

The SOFIA program: astronomers return to the stratosphere

Sean C. Casey *

Universities Space Research Association, NASA MS 144-2, Moffett Field, CA 94035-1000, USA

Received 14 December 2002; received in revised form 10 April 2003; accepted 7 May 2003

Abstract

The Stratospheric Observatory for Infrared Astronomy (SOFIA) is the next generation of airborne astronomical observatories. Funded by the US and German space agencies, SOFIA is scheduled for science flights beginning in late 2005. The observatory consists of a 747-SP modified to accommodate a 2.7-m telescope with an open port design. Academic and government laboratories spanning both the US and Germany are developing science instruments for SOFIA. Using state-of-the-art technologies, SOFIA will explore the emission of astronomical sources with an unprecedented level of angular resolution ($\theta[\text{arc-sec}] = 0.1 \times \text{wavelength} [\mu\text{m}]$) and spectral line sensitivity at infrared and sub-millimeter wavelengths. The current status of SOFIA is available from the observatory web site at <http://sofia.arc.nasa.gov> and is updated frequently.

© 2004 COSPAR. Published by Elsevier Ltd. All rights reserved.

Keywords: Infrared astronomy; Stratosphere; SOFIA program; Airborne observations

1. Introduction

The Stratospheric Observatory for Infrared Astronomy (SOFIA) is a joint effort by the US and German space agencies to develop the next generation airborne infrared observatory (Becklin, 1997; Erickson and Davidson, 1995). After almost two decades of study and development, the SOFIA program is on schedule for first light in the fall of 2005. The SOFIA team consists of international participants from government, industry, and academia.

The 21 year history of science missions aboard the Kuiper Airborne Observatory (KAO) demonstrated the unique capabilities of stratospheric observations at wavelengths inaccessible from the ground. SOFIA provides scientists with a powerful suite of state-of-the-art instrumentation for infrared astronomical imaging and spectroscopy. The observatory's nasmyth configuration telescope with an optical quality primary mirror is expected to produce excellent, diffraction limited imaging at mid-infrared wavelengths and longer.

A combined US and German instrument program enables sensitive spectroscopic measurements covering a

wide range of spectral resolutions. Observations aboard SOFIA range from high-speed occultation instruments in the optical to bolometers, photoconductors, and heterodyne mixers operating at longer far-infrared and sub-millimeter wavelengths. The top-level characteristics expected for SOFIA in 2005 are listed in Table 1. Compared to space-based missions, the SOFIA program provides researchers with project development time scales suitable for graduate student and postdoctoral research programs.

1.1. The science program

Astronomical observations at infrared wavelengths reveal an otherwise hidden universe. Celestial sources emit infrared radiation through a wide variety of physical processes that includes thermal continuum emission and the characteristic line emission of atoms, molecules, and larger biogenic macromolecules. SOFIA science topics include the study of interstellar gas and dust in our Galaxy and other more distant galaxies.

As interstellar gas collapses to form stars, observations at infrared wavelengths can pierce the dusty veil of the surrounding gas cloud to view the centrally concentrated collapsing core. Imaging observations place constraints on the frequency, energetics, and spatial

* Tel.: +1-650-604-2119; fax: +1-650-618-1572.

E-mail address: scasey@mail.arc.nasa.gov (S.C. Casey).

Table 1
SOFIA characteristics

Nominal operational wavelength range	0.3–1600 μm
Primary mirror diameter	2.7 m
System clear aperture diameter	2.5 m
Nominal system f-ratio	19.6
Primary mirror f-ratio	1.28
Telescope's unvignetted elevation range	20–60°
Unvignetted field-of-view diameter	8 arc-min, 13 arc-min at optimum focus
Maximum chop throw on sky	± 4 arc-min (unvignetted)
Diffraction-limited wavelengths	$> 15 \mu\text{m}$
Recovery air and optical temperature in cavity	240 K
Image quality of telescope optics (at 0.6 μm)	1.0" on-axis (80% encircled energy)
Optical configuration	Bent cassegrain, chopping secondary and flat folding tertiary
Chopper frequencies	1–20 Hz for 2-point square-wave chop
Pointing stability	$< 2.0''$ rms for first-light
Pointing accuracy	= 0.5" if on-axis focal plane tracking = 3" if on-axis fine-field tracking
Total emissivity of telescope (goal)	15% at 10 μm with dichroic tertiary 10% at 10 μm with aluminized tertiary
Chopped image quality due to coma for $\pm 4'$ chop throw	= 9.1" for 80% encircled energy diameter = 5.8" for 50% encircled energy diameter

