they recommended the immediate development of the Stratospheric Observatory for Infrared Astronomy as a joint project with the Federal Republic of Germany.[57]

German involvement represented a significant international collaboration at a time when the newly reunified nation's space activities were being reorganized. In 1990, the Deutsche Forschungsanstalt für Luft- und Raumfahrt (DLR), or German Research Institute for Aviation and Space Flight, officially joined the SOFIA program, committing to funding 20 percent of the total project costs and taking responsibility for the construction of the 2.5-meter infrared telescope.[58] This telescope would be built by German engineers and scientists, representing one of Germany's key contributions to the project. As part of the agreement, German astronomers were guaranteed a significant percentage of observing time on SOFIA, ensuring that they would be able to pursue their scientific objectives once the observatory became operational.

This was quickly complicated by a shifting geopolitical landscape. In 1988, NASA and the German Space Agency drafted a Memorandum of Understanding (MOU), just before the November 1989 fall of the Berlin Wall. Rumors about budget cuts to the Deutsche Agentur für Raumfahrtangelegenheiten (DARA) began soon after it became clear that the reunification of the German state would require budget cuts across several government agencies. By 1991, just as the Academy of Sciences' Survey recommended SOFIA as a top priority, DARA did not receive enough funding to maintain its 20 percent stake. SOFIA planning was forced to remain within 80 percent of its initial budget without the support of its anticipated international partner, but thanks to continued lobbying from German scientists, funding was restored by 1995. In December 1996, NASA and DARA (which would soon consolidate into the DLR) signed an MOU on the development and operation of SOFIA. The German DLR awarded a contract to MAN and Kayser-Threde to develop SOFIA's telescope in a newly reunified Germany.[59]

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54 McCray, *Giant Telescopes,* p. 197.

55 Gillett and Houck, "The Decade of Infrared Astronomy."

56 "Astronomy and Astrophysics Panel Report," Executive Summary, p. II-2.

57 Ibid.

58 In 1997, the Deutsche Forschungsanstalt für Luft- und Raumfahrt (DLR) was merged with the Deutsche Agentur für Raumfahrtangelegenheiten (DARA) into the Deutsches Zentrum für Luft- und Raumfahrt, which is abbreviated as the DLR but known in English as the German Aerospace Center.

59 Alfred Krabbe, "The SOFIA Telescope," paper presented at the symposium on *Astronomical Telescopes and Instrumentation 2000* in Munich, March 2000, in "News Clippings 1999–2006," n.d., p. 37, Stratospheric Observatory for Infrared Astronomy (SOFIA) Project Collection, Collection Number ARC24.12, NASA Ames Research Center Archives.

SECTION III

The Development of SOFIA

SOFIA was borne largely out of the successes of the KAO. This genealogical relationship shaped the development of the new observatory in two ways: first, the concept for SOFIA originated as a scaled-up version of KAO, and in 1995 KAO itself was retired to reallocate its $13 million budget to SOFIA's development.[60] NASA and the DLR both saw SOFIA as a successor platform, capable of expanding KAO's observations in infrared by virtue of its much larger telescope mirror.[61] As a result of this relationship, KAO users and their intimate knowledge of infrared airborne observation became an invaluable resource for SOFIA's early development.[62] In 1995, the SSO became the SOFIA Project Office (SPO), headed by Ed Erickson as Project Scientist and Nans Kunz as Chief Engineer.[63]

One of the promising aspects of SOFIA's initial design was its potential to accommodate a flexible suite of new scientific instruments. KAO spanned 20 years between 1975 and 1995, a period that saw radical transformations in computing technology. Hardware evolved from mainframe computers and punch cards to commercially available PCs with diverse software ecosystems and an emergent internet. SOFIA would be designed to accommodate these changes. As instruments were developed to measure information in new ways, they could replace older ones and update the observatory's capabilities using emerging technologies.[64] This was a critical improvement; swapping out astronomical instrumentation on an aircraft with a telescope mirror the same size as the Hubble Space Telescope offered a promising level of flexibility sure to spur technological advancement.[65] SOFIA would be used to train a new generation of astronomers and encourage the development of cutting-edge astronomical tools that would benefit the field at large and cultivate innovation in astrophysics.

Privatization and Partnerships

The encouragement of innovation coupled with cost savings was emblematic of the "faster, better, cheaper" attitude encouraged at NASA in the early 1990s. Daniel Goldin, a former California aerospace

60 Edwin F. Erickson and Allan W. Meyer, "KAO Lessons for the SOFIA MCCS and LOPA Concepts," 1996, Stratospheric Observatory for Infrared Astronomy (SOFIA) Project Collection, Collection Number ARC24.12, NASA Ames Research Center Archives.

61 SOFIA represented a full ten-fold increase in observational area from KAO and promised a similarly scaled increase in collected data.

62 Erickson and Meyer, "NASA's Kuiper Airborne Observatory, 1971–1995."

63 Kunz, "The Making of SOFIA," p. 77.

64 "SOFIA Project Documents Binder" (Ames Research Center, 1996—1997), p. 4, Stratospheric Observatory for Infrared Astronomy (SOFIA) Project Collection, Collection Number ARC24.12, NASA Ames Research Center Archives.

65 "ARC SOFIA Preliminary Feasibility Study," p. 6.

executive, was appointed by George H. W. Bush in the wake of the Hubble cost overruns that prompted the resignation of his predecessor, Richard Truly. Goldin's mandate was to achieve financial stability through downsizing and privatization.[66] In SOFIA's case, cost efficiency was to be facilitated by way of a greater proportion of contractor involvement in the observatory's development.

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Cross reference

SOFIA in the "Reinvented NASA"

NASA's new Vision Statement recommends focussing on smaller, short term science missions, with frequent flight opportunities and lower costs to reduce risks, applying advanced technologies and low cost management approaches to system development. The ultimate program objective is the creation of new knowledge. SOFIA admirably satisfies these criteria, as outlined below:

Science: Highest priority moderate new astrophysics mission for 1990s
Formation of stars and planetary systems
Physics of the ISM and Galactic Center
Structure and composition of solar system objects

Observational emphases:
FIR imaging, high resolution spectroscopy, occultations

Cost:
predevelopment: > $30M (FY93$), through FY93

development: $230M; includes modified aircraft, telescope, integration and test, ground facility, and contingency

(possible development cost offsets: KAO curtailment: $60M
FRG participation: $40M)

less
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operations: $24M/year; 160 flights, 15 instrument PIs, 45 GIs;
includes $8M/year for investigators;
cost per flight comparable to KAO

science/ops: 1/2 (= DA/MO), best of any proposed astrophysics project

cost/investigation: $600k = ($230M + 20yr x $24M/yr)/1200

Investigations: 60 per year, selected by peer review; 20 year lifetime

Risk: ultra reliable vehicle; mission systems maintainable between flights

Technology: state-of-the-art instrumentation throughout lifetime;
hands-on testbed environment for new IR & submm technology

Management: development and operations at NASA Ames, largely using CS;
utilizes experienced personnel
minimizes cost and overrun risk
maximizes maintainability

Education: post-docs, grad students, teachers, media, public

The document "SOFIA in the 'Reinvented NASA,'" illustrates the way the vocabulary of financial efficiency was incorporated into plans for the new observatory. The cost breakdown, written for fiscal year (FY) 1993, initially identified the use of civil servant labor and in-house expertise as a driver of management efficiency. *(Stratospheric Observatory for Infrared Astronomy [SOFIA] Project Collection, Collection Number ARC24.12)*

66 Henry W. Lambright, "Transforming Government: Dan Goldin and the Remaking of NASA," The Business of Government (PricewaterhouseCoopers, March 2001). See also Howard E. McCurdy, *Faster, Better, Cheaper: Low-Cost Innovation in the U.S. Space Program* (Baltimore, MD: JHU Press, 2003),2003 p. 47.

In 1995, NASA Headquarters announced that the SOFIA Science Office at Ames would not serve as the prime contractor in the SOFIA development, but that an external science organization should take on this role. The decision was intended to shape SOFIA into an observatory that was "government-owned, contractor-operated."[67] One of the most detailed accounts of this decision was written by Nans Kunz in his 2016 "The Making of SOFIA," a controversial report that was openly critical of NASA's management of the observatory's development. In an interview about SOFIA's development, Ed Erickson, Kunz's counterpart in the SOFIA Project Office, explained that Kunz felt compelled to write the history to explain that the delays that the observatory was eventually characterized by were not the fault of individual engineers and scientists working on SOFIA, but rather the complicated contract structure that muddled deadlines and diffused accountability.[68] Regardless of Kunz's intentions, "The Making of SOFIA" is useful for its granular retelling of major technical developments over the course of SOFIA's modification. Though Kunz is listed as the sole author, Ed Erickson, the Infrared Program Chief at NASA Headquarters, and Larry Caroff, a SOFIA Program Manager at Ames for two years, helped Kunz complete the work before his passing in 2016.

While Kunz agreed that hiring private commercial companies could be more efficient than undertaking development projects in-house, he felt that moving oversight of SOFIA's modifications out of the SSO (later known as the SPO) was a shortsighted maneuver that overlooked the expertise in airborne observation that Ames had cultivated over the past several decades, particularly that of the former staff of the KAO.[69] As a function of Ames's experience with Galileo, Learjet, and KAO, the research center represented an unusual concentration of expertise in the development of airborne astronomical observatories. In Kunz's telling, the issues with external management of airborne observatories were further exacerbated by the Request for Proposals issued for SOFIA's prime contract, which asked for bids to manage the modifications to the 747SP's airframe, the integration of the telescope, flight operations, and the routine maintenance of the aircraft. In other words, NASA sought a contractor to build a "turnkey" observatory—a functional platform ready for operation upon delivery.

The Universities Space Research Association (USRA), a science missions operations organization composed of over 80 different research universities that won the contract in 1996, was to oversee subcontractors that would handle the bulk of the modifications as well as the flight operations.[70] According to Kunz, the problem was that transforming a former passenger aircraft into a functional airborne observatory was too big and multifaceted a task for the expertise of one single entity. Regardless of whether Ames would have been better poised to manage the development, SOFIA's fabrication and delivery stage would take roughly nine years longer than anticipated.[71] While the planned delivery of SOFIA was scheduled to take place in 2001, the observatory's first flight would not occur until 2010.

Modifications and Delays

Phase C of SOFIA's development began in 1997, after USRA won the contract to develop and operate the observatory on behalf of NASA and purchased a 747SP airframe from United Airlines for $13 million.[72]

67 Kunz, "The Making of SOFIA," p. 88.

68 Edwin F. Erickson and Lois Rosson, "Edwin F. Erickson: SOFIA Oral History Project," June 20, 2024.

69 Kunz, "The Making of SOFIA," p. 78.

70 "Final Memorandum on Audit of the Stratospheric Observatory for Infrared Astronomy (SOFIA) Program Management Effectiveness" (Assistant Inspector General for Auditing: NASA, March 27, 2009), *https://oig.nasa.gov/wp-content/uploads/2024/06/ig-09-013.pdf?emrc=670a4365c989e* (accessed June 16, 2025), p. 7.

71 "NASA's Management of the Stratospheric Observatory for Infrared Astronomy Program," Audit (NASA Office of Inspector General, September 2020), *https://oig.nasa.gov/wp-content/uploads/2024/02/IG-20-022.pdf*, p. 7.

72 Kunz, "The Making of SOFIA," p. 85.

DARA selected Maschinenfabrik Augsburg Nürnberg AG (MAN), a manufacturing and engineering company based of Munich that specialized in commercial vehicles, as well as Kayser-Threde, a systems house with a specialty in optics, to construct the telescope in Germany.[73] The plan was to install the telescope in the United States, once the airframe cavity was completed, by the September 2001 deadline.

In the United States, USRA, Chrysler Technology, and United Airlines formed the winning bid, with work packages that could be conducted by Ames employees under contract supervision.[74] This contract formulation would itself shift around in the coming years: In 1995, Raytheon purchased Chrysler Technology and merged it with E-Systems, Inc., a military contractor that built top-secret spying equipment out of an aircraft modification center in Waco, Texas.[75] The facility, part of the Texas State Technical College airport, would become Raytheon/L3 Technologies in 1998, its name for the bulk of SOFIA's development.[76] Modifications began immediately at the different facilities, but coordination across the different subcontractors proved difficult, and the first structural cut of the aircraft fuselage was not made until March 21, 2000. While the telescope assembly happening in Germany was largely on schedule, the aircraft modifications proved harder to manage. In November 2000, after a Critical Design Review undertaken that summer, USRA announced that the timeline would be re-baselined and the Operational Readiness Review was rescheduled for March 2005.[77] In the summer of 2001, just after the delay was announced, $10 million in upgrades were made to Hangar N-211 at Ames, where USRA planned to house SOFIA in close collaboration with ARC staff.[78] The telescope was shipped to Waco for integration onto the aircraft in September 2002, though the process did not start until 2003.

External geopolitical events in the early aughts contributed to SOFIA's delayed development timeline. In September 2003, United Airlines declared bankruptcy in the aftermath of the September 11 terror attacks, complicating plans for aircraft operation and maintenance after all the modifications were completed. In February 2003, the Space Shuttle Columbia accident prompted increased scrutiny of engineering safety protocols, warranting the formation of the NASA Engineering and Safety Center.

