SOFIA Mission Operations

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ABSTRACT

The SOFIA Airborne Observatory will operate a 2.5 m aperture telescope with the goal of obtaining over 960 successful science hours, per year, at a nominal altitude of 12.5 Km and covering a wavelength range from 0.3 micrometers to 1.6 mm. The observatory platform is comprised of a Boeing 747SP with numerous significant modifications. The ground and flight mission operations architectures and plans are tailored to keep the telescope emissivity low and achieve high observing efficiency.

Key Words: infrared, astronomy, airborne observatory, operations

1. Introduction

The NASA/DLR Stratospheric Observatory For Infrared Astronomy (SOFIA) is a modified Boeing 747SP aircraft with a 2.5 m telescope and instrument configuration to make infrared measurements of a wide range of astronomical objects. It will fly at and above 41,000 ft, where the Earth's atmosphere is transparent for much of the wavelength range from 0.3 to 1600 micrometers.

Figure 1. The SOFIA observatory aircraft enroute to the modification facility in Waco, Texas.

SOFIA will operate over a 20-year period beginning in 2004. The observatory main location of operations will be from Moffett Field, California, in the San Francisco Bay area, where the SOFIA Science Mission Operations Center (SSMOC) and airborne observatory will be housed. Typical science flights will depart and return to Moffett Field. However, since a large

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fraction of the sky is not visible from the northern hemisphere, deployments will be made to the southern hemisphere to access the southern skies. It is currently planned that these deployments will operate out of New Zealand and will occur annually for approximately 8 weeks during the May through August period. SOFIA will also be deployed for occultation and eclipse events. As such events occur briefly and are visible from random places on Earth, these deployments will typically be short and to various sites around the globe.

2. SOFIA Facilities and Systems

2.1 The SOFIA Airborne Observatory. At the heart of the SOFIA program is the airborne observatory including the 2.5 m aperture telescope mounted in the aft fuselage of the heavily modified Boeing 747SP aircraft. In 1977, on the 50^{th} anniversary of the first non-stop New York to Paris flight, the SOFIA aircraft was christened the Clipper Lindbergh by Ann Morrow Lindbergh for Pan American World Airways. In 1986, United Airlines purchased the aircraft. In 1995 it was removed from active service and in 1997 it was purchased by NASA.

The aircraft has a zero-fuel weight of 170,500 Kg and will operate at altitude for approximately 8 to 10 hours, depending on flight profile and mission needs.
Modifications of the aircraft systems include:

- Removal of the aft pressure bulkhead and the installation of a newly designed one that supports the Telescope Assembly (TA),
- The installation of the telescope system of doors and aperture into the aft fuselage,
- The addition of a cooling system that uses approximately 3200 liters of liquid nitrogen to cool down the TA and the cavity, to approximately -40°C, before launch,
- The restructuring of the forward lower lobe to accept the TA hydraulic oil supply and oil supply thermal control systems, and an array of uninterruptable power supplies for the telescope and scientific instrumentation,
- The restructuring of the port-side forward cabin area (formerly first class, and not shown in the drawing below) to accept the array of electronics racks housing the Mission Controls and Communications Systems (MCCS) computers, networking equipment, intercom, power distribution and control system electronics,
- Reorganization of the cabin area for scientist work areas and control consoles, and consoles for Education and Public Outreach participants,
- Strengthening of the cabinway flooring to support the delivery and installation of scientific instruments weighing up to 600 Kg,
- The modification of the upper deck to accept science instrument vacuum pumps and a special air compressor/dryer system that will provide air for the TA pneumatic vibration isolation assembly,
- Also on the upper deck, installed in one of the port-side windows is a Water Vapor Monitor to precisely quantify the water vapor that is visible in the telescope boresight.

