Science Instrument Developers' Handbook

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Revision History

REV	DATE	DESCRIPTION	APPROVAL
-	6/29/2011	Initial Release	PMB
A	6/28/2015	Revision update for Announcement of Opportunity for SOFIA 3rd Generation Instruments (Phase 1). Change details are provided in Appendix F of this document.	
B	1/4/2016	Subsequent revision update to support development of SOFIA 3rd Generation Science Instruments. Change details are provided in Appendix H of this document.	
C	12/08/2017	Revision update to support NASA Research Opportunities in Space and Earth Sciences (ROSES) research announcement solicitation NNH17ZDA001N-SFNXGNI for SOFIA Next-Generation Instrumentation.	
D	9/28/2018	Revision update to support proposal finalists from NASA Research Opportunities in Space and Earth Sciences (ROSES) research announcement solicitation NNH17ZDA001N-SFNXGNI for SOFIA Next-Generation Instrumentation. This revision also incorporates the new SOFIA program agreements documented in the *SI Development Decision Memo* and the *SOFIA Science Instrument Development Process and Deliverable Requirements (SOF-NASA-SOW-PM91-2094) Rev -*.	

Contents

1 Introduction

1.1 Purpose and scope

The Science Instrument Developers' Handbook describes how to develop a science instrument (SI) for the NASA/DLR Stratospheric Observatory for Infrared Astronomy (SOFIA) Program. The handbook provides an overview of the SOFIA instrument program and references all necessary requirement and interface documents for instrument developers; but, the handbook does not supplant the requirements and interface documents. This document contains narrative descriptions of some processes and is intended to assist instrument teams with understanding the requirements and to provide guidance on the design and development of SOFIA instruments. The handbook applies to US and German instruments, except where indicated – "only for US instruments" or "only for German instruments".

This handbook is intended to be a guide and roadmap for instrument developers interested in the following aspects of SOFIA instruments:

- Developing or completing the development of instruments
- Proposing future instruments under an Announcement of Opportunity or other call
- Proposing enhancements to existing SOFIA and/or other instruments to be adapted to operate on SOFIA
- Procedural elements and reviews to be performed for new and/or upgraded instruments
- Overview information concerning SOFIA interfaces and recommendations for optimization based on instrument type

Typically, work for new instruments (as well as for modifications to existing instruments), will be performed via external contracts. The *SOFIA Science Instrument Development Process and Deliverable Requirements* (SOF-NASA-SOW-PM91-2094) and the *SOFIA Science Instrument System Specification* (SOF-AR-SPE-SE01-2028) would become the basis for any contractual Statement of Work (SOW).

1.2 Terminology

It is important to note that this handbook does not define any requirements but does provide guidance and context for applicable SI requirements defined in other SOFIA documents.

Appendix B – Acronyms contains a list of the acronyms and abbreviations used in this handbook. The *SOFIA Lexicon* (SOF-DF-PD-PD-2009) contains a more extensive list of the acronyms, abbreviations, and definitions of terms used by the SOFIA Program.

The science instruments are frequently abbreviated as "SI." The term "PI" is often used to describe items related to the Science Instrument Principal Investigator (i.e., PI rack, PI patch panel). There are other Principal Investigators associated with the SOFIA Observatory. Any reference to the PI in this document refers to the Science Instrument Principal Investigator unless otherwise noted.

When describing relative locations on the aircraft, we will use the terms: fore, aft, port, and starboard. Port is on your left when facing the front of the plane and on your right when facing aft toward the telescope. Many of the seats on the Observatory face aft, thus using "right" and "left" may generate confusion. Just remember that the telescope looks out "the port" side of the airplane.

Instrument Team or SI developer– refers to the Science Instrument team working for the instrument Principal Investigator to build an individual instrument.

SOFIA Science Instrument Development Team – refers to the Observatory staff that works at the SOFIA Science Center (NASA Ames Research Center) and at the SOFIA Operations Center (NASA Armstrong Flight Research Center Building 703) and reports to the SOFIA Science Instrument Development Manager. The SOFIA SI Development Team consists of personnel from NASA, USRA, and other contractors.

Instrumentation – refers to sensors on the aircraft to measure parameters such as temperature, pressure, acceleration, etc. To clearly distinguish between aircraft and test instrumentation and the science instruments mounted on the telescope, the latter is referred to as the Science Instrument (SI).

Safety Critical— is defined as, a failure to meet the flight hardware or software requirements for that characteristic could cause or lead to severe injury, major damage, or mission failure if performed or built improperly, or allowed to remain uncorrected. The loss of the SI by itself does not constitute a mission failure.