extent of these regions. Spectroscopic observations provide details of the collapse kinematics along with the abundance of excited atoms and molecules within the infalling envelope. The abundance of atomic and molecular species in many cases depends upon the energetics and history of the collapsing gas cloud. In addition to the study of star formation, the SOFIA science program will include the study of planet forming disks, planetary atmospheres, comets, and other solar system type objects.

SOFIA observations should also address studies such as the nature of our own Galactic center where a massive black hole is widely surmised to exist. Research studies can further compare our Galactic center to the central regions of other galaxies where signatures of black hole accretion are considerably more volatile.

With refinements in instrument sensitivities, SOFIA should detect and resolve the faint emission of the first galaxies at sub-millimeter wavelengths. The SOFIA program provides a broadly based scientific tool set for studies of many obscured and yet to be resolved star forming regions (Krabbe and Röser, 1999).

2. Observatory development

SOFIA is a cooperative 25-year program between the US and Germany under a formal memorandum of understanding. The success of the observatory development is a by-product of working together in a cooperative and constructive fashion. Under this agreement, the US is to provide the aircraft, the air-

craft modifications, onboard mission control systems, ground support systems, science operations center, systems integration, certification from the US Federal Aviation Administration (FAA), and 80% of the operations costs. Germany is to provide the telescope assembly, support for integration, and 20% of the operations costs. Science teams throughout the US and Germany provide the astronomical instruments for SOFIA. During observatory operations, the US and Germany will share telescope time in approximately the same 80:20 proportion.

2.1. The SOFIA team

NASA selected the Universities Space Research Association (USRA) as the single prime contractor for US development and operations. The German aerospace agency, Deutsches Zentrum für Luft und Raumfahrt (DLR), selected MAN Technologies and Kayser-Threde for the joint development of the SOFIA telescope assembly.

As a prime contractor, USRA¹ is responsible for project and scientific management during the development and operations phases of SOFIA. The USRA SOFIA team consists of: L-3 Communications Integrated Systems for engineering design, airframe modifications, and all flight testing activities; United Airlines will provide aircraft and maintenance crews during both

¹ The USRA was incorporated in 1969 in the District of Columbia as a private nonprofit corporation under the auspices of the National Academy of Sciences as a mechanism for universities, government, and industrial centers to cooperate for the benefit of space science and technology.



Fig. 1. The “Clipper Lindbergh” painted with the colors of United Airlines as purchased by NASA in January 1997.

the development and operations phases; The University of California at Berkeley, Los Angeles, Irvine, and Santa Cruz will provide for mirror coating and cleaning experience, data archiving expertise, instrument development and user interface software, along with needed science support activities; The Astronomical Society of the Pacific and the SETI Institute will provide for education and public outreach initiatives. Outreach includes provisions for engaging educators in the research process while flying aboard SOFIA and participating in astronomical research missions.

Aircraft modifications and the integration of the German telescope assembly are taking place in L-3’s Waco, Texas facility. From the beginning of the SOFIA operations program, the observatory will be certified under a supplemental type certificate from the US FAA. Certification is required for both safe operation of the facility and for the effective participation of United Airlines as a partner with USRA during the operations phase of the program. Following successful completion of the SOFIA airworthiness test flights, the integrated aircraft/telescope system will be flown to Moffett Field, California for commissioning flights and first light science observations at the NASA Ames Research Center.