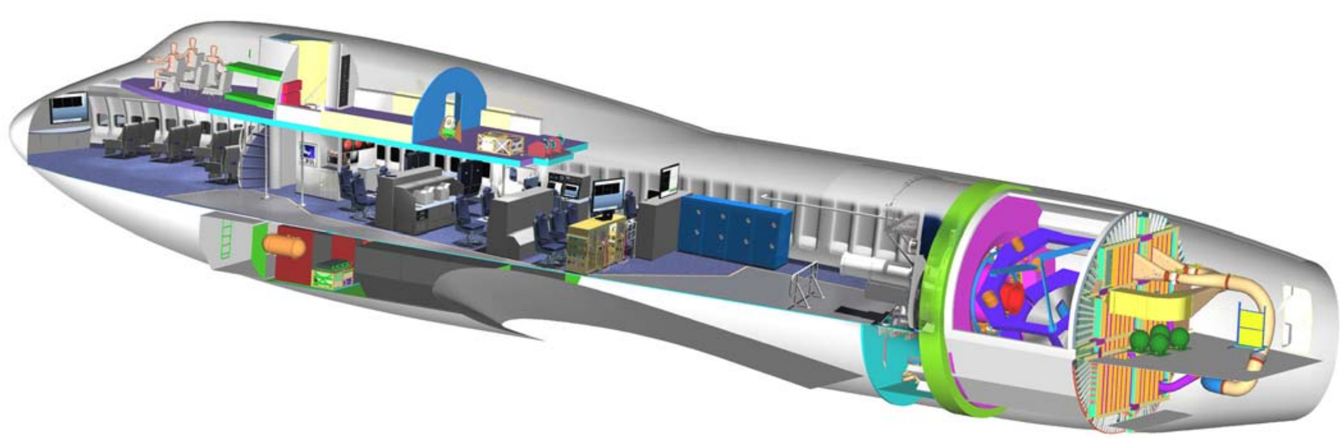

Figure 2. Computer rendering of the interior of the SOFIA airborne observatory.

2.2 The SOFIA Science and Mission Operations Center. The SOFIA airborne observatory (AO) and all of the facilities required to operate and maintain the AO will be housed in the SOFIA Science and Mission Operations Center (SSMOC). This center also includes science and education staff to coordinate and support the science and education communities enabling efficient and productive science output from SOFIA and its communication to the community at large. The SSMOC manages the suite of SOFIA science instruments and integrates them onto the AO. The direction for the continued development of these science instruments is from the science community via the peer review process.

3. Operations Team Organization

Under contract to NASA, Universities Space Research Association (USRA) will manage all aspects of operating, maintaining and upgrading the SOFIA system in order to meet science mission objectives for 20 years. As seen in Figure 3, the SOFIA observatory directorate oversees the observatory staff. A Safety Reliability Maintainability and Quality Assurance (SRM & QA) group has the responsibility to independently assure consistent implementation of sound processes and procedures for SRM & QA. The five functional organizations below the directorate include the support groups for science mission and aircraft operations support, a science group to coordinate interaction and support activities with a broad community of science users as well as engage in leading edge infrared astronomy research, an education and public outreach group that organize and support in-flight educational uses of the SOFIA observatory and finally an engineering group that provide continuous improvement development for the facility.

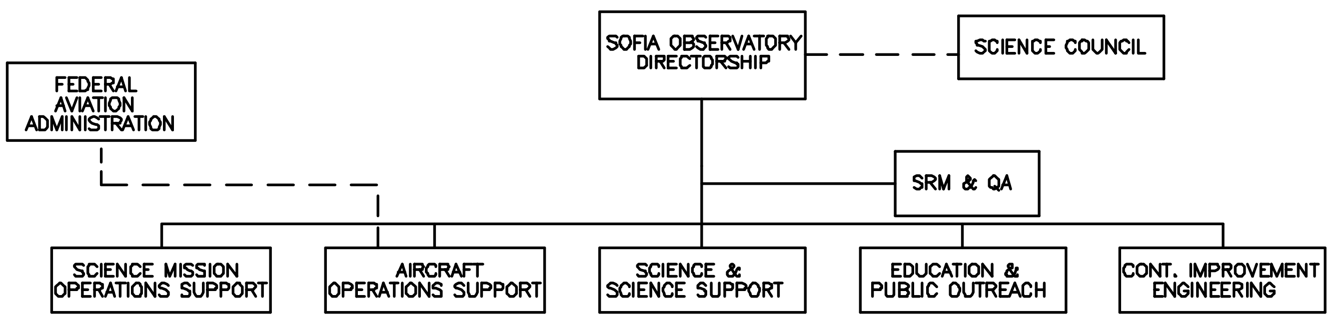

Figure 3. Organizational diagram for SOFIA observatory operations staff.