1.3 *SOFIA document library*

NASA maintains the SOFIA Program document library using servers running Windchill software. This library is located at https://sofiacm.arc.nasa.gov and is accessible from the NASA network or using a VPN connection to the NASA network. Each instrument team should have team members with Windchill accounts so the team has access to the full SOFIA document library and the latest document versions.

Instrument teams should contact the SOFIA SI Development Manager for information on obtaining an account on Windchill. Tutorials and training materials for using Windchill are available in the /.Help library on Windchill.

2 SOFIA Program Overview

SOFIA consists of a German-built 2.7-meter (2.5-meter useable) telescope mounted in a Boeing 747-SP aircraft supplied and modified by NASA. Operations costs and observing time are shared by the United States (80%) and Germany (20%). Flying at altitudes up to 45,000-feet, SOFIA observes from above more than 99 percent of Earth's atmospheric water vapor, thereby opening windows to the universe not available from the ground. SOFIA offers international science teams approximately 1000 cloud-free high-altitude science observing hours per year during its two decade design lifetime. Science proposals will be selected through a competitive peer review process. Although the primary impact of SOFIA will be its science return, it will yield other returns as well. Compelling discoveries will follow the development of new technologies that can be demonstrated readily on SOFIA. Young scientists-in-training, educators, and journalists will also fly on SOFIA, making it a valuable training platform and public ambassador.

SOFIA observes at wavelengths from 0.3 μm to 1.6 mm. SOFIA's diffraction-limited imaging longward of 25 μm can produce the sharpest images of any current or planned IR telescope operating in the 30 to 60 μm region.

The SOFIA Observatory concept embodies a number of key advantages that make it a unique tool for astronomy in the coming decades:

- SOFIA is a near-space observatory that comes home after every flight. Its scientific instruments can be exchanged regularly, accessed for repairs or cryogenic servicing, to accommodate changing science requirements, and to incorporate new technologies.

- SOFIA has unique capabilities for studying transient events. The observatory can operate on short notice from airbases worldwide, in both the northern and southern hemispheres, to respond to new and transient scientific opportunities.

- SOFIA's diverse range of instrumentation facilitates a coordinated program of analysis of specific targets and science questions. SOFIA's 20-year design lifetime enables long-term studies and follow-up of work initiated by SOFIA itself and by other observatories, such as the Hubble Space Telescope, Chandra X-ray Observatory, Spitzer Space Telescope, Herschel Space Observatory, Submillimeter Array, and Akari (Astro-F), as well as future facilities.

- SOFIA presents an ideal venue in which to educate students, where they can participate in hands-on, cutting-edge space technology developments.

- Because of its accessibility, SOFIA includes a vigorous, highly visible Education and Public Outreach (E/PO) program designed to exploit the unique and inspirational attributes of airborne astronomy (see https://www.sofia.usra.edu/multimedia/sofia-outreach).

SOFIA, with its large suite of science instruments and broad wavelength coverage, is capable of undertaking a huge breadth of different investigations.

The *Science Vision for the Stratospheric Observatory for Infrared Astronomy* (USRA-DAL-SSMOC-SCIN-REP-1018) summarizes the unique capabilities that SOFIA will offer to the astronomical community, and describes a number of exciting science programs that are representative of SOFIA's potential contributions. It and additional general information on SOFIA may be found at https://www.sofia.usra.edu.

A description of the SOFIA Program organization structure can be found in the *Program Plan for SOFIA* (SOF-DF-PLA-PM01-1000).

The *SOFIA Concept of Operations* (SOF-DA-PLA-PM17-2000) is a useful resource for understanding the SOFIA Observatory System, the Operational Phases section may be of particular interest as it provides an overview of observatory certification and commissioning, flight series preparation, science mission operations, and post-flight operations, all of which a science instrument and instrument team are an integral part of.

3 Instrument Overview

The SOFIA Observatory supports a complement of instruments, which are categorized into classes depending on how the instrument is to be used. The three classes are: Facility-class SI (FSI), Principal Investigator-class SI, and Technology Demonstration-class SI. This handbook reflects changes to these earlier classification of science instruments stemming from the 2017 Research Opportunities in Space and Earth Sciences (ROSES) NASA Research Announcement (NRA) solicitation for SOFIA Next Generation Instrumentation. The new Next-Generation Science Instruments (NGSI) to be used in the SOFIA extended mission has eliminated these classifications in favor of a single and simpler development approach.

The solicitation provides a comprehensive summary of the proposal, development, commissioning, and acceptance process for SOFIA instruments; refer to the solicitation for timeline and details.