Structural safety was taken very seriously in SOFIA's case because of the extent of the airframe's modifications. Outer panels were to be removed from the fuselage and replaced with new ones specifically shaped to leave an opening for the telescope. The observatory's open-air cavity meant a new pressure bulkhead was needed to maintain cabin pressure throughout the rest of the aircraft. The bulkhead reconstruction represented a weighty modification—pressure bulkheads carry remarkably large weight loads, and if they fail, the resulting explosive decompression can send an aircraft crashing to the ground. This happened in 1985 on Japan Airlines Flight 123, a domestic passenger flight from Tokyo to Osaka, when a botched bulkhead repair blew off the plane's vertical fin. The structural failure occurred just 12 minutes into the flight, killing all 15 crew members and 505 of the 509 passengers onboard.[79]

73 MAN was eventually acquired by Volkswagen.

74 Kunz, "The Making of SOFIA," p. 81.

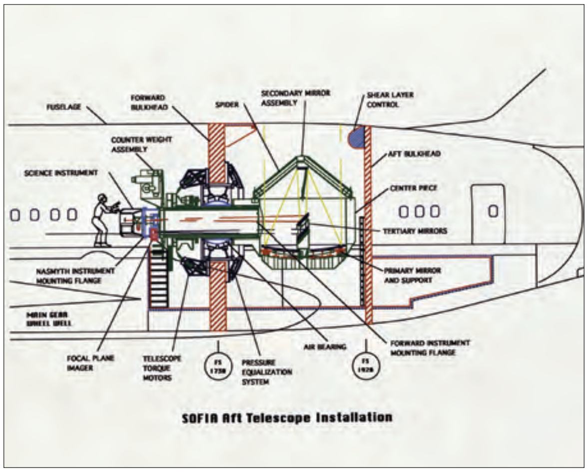
75 Kathyrn Jones, "Raytheon Offers $2.3 Billion for E-Systems," *New York Times* (April 4, 1995).

76 Greater Waco Chamber, "Post-Merger, L3Harris Technologies Still Flying High in Waco," *Greater Waco Business Magazine*, Summer 2020, *https://issuu.com/wacochamber/docs/2q20_layout-issuu/s/11041314*

77 Kunz, "The Making of SOFIA," p. 107.

78 Ibid., p. 113.

79 "Boeing 747-SR100 | Federal Aviation Administration," *https://www.faa.gov/lessons_learned/transport_airplane/accidents/JA8119* (accessed December 6, 2024).



1992 schematic illustrating the integration of the telescope with SOFIA's pressure bulkhead and science instruments. *(NASA ID: AC92-0296-002)*

Photograph of telescope cavity installation at the L3 facility in Waco, Texas. *(NASA ID: ACD03-0160-143/Eric James)*

The other major engineering complexity had to do with the fact that scientific instruments on board needed to be able to receive information from the telescope on the other side of the pressure bulkhead. The infrared sensors were to be carried in the pressurized part of the cabin, meaning that faint light detected by the telescope mirror needed to be carried through the pressure bulkhead by a metal pipe that doubled as the telescope's pivoting azimuth pointing system.[80] All of these elements were contained inside the telescope cavity, which was designed at Ames using its wind tunnels on a work package USRA oversaw, necessitating team-wide travel from Ames to Waco, Texas.

These engineering challenges were compounded by the fact that the airframe being refurbished was first built in 1975. In 2005, the cavity door installation was still underway in Waco, but by that point, most of the delays holding up the Operational Readiness Review—which had initially been promised in 2001—had to do with the routine maintenance of the aging aircraft. SOFIA's airframe, formally known as the Clipper Lindbergh, had lived a full life as a passenger vehicle. By 2005, the 747SP had been taken out of service by United Airlines, making normal upkeep a challenge that technicians at L3 lacked the infrastructure to undertake.[81]

2006 Cancellation and the Move to Armstrong Flight Research Center

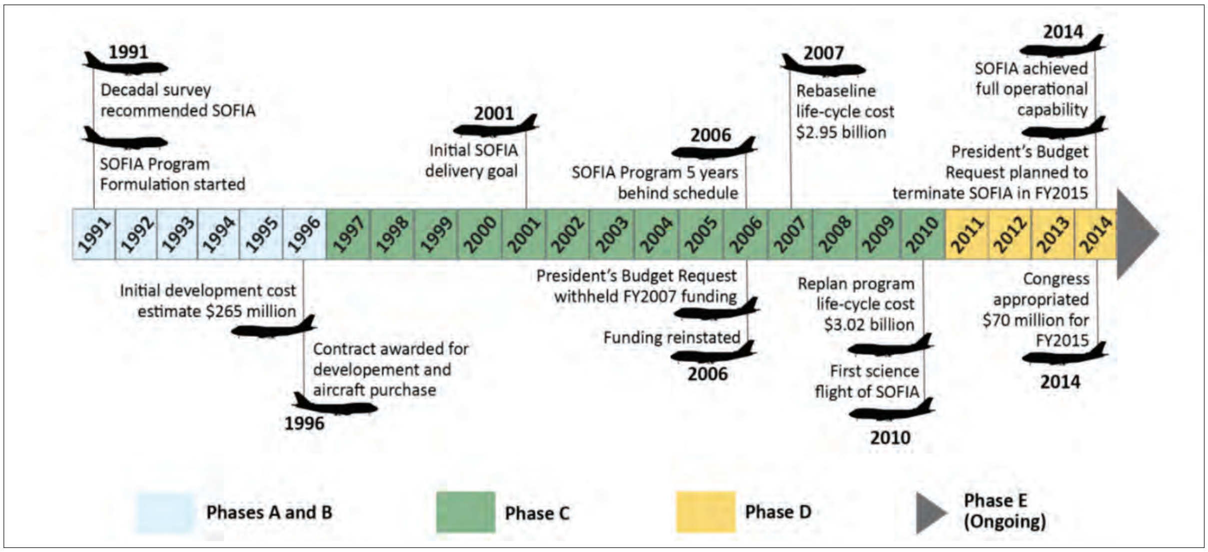
By 2006, SOFIA's development costs had ballooned far beyond initial projections, and the program was nearly five years behind schedule. Initially estimated to cost around $265 million, program spending had by this point exceeded $500 million.[82] The increasing costs prompted concerns within NASA and external oversight bodies about the project's feasibility and financial management. In February 2006, NASA considered cancelling the SOFIA project altogether due to these rising costs and repeated complications. The project had already been delayed by several years, and there was skepticism about whether SOFIA could

80 "News Clippings, 2013–Folder 2," 2013, p. 11, Stratospheric Observatory for Infrared Astronomy (SOFIA) Project Collection, Collection Number ARC24.12, NASA Ames Research Center Archives.

81 Kunz, "The Making of SOFIA," p. 182.

82 "NASA's Management of the Stratospheric Observatory for Infrared Astronomy Program," p. 7.

deliver the expected scientific returns for the investment.[83] As a result of these concerns, the President's Budget Request eliminated SOFIA's budget for fiscal year 2007.[84] In particular, NASA identified that there was insufficient oversight and integration of the work being done by the various partners involved in the project, including the Deutsches Zentrum für Luft- und Raumfahrt (DLR) and the contractors responsible for the aircraft modifications.



Timeline of SOFIA's Phase C delays, reprinted in NASA Office of Inspector General Audit of SOFIA. *(NASA OIG Presentation of Agency Data. Report No. IG-20-022)*

NASA formed the SOFIA Option Review Team (SORT) to present its findings to the Science Mission Directorate in April 2006.[85] The team determined that the delays were not prompted by insurmountable hardware issues, but rather by poor management. NASA recommended reinstating SOFIA's funding but took over control of SOFIA's management, assigning the function to Dryden Flight Research Center (now known as Armstrong Flight Research Center or Armstrong).[86]

Armstrong was selected because of its familiarity with experimental aircraft and expertise in airworthiness certification. In this new organizational structure, SOFIA's science would all still be managed out of Ames, but anything flight-related would fall under Armstrong's auspices. This was crucial to salvaging the mission; after all of the technical problems incurred in Waco, the aircraft was not able to safely fly.[87] The inclusion of Armstrong as a partner meant SOFIA could be flight certified at Armstrong using the NASA research aircraft certification process, shifting responsibility away from USRA for Federal Aviation Administration (FAA) flight readiness certification.[88] The move also represented shifting attitudes at Ames about its status as a flight operations hub. The U.S. Navy ceased regular flights out of Moffett Field in 1994, and air

83 Ibid.

84 "Final Memorandum on Audit of the Stratospheric Observatory for Infrared Astronomy (SOFIA) Program Management Effectiveness," p. 2.

85 Ibid., p. 8.

86 Ibid.

87 Eddie Zavala and Lois Rosson, "Eddie Zavala: SOFIA Oral History Project," June 18, 2024, p. 13.

88 "Final Memorandum on Audit of the Stratospheric Observatory for Infrared Astronomy (SOFIA) Program Management Effectiveness," p. 8.

traffic at both San Francisco International and San Jose was increasing dramatically as a function of the dot-com boom.[89]

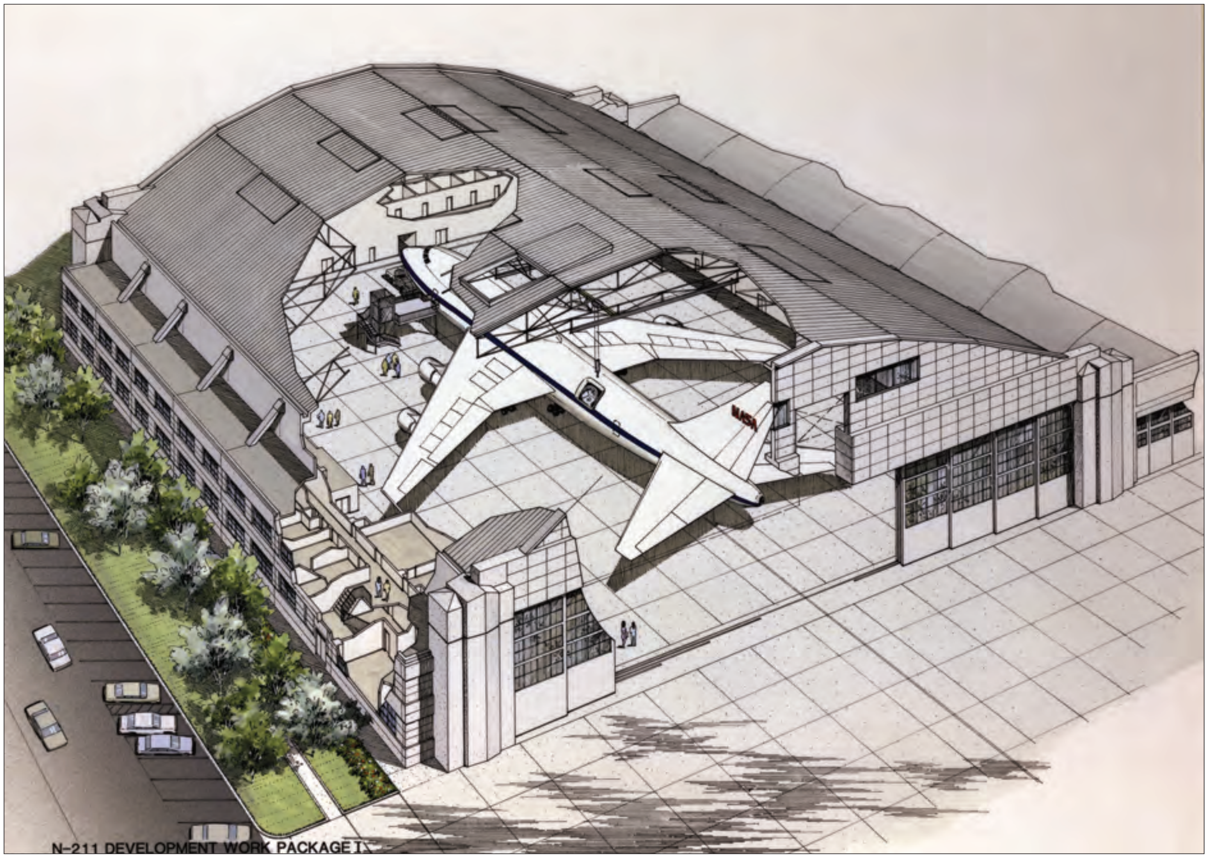


Illustration of proposed SOFIA facilities for building N-211 at Ames Research Center. Cutaway art one of many created for Development Work Package 1, October 1993. *(NASA ID: AC93-0491-003)*

Regardless of the reason, for many of those who worked on SOFIA from the observatory's initial planning stages, this was a devastating blow. Hangar N-211 at Moffet Field had been modified and optimized for SOFIA operations, drawing on 20 years of knowledge gleaned from the operation and modification of KAO.[90] The roughly $10 million in hangar refurbishments included the development of a mirror-coating facility, a notch cut above the main hangar door designed to accommodate the tallest point of the 747SP's tail, and a two-story ramp to facilitate the installation of scientific instruments.[91] The purpose was to house everything needed for SOFIA in one central location. This work plan included former United Airlines employees, who joined SOFIA outright after the company's withdrawal from aircraft operations and set up offices within N-211. So much infrastructure was developed through this process that building N-211 achieved certification as an official FAA maintenance station.[92]

89 Charles Kaminski and Lois Rosson, "Charlie Kaminski: SOFIA Oral History Project," November 6, 2024, p. 9.

90 Kunz, "The Making of SOFIA," p. 204.

91 Ibid., p. 217.

92 Ibid., p. 204.

Of all the criticisms in Nans Kunz's "The Making of SOFIA," the most explicit is a critique of NASA's decision to move SOFIA operations to Armstrong. Kunz felt this decision created some of SOFIA's most significant setbacks. Instead of streamlining efficiency, the move incentivized delays as Armstrong administrators retained control of the project and its $70 million annual budget until SOFIA was deemed fully operational. This financial arrangement gave Armstrong a vested interest in postponing milestones, Kunz contended, thereby extending their control over the program and its associated funding.[93]

Kunz disagreed with the rationale for the decision, illustrating broader disagreements over who was at fault for delays and how they might best be addressed. According to Kunz, the transition to Armstrong was justified on claims of mismanagement at Ames, even though SOFIA had passed the rigorous SORT review with strong results under Ames's oversight. While administrators at NASA Headquarters maintained that Ames's mismanagement of SOFIA was well-documented in internal reviews, Kunz attributed the earlier cost and schedule overruns to NASA Headquarters' mandated privatization policies.[94] There was, of course, disagreement on this point—but many of these early reviews were not made widely available due to the sensitive nature of information contained within them.[95] For Kunz, regardless of where the mismanagement was located, the transition to Armstrong presented new problems—engineers and managers in Palmdale had the authority to overhaul systems and methods that were nearing completion, often disregarding the lessons learned from decades of experience with SOFIA and KAO. These changes further delayed progress, and in Kunz's estimation, Armstrong set unreasonably high milestone standards that prolonged the path to operational status and deprioritized the need to start delivering scientific results.