2.2. The Boeing 747-SP aircraft

The founder of Pan Am, Juan Trippe, originally proposed and campaigned to bring Boeing 747s into commercial service during the mid 1960s following an unsuccessful bid by Boeing to build a large US military transport. Trippe later requested Boeing to modify the original 747 designs to support longer, non-stop Pan Am routes. The special performance (SP) specification of the SOFIA aircraft corresponds to a reduced weight and a shorter 747 fuselage. As engineered by Boeing and purchased by Pan Am, the 747-SP had a range of 7000 miles and could fly non-stop from New York to Tokyo in just 13 hours. With the demise of Pan Am under growing competition, United Airlines purchased several 747-SP

aircrafts from the Pan Am fleet in February 1986. The United 747-SP (production number 21441) proposed by USRA for the SOFIA program had been christened the Pan Am “Clipper Lindbergh” by Anne Morrow Lindbergh in May 1977 on the 50th anniversary of Charles Lindbergh’s historic solo flight from New York to Paris (<http://www.charleslindebergh.com>).²

With the selection of the USRA proposal, NASA purchased the “Clipper Lindbergh” 747-SP aircraft from United Airlines in January 1997 (see Fig. 1). The SOFIA aircraft was flown to the San Francisco International Airport (SFO) in April of 1997 for an official dedication ceremony. The “Clipper Lindbergh” was later flown to the L-3 facility in Waco, Texas, for the modifications required for the SOFIA development program. Overall aircraft modifications included major revisions to the aircraft’s aft structure, modifications of the aircraft interior for scientists and educators, creating a cavity in the aircraft fuselage to house the German telescope, and installing all the required observatory support systems. The final observatory layout of personnel accommodations includes workstations for a mission director, telescope operator, and computer specialist, as well as work areas designated for scientists and educators. At its 41,000 foot-plus operating altitude, the aircraft is maintained with a cabin pressure of 8000 feet which is typical of commercial aircraft. A single pressure bulkhead separates the shirt-sleeve working environment of the aircraft cabin and the telescope cavity’s ambient ($-50\text{ }^{\circ}\text{C}$) at-altitude environment.

A critical component of the L-3 aircraft modification amounted to cutting a 14×20 foot hole in the SP fuselage. The aircraft’s cavity door is termed the ‘partial external door’ and is divided into several sections. The fuselage fairing creates an aerodynamic surface over the individual door components and minimizes the drag and aero-acoustic disturbance inside the cavity. The upper rigid door and lower flexible door move along tracks underneath the aluminum fairing. The upper rigid door closes over the top of the cavity aperture and is used to seal the cavity while the aircraft is on the ground. The lower flexible door connects below the

² Charles Lindbergh, flying with his wife Anne Morrow, supported the nascent years of Pan Am operations during the early 30s by exploring new air routes to South America, Asia, and Europe. In the late 30s, Lindbergh played an important role as chair of a Special Committee on Aeronautical Research Facilities that led to establishing the Ames Aeronautical Laboratory at Moffett Field – which today is the NASA Ames Research Center. Some 30 years later, Charles Lindbergh was still closely tied with the efforts of Juan Trippe and is credited in working with Boeing to bring the original 747 designs into commercial service. Charles Lindbergh passed away in 1974 – the same year NASA Ames began research flights aboard the KAO. The connection between Charles Lindbergh, the NASA Ames Research Center, and SOFIA aircraft is both notable and remarkable.