Certain aspects of the new development process are highlighted here in the handbook to reinforce some of the key aspects of NGSI development, in particular ownership of the instrument will transition to the SOFIA Program through an acceptance process following completion of instrument commissioning and the instrument's Legacy Science Program (LSP), a period of usage of the instrument by the general science community, and completion of documentation deliverables. The time period from when an instrument proposal is selected for development to delivery of the instrument for commissioning is approximately 3 years; the transition of the instrument to the SOFIA Program, including the completion of the LSP and earlier mentioned items, will occur approximately 2 years thereafter.

3.1 *Facility Science Instruments*

This categorization applies to instruments that have completed the Acceptance Review and have transitioned to the SOFIA Program to maintain and operate.

3.2 *PI Science Instruments*

Principal investigator science instruments (PSI), or PI-class SIs, refers to the science instrument when it is still under the control of the PI. When in this category the instrument developer is responsible for the development, operation, and maintenance of the instrument, including operation of the instrument for general observer (GO) science observations.

NGSI development and management will closely follow the development approach for PI-class instruments up until the instrument transitions to NASA and is accepted as an FSI.

3.3 *Technology Demonstration Science Instruments*

Technology demonstration science instruments (TDSI) are developed for the purpose of maturing and demonstrating, through a focused science investigation involving a limited number of SOFIA flights, new capabilities and methodologies of value to SOFIA and future NASA missions.

4 *Instrument description*

4.1 *Science Instrument System*

A SOFIA Science Instrument System installed onboard SOFIA generally consists of the following hardware components:

- Instrument Assembly – the portion of the instrument that mounts to the telescope assembly instrument mounting flange. The instrument assembly includes the instrument optical bench, cryostat(s), detectors, and electronics. Once installed, the instrument assembly will move with the telescope and thus will need to operate through the operating range of the telescope assembly. Access to the instrument assembly during flight is controlled and limited; Section 6.3 provides additional details about the access of instruments in-flight.

- Counterweight Rack (CWR) – the counterweight rack is a 19" equipment rack mounted to the telescope assembly counterweight plate. The mounting location of the Counterweight Rack on the telescope assembly is in close proximity to the instrument assembly. Like the instrument assembly, the Counterweight Rack operates through the operating range of the telescope assembly whenever the rack is installed. Access to equipment in the counterweight rack during flight is extremely limited due to the elevated height and position of the counterweight rack above main deck floor at most telescope elevation angles. This rack frame structure is provided by NASA to the instrument developer.

- PI Rack(s) – the science instrument principal investigator racks are 19" equipment racks mounted over the center wing section of the main deck floor. Equipment which needs to be accessed routinely or frequently by the instrument team during flight should be located in these racks. Instrument teams can utilize up to three PI racks to support their instruments. These dual-bay, 19-inch rack frame structures are provided by NASA to the instrument developer.

- Pressure Coupler or Optical Window Assembly (optional) – an instrument component mounted to the gate valve pressure plate (GVPP) interface inside the telescope assembly instrument flange tub (INF). This hardware typically forms part of the pressure seal between the TA cavity and cabin of the aircraft.

- Chopper interface electronics (optional) – the instrument electronics used to drive the telescope assembly secondary mirror assembly (SMA).

Non-flight ground support equipment provided by the instrument developer for supporting operations of the Science Instrument System at Armstrong Building 703 are:

- Instrument Installation Cart – the cart used to transport the SI through the ground facility, onto the aircraft, and install the instrument to the Telescope Assembly instrument flange.

- Lab cart/stand or ancillary equipment (optional) – any ground support equipment required for routine maintenance of the instrument.

Figure 4.1-1 shows an instrument assembly (FORCAST) and its Counterweight Rack mounted to the telescope assembly; the photograph view is looking "aft" in the aircraft towards the aircraft cavity forward pressure bulkhead.