Independently of assigning blame, the "unreasonably high milestone standards" Kunz identified do speak to an underlying cultural tension identified by other members of the SOFIA team. Teams at Ames wanted to optimize SOFIA for science productivity, while teams at Armstrong were trained to optimize for flight safety in a period characterized by heightened attention to safety protocols. The Armstrong Flight Safety Review Board was charged with certifying SOFIA as airworthy and proving that the mechanically involved modification process had mitigated any outstanding risks. In SOFIA's case, not only was the airframe itself heavily modified, but it was intended to fly with cryogens on board to cool the telescope, which added hazards like flammability and asphyxiation from leaking materials.[96]

Despite the tensions chronicled in "The Making of SOFIA," Armstrong proved to be an invaluable collaborator. David McBride, a former center director of Armstrong, did not remember the transition as contentious, but rather as a partnership that was mutually beneficial for both parties. Besides, this was not an unusual arrangement: most big projects at Armstrong were partnerships with other centers, helping solve issues with aircraft or flight.[97] In SOFIA's case, the modification delays with L3 and problems the subcontractor was having with aircraft modification made Armstrong a contender for overseeing the observatory's remaining milestones. While L3 incurred a stream of technical issues that delayed FAA certification, Armstrong had the expertise necessary to get SOFIA certified as flightworthy.[98] In McBride's view, SOFIA's

93 Ibid.

94 Ibid.

95 In a forthcoming paper on the evaluation of science using SOFIA as a case study, Borgman, Mayernik, Morris, Becklin, and Zinnecker argue that a lack of transparency around evaluation results in unclear expectations, ultimately inhibiting judgments around productivity. "How to Evaluate Scientific Infrastructures Scientifically: Lessons Learned from the SOFIA Mission," article in preparation for *Nature Astronomy* as of April 16, 2025, p. 17. Shared courtesy of the authors.

96 Paul Martinez and Lois Rosson, "Paul Martinez: SOFIA Oral History Project," August 1, 2024, p. 5.

97 David McBride and Lois Rosson, "David McBride: SOFIA Oral History Project," January 12, 2025, p. 4.

98 Eddie Zavala and Lois Rosson, "Eddie Zavala: SOFIA Oral History Project," June 18, 2024, p. 13.

management had previously underestimated the importance of aircraft modifications: "there was no value if you couldn't get it up to altitude and stable…. It really did take an aircraft-centered organization to get it operational."[99] This became especially necessary after United Airlines, the contractor initially responsible for SOFIA's maintenance and flight, filed bankruptcy in December 2002.[100] After United Airlines pulled out of the contract, Armstrong's cache of pilots and flight operators became even more crucial to the project.

SOFIA's 2006 cancellation resulted in a dramatic restructuring of the project's management. What began as a contractor-led, government-supported program was now a government-led, contractor-supported one. Armstrong would oversee the rest of SOFIA's development, and when it reached Full Operational Capability (referred to as FOC, a key milestone introduced by NASA), it would remain stationed and supported in Palmdale while USRA managed the science out of NASA Ames.

2014 Cancellation and Reinstitution

In 2007, after the move to Armstrong, NASA baselined SOFIA once again, this time establishing a total life-cycle cost of $2.95 billion, made up of $955 million for formulation and $2 billion for 20 years of operations.[101] At this point, the agency estimated SOFIA would reach FOC by December 2013. On the ground at Armstrong, SOFIA's development was shifted away from the facility as a whole and broken up into incremental pieces focused separately on telescope integration with the aircraft, closed-door development, and finally demonstrations of open-door capabilities.[102] By October 2010, FOC estimations were pushed up to December 2014, though the milestone would be reached by February, technically 11 months ahead of the new deadline.

SOFIA began science flights in 2010, shortly after its first-light observations, but was not yet fully equipped to conduct its planned scientific missions at maximum capacity. Despite modest gains in operational readiness achieved in collaboration with Armstrong, uncertainties around SOFIA's development and projected budget persisted. An audit completed in 2009 cited the general unreliability of total cost projections related to SOFIA as a key problem that exacerbated unclear cost controls, timelines, and evaluations of contractor performance.[103] Between 2010 and 2014, delays were made worse by concerns regarding SOFIA's anticipated scientific performance and operational costs. Because of the price of jet fuel for an aircraft the size of a 747, the cost of a crew of operators, and all the logistics that needed to be put in place prior to flight, SOFIA's hourly operating costs were also expensive. In 2022, a report from NASA's Office of Inspector General estimated the numbers to be approximately $172,000 per observational hour.[104]

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99 McBride and Rosson, "David McBride: SOFIA Oral History Interview," p. 3.

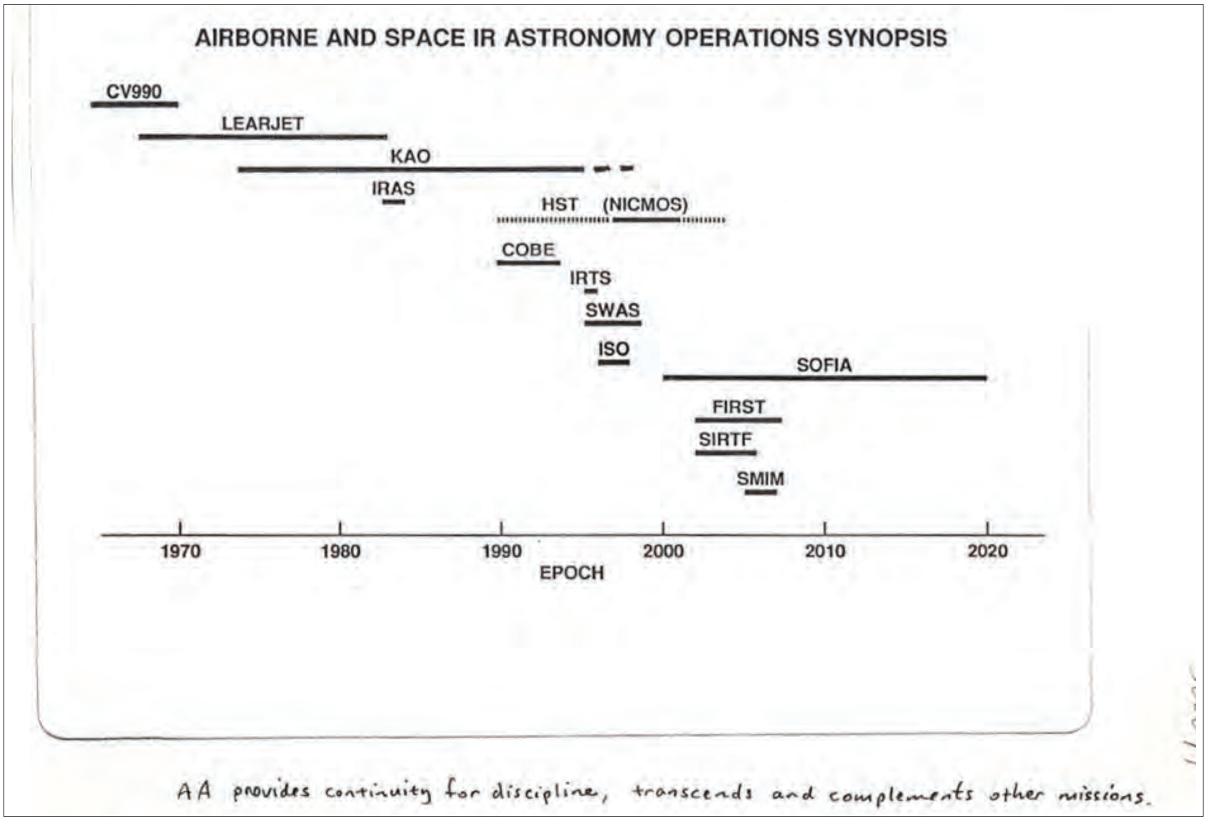
100 "12/09/2002: United Airlines Files for Chapter 11 Bankruptcy," *Airways Magazine, https://www.airwaysmag.com/legacy-posts/12-09-2002-united-chapt-chpt-11.*

101 "NASA's Management of the Stratospheric Observatory for Infrared Astronomy Program," p. 7.

102 Zavala and Rosson, "Eddie Zavala: SOFIA Oral History Project," p. 3.

103 "Final Memorandum on Audit of the Stratospheric Observatory for Infrared Astronomy (SOFIA) Program Management Effectiveness," p. 14.

104 This number included aircraft maintenance, fuel, crew salaries, and scientific operations. The report compares SOFIA's $172,000 hourly operating costs to the Herschel Space Observatory's $51,000. Both numbers were tabulated by dividing the total life cycle cost (including development) by observational hours. "NASA's Management of the Stratospheric Observatory for Infrared Astronomy Program," p. 12.



Plan for continuities with other infrared missions. *(Stratospheric Observatory for Infrared Astronomy [SOFIA] Project Collection, Collection Number ARC24.12)*

In February 2014, just after reaching FOC, NASA attempted once again to terminate SOFIA by reducing its annual operating budget from $87 million to $12.3 million for fiscal year 2015.[105] Despite the NASA Science Mission Directorate's assertions that SOFIA's annual operating budget could be put to better use elsewhere in NASA's budget, the request was unpopular with the House Science Committee, which expressed bipartisan support to keep SOFIA in operation.[106] Steven Palazzo, a Republican representative from Mississippi, asked why Congress had invested American taxpayer dollars into "something that was extremely important to NASA, and with just the wave of a wand, is no longer important."[107] Other representatives were eager to keep SOFIA in operation to preserve international collaborations with the German DLR.[108] Congress stepped in, appropriating $70 million for SOFIA's operating costs, setting the observatory up to finally begin its work, albeit on a leaner budget.

SOFIA's achievement of FOC in 2014 occurred 13 years after the project's initial 2001 delivery goal. With development finally completed and a $70 million operating budget reinstated by Congress, the facility

105 "NASA's Management of the Stratospheric Observatory for Infrared Astronomy Program," p. 8.

106 "Proposed SOFIA Cancellation Rankles Congress, Scientists," *https://spacepolicyonline.com/news/proposed-sofia-cancellation-rankles-congress-scientists/* (accessed January 14, 2025).

107 Jeff Foust, "House Science Committee Questions Decision to Cancel SOFIA," SpaceNews, March 27, 2014, *https://spacenews.com/40004house-science-committee-questions-decision-to-cancel-sofia/* (accessed June 17, 2025).

108 McBride and Rosson, "David McBride: SOFIA Oral History Interview," p. 3.

was poised to begin conducting science. In 2016, NASA requested the full $85 million operating budget, reversing course completely from 2014 and bolstering SOFIA's performance with upgraded technology.[109]

While SOFIA still had a 20-year capability requirement, meaning the facility could operate for a full 20 years, NASA modified its Technical Performance Commitment by adding a prime mission duration of five years. The purpose of this modification was to implement a review process to assess cost efficiency, conducted by way of a Senior Review. This practice was introduced agencywide with the NASA Transition Authorization Act of 2005 to institutionalize biennial reviews of post-prime missions within each of NASA's science divisions. In 2017, the NASA Authorization Act of 2017 lengthened the review cadence from two years to three.[110] In this system, at the conclusion of a prime mission, NASA would convene a panel of members affiliated with academic institutions, museums, and research centers to evaluate the science performance, management, and future of a given mission.

SOFIA emerged as a hybrid system that required operating procedures that blended astronomical observation with the specific logistics of flight operations. This was mirrored by the program's administrative apparatus, which required collaboration from several different institutional players. The observatory was managed between Ames and Armstrong, two different NASA centers roughly 330 miles apart, with input from German collaborators by way of the Deutsches SOFIA Institut at the University of Stuttgart. From an administrative standpoint, the SOFIA Project Office housed the project scientist and program manager, positions that functioned as the official NASA interface and oversight mechanism for USRA, who was still managing the science operations out of Ames.[111] SOFIA Mission Operations (SMO, operated by USRA) would solicit proposals for observatory time from the astrophysics community, and the subsequent plan for operations would give managers at Armstrong a general sense of how many flights were needed.[112]

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109 Dan Leone, "NASA Does About-Face on SOFIA, Requests Full Funding," SpaceNews, February 2, 2015, *https://spacenews.com/nasa-does-about-face-on-sofia-requests-full-funding/* (accessed June 17, 2025).

110 "NASA's Management of the Stratospheric Observatory for Infrared Astronomy Program," p. 8.