3.1 Aircraft Operations & Support Group. The Aircraft Operations & Support (AOS) Group is responsible for the operations and support, including all maintenance, of the Aircraft System and continued airworthiness and certification. A significant departure from previous NASA airborne platform operations, the SOFIA Airborne Observatory (AO) will operate with Federal Aviation Administration (FAA) airworthiness certification. UAL is one of the collaborating team partners and have the responsibility to fly and maintain the SOFIA aircraft and to oversee airworthiness aspects of the observatory as a whole. They will provide training and certified technical staff members to ensure that the observatory configuration and flight crew meet FAA requirements. FAA-approved United Airlines (UAL) procedures will be followed for all maintenance performed on the AO and the science instruments installed on the AO. The UAL Maintenance and Operations Center, based at the San Francisco International Airport, will interface with the AOS Group and the FAA to address any FAA concerns and will conduct quality assurance audits periodically to demonstrate compliance with procedures and regulations.

3.2 Mission Operations & Support Group. The Mission Operations & Support (MOS) Group is responsible for the operations and support, including all maintenance, of the mission system, which includes the Telescope Assembly and subsystems, mission controls and communications systems (MCCS) and software, the cavity environment control system and a number of the SSMOC facilities such as the mirror coating facility, and the mission integration labs and simulators. With assistance from the Science Support Group, the MOS group are responsible for planning and generating mission flight plans and preparing the science instrument and the mission crew for flight.

4. Flight Missions

4.1 Operating crew functions. On a typical SOFIA science mission, the mission crew and participant manifest might include an in-flight director, a telescope operator, members of the investigator team (including one principal investigator, one or more guest investigators, and supporting team members), one education and public outreach (EPO) flight facilitator and a number of EPO Guests. Non-typical science mission flights include the first nights of sequences with a new instrument configuration and flights with planned engineering for new instrumentation or other system upgrades. For these flights the onboard crew will be enlarged to include an in-flight computer specialist with responsibility for verifying the proper operation of computers and software, interfaces, networks and peripherals to ensure the acquisition of scientific and housekeeping data.

The In-Flight Director (IFD) has command and control of the mission area of observatory. He or she are trained as a member of the flight crew and has safety responsibilities for the participants flying in the mission area, similarly to a head flight attendant or head purser on a commercial airline flight crew. The IFD is the vital communication and coordination interface between the flight deck and the investigator team. As the needs and requirements of these two teams evolve during the science mission the IFD is tasked to coordinate the efforts required to execute an efficient mission flight plan.

The telescope operator (TO) controls and monitors the pointing and tracking of the telescope assembly and the AO doors and aperture, including relevant support systems, such as hydraulic and pneumatic supplies. The TO is responsible for acquiring object and star fields and determining TA attitude and boresights. The TO also coordinates shared control of TA with the investigator team

Investigator team members control and monitor the scientific instrument package, control and monitor telescope assembly pointing and tracking and acquire and analyze scientific data.

EPO Flight Facilitators will be aboard routinely as SOFIA represents a unique opportunity to bring educators and students to the world of scientific research discovery. The flight facilitators will conduct classroom course work, introducing EPO Guests to the flying classroom with access to virtually all of the cameras and information displays.

4.2 Flight mission preparations. During the weeks leading up to a series of science flights, the MOS and Science Support groups will ensure that the science instrumentation and investigator teams are prepared to gain efficient usage of the SOFIA AO. Lab space, test equipment and expertise will be available and scheduled to setup and demonstrate instrument standalone performance. As the date for mission flight approaches the science instrumentation will be integrated into the SOFIA Integration Laboratory (SIL) to demonstrate the needed network based command and communications compatibility. A few days before flight, the instrument will be brought to the Pre-Flight Integration Facility (PIF) where it will be mounted to a telescope mount simulator that enables the calculation of the instrument mass and center of gravity, needed for balancing the telescope. The simulator also has optical features that enable the calibration of the instrument boresight and focus position with the telescope optics.

On the morning of the first flight in an experiment series, the science instrument is rolled into the AO on a special cart and mounted to the Nasmyth focus of the telescope. The instrument electronics are installed, grounding systems are checked, the telescope balance is checked and the instrument system is electrically powered up. Subsystem checks, such as telescope blind pointing, gyro stabilization, and chopping secondary control, and instrument control and monitoring of internal optics and sensors, are performed. Full system checks are performed to verify control and communication between the telescope, the mission computer system computers and the instrument. These checks include the science instrument interactions needed for synchronized data acquisition with telescope nodding and secondary chopping.