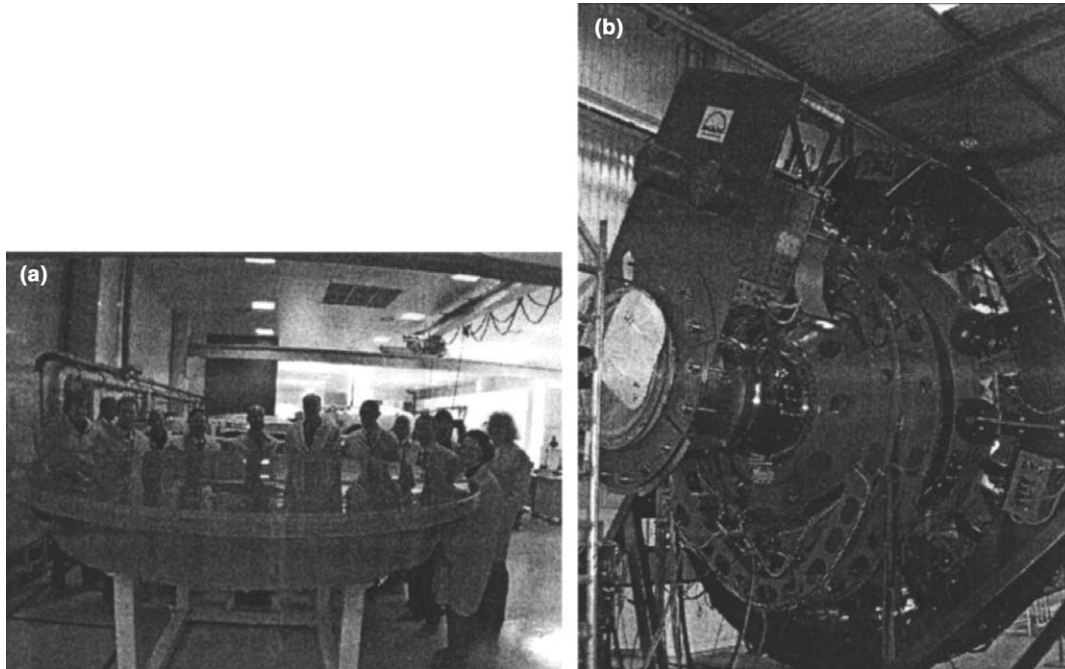


Fig. 2. (a) SOFIA engineers, scientists, and managers with the observatory's primary mirror after successful optical testing in Germany. (b) The completed telescope assembly during testing in Augsburg, Germany. The nasmyth tube is capped with the counter weight plate for mounting of the science instruments.

cavity aperture and follows the non-cylindrical portion of the aircraft's fuselage. Aft of the cavity aperture is the carbon fiber "D-shaped" ramp that reattaches the airflow from the forward faring and smoothes the transition from open port cavity to fuselage surface. The rigid and flexible doors and the "D-shaped" ramp all move in unison with changes in telescope elevation. An inflatable rubber gasket seals the cavity for pre-cooling of the telescope on the ground and during ascent or descent from 41,000 feet. The door design and implementation is a joint effort between the NASA ARC engineering directorate and the engineers of L-3 Communications.

2.3. The German telescope

After nearly 15 years of engineering design and analysis, the final SOFIA telescope design is a layered approach to achieve precision telescope pointing control. A largely passive air spring system provides vibration isolation between the telescope and the aircraft; an active fiber optic gyro based control provides inertial stabilization; accelerometers provide the needed information for automatic compensation of basic telescope static and dynamic flexures; and optical sensors provide low frequency closed loop tracking on celestial sources.

A large single pressure bulkhead and the telescope mount itself separate the telescope cavity from the

shirtsleeve environment of the aircraft. The bulkhead has a central opening approximately 3.6 m in diameter to accommodate the telescope suspension assembly. The outer cradle of the telescope suspension assembly attaches to the bulkhead with an array of lateral and tangential air springs. The springs attenuate high frequency vibrations from the aircraft. This outer cradle provides coarse elevation pointing and supports the inner cradle section of the telescope mount.

Precision pointing and fine level stabilization is achieved via a three-axis spherical motor within the inner cradle and includes a nearly frictionless spherical hydrostatic journal bearing. A set of spherical bearing rings in the inner cradle provides a flow of oil to float a single cast iron sphere that was precision ground to match the spherical shape of the bearing rings. This floated sphere is rigidly attached to the telescope nasmyth tube that connects the telescope and science instrument. The weight of the entire telescope is supported on a film of oil within the bearing. The nominal inlet pressure for this hydraulic support is approximately 40 bar.

The spherical torque motor that positions the telescope consists of rotor magnet segments that rigidly connect to the nasmyth tube and are surrounded by stator coil assemblies that attach to the inner cradle. The spherical motor has limited range of $\pm 3^\circ$ in each of the three rotational axes. During normal flight operations, this motor is driven to keep the telescope

inertially stabilized with feedback from a three-axis inertial sensor.³

The telescope's primary mirror is 2.7 m in diameter. The primary is a light weighted honeycomb structure of zerodur and took approximately 4 1/2 years to manufacture (Fig. 2a). Interferometric measurements of the primary mirror surface indicate a RMS surface error of approximately 280 nm over a range of telescope elevations typical of SOFIA science operations (20–60°).