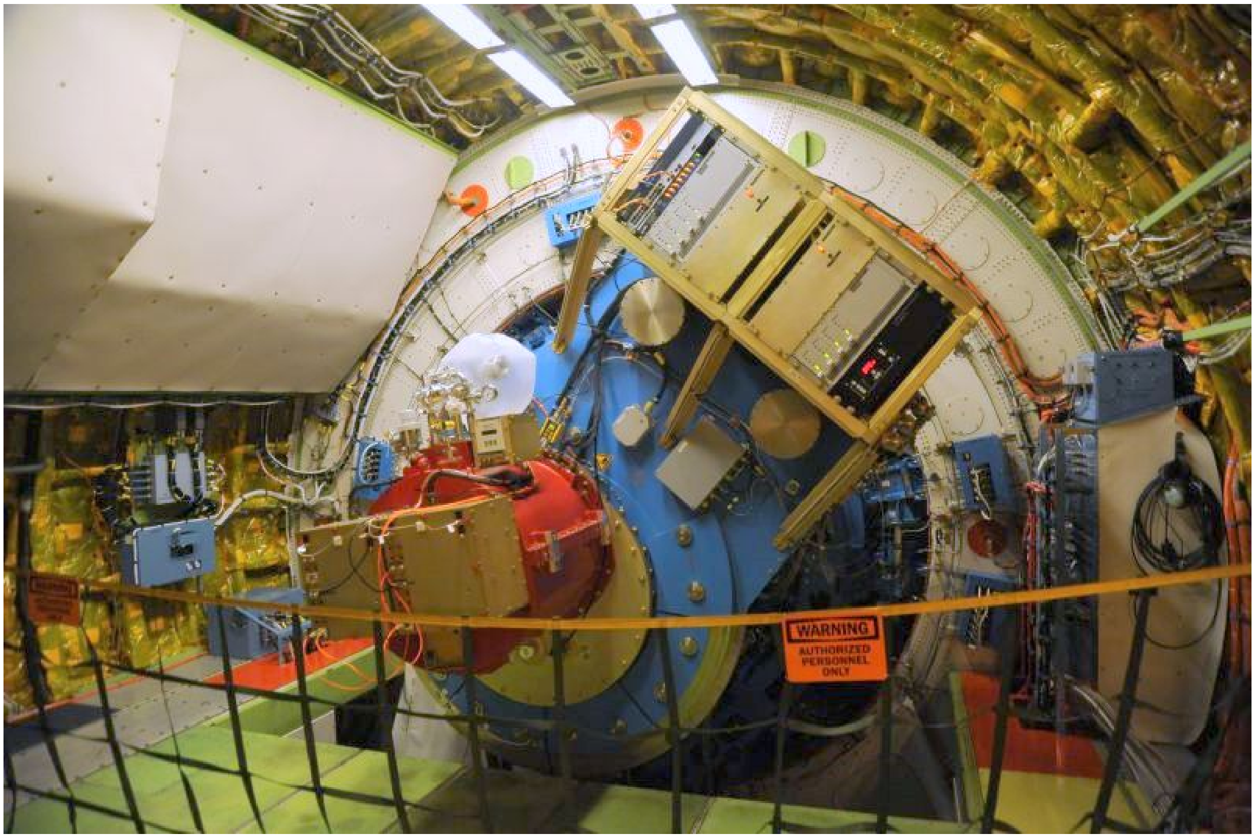

Figure 4.1-1: The FORCAST instrument assembly and counterweight rack mounted on the telescope assembly

Figure 4.1-2 shows two PI Racks installed near the PI Patch Panel; this photograph view is looking "forward" in the aircraft.