111 Naseem Rangwala and Lois Rosson, "Naseem Rangwala: SOFIA Oral History Project, Part 1," May 30, 2024, p. 7.

112 Ibid., p. 8.

SECTION IV

Eight Years of Project Science

How to Operate an Airborne Observatory

SOFIA reached FOC in 2014, increasing the amount of science flights it had been conducting since 2010. The onset of SOFIA's operational status further underscored the close working relationship necessary between science teams and a flight crew operating an experimental aircraft. SOFIA required an aircraft, and this also warranted a flying mission control room, a payload, scientists, engineers, pilots, and technicians.[113] By 2021, SOFIA was staffed to fly four 10-hour flights per week, Monday through Thursday, with Friday as a contingency day should any of the other flights be canceled. SOFIA's schedule during the week was a full one: the aircraft would land at 5 a.m. from the previous evening's excursion and be ready for takeoff again by 8 p.m.[114] A day shift would prepare the aircraft for flight, with a night crew in place to launch the aircraft and operate the observatory. On weekends, maintenance crews would fix technical issues and perform instrument swaps.[115]

Planning for each flight series with a single instrument began 10 weeks in advance. At 36 and 12 hours prior to takeoff, the flight plan would be updated with new weather or air traffic information.[116] On the day of a science mission, a briefing would take place 2 hours before the approximately 10-hour flight. Everyone scheduled to fly would be on board roughly 1 hour prior to departure to prepare for takeoff. Because the 747 had two decks, the crew used headsets with microphones to communicate readiness levels throughout the various parts of the aircraft. Nancy McKown, who flew on both SOFIA and its predecessor KAO, likened the difference to riding on a motorcycle versus sitting on a school bus, both in terms of the size of machinery and number of people present.[117]

Flying SOFIA was different from flying commercial aircraft, in which pilots are trained to fly from one location to another as safely and quickly as possible. The pilots flying SOFIA needed to fly a specific route with tight time parameters, and at the upper end of the aircraft's flight envelope to facilitate better astronomical data collection.[118] Though the telescope door could be opened at 28,000 feet, the telescope itself could not be used lower than 35,000 feet due to the presence of light-blocking water in the air, so it would take roughly 20–30 minutes after takeoff before the telescope could be unlocked.[119] Whereas most

113 Zavala and Rosson, "Eddie Zavala: SOFIA Oral History Project," p. 4.
114 Naseem Rangwala et al., "SOFIA Status & Future Prospects 2022," 2022, p. 27.
115 Ibid., p. 22.
116 Ibid., p. 15.
117 Nancy McKown and Lois Rosson, "Nancy McKown: SOFIA Oral History Project," July 31, 2024, p. 4.
118 Elizabeth S. Ruth and Lois Rosson, "Elizabeth Ruth: SOFIA Oral History Project," July 30, 2024, p. 9.
119 Kaminski and Rosson, "Charlie Kaminski: SOFIA Oral History Project," p. 13.

commercial airliners cruise at 35,000 feet, SOFIA would spend the bulk of its science missions between 38,000 and 45,000 feet.[120] Planners at Ames would arrange different observations into a roughly 9.5-hour window, and then navigational planners at Armstrong translated this itinerary into a flight plan filed with air traffic control. A successful flight, one in which all astronomers got to see their intended targets, meant keeping the aircraft to a strict schedule: pilots needed to bring SOFIA to each turn point on the flight plan within 2 minutes of the allotted time, a process susceptible to changes in wind, altitude, and airspeed.[121] When Elizabeth Ruth, one of SOFIA's roughly 20 pilots, remarked to a copilot in flight that she was pleased about making it to a target on time, he remarked, "No, you're 17 seconds late."[122] If takeoff was delayed by even a few minutes, entire legs of the journey would have to be scrubbed.[123]

As winds changed and Earth rotated, SOFIA's mission director would give the pilots alterations in 1-degree increments. If the observatory turned more than 1 degree at a time, it risked losing the telescope's lock on whatever object it was looking at.[124] In reference to the complex timing necessary to maximize observations, Paul Hertz described SOFIA as a telescope flying an airplane: "when they were observing, the telescope controlled the autopilot for the plane, and the plane jiggled around the telescope while the telescope held still. The telescope was flying the plane." According to Hertz, this was the most difficult component of the whole system because it combined safety and airworthiness and science achievement all into one technology.[125]

The German-made telescope, managed by the Deutsches SOFIA Institut (DSI) at the University of Stuttgart, represented both a successful technical integration and collaboration across international lines. The 2.5-meter telescope, roughly 8.2 feet in diameter, used a Cassegrain reflector with a Nasmyth focus. This modification included a tertiary mirror that redirected light to the side of the telescope, allowing instruments to be mounted in a fixed position closer to the aircraft's center of gravity. This was crucial: the telescope weighed 17 metric tons, which amounted to nearly 40,000 pounds of extra weight.[126] The telescope itself floated on a spherical bearing with 17 microns of oil that allowed it to rotate. According to Eddie Zavala, when on the ground, "you could take that telescope and you could move that mass that was on that spherical bearing effortlessly with two fingers." DSI, which maintained a presence at both Ames and Armstrong, developed the vibrational and rotational isolation systems, as well as the interface between the telescope and its tracking system. Zavala described the German team's commitment as steadfast, emphasizing tremendous personal sacrifice required by expatriation: "the collaboration with the German partner[s] was truly phenomenal."[127]

The extensive modifications SOFIA underwent over the decade prior were finally on full display, one of the most impressive being the garage-door-sized opening built into the fuselage to accommodate a 2.5-meter telescope. The opening represented a tremendous affirmation of the extensive wind tunnel testing performed at Ames during SOFIA's development. If the aerodynamic calculations were off, the acoustic resonance of moving air would have turned the observatory into a flying train whistle, negatively impacting

120 "SOFIA," *https://science.nasa.gov/mission/sofia/* (accessed August 14, 2024).

121 Ruth and Rosson, "Elizabeth Ruth: SOFIA Oral History Project," p. 9.

122 Ibid., p. 10.

123 Kaminski and Rosson, "Charlie Kaminski: SOFIA Oral History Project," p. 15.

124 Ruth and Rosson, "Elizabeth Ruth: SOFIA Oral History Project," p. 23.

125 Paul Hertz and Lois Rosson, "Paul Hertz: SOFIA Oral History Project," January 21, 2024, p. 4.

126 "SOFIA Technical Information," *https://irsa.ipac.caltech.edu/data/SOFIA/docs/sites/default/files/SOFIAtech.pdf* (accessed February 1, 2025).

127 Zavala and Rosson, "Eddie Zavala: SOFIA Oral History Project," p. 19.

the fatigue life of the aircraft and disturbing the smooth laminar flow that enabled sharp image capture.[128] When the telescope door was open, however, no one in the cabin could feel a noticeable difference—a light inside would indicate to passengers whether the door was up.[129]

These elements combined to make an exceptionally mobile astronomical observatory capable of novel observations. Similarly to SOFIA's eclipse-chasing predecessors, the observatory could observe celestial phenomena while in motion. In June 2011, the observatory chased down Pluto's occultation of a distant star, which was visible only from a specific location over the Pacific Ocean.[130] As Pluto moved in front of the star, SOFIA flew in its shadow, capturing light that passed through the planet's atmosphere to analyze its characteristics.[131] The shadow moved at 53,000 miles per hour, and the precise position of Pluto in relation to Earth could not be pinpointed until just before the event took place. Astronomers at the U.S. Naval Observatory and the Massachusetts Institute of Technology used photographs of Pluto to make more precise predictions, delivering the positioning news to SOFIA 2 hours before occultation, while the observatory was 1,800 miles out over the Pacific.[132]

Maintaining SOFIA's airframe and telescope operability was just as complex as designing a science program that identified in-flight targets. Originally designed in the 1960s, the 747SP was by 2015 no longer supported by usual commercial supply chains. Eddie Zavala, SOFIA's program manager at Armstrong, described an instance when a cracked motor mount required a new engine while SOFIA was on deployment in New Zealand: "We were…right next door to a…Pratt & Whitney facility. They were the makers of the engines that SOFIA uses. But they weren't fleet-supported. I couldn't get a spare engine from them if I wanted to...because they didn't provide the support for it."[133] It became NASA's job to nurture remaining expertise on the repair and maintenance of the engines used by SOFIA, which it did by way of contracts with experts from industry. Maintenance was supported by Lufthansa until 2014, when the company announced they no longer serviced the type of engine SOFIA used. Their recommendation, Zavala recalled, was to buy as many spare engines as they could. To keep SOFIA in the air, operations managers at Armstrong bought 16 spare engines.[134]

Because the 747SP was no longer fleet-supported, it was easier to source spare parts from other retired 747SPs located in boneyards across the American Southwest and, in some cases, museums.[135] Shuttle Carrier N911NA contributed landing gears to SOFIA while on display at the Joe Davies Heritage Airpark in Palmdale.[136] Ultimately, SOFIA's collection of spare parts grew to over 130,000 items cataloged on the fourth floor of the 703 complex at Armstrong. This was critical to the certification of SOFIA's mission timeline: when SOFIA was on deployment to New Zealand and could not source a local engine from Pratt & Whitney, it had one delivered from its warehouse in Palmdale.[137]

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128 According to Eddie Zavala, *any* acoustic resonance would have exhausted the fatigue life of the airframe in 20 minutes. Ibid., p. 15.

129 Ruth and Rosson, "Elizabeth Ruth: SOFIA Oral History Project," p. 7.

130 "NASA's SOFIA Flying Telescope May Be Mothballed This Year," *https://www.space.com/24924-nasa-budget-2015-sofia-observatory.html* (accessed January 30, 2025).

131 "Mission Success: Pluto Fever Is Contagious—SOFIA Southern Deployment," July 9, 2015, *https://blogs.nasa.gov/sofia-southern-deployment/2015/07/09/mission-success-pluto-fever-is-contagious/* (accessed June 17, 2025).

132 "SOFIA's Telescope Views Pluto Occultation," *https://www.nasa.gov/news-release/sofias-telescope-views-pluto-occultation/* (accessed January 30, 2025).

133 Zavala and Rosson, "Eddie Zavala: SOFIA Oral History Project," p. 6.

134 Ibid., p. 7.

135 Desert climates are preferable for aircraft storage to prevent corrosion. Ibid., p. 8.

136 Ibid., p. 9. For more on spare parts sources from Shuttle Carrier Aircraft (SCA): *https://web.archive.org/web/20170622185515/https://www.nasa.gov/centers/dryden/Features/sca_911_final_flight.html* (accessed June 17, 2025).

137 Ibid., p. 9.

Education

SOFIA's onboard education program was a part of the observatory's design from its very inception, building off the programs successfully developed and implemented by the KAO for several years. One program, Flight Opportunities for Science Teacher EnRichment (FOSTER), flew teachers during active research missions to teach them about infrared astronomy.[138] FOSTER was managed by the SETI Institute (Search for Extraterrestrial Intelligence) from 1991 to 1995.[139] A more intensive program, "Science in the Stratosphere," emerged in 1992, embedding two K–5 educators with project scientists and staff for nearly a week. In 1995, KAO hosted "Live from the Stratosphere," three live in-flight television broadcasts that allowed students to control the telescope and ask scientists questions about scientific research in real time.[140]

It was anticipated that SOFIA would greatly expand the education program piloted on KAO after the observatory's 1997 retirement.[141] As with KAO, the educational programming design for SOFIA was intended to be grassroots, focusing on teachers, school planetariums, and small museums unserved by splashy scientific findings circulated in the press.[142] SOFIA's Education and Public Outreach plan (EPO) was drafted by Edna DeVore, SETI's then-director of education, as part of USRA's successful proposal to create and manage the observatory. A key component of this plan featured a professional development program for teachers focused explicitly on infrared astronomy. The SETI-managed STEM-immersion experience became known as the Astronomy Activation Ambassadors (AAA) program.[143]

Though SOFIA did not reach FOC until 2014, the phased development plan implemented at Armstrong meant that groups of teachers could begin flying as early as 2011. The first flight test of the program included six educators provided with a science webinar series, one week at Armstrong embedded in the flight facility, and two science flights on board SOFIA. Between 2011 and 2016, SOFIA flew 106 educators estimated to reach 12,000 students.[144] In 2016, NASA ended all mission-embedded Education and Public Outreach programs, launching instead a Science Activation program managed by the Science Mission Directorate. The project was renamed the Airborne Astronomy Ambassadors (AAA) but remained largely the same. SETI redesigned the program around STEM learning and expanded the program to include middle school and community college instructors as well as high school teachers.[145] Because SOFIA was not FAA-certified as a passenger aircraft, everyone who flew was technically trained as crew, prohibiting actual children from flying.[146]

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138 Jeffrey O. Bennett and Cherilynn A. Morrow, "NASA's Initiative to Develop Education Through Astronomy (IDEA)," *Basic Space Science; United Nations (European Space Agency Workshops for Developing Countries, 2nd, Bogota, Columbia, November 9–13, 1992),* A95-61520 214 (April 1, 1994), *https://doi.org/10.1007/BF00982339* (accessed June 17, 2025).

139 "Astronomy Activation Ambassadors Program: A New Era," *https://www.seti.org/astronomy-activation-ambassadors-program-new-era* (accessed February 1, 2025).

140 Doyal A. Harper, "Real Time Data/Video/Voice Uplink and Downlink for Kuiper Airborne Observatory," January 1, 1997, *https://ntrs.nasa.gov/citations/19990008183* (accessed June 18, 2025).

141 Dan Lester, "Science in the Stratosphere," August 29, 1997, *https://ntrs.nasa.gov/citations/19980006745* (accessed June 18, 2025).

142 This type of outreach was cast as fundamentally different from that of Hubble, which emphasized images that could circulate in the press. "The track record at the Space Telescope Science Institute is to focus almost exclusively on the media and national visibility. Overall, they lack the grassroots educational programs which is the focus of our proposal…. Educators—in particular the large community of planetariums in schools and small museums—do not have access to the up-to-date photographic prints and press releases in any form except the internet. I am particularly critical of the lack of service to this community." "SOFIA Project Documents Binder," p. 61, NASA Ames Research Center Archives, Stratospheric Observatory for Infrared Astronomy (SOFIA) Project Collection, Collection Number ARC24.12.

143 "Astronomy Activation Ambassadors Program: A New Era."