The secondary mirror is made from silicon carbide and is undersized to form a pupil stop for operation in the infrared. The size of the secondary mirror limits the effective telescope aperture to 2.5 m. Optical testing of the secondary mirror surface indicates an RMS surface error of 16 nm.

To automatically compensate for changes in the telescope's focus and image quality over the full range of telescope elevations, the secondary mirror mounts to an articulated hexapod support. The articulated secondary mirror support also drives "chopping" at any angle relative to the elevation axis. Dynamic flexure of the telescope structure, primarily the nasmyth tube, under flight accelerations is measured via accelerometers. The low frequency components of these flexures, less than about 6 Hz, are applied to drive the telescope mount; the high frequency components are applied to the wideband secondary mirror tip-tilt control.

During normal flight operations, two smaller telescopes are needed for field recognition and timely target acquisition. The wide field imager provides a field of view of $\pm 3^\circ$ with a limiting magnitude of 10 for a 1 s integration. The fine field imager provides a field of view of ± 33.5 arc-min with a limiting magnitude of 13.4 and a similar integration time. A facility focal plane imager shares the science instrument focal plane through a dichroic tertiary mirror and has a field of view of ± 4.83 arc-min with a 1 s limiting magnitude of 15.2. Each imager is equipped with a series of broadband neutral density filters.

In mid-summer of 2002, the key components of the DLR telescope's structure were assembled in Augsburg, Germany, to test its integrated system behavior (Fig. 2b) before shipping all of the components to Waco, Texas. As designed, many of the telescope's components are lightweight, compared to the comparable structural components of ground-based observatories. The systems tests in Augsburg, Germany, demonstrated the satisfactory balancing of the telescope assembly, the leak-

free and frictionless operation of the spherical hydrostatic bearing, and the successful inertial stabilization of the telescope. Ground operation of the telescope assembly was supported by software developed by MAN for closed loop inertial servo-mechanical control. Kayser-Threde developed the image processing software that augments inertial telescope control.

Following a successful pre-ship review in August 2002, the DLR telescope was shipped to the US aboard an Airbus Beluga jet aircraft. The telescope assembly cleared US customs in Buffalo, New York, and arrived in Waco, Texas, on September 4, 2002. The telescope's main optical support (metering structure), suspension assembly, and primary mirror assembly were unloaded the same day and are now being readied for integration within the SOFIA aircraft (see Fig. 3).

2.4. The observatory software

The software for SOFIA is under development by groups throughout the SOFIA program. In Germany, the telescope software has been developed to servo-control telescope motions with outputs from the three-axis gyroscope package. This software keeps the telescope inertial stable and pointed at fixed positions on the sky. Additional software handles the imaging data from any one of the three imagers for fine corrections to the inertial servo-control software. The camera software allows one to specify areas of interest containing stars within the field of view and smoothly move the telescope from one sky position to another.

The US developers provide user interface software for communicating to the German telescope systems. The US mission control software (MCS) synchronously drives cavity door motions to follow motions of the telescope and thus provides an unvignetted field of view of the telescope's imagers and science instruments. The

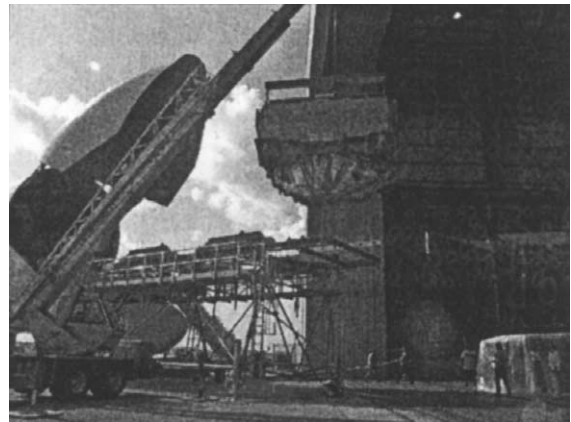


Fig. 3. The telescope's main optical support, suspension assembly, and the primary mirror assembly arrived in Waco, Texas on September 4, 2002.