When the mission systems, including peripheral audio and video switching systems, are declared operational, aircraft checks are performed. These checks and additional system checks to verify needed communication between mission systems and aircraft flight management systems are evaluated to determine whether to proceed with the mission or not. If the decision is to go ahead with the mission, the cavity environment control system (CECS) is activated. The CECS uses an external supply of liquid nitrogen to pre-cool the telescope and cavity to -40°C. This is necessary because the 2 hour time constant of the telescope would require on the order of 6 hours to become isothermal with the cavity air at flight levels. During the return leg of the flight the CECS supplies warm dry air to bring the cavity back to ambient temperatures without condensation.

The CECS uses approximately 3200 liters of liquid nitrogen over 5 hours during this procedure. An additional 1200 liters is transferred into onboard storage tanks. The onboard supply is used to keep the cavity cold during taxi, takeoff and climb to altitude. After reaching about 20,000 feet the onboard supplies are vented until exhausted. During taxi, takeoff and climb, the telescope hydraulic bearing is supported on oil and the telescope fine drive brakes are engaged.

4.3 Climb to altitude and science data observations. At about 10,000 feet, the Water Vapor Monitor (WVM) is turned on and checked and the telescope and instrument systems are fully checked again. Typically the cavity door will be opened at about 35,000 feet, and a climb heading will be chosen to point to a star that is appropriate for telescope boresight calibration, focus adjustments and closed loop tracking tests, including the low frequency tracking loop that provides heading correction signals to the aircraft flight management system, based on telescope position information.

As seen in figure 4, the ground track of a mission flight represents the heading that the aircraft must maintain to place and keep the object of interest in the science instrument. As well, the flight profile is a reflection of the altitudes chosen to keep the line of sight water vapor below the threshold required to make the observations. During the mission preparation period, flight planning efforts, using estimated winds and other meteorological information, are engaged in to design a sequence of flight legs that map out the attitude of the aircraft for the objects that will be studied. During the course of the flight, different and evolving conditions, combined with updated observing strategies by experimenters will require the mission flight crew to continually review the flight plan that has been filed with the FAA, for possible modifications that may yield more science.

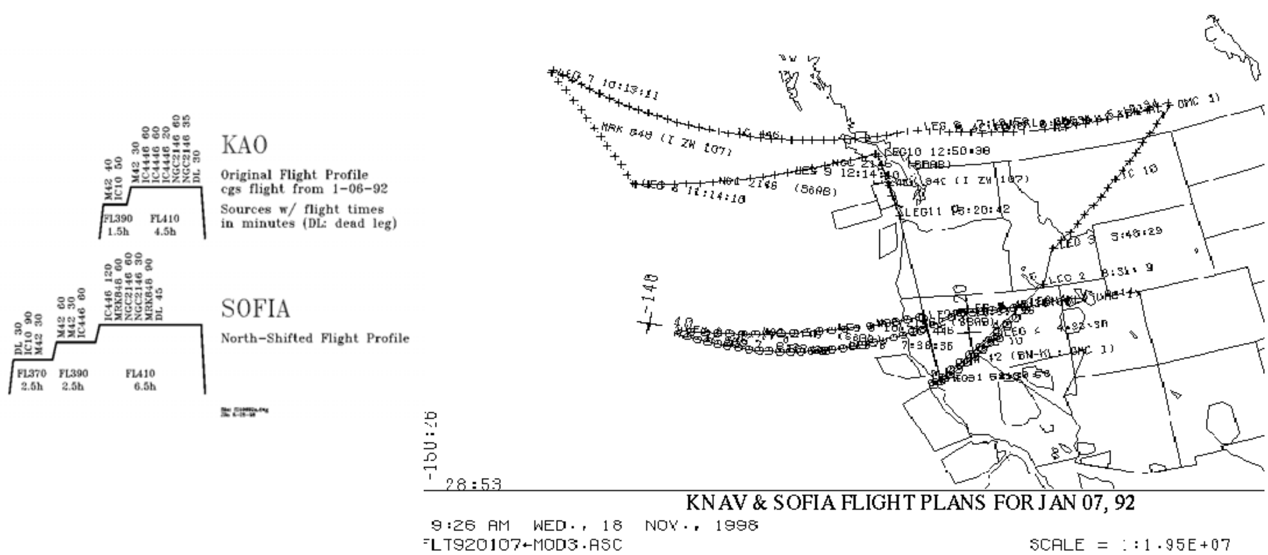

Figure 4. Elevation profile and ground track of mission flights (as compared with Kuiper Airborne Observatory flights).