144 Ibid.

145 Ibid.

146 Hertz and Rosson, "Paul Hertz: SOFIA Oral History Project," p. 14.

According to David McBride, then center director at Armstrong, the project multiplied outreach efforts for very little cost because two to three additional people on a 747 meant virtually nothing from a weight perspective. "They wouldn't just go back to their classroom of thirty students. They'd go back to the whole district…and put together lesson plans and teach other teachers how to talk about infrared astrophysics and improve science curriculum."[147] McBride compared the hands-on nature of SOFIA's Ambassadors program to the Teacher in Space Project (TISP) planned for the Space Shuttle Program prior to the Challenger disaster in 1986. TISP's successor program, the Educator Astronaut Project, required participants to be fully trained as mission specialists. SOFIA did not have such a high barrier of entry for civilians eager to fly and successfully opened its platform to hundreds of K–12 educators. After SOFIA's conclusion in 2022, the program pivoted to STEM immersion experiences on Maunakea, and returned to its old name, the Astronomy Activation Ambassadors program.[148]

Science Diplomacy

One of SOFIA's most unique advantages was its ability to travel to the Southern Hemisphere to observe celestial subjects not visible from the United States. This mobility allowed SOFIA to take advantage of winters below the equator when long summer days in Palmdale crept into the evening's darkness. Over the course of its operational lifetime, SOFIA conducted 12 deployments abroad, 7 of which occurred in Christchurch, New Zealand. In 2021, due to COVID-19 travel restrictions, SOFIA deployed to Tahiti, French Polynesia, instead of Christchurch.[149] In March 2022, the observatory operated out of Santiago National Airport for two weeks, a "short deployment" aimed at increasing deployment tempo and efficiency.[150]

Scientific collaboration between the United States and New Zealand has been a crucial component of the diplomatic relationship between the two countries for over a century. The onset of this alliance can be traced back as early as 1874, when astronomers from both countries came together to witness the transit of Venus in a formal scientific collaboration on Chatham Island.[151] Scientific relationships were strengthened over the course of the 20th century by mutual scientific interests in the Antarctic region and the 1959 establishment of the U.S. Antarctic Program at the Christchurch International Airport.[152] Flying during Southern Hemispheric winters, SOFIA operated out of the National Science Foundation's Antarctic Program facility.

Once SOFIA began regularly deploying to Christchurch, it quickly became one of most publicly engaging scientific collaborations between the United States and New Zealand. According to Philip McKenna, Political and Economic Specialist at the U.S. Consulate in Auckland, SOFIA was regarded as a jewel in the crown of the scientific partnerships between the two nations.[153] The other active NASA project in New

147 McBride and Rosson, "David McBride: SOFIA Oral History Interview," pp. 17–18.

148 "Astronomy Activation Ambassadors Program: A New Era."

149 "A New Springboard to the Southern Sky: SOFIA Deploys to French Polynesia—SOFIA: Stratospheric Observatory for Infrared Astronomy," July 20, 2021, *https://blogs.nasa.gov/sofia/2021/07/20/a-new-springboard-to-the-southern-sky-sofia-deploys-to-french-polynesia/* (accessed June 18, 2025).

150 U.S. Mission Chile, "Science in the Southern Hemisphere: SOFIA Deploys to Chile," U.S. Embassy in Chile, March 21, 2022, *https://cl.usembassy.gov/science-in-the-southern-hemisphere-sofia-deploys-to-chile/* (accessed June 18, 2025).

151 U.S. Mission New Zealand, "Celebrating 150 Years of US-NZ Scientific Collaboration 150—A Milestone of Mutual Discovery," U.S. Embassy & Consulate in New Zealand, Cook Islands and Niue, September 30, 2024, *https://nz.usembassy.gov/150-years-us-nz-science/* (accessed June 18, 2025).

152 U.S. Mission to New Zealand. "Christchurch," U.S. Embassy & Consulate in New Zealand, Cook Islands and Niue, accessed February 2, 2025, *https://nz.usembassy.gov/christchurch/* (accessed June 18, 2025).

153 Philip McKenna and Lois Rosson, "Philip McKenna: SOFIA Oral History Project," July 23, 2024, p. 2.

Zealand at the time was the Scientific Balloon Program managed out of Wānaka Airport.[154] Of the two programs, SOFIA quickly became the more publicly visible. According to McKenna, "the Super Pressure Balloon was and is great. But there's very limited public scope for involvement or engagement with that." Not only was SOFIA NASA-branded, but the observatory could fly a range of different people on board. Educators, students, opinion leaders, and government officials were all invited to participate: "that's what really made [SOFIA] stand out as the premier science relationship program. Government to government."[155]

SOFIA's ability to fly civilians made it a powerful diplomacy tool during international deployments, especially for building relationships with decision-makers within New Zealand's government. Members of the Consulate were typically contacted by NASA on the operational side, "the guys on the ground in Christchurch." According to McKenna, planners prioritized flights for those who could help cement both scientific relationships and also broader bilateral ones.[156] This included ministers, policy-makers within departments, down to local Christchurch officials and members of Parliament. Many of the people selected to fly on SOFIA were senior policy advisors to ministers who were looking specifically at scientific relationships. McKenna recalled that one midcareer government administrator invited to fly on SOFIA eventually became "second or third in charge at the New Zealand Space Agency…we had several people like that who went on to be actively engaged."[157]

SOFIA's presence in New Zealand overlapped with the development of the country's own space program in 2016, the New Zealand Space Agency. "There is absolutely no doubt that they looked to NASA as the exemplar, as the partner of choice, to put the framework together to launch rockets from New Zealand," McKenna explained.[158] This was never obvious or inevitable: the government of New Zealand has relationships with a host of other countries' space agencies. "But they chose to basically model the New Zealand Space Agency on a little mini version of NASA. I think SOFIA definitely fed into that."[159]

SOFIA's relationship-building extended also to Māori Ngai Tahu leaders, the historic owners of the land on which the observatory was operating. SOFIA had incorporated Māori iconography and motifs on most mission patches designed for deployments in New Zealand. For the final VIP mission, just prior to SOFIA's cancellation, Project Scientist Naseem Rangwala made sure the Māori leader of the South Island was included. "When we took off the weather was beautiful. We took off a little early so they could see their land from SOFIA…they have taken other flights. But it was just special. They were on a NASA observatory with us. We had U.S., Germany, New Zealand ministry, and the Māori leader and they were there together. We were celebrating science and collaboration."[160] Lisa Tumahai, chair of the Ngai Tahu iwi, participated in the last flight, signing the pressure bulkhead alongside the other educators and special guests to travel on SOFIA.[161]

154 "Super Pressure Balloon Marks First Continental Crossing," April 2, 2015, *https://www.nasa.gov/centers-and-facilities/wallops/super-pressure-balloon-marks-first-continental-crossing/* (accessed June 18, 2025).

155 McKenna and Rosson, "Philip McKenna: SOFIA Oral History Project," p. 3.

156 Ibid., p. 3.

157 Ibid., p. 11.

158 Ibid., p. 12.

159 Ibid.

160 Rangwala and Rosson, "Naseem Rangwala: SOFIA Oral History Project, Part 1," p. 20.

161 McKenna and Rosson, "Philip McKenna: SOFIA Oral History Project," p. 14.

SOFIA logo from 2019 deployment, showing silver fern. The silver fern is a symbol in Māori art symbolizing growth and is the national symbol of New Zealand. *(Image Credit: NASA)*

Lisa Tumahai, Māori leader of the South Island, signing the "wall of fame" onboard SOFIA in 2022. *(Photo Courtesy of Naseem Rangwala)*

In addition to SOFIA's diplomatic work in New Zealand, the observatory was able to capitalize on the cold, dry conditions found on winter evenings in the Southern Hemisphere. More importantly, SOFIA could observe celestial objects that were too low in the sky or not visible from its base in Palmdale. From on board SOFIA, astronomers could observe the Large Magellanic Cloud, the center of the Milky Way, Saturn's moon Titan, and another 2015 occultation of Pluto.[162] Southern deployments enabled a range of studies of different astrophysical phenomena, peering into clouds of dust to study their structure.[163] Observing time during SOFIA's Southern Hemisphere deployments was scientifically valuable and had a high rate of oversubscription.[164]

Major Discoveries

SOFIA's telescope saw first light on May 26, 2010, and quickly became a critical component of NASA's broader astrophysics portfolio. The observatory's instrument suite enabled imaging, spectroscopic, and polarization observations in the full mid-infrared and far-infrared wavelength range—all of which were inaccessible from the ground.[165] As a result, SOFIA offered multiple synergies with the James Webb Space Telescope (JWST), as well as the Atacama Large Millimeter Array (ALMA). SOFIA offered high-resolution spectral observations in the wavebands where most normal galaxies and star-forming regions emit the most energy, but in a range too long for JWST and too short for ALMA.[166] SOFIA was also a complement to balloon missions in NASA Astrophysics like GUSTO and BLASTPol, which offered wide-area surveys of which later missions could follow up. Balloon missions could also increase the technology readiness levels of

162 "SOFIA to Study Southern Skies in New Zealand," *https://irsa.ipac.caltech.edu/data/SOFIA/docs/publications/science-results-archive/sofia-study-southern-skies-new-zealand/index.html* (accessed February 3, 2025).

163 "New Zealand Science Summaries," *https://irsa.ipac.caltech.edu/data/SOFIA/docs/multimedia/science-results-archive/new-zealand-science-summaries/index.html* (accessed February 3, 2025).

164 Rangwala and Rosson, "Naseem Rangwala: SOFIA Oral History Project, Part 1," p. 17.

165 Rangwala et al., "SOFIA Status & Future Prospects 2022," p. 13.

166 Ibid., p. 14.

instruments designed for SOFIA. This was true also in the reverse—HAWC+, a Facility Science Instrument on SOFIA, served as a prototype for the Far-Infrared Imager and Polarimeter instrument concept for the Origins Space Telescope.[167] In 2021, the SOFIA user community was estimated at 2,000 investigators and authors, with an anticipated 12 percent growth rate.[168] Observing time was split 80/20 between the United States and Germany, with U.S. time open to the international community as well.

One of SOFIA's most exciting early observations was its 2015 observation of Pluto while the observatory was on deployment in New Zealand. On June 29, Pluto passed in front of a distant star, allowing astronomers to examine how the starlight dimmed and changed as it passed through Pluto's atmosphere. What made this observation especially useful was its timing—it occurred just two weeks before NASA's New Horizons spacecraft flew past Pluto, and it offered an independent measurement of Pluto's atmospheric structure against which New Horizons' data could be compared.[169]

In 2019, SOFIA discovered helium hydride (HeH+), the first type of molecule to form in the universe after the Big Bang. While astronomers had anticipated the existence of the molecule, it had never been observed outside of a laboratory setting.[170] Using German Receiver for Astronomy at Terahertz Frequencies (GREAT), SOFIA was able to detect the molecule in planetary nebula NGC 7027 from about 3,000 light-years away. The molecule was found in the hot, ionized gas surrounding the dying star, where conditions tend to mimic those of the early universe. The detection of HeH+ helped resolve a long-standing gap in our understanding of how the first chemical bonds in the universe were formed. SOFIA was uniquely poised to make the discovery, as Earth's atmosphere blocks the critical 2-THz spectral line needed to identify HeH+.[171]

In October 2020, SOFIA announced what would become its most famous scientific discovery—water on the sunlit surface of the Moon. The discovery was significant, changing our understanding of lunar hydration.[172] Using the Faint Object InfraRed CAmera for the SOFIA Telescope (FORCAST), SOFIA detected specific infrared wavelengths associated with molecular water in Clavius Crater. The discovery suggested that water is more widespread across the Moon than previously thought, even in areas exposed to sunlight.[173] The finding is especially important for future lunar exploration since it indicates that water might be available for resource utilization outside of permanently shadowed regions.[174]

167 Ibid.

168 Ibid., p. 16.

169 Michael J. Person et al., "Haze in Pluto's Atmosphere: Results from SOFIA and Ground-Based Observations of the 2015 June 29 Pluto Occultation," *Icarus*, Pluto System, Kuiper Belt, and Kuiper Belt Objects, 356 (March 1, 2021): 113572, *https://doi.org/10.1016/j.icarus.2019.113572*.

170 "First Astrophysical Detection of the Helium Hydride Ion," *https://www.mpifr-bonn.mpg.de/pressreleases/2019/5* (accessed February 3, 2025).

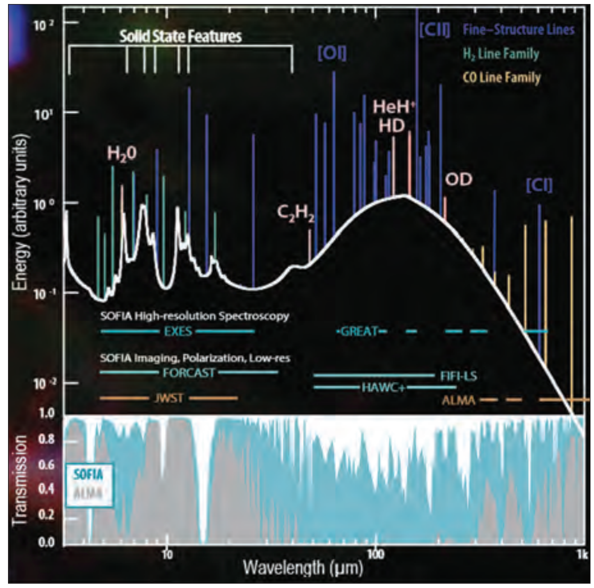
171 Rolf Güsten et al., "Astrophysical Detection of the Helium Hydride Ion HeH+," *Nature* 568, no. 7752 (April 2019): 357–359, *https://doi.org/10.1038/s41586-019-1090-x* (accessed June 18, 2025).

172 "NASA's SOFIA Discovers Water on Sunlit Surface of Moon," *https://www.nasa.gov/news-release/nasas-sofia-discovers-water-on-sunlit-surface-of-moon/* (accessed February 3, 2025).

173 "Molecular Water Detected on the Sunlit Moon by SOFIA," *https://www.nature.com/articles/s41550-020-01222-x#_blank* (accessed February 3, 2025).

174 Sharmila Kuthunur, "1st Map of Moon Water Could Help Artemis Astronauts Live at the Lunar South Pole," Space.com, March 20, 2023, *https://www.space.com/moon-water-1st-map-sofia-artemis* (accessed June 18, 2025).