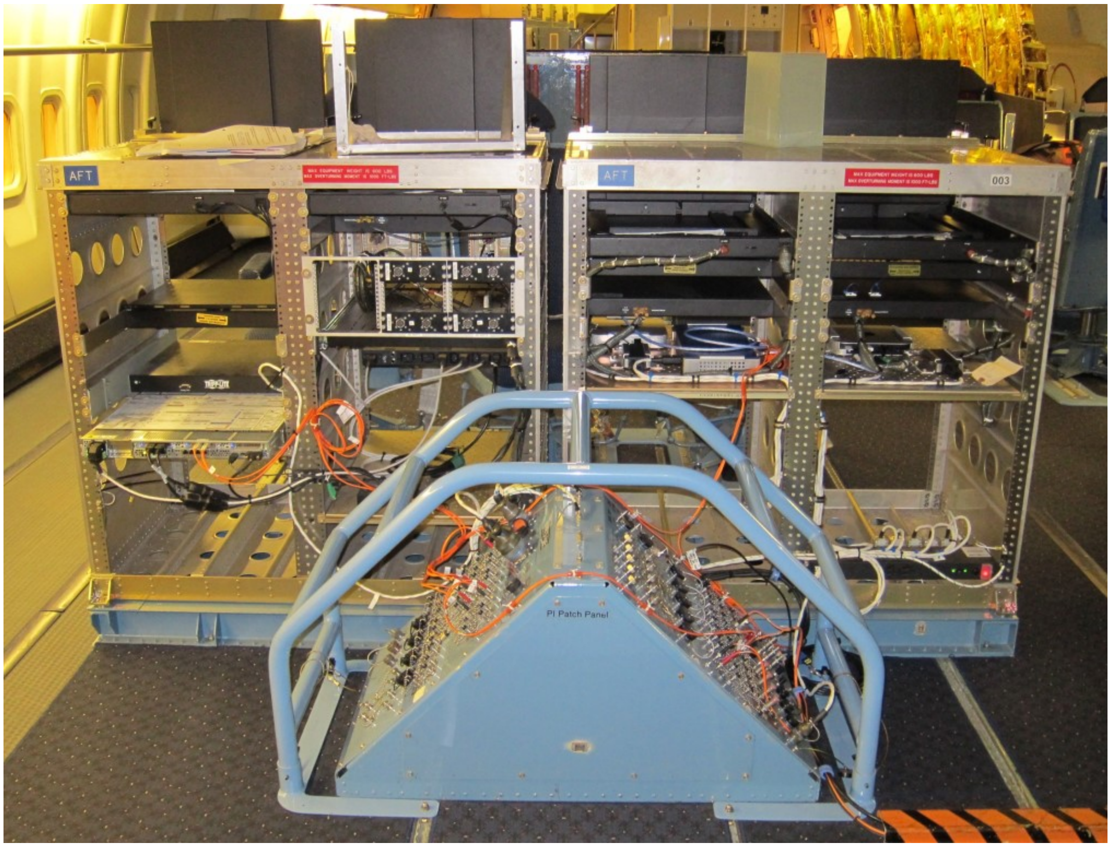

Figure 4.1-2: Two instrument PI racks mounted in the Observatory next to the PI patch panel

4.2 *Other equipment*

The proposed investigation may require additional equipment that is not part of the current observatory (i.e., alternate secondary mirror button, tertiary mirror with alternate coating, instrument rotator, secondary spider baffles, etc.). The SOFIA Program will determine whether such additional equipment can be incorporated as part of the Observatory and developed by the SOFIA Program with input from all the Instrument teams, or whether this equipment should be developed and provided by the Instrument team under the instrument contract.

4.3 *Government Furnished Equipment*

The SOFIA Program will support integration of selected science investigations with the Observatory with equipment, services, and facilities. Government furnished items include:

- PI rack(s),
- PI rack installation dolly,
- Auxiliary rack,
- Counterweight rack,
- Counterweight rack installation cart,
- Laboratory space at Armstrong Building 703 for integration activities,
- Technicians and supplies to support integration,
- On-aircraft vacuum system,
- On-aircraft cryocooler system,

- Cryogens for use in the laboratories at Building 703 and on the Observatory,
- Secondary mirror buttons, and
- Shipping assembly for instruments participating in SOFIA deployments

5 Requirements and interfaces

The *SOFIA Science Instrument System Specification* (SOF-AR-SPE-SE01-2028) and *SOFIA Science Instrument Development Process and Deliverable Requirements* (SOF-NASA-SOW-PM91-2094) contain the requirements for airworthiness, safety, mission assurance, and quality assurance for Science Instruments. The parent specification of the *SI System Specification* is the *SOFIA System Specification* (SOF-DF-SPE-SE01-003), which contains the top-level requirements for the SOFIA Observatory. The *SI System Specification* is the instrument product specification and contains the verifiable design requirements for the science instrument system hardware and software. Within this specification are requirements to comply with 15 interface control documents (ICDs).

5.1 Science Instrument System Specification

The *SOFIA Science Instrument System Specification* (SOF-AR-SPE-SE01-2028) is a Level 2 specification in the *SOFIA Specification/Product Tree* (SOF-DF-SPE-SE01-068). The SI System Specification contains the verifiable system requirements that all SIs must meet. This includes airworthiness, mission assurance, and safety requirements.

Because the instrument science and technical performance requirements (science and performance requirements) are specific to the instrument type and scientific investigation proposed, such requirements are outside the scope of the *SE01-2028 SI System Specification.* The minimum performance requirements presented in the instrument proposal will form the basis of the top-level science and performance requirements for the instrument. The final top-level science and performance requirements will be negotiated with the SOFIA Program prior to the Step 2 Proposals Review (PR). After completion of a series of flights dedicated for collecting commissioning data, the instrument team will present at its Legacy Science Program (LSP) Review how its top-level science and performance requirements were met. Details of the LSP Review are described in the *SOFIA Science Instrument Development Process and Deliverable Requirements* document (SOF-NASA-SOW-PM91-2094).

To ensure the safety of the personnel onboard SOFIA and the Observatory itself, all equipment onboard the aircraft needs to be declared airworthy before it can be flown. The airworthiness approval process for science instruments is described in Section 8 of this document.

5.2 Science Instrument Process and Deliverable Requirements

The *SOFIA Science Instrument Development Process and Deliverable Requirements* (SOF-NASA-SOW-PM91-2094) lists the processes the SI developer is required to follow, to support NASA and SOFIA processes and life cycle reviews needed for the SOFIA team to evaluate the SI and associated deliverables. The SOFIA Program will provide some document templates and content synopses to the SI developer to assist the SI developer in developing the deliverable documentation products.