³ The SOFIA telescope is the first in astronomy to use high performance fiber optic gyros for inertial sensor feedback. In each of the three axes, a fiber optic gyro with a single 3 km fiber coil is used. Light is launched into both ends of the fiber coil – two counter-propagating waves. If the fiber coil is motionless the beams exit with a fixed phase relationship; if the ring is rotating there is a phase shift proportional to the rotation rate and the area of the ring.

MCS also handles the task of collecting, displaying, and storing all observatory housekeeping data. Observatory housekeeping data include output from the three observatory imagers, many of the telescope's monitoring sensors, details of cavity door operations, the observatory's water vapor monitor, and other aircraft subsystems. Observatory staff members use the MCS software to monitor and control observatory subsystems.

For the science instruments during normal operations, the MCS software processes telescope commands before sending the commands off to the telescope subsystems. For general investigators and the observatory's science staff, the US software development effort also includes packages for handling the requests of the general investigator community. Known as the SOFIA data cycle system (DCS), the software is envisioned as 'enterprise software' for assisting observatory staff scientists in the handling of requests for observing time by the general investigator community using the SOFIA facility instruments. The tasks of the DCS are to handle requests for telescope time, the scheduling of science programs among many separate flights, the collection and pipelining of data, and the archival storage of the raw data along with any final data products and the pipelines that produced these products. Traditionally, many of these tasks had been done using a combination of notebooks, filing systems, and software. The core-DCS software is intended to provide a unified framework in which different software packages can communicate for the improved operational efficiency of the observatory staff and the general

investigator community. The integrated functionality of the DCS is expected to improve over the lifetime of SOFIA.

3. Science instrument suite

SOFIA instruments bring state-of-the-art technologies on-line to enable new science programs. In response to the US call for instrument proposals issued on April 8, 1997, USRA received 19 proposals by the July 15, 1997 deadline covering a wide range of wavelengths and functionalities. All proposals were reviewed by a panel of scientific peers at the Lunar and Planetary Institute in Houston, Texas, on September 4–5, 1997. Recommendations for selection were made to Dr. Eric Becklin, the USRA Chief Scientist. NASA management approved the final selection of US first-light instruments for the SOFIA program and for USRA to begin funding instrument teams in October 1997. Table 2 lists the US and German instruments under development and their respective principal investigators. Each instrument operates close to the diffraction-limited performance of the observatory ($\theta[\text{arc-sec}] = 0.1 \times \text{wavelength} [\mu\text{m}]$).

The SOFIA science instruments fall into one of three distinct classes – speciality instruments, principal investigator instruments, and facility instruments. Speciality science instruments are typically instruments with specifically designed functionalities and narrowly focused science objectives. The principal investigator or PI instruments are developed and operated in a fashion very

Table 2
SOFIA's funded suite of first light instruments

Instrument	PI	Institute	Type of instrument	Instrument class
HAWC	D.A. Harper	University of Chicago	Far-infrared bolometer camera 50–240 μm	Facility instrument
FORCAST	T. Herter	Cornell University	Mid-infrared camera 5–40 μm	Facility instrument
FLITECAM	I. McLean	UCLA	Near-infrared test camera 1–5 μm	Facility instrument (Test instrument)
EXES	J. Lacy	University of Texas	Echelon spectrometer 5–28 μm $R = 10^5, 10^4, 3000$	PI instrument
CASIMIR	J. Zmuidzinas	Caltech	Heterodyne spectrometer 250–600 μm	PI instrument
SAFIRE	H. Moseley	NASA-GSFC	Imaging Fabry–Perot Bolometer array spectrometer 145–655 μm $R = 1000–2000$	PI instrument
FIFI-ls	A. Poglitsch	MPE, Garching	Imaging grating spectrometer 42–210 μm	PI instrument
GREAT	R. Guesten	MPIfR KOSMA DLR-WS	Heterodyne spectrometer 60–200 μm	PI instrument
HIPO	T. Dunham	Lowell Observatory	High-speed imaging photometer for occultations 0.3–1.1 μm	Specialty instrument (Test instrument)

similar to science programs aboard the KAO and are available on a shared risk basis. General investigators interested in science data obtained with a PI instrument work closely with the PI instrument team in proposing their observations, planning the data acquisition, reducing and analyzing the data, and publishing their final results. PI instruments have the flexibility to use the latest technologies and quickly make those capabilities available to the general investigator community.