Science image taken by SOFIA of magnetic fields at the center of our galaxy, which could be imaged only from the Southern Hemisphere. Researchers combined mid- and far-infrared images from cameras onboard SOFIA to produce the final picture. *(Credit: Data visualization overlay of Galactic Center dust and magnetic fields: NASA/SOFIA, star field image: NASA/Hubble Space Telescope/NICMOS)*



Top portion of chart illustrates that more than half of the typical energy output for a star-forming galaxy is in the form of mid- to far-infrared. Graphic emphasizes the spectral gap between JWST and ALMA filled by SOFIA. Bottom portion of chart illustrates that atmospheric transmission for SOFIA at 41,000 feet is superior to even the driest, highest-altitude site on Earth. Chart uses ALMA at 16,000 feet for comparison. *(Figure 1-1, printed in Naseem Rangwala et al., SOFIA: Status and Future Prospects, 2022, p. 3)*

In 2024, two years after SOFIA's conclusion, astronomers unveiled a detailed map of the magnetic fields at the center of the Milky Way galaxy. SOFIA data obtained from nine different flights were used to create an infrared map that spanned 500 light-years across the center of the Milky Way.[175] The map visualized a complex network of magnetic field lines, suggesting that these fields play a significant role in governing the dynamics of both dust and gas.

Publicly, SOFIA's discoveries—especially the discovery of water on the Moon—generated widespread media coverage and excitement. Its ability to fly to the Southern Hemisphere gave it new vantage points from which to observe objects unseeable in North America, and its mobility made observations of stellar occultations possible in new and exciting ways. Though these scientific contributions were recognized as important, SOFIA's reputation in broader astronomy and space science communities was still clouded by debates over the observatory's cost-effectiveness.

175 "Scientists Reveal Never-Before-Seen Map of the Milky Way's Central Engine (Image)," *https://www.space.com/milky-way-heart-central-engine-stunning-map* (accessed February 3, 2025).

SECTION V

Conclusion of SOFIA

On September 20, 2019, SOFIA completed the five-year prime mission funding period that began when it reached FOC in 2014, inaugurating a new phase of mission evaluations.[176] SOFIA was initially scheduled to be included in the 2019 Astrophysics Senior Review by NASA's Science Mission Directorate (SMD). The senior review, an evaluation process that functioned as NASA's highest-level form of peer review, was used to assess the post-prime missions in SMD's portfolio and establish criteria for terminating missions.[177] A 2018 report written in the House of Representatives for the Commerce, Justice, Science, and Related Agencies Appropriations Bill, however, expressed trepidation over reviewing SOFIA after such a brief amount of operation time.[178] While the Senate report encouraged the review process as a normal part of NASA's evaluation of mission performance, SOFIA was excluded from the senior review process.[179]

Instead, SOFIA was subject to a two-part review process: the SOFIA Five Year Flagship Mission Review (S5YFMR or FMR), designed to evaluate SOFIA's science progress and assure the observatory's scientific productivity, and the SOFIA Operations and Maintenance Efficiency Review (SOMER), an evaluation of SOFIA's aircraft operations and maintenance.[180] The SOMER was completed in April 2019 and concluded that significant changes would be necessary to reduce program operations and maintenance costs. The FMR was completed the following month, and it similarly concluded that widescale changes would be necessary to cement SOFIA's status as a flagship-class observatory.[181] While both reviews raised concerns about SOFIA's high yearly operating costs—which were now roughly $85 million—each panel recommended ways to improve SOFIA's efficiency but did not call for the mission's cancellation. In January 2020, the SOFIA

176 Despite the conclusion of the 5-year prime mission, SOFIA still had a 20-year capability requirement. The Senior Review process was introduced across the agency with the NASA Transition Authorization Act of 2005, institutionalizing biennial reviews within each of NASA's science divisions. The NASA Authorization Act of 2017 lengthened the review cadence from two years to three. In this system, at the conclusion of a prime mission, NASA would convene a panel of peer reviewers to evaluate performance.

177 "2019 Senior Review of Operating Missions," September 19, 2018, *https://science.nasa.gov/astrophysics/resources/documents/2019-senior-review-operating-missions/* (accessed June 18, 2025).

178 "The Committee is concerned with NASA's proposed inclusion of SOFIA in the 2019 Senior Review, given it began its prime mission in 2014 and has 15 years of prime mission lifetime remaining. Accordingly, the Committee directs NASA to only undertake a Senior Review of SOFIA at the time SOFIA completes its planned mission lifetime. For the purposes of this section, announcing, scheduling, or undertaking a Senior Review is deemed preparation for shutdown." "House Report 115-704—Commerce, Justice, Science, and Related Agencies Appropriations Bill, 2019," *https://www.govinfo.gov/content/pkg/CRPT-115hrpt704/html/CRPT-115hrpt704.htm* (accessed March 21, 2025).

179 Jeff Foust, "NASA Planning Alternative Reviews of SOFIA," SpaceNews, September 21, 2018, *https://spacenews.com/nasa-planning-alternative-reviews-of-sofia/* (accessed June 18, 2025).

180 Paul Hertz, "NASA Response to the 2019 Independent Reviews of the Stratospheric Observatory for Infrared Astronomy (SOFIA) Program," August 12, 2019, *https://science.nasa.gov/wp-content/uploads/2023/04/NASA_Response_to_SOFIA-Reviews_Final_TAGGED.pdf* (accessed June 18, 2025).

181 "NASA's Management of the Stratospheric Observatory for Infrared Astronomy Program," p. 9.

Program submitted an implementation plan to the Science Mission Directorate responding to suggestions laid out in both reviews.

In March 2020, just three months after submitting its implementation strategy, the SOFIA team dramatically pared down its operations in response to the onset of the COVID-19 pandemic. By July 2020, the SOFIA operations team had implemented a COVID safety plan to get the aircraft off the ground, starting with two flights per week and then working the observatory back up to four. Naseem Rangwala, who took over as NASA project scientist for SOFIA in 2019, recalled the attitude of perseverance necessitated by the pandemic's interruption of the efficiency plans articulated to address the FMR and SOMER: "At that time, one would think, 'This mission is ended.... You can't fly. You're done.' We said, 'No, we're going to fly and we're going to fly in four months.'" What was more, the space-based telescopes in the SMD Astrophysics portfolio to which SOFIA's productivity was often compared, like Hubble, Spitzer, and Chandra, were still able to collect data uninterrupted.[182]

The two biggest changes enacted in response to the 2019 reviews of SOFIA were the implementation of a large, coordinated legacy program—designed to create a substantial and coherent database of archived observations—and a flight schedule that included one weekly contingency flight in case a technical or weather issue grounded the observatory during its normal observation schedule.[183] In addition to this new flight schedule, the team prepared more frequent and shorter deployments to the Southern Hemisphere, including Chile and French Indonesia. SOFIA's user base also expanded: over the three-year period between 2019 and 2022, the mission implemented community outreach efforts that added 600 new astronomers to SOFIA's user community of about 2,000 investigators.[184] This included a Thesis Enabling Program that increased financial support for doctoral theses based on SOFIA observations, supported early career development in astrophysics, and increased the number of publications related to SOFIA's scientific output.[185]

2020 Decadal Survey

In the period immediately following the 2019 FMR and SOMER panel reviews, SOFIA made substantive improvements despite the operational constraints presented by the COVID-19 pandemic and prepared for inclusion in the 2022 NASA Astrophysics Senior Review.[186] In 2021, however, the National Academy of Sciences recommended concluding the program in its Decadal Survey. This survey was the same solicited policy recommendation that had advocated for SOFIA's creation in 1990, when the Academy declared the Decade of Infrared.[187]

The 2020 Decadal Survey in Astronomy and Astrophysics (abbreviated as Astro2020, though it was not released until 2021) was more suspicious of SOFIA's ability to operate more efficiently than the 2019 reviews were, which urged improvement but did not call for the mission's cancellation. The inclusion of SOFIA in the survey was unusual—because NASA supported the Astrophysics Senior Review of Operating Missions, the decadal surveys did not typically weigh in on individual operating missions. But because SOFIA did not undergo the 2019 Senior Review panel, it was included in the survey's review, which used the results from

182 Naseem Rangwala and Lois Rosson, "Naseem Rangwala: SOFIA Oral History Project, Part 2," June 20, 2024, p. 8.

183 Ibid., p. 9.

184 Rangwala et al., "SOFIA Status & Future Prospects 2022," p. 2.

185 Ibid., p. 14.

186 The report "SOFIA Status & Future Prospects 2022" was created out of material originally compiled for use in the 2022 NASA Astrophysics Review.

187 National Research Council, *The Decade of Discovery in Astronomy and Astrophysics* (Washington, DC: The National Academies Press, 1991), *https://doi.org/10.17226/1634* (accessed June 18, 2025).

both the SOFIA FMR and SOMER to draw its own conclusions about which missions to prioritize over the next decade.[188] This choice of material served as the primary critique of the Astro2020 survey, which included few of the efficiency improvements the SOFIA mission implemented after 2020.

Table 4-2 **Response to the Astro2020 Decadal Comments on SOFIA**

The 2020 Decadal Committee strongly expressed the importance and effectiveness of the NASA Senior Review process for setting funding priorities, and for establishing criteria and a decision process for terminating missions [Astro2020, section 5.2]. Since SOFIA was not included in the 2019 Senior Review, Astro2020 recommendations for SOFIA were based on the findings of NASA's FMR and aircraft reviews from June 2019 [Astro2020, section 5.2.1].

The data used by the Decadal Committee was more than two years old. Over that time period, the SOFIA mission transformed under the new leadership (§7) and by following guidance from these two NASA reviews (§4.1). This proposal, prepared for the 2022 Senior Review, clearly demonstrates that transformation and the promise of greater scientific productivity and impact over the next three years. Table 4-2 directly addresses the concerns raised in the 2020 Decadal Survey report.

Astro2020 Comments on SOFIA[†]	SOFIA Mission Response
"…SOFIA performs mostly Northern Hemisphere…and spends a smaller fraction of the year in the Southern Hemisphere…"	In 2021, SOFIA increased observing time in the Southern Hemisphere by a factor of 2. §5.1, 6.7
"…The NASA portion of SOFIA's operating budget is $86 million a year, of which$4 million goes to Guest Observers for data reduction and analysis.…"	SOFIA provides $10,000 per observing hour, which is comparable to other NASA observatories. Since total observing time on an airborne platform like SOFIA is lower than space observatories, the total GO funding is proportionally lower. SOFIA is now additionally funding GO archival research and has established a minimum grant funding threshold of $75K. SOFIA additionally invests $5M (annually) in the community by funding development of new instruments and operations upgrades to improve efficiency. §3.3, 5.6
"…For this investment, the science productivity to date is very low…The science impact is also low…"	SOFIA's growth in publication and impact (citations) has recently passed an inflection point and is on the rise. SOFIA doubled its publication over the last three years and citations are growing exponentially. Growth will continue due to a ~50% increase in observing time. §5.7
"…ESA's Herschel mission, was, like SOFIA, a flagship scale mid-to-far-infrared facility, which saw nearly 900 peer-reviewed papers in the 6 years following launch…"	Herschel completed 22,000 hours of data collection over 3.5 years of its mission lifetime (2009-2013). SOFIA being an airborne platform has collected ~4000 hours of scientific data since 2010, about 18% of the total Herschel observing hours. This translates roughly to 160 Herschel publications (18% of 900). SOFIA has about 300 peer-reviewed science papers, 50% more than Herschel over the same amount of observing time. Over SOFIA's operational lifetime of 20 years, it is expected to have the same or better scientific productivity compared to Herschel. §5.7
"…SOFIA directly addresses three of the thirty priority science Questions… therefore minimal overlap of the Astro2020 Panels' science priorities with SOFIA capabilities…"	SOFIA contributes to fifteen of the thirty Astro2020 science priorities. §1; Table 1-1
"…There is significant down time in each year for necessary airplane maintenance…"	Starting 2021, observatory down time for FAA-mandated maintenance is consolidated to 5-6 weeks annually, increasing time for science observations. §5.1
"…With a typical ~1000 flight hours per year, and a relatively modest 60 percent of programs being completed, and 60 percent of these turning into peer-reviewed publications, only a few percent of total yearly calendar hours are turned into peer-reviewed science, an order of magnitude less than other astronomical observatories…"	Flight hours have increased to 1500 starting 2021 and will increase to 1700 starting 2022. §5.1 Program completion rate is increasing (Figure 3-3). It reached 70% in one of the recent cycles even with the COVID-19 impacts. Several initiatives have been implemented and more are planned to promote faster publications. §5.7
"…The survey committee found no evidence that SOFIA could, in fact, transition to a significantly more productive future. There have been only modest improvements in productivity over the past 2 years…"	SOFIA has transformed over the last two years (since early 2020) by implementing all the recommendation of the FMR and taken bold initiatives to increase observing time in both hemispheres. Sections 3 and 5 of this proposal strongly demonstrate this progress and promise of continued success. §3, 5, 7
"…the SOFIA team has responded to NASA that… major recommendations from … reviews are not feasible to implement, suggesting any future improvements would still be modest…"	SOFIA mission has addressed all the recommendations of the flagship mission review. §4.1
"…the survey committee found no path by which SOFIA can significantly increase its scientific output or relevance to a degree that is commensurate with its cost…"	SOFIA has transformed over the last two years by implementing all the recommendations of the FMR and taken bold initiatives to increase observing time in both hemispheres. Sections 3 and 5 of this proposal strongly demonstrate this progress and promise of continued success. §3, 5, 7

[†]From page 5-11 and 5-12 of the Pathways to Discovery in Astronomy and Astrophysics for the 2020s (2021) [Astro2020]

Responses from SOFIA program to comments made in Astro2020 advocating for the mission's termination. *(Table 4-2, printed in Naseem Rangwala et al., SOFIA: Status and Future Prospects, 2022, p. 18)*

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188 The survey explained that the "senior review is the best mechanism for advising NASA about budgetary levels or advising when a mission should be terminated because its scientific return is not commensurate with the requisite investment. As such, decadal surveys do not typically weigh in on individual operating missions. However, SOFIA was not considered by the last Senior Review panel, and the value of continuing operations of SOFIA beyond 2023 is of concern with respect to the other priorities of this report." National Academies of Sciences, Engineering, and Medicine, 2023, *Pathways to Discovery in Astronomy and Astrophysics for the 2020s* (Washington, DC: The National Academies Press), *https://doi.org/10.17226/26141* (accessed June 4, 2024), p. 168.