5.3 Science Instrument Performance Specification

The instrument proposals include a list of performance requirements that the science instrument needs to achieve in order to execute the scientific objectives of the proposed investigation. These minimum performance requirements will form the basis of the top-level science and performance requirements. The final instrument top-level science and performance requirements will be negotiated with the SOFIA Program prior to the Step 2 Proposals Review.

5.4 *Interfaces*

5.4.1 Introduction

The SOFIA science instrument interfaces are defined by fifteen interface control documents (ICDs). Figure 5.4.1-1 is a block diagram of the Observatory subsystems which shows the interfaces to the science instruments and the ICDs which governs that interface. Table 5.4.1-1 lists each ICD and its corresponding SOFIA document number.

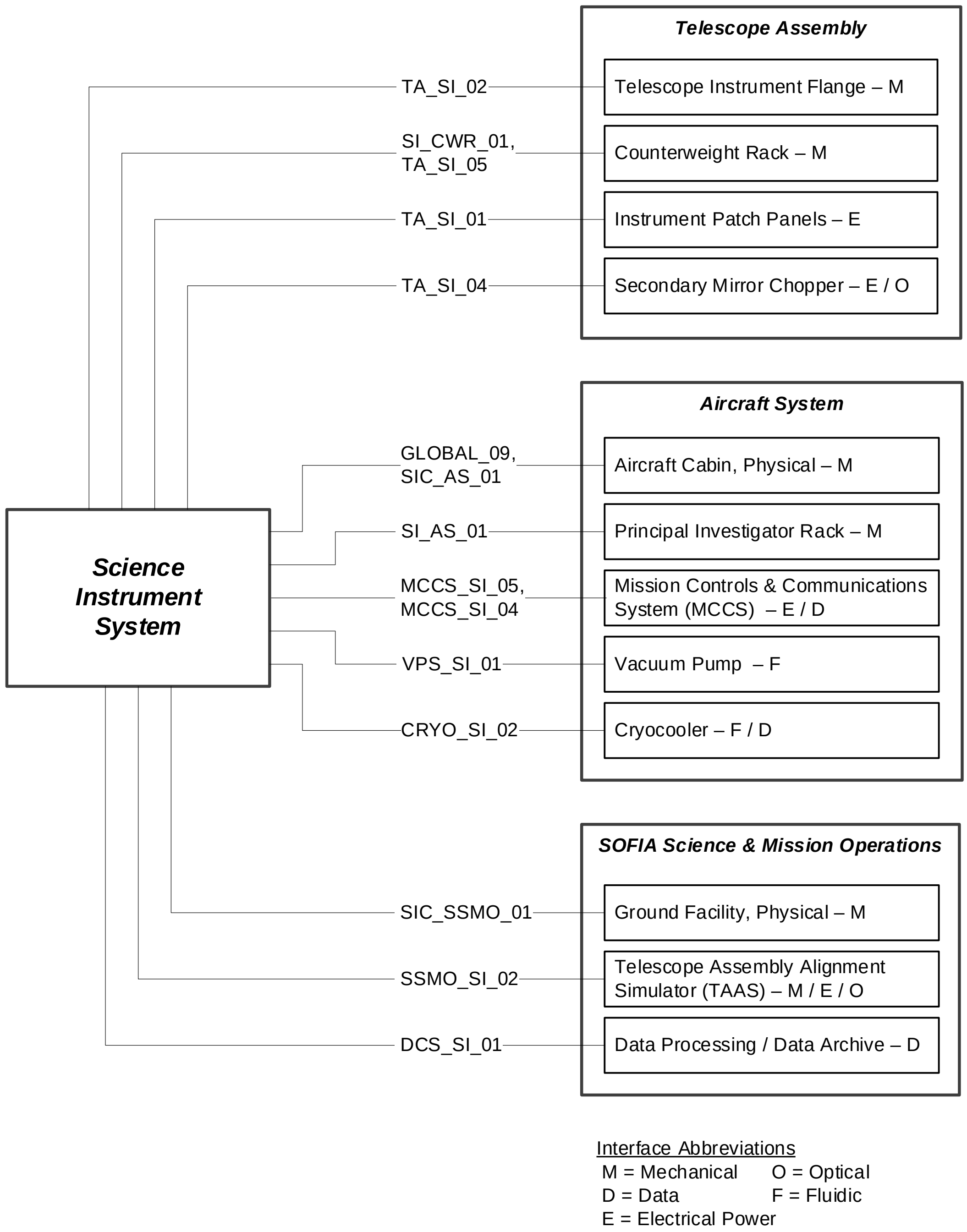

Figure 5.4.1-1: Science Instrument interface block diagram

Table 5.4.1-1: Table describing science instrument interface control documents

ICD Designator	Document Number	ICD Title	Scope
GLOBAL_09	SOF-DA-ICD-SE03-002	Science Instrument Envelope	The instrument dynamic, static, and installation spatial envelopes
TA_SI_01	SOF-DA-ICD-SE03-036	Cable Load Alleviator Device/Science Instrument Cable Interface	TA patch panel electrical interfaces to the counterweight rack and instrument assembly
TA_SI_02	SOF-DA-ICD-SE03-037	Telescope Assembly/Science Instrument Mounting Interface	Mechanical interface between the instrument assembly and the telescope flange
TA_SI_04	SOF-DA-ICD-SE03-038	TA Chopper Processor/Principal Investigator Computer Direct Analog Interface	Analog and TTL trigger interface between the instrument and chopper
TA_SI_05	SOF-DA-ICD-SE03-051	SI Equipment Rack/TA Counterweight Interface	Mechanical interface between the counterweight rack and the TA
SI_CWR_01	SCI-AR-ICD-SE03-2027	SI Equipment to Counterweight Rack	Requirements for installed equipment in the counterweight rack
SI_AS_01	SOF-DF-ICD-SE03-2015	Principal Investigator Equipment to PI Rack to Aircraft System	Requirements for installed equipment in the PI hardware racks
MCCS_SI_05	SOF-AR-ICD-SE03-2029	PI Patch Panel to PI Equipment Rack(s)	PI patch panel electrical connections to PI racks
MCCS_SI_04	SOF-DA-ICD-SE03-052	MCCS to SI Software Interface (Functional)	Commands and syntax for instrument software command to the observatory control software
DCS_SI_01	SCI-US-ICD-SE03-2023	Data Cycle System to Science Instrument	Defines data file interface for instrument data archived by the Data Cycle System
VPS_SI_01	SOF-DA-ICD-SE03-2022	SI to Aircraft Vacuum Pump	Interface to on-aircraft vacuum pump system (LHe pumping and other uses)