Facility instruments are developed under principal investigators and are delivered to USRA for operation aboard SOFIA. Facility instruments are generally designed for broader community use, incorporate more established technologies, and are capable of supporting a greater number of missions per year. General investigators seeking to obtain science data from SOFIA'S facility instrument program work with the observatory's science staff in preparing their proposals, planning their observations, and reducing their data. The SOFIA facility instrument program is assisted by the development of the SOFIA data cycle system. Facility instruments also enable the USRA science staff to monitor observatory performance on a regular basis beyond the previous capabilities of the KAO program.

The US instrument selection includes three facility-class instruments. Two instruments are scheduled for commissioning of the observatory prior to science flights in 2005. The two instruments – HIPO and FLITECAM – are expected to commission an initial suite of observing modes needed for successful operation of the other science instruments. Telescope operating modes include those associated with inertial pointing of the telescope, chopping and nodding, and continuous scanning or rastering of the telescope. Details on all SOFIA science instruments are available from the SOFIA web site (http://www.sofia.arc.nasa.gov/Science/instruments/sci_instruments.html).

4. Science and mission operations center

As proposed by USRA, SOFIA operations are directed from a government owned/contractor operated facility at the NASA Ames Research Center, which is adjacent to the Moffett Federal Airfield and just outside of Mountain View, California. Following the successful commissioning of the observatory in 2005, all observatory operations will be conducted under USRA in Building N211 located within the NASA Ames Research Center Campus. SOFIA will use runways at the Moffett Federal Air Field.

All of SOFIA'S observatory support groups, consisting of scientists, engineers, technicians, and educators, will occupy renovated office space in the N211 building. This support includes employees from USRA, United Airlines, and the German SOFIA Science Insti-

tute. For the SOFIA education and public outreach program, a special conference room is provided with a large picture window for the public and school groups to view SOFIA operations without interfering with day-to-day observatory operations.

4.1. The N-211 aircraft hangar facility

Operations and science staff are located in Building N211 with the SOFIA aircraft. The hangar includes a mirror coating facility for re-aluminizing the SOFIA primary mirror, laboratory facilities for science instruments, library facilities for researchers and staff, and bonded storage facilities for all spare aircraft components. Facilities within the SOFIA Science and Mission Operations Center (SSMOC) provide for testing and verification of science instrument interfaces before their installation aboard the aircraft. Additional support is provided for instrument calibration and alignment. Laboratory space is provided for the observatory's suite of science instruments, since facility instruments reside permanently with the SSMOC. Visiting instruments arrive with their respective principal investigator research teams for which separate laboratory facilities are dedicated.

The 50-year-old, 90,930 square foot facility required significant modification for SOFIA operations. Work began on the facility after a three-year design period starting in 1997. The hangar door of N211 was modified to accommodate the 66 foot tall vertical stabilizer of the 747-SP. On June 17, 1999, United Airlines performed a "fit to function" test using the NASA shuttle carrier – a 747-400 – from the NASA Johnson Space Center. The test validated operational expectations for running the "Clipper Lindbergh" aircraft at Moffett Field. A nose dock provided by United Airlines allows observatory staff easy access to the aircraft through door left one and two and door right one. Science instrument teams will load their instruments through door one left, while observatory maintenance crews can access the facility through door one right. The nose dock also allows a partial docking of the aircraft that enables the observatory to run off of the aircraft's auxiliary power unit (APU) while on the ground. Science instruments are brought on board through a permanent 50-foot walkway that connects to the second floor of N211.