The survey committee framed its concerns about SOFIA around the observatory's high costs and modest scientific productivity, especially in comparison to other missions.[189] The yearly budget it listed, roughly $86 million per year, was "in a range comparable to NASA's flagship space telescopes Hubble and Chandra ($98 million and $62 million in fiscal year 2019, respectively)."[190] It is important to note, however, that the $86 million represented the congressional appropriation SOFIA was required to spend, which factored in instrumentation development and swapping, which was technically not part of usual operations. SOFIA leadership asserted that responses to the 2019 FMR lowered the operating budget to $80 million.[191] Other criticisms were related to the survey's comparison involving the amount of publications generated by space-based observatories like Hubble and Chandra in their first six years of operation: the survey pointed out that while SOFIA had produced only 178 papers, Hubble and Chandra "produced more than 900 and 1,800 total papers, respectively" in the same amount of time and for a comparable operating budget.[192] The problem, according to the SOFIA leadership team, was that UV and visible light observations were fundamentally different from mid- to far infrared—observations were more tedious and had a much smaller user base with which to proliferate scientific publications. According to the SOFIA team, the ESA's Herschel mission, a flagship scale observatory that also operated in the mid- to far infrared, represented a better comparison, depending on how the comparison was shaped:

> Herschel completed 22,000 hours of data collection over 3.5 years of its mission lifetime (2009–2013). SOFIA being an airborne platform has collected ~4000 hours of scientific data since 2010, about 18% of the total Herschel observing hours. This translates roughly to 160 Herschel publications (18% of 900). SOFIA has about 300 peer-reviewed science papers, 50% more than Herschel over the same amount of observing time. Over SOFIA's operational lifetime of 20 years, it is expected to have the same or better scientific productivity compared to Herschel.[193]

Despite ambiguities around how SOFIA's operating budget should be tabulated with respect to its scientific output, the Astro2020's concerns about the observatory had to do with the format itself. The survey pointed out that SOFIA's ability to provide consistent long-term observations was limited by its restricted flying hours and the maintenance costs associated with an airframe manufactured in the 1970s. The most eye-watering sum cited in the report was the total life-cycle cost for SOFIA, which was nearly $1.5 billion because of the extensive modifications necessary to create an airborne platform in the first place.[194] The committee cited the complexities of operating a telescope on an aircraft as an issue, and the significant downtime required each year for necessary airplane maintenance as another. It also framed the international collaboration with German partners—an aspect of the mission that had been an early selling point—as potentially lopsided: "SOFIA's clearly unique capabilities across these important wavelength ranges have not translated into high utilization of the observatory by the astronomical community. For instance, only 9 of

189 Ibid., p. 168.
190 Ibid.
191 Rangwala et al., "SOFIA Status & Future Prospects 2022," p. 37.
192 National Academies of Sciences, Engineering, and Medicine, *Pathways to Discovery in Astronomy and Astrophysics for the 2020s,* p. 168.
193 Rangwala et al., "SOFIA Status & Future Prospects 2022," p. 18.
194 National Academies of Sciences, Engineering, and Medicine, *Pathways to Discovery in Astronomy and Astrophysics for the 2020s,* p. 2.

the 35 SOFIA-related Ph.D.s are from U.S.-based students, as of fall 2019, and the single largest producer of SOFIA's scientific publications to date is Germany's Max Planck Institute for Astronomy."[195]

Unlike the 2019 FMR and SOMER panel reviews, which were staffed by scientists and engineers close to SOFIA's mission deliberating on the specifics of program efficiency, the Astro2020 Decadal Survey was charged with making broad policy recommendations for the future of NASA's Astrophysics portfolio. The survey emphasized that funds allocated to SOFIA—a mission with roots 30 years in the past—could be better used in supporting newer, higher-priority space missions and next-generation observatories with greater potential for breakthrough discoveries. As a result of the Astro2020 survey's deliberations on SOFIA, the scheduled 2022 Senior Review of the program was canceled. In April 2022, NASA and the DLR announced that SOFIA would cease operations by September 30 of the same year.

Productivity in Science

While acknowledged as an innovative blend of ground- and space-based observation formats, SOFIA is still most often described as a facility that was never productive enough to justify its hefty price tag. To recapitulate numbers discussed earlier in this report, in 1991 the project was originally projected to cost $230 million. SOFIA's development eventually soared to $1.5 *billion*—more than 600 percent of the initial estimate. This was coupled with an additional $85 million in annual operating costs and a 13-year delay that stretched across Phase C of the observatory's development.[196]

While SOFIA did far exceed its initial budget projections, the observatory offers a provocative case study for evaluating the meaning of scientific productivity in a climate where cost overruns are typical in the development of large observatories. Part of the challenge of historicizing the value of SOFIA's contributions is that it was so unlike other observatories. Like satellite-based telescopes, SOFIA could conduct infrared observation above the bulk of Earth's atmosphere to see wavelengths otherwise invisible from the ground.[197] Like ground-based telescopes, it could be serviced regularly, and its cryogen stores replenished.[198] Unlike either of these models, SOFIA was both crewed and mobile—it could alter flight paths to see specific astronomical phenomena, spend monthslong deployments in the Southern Hemisphere, or invite educators on board to observe data collection firsthand.[199]

If SOFIA is to be understood through comparison, it is most easily compared to the KAO, the airborne astronomy platform that both inspired and informed its development. This is still an imperfect comparison due to differences in scale between the two observatories—SOFIA was larger and held to more stringent regulatory requirements, making it more complex to operate—and differences in contract bids. Though KAO was also an open-port observatory mounted on a former military transport aircraft, it managed to avoid many of the delays that plagued its successor. The major difference between the two platforms was privatization: with SOFIA, NASA outsourced the modification and operation of its new observatory in an

195 Ibid., p. 169.

196 "NASA'S Management of the Stratospheric Observatory for Infrared Astronomy Program," Audit (NASA Office of Inspector General, September 14, 2020), *https://oig.nasa.gov/wp-content/uploads/2024/02/IG-20-022.pdf* (accessed June 18, 2025), p. 7.

197 Rangwala et al., "SOFIA Status & Future Prospects 2022."

198 Cryogens are often a limiting factor for satellite-based observatories conducting infrared research, which can only bring them in limited amounts. One of SOFIA's biggest advantages was that the aircraft was certified to fly with cryogenic systems on board that could be replenished upon landing. "Special Conditions: Boeing Model 747SP; NASA Stratospheric Observatory for Infrared Astronomy (SOFIA); Cryogenic Systems Using Liquid Nitrogen and Liquid Helium," Federal Register, June 8, 2005, *https://www.federalregister.gov/documents/2005/06/08/05-11324/special-conditions-boeing-model-747sp-nasa-stratospheric-observatory-for-infrared-astronomy-sofia* (accessed June 18, 2025).

199 "NASA Selects Classroom Teachers for SOFIA Science Flights," *https://www.nasa.gov/news-release/nasa-selects-classroom-teachers-for-sofia-science-flights/* (accessed November 21, 2024).

attempt to cut costs. The result was a network of subcontractors that diffused both resources and technical expertise. One of the reasons cited for KAO's success was that it was developed and managed out of Ames, which by the 1970s had amassed significant experience with airborne science.

A common critique of SOFIA's operations that hinged on productivity—one similar to that found in the Astro2020 survey—noted that the observatory had a telescope mirror the same size as the Hubble Space Telescope's, as well as a comparable operating budget, and yet SOFIA produced a fraction of the publications.[200] Yet this comparison overlooks crucial differences: Hubble, positioned in orbit, did not need to wait for nighttime observing conditions, while SOFIA's observing time was limited to 8–10 hours per night during flights.[201] Hubble's launch and servicing costs—which ranged between $1.7 billion to $2.4 billion *per* servicing mission—make cost comparisons largely untenable.[202]

In SOFIA's case, productivity outlined in audits conducted by the NASA Office of Inspector General judged the observatory's productivity with metrics that divided the project's cost by number of scientific publications, to establish a general rate of science conducted per dollar spent. One such audit quantified SOFIA's output in terms of h-index, a metric designed in 2005 by Jorge E. Hirsch designed to gauge the productivity of individual researchers.[203] The same year the audit was published, Hirsch circulated a letter in *Physics and Society* warning that use of the h-index for comparison could "fail spectacularly" and have "severe unintended negative consequences."[204] Hirsch wrote specifically of the h-index's use in comparing individual researchers, to say nothing of the complexities inherent in applying the metric to entire facilities. The paper cited in the 2020 SOFIA audit noted the challenges of producing a normalized comparison, urging that h-index values must be taken in context.[205]

Many of SOFIA's most valuable aspects fall outside traditional productivity metrics. As a crewed mission, it was invaluable for science education, allowing teachers to experience astronomy firsthand and bring those insights into the classroom. It also offered hands-on experience to early-career astronomers who could not interface with a space-based telescope to the same degree. Though SOFIA lacked the degree of flexibility originally planned for its suite of instruments, postdocs and early-career astronomers were able to fly on board the observatory as the telescope collected data.[206]

Internationally, SOFIA was a powerful tool for science diplomacy, fostering collaboration with Germany's DLR, which held a 20 percent stake in the project. SOFIA's operations, though costly, created avenues for international partnerships and educational outreach, domains rarely captured in simple publication counts.

Further complicating its evaluation, SOFIA reached peak operational efficiency shortly before its termination. There was a steep learning curve to optimize flight operations with a complex suite of scientific

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200 "NASA's Management of the Stratospheric Observatory for Infrared Astronomy Program," p. 21.

201 Hubble does not operate continuously, since Earth blocks its view of astronomical targets during portions of its orbit. When not observing, the telescope is still operating, though, performing several housekeeping functions like reorientation or data downlinking.

202 "Space Shuttle Costs for Hubble Servicing Mission and Implementation of Safety Recommendations Not Yet Definitive," Report to the Subcommittee on VA/HUD-Independent Agencies, Committee on Appropriations, U.S. Senate (United States Government Accountability Office, November 2004), *https://www.gao.gov/assets/gao-05-34.pdf* (accessed on June 18, 2025).

203 "NASA's Management of the Stratospheric Observatory for Infrared Astronomy Program," p. 22.

204 J. E. Hirsch, "Superconductivity, What the H? The Emperor Has No Clothes," *Physics & Society Newsletter* 49, no. 1 (January 26, 2020), *https://doi.org/10.48550/arXiv.2001.09496* (accessed June 18, 2025).

205 Jenny Novacescu, "Comparative H- and M-indices for Fifteen Ground- and Space-Based Observatories" (Baltimore, MD: Space Telescope Science Institute, 2016).

206 Ruth and Rosson, "Elizabeth Ruth: SOFIA Oral History Project," p. 20.

instrumentation on board, and data suggest that SOFIA achieved peak efficiency just as the mission was canceled.[207]

While the project's delays and budget overruns are undeniable, they are hardly unusual in large-scale NASA projects. Hubble itself—now celebrated as one of the most productive telescopes ever built—was once the target of similar criticism, threatened with cancellation and viewed as emblematic of government inefficiency. Ultimately, SOFIA's cancellation highlights the benefits of broadening our definitions of productivity in scientific research. Metrics that over-prioritize publication counts are coming under increased scrutiny in other scientific disciplines.[208] SOFIA underscores the importance of recognizing qualitative impacts—those that do not translate neatly into dollars per publication but nonetheless advance science, education, and diplomacy. Projects that defy conventional categorization, like airborne observatories, require context-sensitive metrics that account for their unique roles and contributions.

The point of this report is not to deliberate further on SOFIA's value, but to explain the arguments that led to the mission's conclusion. Despite its issues, SOFIA made substantial discoveries in the field of infrared astronomy. It detected concrete evidence of water on the sunlit portions of the Moon, provided clear views into the dusty environments that characterize star formation, revealed the complex magnetic field structures that shape galaxies, and confirmed the existence of the oldest type of molecule in the universe. While many who worked on SOFIA were disappointed with the mission's premature conclusion, many others were not surprised. In several interviews, former crew members gestured to the fact that the types of programmatic issues endemic to SOFIA are not unusual for large NASA flagship-scale science missions.

207 Rangwala et al., "SOFIA Status & Future Prospects 2022."

208 David Robert Grimes, Chris T. Bauch, and John P. A. Ioannidis, "Modelling Science Trustworthiness Under Publish or Perish Pressure," *Royal Society Open Science* 5, no. 1 (January 10, 2018): 171511, *https://doi.org/10.1098/rsos.171511* (accessed June 18, 2025).

APPENDIX A

Sources and Methodology

SOFIA's history spanned a roughly 50-year period, from the early feasibility studies of the late 1980s to the mission's conclusion in 2022. As such, material related to the observatory's history spanned across both paper and digital formats. This report intends to offer researchers a broad overview of SOFIA's history, and thus it is not an exhaustive review of available archival material, which is still being processed at the time of this report's publication. Material in Section I: Precursors in Airborne Observation and Section II: The Kuiper Airborne Observatory draws heavily from secondary source literature on the history of astronomy, primarily airborne and infrared.

The bulk of the historical material used to produce this report came from documents accessioned into the archive at Ames, material uploaded to the Windchill system at Armstrong, newspaper articles about SOFIA, and reports issued by both the National Academy of Sciences and the NASA Office of Inspector General (OIG).

The report also draws heavily from 18 oral histories conducted with former members of the SOFIA team from Ames, Armstrong, USRA, and the DLR. Oral histories are not used as evidence in the same way as documents sourced from the archive; they function as evidence of an individual's experience of events, but not the event itself. In other words, if an individual claimed in an interview that SOFIA's deployments were characterized by a sense of merriment, that claim is recorded as valuable first-hand evidence of their experience, rather than as an unequivocal fact about the nature of the event in question.