SIC_AS_01	SOF-AR-ICD-SE03-205	SI Handling Cart to Aircraft System	Requirements on the instrument installation cart to ensure safe transportation onto and through the aircraft
SIC_SSMO_01	SCI-AR-ICD-SE03-2017	SI Handling Cart to SSMO Facility Interface	Ground facility constraints on instrument lab carts and stands
SSMO_SI_02	SCI-AR-ICD-SE03-2020	Telescope Assembly Alignment Simulator (TAAS)/Science Instrument (SI) ICD	Interfaces between instrument and the telescope assembly alignment simulator
CRYO_SI_02	SOF-NASA-ICD-SE03-2066	Phase 2 Cryocooler System to Science Instrument (SI) ICD	Defines the electrical power, electronic signaling, and fluidic interfaces

5.4.2 Optical

The SOFIA telescope is a two-mirror bent Cassegrain design with a single Nasmyth instrument mount fed by a flat tertiary. The telescope effective aperture is 2.5 meters and provides an f/19.5 beam to the instruments (at nominal focus). The primary and secondary mirrors have aluminum coatings. The dichroic tertiary mirror has a gold coating, while the fully-reflective tertiary mirror will have either an aluminum or a protected silver coating.

The secondary mirror provides a peak-to-peak chop amplitude of 10 arcminutes between 0 and 20 Hz. The visible beam is fed into the Focal Plane Imager (FPI), which is an optical focal plane guiding system. Independent of the FPI there are two other optical imaging and guiding cameras available: a Wide Field Imager (WFI) and Fine Field Imager (FFI). Both of these cameras are attached to the front ring of the telescope.

Focusing is accomplished with an actuated secondary providing an adjustment range of ±60 cm referenced to the nominal Nasmyth focal plane location. The telescope unvignetted elevation angles range from 23 to 58 degrees, thus the instrument should be capable of supporting a rotation of ±20 degrees about the optical axis. The unvignetted field-of-view is a circle with a diameter of 8 arcminutes.

The secondary mirror chopper may be triggered from an external TTL waveform from the science instrument or from an internal signal from MCCS. This interface is described *in TA Chopper Processor/Principal Investigator Computer Direct Analog Interface TA_SI_04* (SOF-DA-ICD-SE03-038). Chopping may be performed a number of ways, depending on the preferred method of an instrument developer. The chop sync signal can be generated internally by MCCS and the TA or provided externally by the instrument developer via supply of an external TTL waveform to the chopper junction box. Establishing the chop profile can be defined and controlled using MCCS or by external analog input signals to the chopper junction box provided by the instrument developer. SOFIA instruments that chop have typically chosen to define their chop profile within MCCS and have furnished an external TTL chop sync signal at the chopper junction box interface.