N211 modification also includes a large, mirror-coating chamber for the annual coating of the SOFIA primary mirror. Fabricated from stainless steel, the SOFIA mirror-coating facility measures 4.3 m in diameter by 4.9 m in height and weighs 10 metric tons. Operating under a vacuum of 10^{-6} torr, the chamber coats the primary mirror with pure aluminum to a thickness of 0.15 μm . A separate cleaning and stripping room is adjacent to the mirror coating facility for preparation of the primary mirror surface prior to

coating. While mounted in the aircraft's telescope cavity and in between fresh aluminum coatings, regular dry CO₂ snow cleaning is used to clean the telescope's mirror surface with periodic water washing. Ballistic CO₂ snow particles remove material otherwise resilient to a simple dry gas blowing.

4.2. *The schedule for science proposals and mission operations*

It is planned that the observatory shake down period will extend throughout 2005. Following the transition to stable operations, the observatory expects to fly close to 160 flights per year. The anticipated flight rate for SOFIA is nearly twice the flight rate achieved during any year of the KAO's 21 year history of operations (Larson, 1995). Each flight aboard SOFIA is expected to last at least 6 hours at altitudes of 41,000 feet or above. NASA expects SOFIA to attain 1200 successful science hours during the first several years of operations with 960 successful science hours per year starting in year four of the program. As a mobile observatory, SOFIA will make frequent deployments to the southern hemisphere. Aboard the KAO, southern hemisphere operations were often staged from Christchurch, New Zealand.

The USRA team plans to release a call for science proposals in January 2005 for US observing time (80%) with science observations beginning in late 2005. The US call for science instrument proposals will probably occur in the spring of 2006. A separate call for science proposals will be released in Germany for the German fraction of telescope time (20%). The first science observations aboard SOFIA will be on a shared-risk basis. SOFIA time at altitude will probably be very similar to that of the KAO. However, the lower telescope elevation range of SOFIA (20–60° versus 35–75°) will enable investigators to fly farther north into Canada where the tropopause is lower and productive science time is available at lower flight altitudes (37,000 feet). The lower telescope elevation range of SOFIA also allows the facility to observe the Galactic center when operating as far north as Moffett Field, California.

5. Conclusions

SOFIA is expected to provide scientists with a unique and powerful vehicle for infrared astronomy over the

next 20 years. The program's strengths lie in a sub-orbital observatory that can quickly field novel technologies that can then enable new science missions. These novel technologies and the science programs they enable are expected to evolve and feed into next generation space missions. The advantage of SOFIA will always be ready access to a 2.5-m telescope at 41,000 feet. As new space missions come online, the SOFIA program will work to fund further innovations in larger and more sensitive detectors, thus providing an established and long-lived niche for airborne astronomers and their instruments in the years to come.

Acknowledgements

A great deal of the information contained in this paper is available from the SOFIA web site at <http://sofia.arc.nasa.gov>. Many details of the SOFIA telescope were presented by MAN and Kayser-Threde engineers at the "Airborne Telescope Systems II" session of the 2002 SPIE Conference on "Astronomical Telescopes and Instrumentation". Additional descriptive text of the telescope was received from Patrick Waddell. I thank Eric Becklin, Ed Erickson, Tom Greene, and Chris Wiltsee for their timely review of this manuscript.

References

- Becklin, E.E. The Stratospheric Observatory for Infrared Astronomy (SOFIA), The Far Infrared and Submillimetre Universe. ESA SP-401, ESA publications Division, ESTEC, Noordwijk, The Netherlands, pp. 201–206, 1997.
- Erickson, E.F., Davidson, J.A. SOFIA: The future of airborne astronomy, in: Haas, M.R., Davidson, J.A., Erickson, E.F. (Eds.), Proceedings of the Airborne Astronomy Symposium on the Galactic Ecosystem: From Gas to Stars to Dust, vol. 73. Astronomical Society of the Pacific, San Francisco, CA, 1995.
- Larson, H.P. The NASA airborne astronomy program, in: Haas, M.R., Davidson, J.A., Erickson, E.F. (Eds.), Proceedings of the Airborne Astronomy Symposium on the Galactic Ecosystem: From Gas to Stars to Dust, vol. 73. Astronomical Society of the Pacific, San Francisco, CA, 1995.
- Krabbe, A., Röser, H.P. SOFIA astronomy and technology in the 21st century, in: Schieliche, R.E. (Ed.), Reviews of Modern Astronomy, vol. 12. Astronomische Gesellschaft, Hamburg, Germany, 1999.