As with any historical event involving multiple organizations and any form of budgetary constraint, SOFIA prompted a plurality of viewpoints. Several documents in SOFIA's history were written in the service of specific arguments but also serve as valuable snapshots of the observatory's history. First, early preliminary studies advocating for SOFIA's development relied heavily on the precedent established by the Kuiper Airborne Observatory developed at Ames. These studies were amplified by entities like the National Academy of Sciences, which established a flying infrared observatory as a high priority for NASA in the early 1990s. These reports, like the "Astronomy and Astrophysics Panel Report" published by the National Academy as part of its 1991 Decadal Survey, emphasized the cost-saving measures a platform like SOFIA represented while outlining ambitious scientific goals intended to make the funding recommendations more palatable. As a result, early preliminary feasibility studies relied heavily on information about KAO and imagined SOFIA as a scaled-up version of the earlier observatory instead of as an idiosyncratic platform with unique issues.

The impact of KAO on SOFIA's design was continued after SOFIA entered development, since many of the engineers and astronomers who worked on the earlier observatory were tasked with developing the new one. One controversial example is Nans Kunz's "The Making of SOFIA," which was printed as an official NASA Publication (NP-2016-09-842-LaRC) in 2016. Kunz's account is one of the most granular overviews of SOFIA's development, providing detailed timelines of both technical milestones and delays. According to Edwin Erickson, Kunz wrote the 266-page document to shift blame for SOFIA's delays away from the engineers developing SOFIA and onto those managing the aircraft's intensive modifications.[209] To exculpate those on the technical end, Kunz offered a detailed breakdown of testing schedules and modifications, now of tremendous use to historians attempting to make sense of SOFIA's muddled development timeline. Inclusion of this report, however, is incomplete without discussion of the controversy it generated. Some dismissed "The Making of SOFIA" as a disgruntled calumniation aimed at Kunz's colleagues at Armstrong, which took over flight operations from Ames in 2006. One anonymous review characterized it as a work of speculation that was at once self-congratulatory and a wholesale dismissal of Armstrong's expertise in flight operations and aircraft integration.[210]

The dates and timelines in Kunz's "The Making of SOFIA" were crosschecked by the author with the multiple audits of SOFIA conducted by NASA's OIG. These audits typically included brief overviews of SOFIA's development in attempts to identify and explain the source of delays and budgetary overruns. This report includes some discussion of the NASA OIG's 2020 audit of SOFIA, which uses the h-index to compare SOFIA's output with that of other observatories. Material at the end of this report, on SOFIA's performance once flight operations were optimized, is drawn from "SOFIA Status & Future Prospects," a report that was initially produced for SOFIA's 2022 Senior Review, which was canceled just before the mission was concluded.[211] The 2014 audit included observation of one of SOFIA's science flights.

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209 Vorobets, Valdez, and Sangbouasy, "Interview with Ed Erickson—NASA."

210 "Anonymous Memo on The Making of SOFIA," n.d., Stratospheric Observatory for Infrared Astronomy (SOFIA) Project Collection, Collection Number ARC24.12, NASA Ames Research Center Archives.

211 Rangwala et al., "SOFIA Status & Future Prospects 2022."

APPENDIX B

Instruments On Board SOFIA

One tension between teams at Ames and Armstrong that emerged after SOFIA's move in 2005 was the utilization of the Mission Control and Communication System (MCCS). The team at Ames had been working on the development of an MCCS that was based off the 20 years of operational experience gained from SOFIA's predecessor, the KAO. The Ames MCCS was designed to manage and monitor SOFIA's observatory mission systems, interface with the aircraft's systems, and facilitate communication between participants on board. By 2006, this MCCS was almost fully complete after nearly a decade in development. When the SOFIA program transferred to Armstrong, however, there was disagreement over the safety of a commercial off-the-shelf system and the Linux operating system at the core of the software interface. Armstrong, a hub for the development of experimental aircraft, had its own protocols and standards for software. In Nans Kunz's explanation of the story, a manager at Armstrong insisted on a more complicated, redundant computer system based on VxWorks.[212]

From a scientific perspective, the resulting MCCS proved less compatible with SOFIA's suite of instruments. The system lacked crucial features, such as the automated Heading Turner for keeping the telescope aligned, and it suffered from frequent crashes—approximately once per observing flight even years later.[213] The change also fundamentally altered SOFIA's operational concept, moving away from the KAO-inspired philosophy of flexible, modular systems that could be easily modified to support state-of-the-art scientific instruments. Exacerbating this were reductions in funding allocated to the development of SOFIA's scientific suite. Whereas KAO was able to develop and integrate more than 50 instruments over its 21-year operational life, SOFIA developed 8 over the course of its lifetime.[214]

To complicate instrument development even further, after program funding reductions in 2005, money was diverted from the development of science instruments to airframe modifications.[215] Despite the changes, six tools were developed for SOFIA's suite of instruments that could be swapped out depending on the scientific goals of each flight. This versatility allowed SOFIA to explore a wide range of phenomena, from star and planet formation to the structure of distant galaxies and the atmospheres of planets in our solar system.

212 Kunz, "The Making of SOFIA."

213 Kunz, "The Making of SOFIA," p. 210.

214 "NASA's Management of the Stratospheric Observatory for Infrared Astronomy Program," p. 15.

215 "…Roughly $3.4 M per year of SI [scientific instruments] funding was to be fenced from the aircraft budget. Development of the approved U.S. SIs began in late 1996. When severe cost overruns for the aircraft development were revealed in 2000, budgets for the U.S. SI teams were cut dramatically, and the highest priority SI was cancelled. The relatively small SI development teams attempted to cope with their reduced budgets, which of course resulted in increased development costs and delays. Subsequently, two more SIs were cancelled." Kunz, "The Making of SOFIA," p. 57.

One of the key instruments on SOFIA was the Faint Object InfraRed CAmera for the SOFIA Telescope (FORCAST), which provided imaging and spectroscopic capabilities in the mid-infrared range, detecting wavelengths from 5 to 40 microns.[216] FORCAST captured detailed images of regions where stars were forming, supernova remnants, and the warm dust surrounding young stars. It also enabled the study of the chemical composition and structure of dust and gas clouds, shedding light on the processes that lead to the birth of stars and planets.[217]

The German REceiver for Astronomy at Terahertz Frequencies (GREAT) was a heterodyne spectrometer that observed far-infrared and submillimeter wavelengths ranging from 60 to 240 microns.[218] GREAT was useful for studying the cold, molecular gas in star-forming regions. It could detect molecules like water, carbon monoxide, and ionized carbon, providing critical insights into the chemical processes that occur during the formation of stars and planets. This instrument allowed astronomers onboard SOFIA to study interstellar medium with new precision.

The Field Imaging Far-Infrared Line Spectrometer (FIFI-LS) offered both imaging and spectroscopic capabilities in the far-infrared range (51–120 microns and 115–203 microns).[219] FIFI-LS was designed to map the distribution and motion of gas in galaxies, nebulae, and other astronomical objects. It played a key role in studying the dynamics of star formation in distant galaxies, helping to reveal the complex interplay between gas, dust, and magnetic fields in these regions. Its ability to produce detailed spectral maps provided data for understanding the evolution of galaxies and the structure of the interstellar medium.

The High-resolution Airborne Wideband Camera Plus (HAWC+) was a far-infrared camera and polarimeter.[220] HAWC+ operated in the 50- to 240-micron range and was unique in its ability to measure both the intensity and polarization of infrared light. This capability made it possible to study magnetic fields in star-forming regions, galactic centers, and other cosmic environments. By observing how magnetic fields influence the formation of stars and the dynamics of galaxies, HAWC+ facilitated a deeper understanding of the forces shaping the universe.

The Echelon-Cross-Echelle Spectrograph (EXES) was another mid-infrared instrument on SOFIA, covering wavelengths from 4.5 to 28.3 microns.[221] EXES provided high-resolution spectra, making it an essential tool for studying the composition and dynamics of planetary atmospheres, circumstellar disks, and molecular gas in star-forming regions.

The High-speed Imaging Photometer for Occultations (HIPO) was designed for high-speed photometric observations during stellar occultations—events in which a distant star passes behind a planet or other object, allowing scientists to study the object's atmosphere and other characteristics.[222] Sensitive to both visible and near-infrared wavelengths, HIPO captured data at high frame rates.

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216 Faint Object infraRed CAmera for the SOFIA Telescope (FORCAST), *https://irsa.ipac.caltech.edu/data/SOFIA/docs/instruments/forcast/index.html* (accessed June 18, 2025).

217 SOFIA Instrument Suite, *https://irsa.ipac.caltech.edu/data/SOFIA/docs/instruments/sofia-instruments-suite/index.html* (accessed June 18, 2025).

218 German REceiver for Astronomy at Terahertz Frequencies (GREAT), *https://irsa.ipac.caltech.edu/data/SOFIA/docs/instruments/great/index.html* (accessed June 18, 2025).

219 Far Infrared Field-Imaging Line Spectrometer (FIFI-LS), *https://irsa.ipac.caltech.edu/data/SOFIA/docs/instruments/fifi-ls/index.html* (accessed June 18, 2025).

220 High-resolution Airborne Wideband Camera Plus (HAWC+) *https://irsa.ipac.caltech.edu/data/SOFIA/docs/instruments/hawc/* (accessed June 18, 2025).

221 Echelon-Cross-Echelle Spectrograph (EXES) *https://irsa.ipac.caltech.edu/data/SOFIA/docs/instruments/exes/index.html* (accessed June 18, 2025).

222 High Speed Imaging Photometer for Occultations (HIPO), *https://irsa.ipac.caltech.edu/data/SOFIA/docs/instruments/hipo/index.html* (accessed June 18, 2025).

APPENDIX C

Timeline

1965
Gerard P. Kuiper uses NASA Ames's Galileo Airborne Observatory to study the atmosphere of Venus.

1968
Frank J. Low uses the Ames Learjet Observatory to study Jupiter.

1969
Formal plans are made to mount a 36-inch telescope on an aircraft to perform astronomy from the stratosphere.

1975, May 21
Dedication of the Kuiper Airborne Observatory, a heavily modified Lockheed C-141A Starlifter jet transport aircraft with a telescope designed for observation in the 1 to 500 µm spectral range.

1977, April 25
Boeing 747SP No. 21441-306 completes its first flight.

1977, May 20
Pan Am names the Boeing aircraft in honor of Charles Lindbergh.

1986, February 13
United Airlines purchases plane from Pan Am; it receives a new aircraft registration, N145UA.

1991
National Academy of Sciences recommends development of an airborne observatory for infrared observation.

1995, December
United Airlines places aircraft in storage near Las Vegas.

1996
USRA is awarded NASA contract for development of SOFIA. German Deutsches SOFIA Institute will manage telescope development and maintenance.

1997, October 27
Aircraft is purchased by USRA.

1998
Raytheon designs and installs an 18- × 13.5-foot-wide door on the left side of the fuselage.

1999, December
Polishing of telescope's primary mirror is completed.

2001
Project development is delayed by three subcontractors going out of business. United Airlines enters bankruptcy protection and withdraws from project as aircraft operator

2002
Main components of telescope are assembled in Augsburg, Germany.

2004
Telescope is delivered to the United States from Germany for mounting in airframe and initial ground observations.

2004, August 19
SOFIA completes its first ground-based test by taking an image of Polaris.

2006, February
After development costs increase from $185 million to $330 million, NASA puts SOFIA under review and removes the project from its budget.

2006, June
SOFIA passes review.

2007, April 26
SOFIA's first test flight occurs.

2007, May 31
SOFIA is moved to NASA Armstrong Flight Research Center at Edwards Air Force Base.

2007
Charles Lindbergh's grandson Erik Lindbergh re-christens the aircraft Clipper Lindbergh to celebrate the 80th anniversary of Charles's transatlantic flight, at NASA's invitation.

2009
SOFIA performs its first test flight in which the telescope door fully opens.

2010, May 26
SOFIA's telescope sees first light.

2010, December
Initial routine science observations begin.

2013, July
SOFIA's first deployment takes place in Christchurch, NZ. It is billed as its inaugural mission.

2014
SOFIA reaches its full capability at 100 flights per year.

2021, November 11
National Academy of Sciences' Decadal Survey recommends concluding SOFIA operations by 2023, given the project's high cost and "modest scientific productivity."

2022, September 29
SOFIA's final flight takes place.

About the Author

Lois Rosson is a Historian in the NASA History Office. She earned her Ph.D. in History from the University of California at Berkeley in 2022, with a focus on the cultural history of science. Her work has been supported by the Smithsonian National Air and Space Museum, Lawrence Livermore National Laboratory, the Berggruen Institute, the University of Southern California, and the American Philosophical Society. At NASA, she contributes to public scholarship on the agency's programs, people, and the lessons offered by historical hindsight.

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NASA's Stratospheric Observatory for Infrared Astronomy (SOFIA) was an airborne observatory that operated from 2010 to 2022. Developed out of a former passenger aircraft, SOFIA flew a 2.7-meter infrared telescope above the bulk of the water vapor in Earth's atmosphere, allowing scientists to observe infrared light difficult to see from the ground. Operated in partnership with the German Aerospace Center, SOFIA provided flexibility in targeting astronomical subjects and made significant contributions to the study of magnetic fields, star formation, and the chemistry of interstellar clouds.

This report is the first retrospective look at SOFIA since the mission's conclusion in 2022. It is compiled from archival records and oral histories with astronomers, project managers, flight crew, and international partners. It situates SOFIA in a broader history of airborne observation at NASA and narrates the observatory's development, operations, and legacy. Though SOFIA was retired in 2022, it functioned as a bridge between ground- and space-based infrared astronomy, and its data sets continue to offer valuable insights into the shape and composition of our universe.

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