The line of sight precipitable water vapor criterion for science data acquisition is less than 10 microns. Figure 4 shows the outcome of recent studies indicating that Northern flights from Moffett Field, or Southern from New Zealand, can allow the start of science observations at lower altitudes than is possible from lower latitudes. This yields longer observation durations for each flight with the ability to start at 37,000 ft, 39,000 ft, or 41,000 ft, depending upon water vapor overburden. Figure 5 shows some of the data from this study by Jochen Horn while at UCLA.

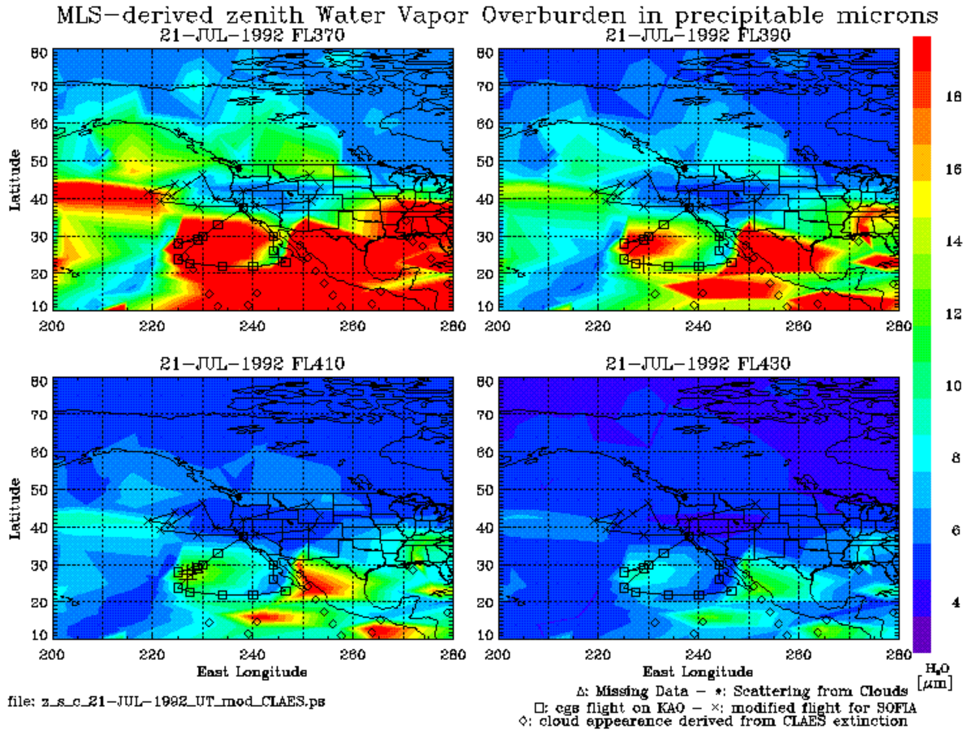

Figure 5. Net precipitable water vapor over the Northern hemisphere for 4 different elevations above the surface of the Earth: 37,000; 39,000; 41,000 and 43,000 feet.

5. Summary and Acknowledgements

The target of 960 successful flight hours per year is aggressive. The SOFIA developers are planning to engage in flight missions at a rate of 4 flights per week for approximately 40 weeks per year. These flights will be at altitudes required to acquire scientific data for over 8 hours each. It is believed that these goals can be reached and that they will be achieved with a well trained staff and the use of efficient systems for assessing science instrument readiness and for simulating and calibrating the telescope optics and balance conditions. Research into global phenomena, such as those that indicate the advantages of northerly routes, will yield important benefits. Care has been taken in mission operations development to invest in support equipment and planning tools to gain added efficiency at altitude.

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