5.4.3 Mechanical

The Instrument Assembly mounts to the 41-inch diameter instrument mounting flange on the telescope assembly. This mechanical mounting interface is defined in the *Telescope Assembly/Science Instrument Mounting Interface* (SOF-DA-ICD-SE03-037). The allowable instrument dynamic, static, and installation spatial envelopes are *Science Instrument Envelope GLOBAL_09* (SOF-DA-ICD-SE03-002).

Science Instrument components mounted inside the PI and Counterweight 19-inch racks are required to meet airworthiness and crash load requirements to ensure the safety of personnel onboard SOFIA. The document *Principal Investigator Equipment to PI rack to Aircraft System ICD SI_AS_01* (SOF-DA-ICD-SE03-2015) defines the requirements on installed SI hardware, limitations on rack loading, use of support trays, and NASA review process for any proposed structural modification or configuration change to the rack structure if deemed necessary by the instrument developer. The empty PI and Counterweight Rack structures furnished by the SOFIA Program are themselves certified to be airworthy before first delivery of the racks to instrument developers. Airworthiness of the rack structures themselves is maintained as long as the load limits are not exceeded and no structural or configuration changes are made to the rack structures.

The *Interface Control Document Science Instrument Equipment to Counterweight Rack SI_CWR_01* (SCI-AR-ICD-SE03-2027) provides the requirements for installed SI hardware and limitations on rack loading. Requirements on the total mass and mass properties of the loaded counterweight rack are in

Interface Control Document SI Equipment Rack / TA Counterweight Interface TA_SI_05 (SOF-DA-ICD-SE03-051).

Instruments that choose to connect to the onboard vacuum pump system will connect to the interface described in the *Vacuum Pump System to Science Instrument ICD VPS_SI_01* (SOF-DA-ICD-SE03-2022).

5.4.4 Pressure

To provide the greatest flexibility in wavelength coverage for the observatory, no window is installed in the optical path of the Nasmyth beam. A mechanical gate valve is installed between the instrument flange in the main cabin and the Nasmyth tube in the cavity for safety. This valve is opened when the observatory is operating. Once the gate valve is opened, the Instrument assembly becomes part of the pressure barrier of the main cabin; the Instrument assembly defines the interface between the shirt-sleeve laboratory environment in the main cabin and the stratospheric environment in the cavity. The pressure seal interface is defined in the *Telescope Assembly/Science Instrument mounting Interface* (SOF-DA-ICD-SE03-037). The ICD also defines the mounting interface for a pressure coupler or optical window assembly, if a science instrument chooses provide and install one to the gate valve pressure plate (GVPP) mounting interface.

It is at the discretion of the instrument developer whether or not to install a window in the path of their optical beam. If a highly hygroscopic material is selected, procedures for protecting those windows should be developed by the Instrument team and an appropriate window spare complement should be provided with the instrument.

5.4.5 Electrical

Electrical connections to the Mission Controls and Communications System (MCCS) include power, local area network, GPS, and IRIG-B timing. These interfaces are located on the PI Patch Panel near the PI Racks and are described in the *Interface Control Document Principal Investigator Patch Panel to Principal Investigator Equipment Rack(s) MCCS_SI_05* (SOF-AR-ICD-SE03-2029).

The PI racks and the telescope assembly are separated by about 25 feet. The aircraft has permanent cable installations under the cabin deck, including a set of cables which are routed through the cable load alleviator (i.e., telescope cable wrap), providing electrical and fiber optic connections between the PI Patch Panel and the TA Patch Panels. The PI Patch Panel electrical interface is described in *Interface Control Document Principal Investigator Patch Panel to Principal Investigator Equipment Rack(s) MCCS_SI_05* (SOF-AR-ICD-SE03-2029). The TA Patch Panel electrical interfaces located near the Counterweight Rack are described in *Cable Load Alleviator Device/Science Instrument Cable Interface TA_SI_01*, (SOF-DA-ICD-SE03-036).

All electrical interface connections between the instrument and Observatory patch panels will be achieved through SI-supplied jumper cables. The instrument is also responsible for supplying all “intra-SI” jumper cables—that is, direct connections within the instrument system (e.g., jumper cables connecting Counterweight Rack electronics to the instrument assembly). Appendix C of this handbook provides distance information between the various physical interfaces and locations, such as the distance between the PI Racks and the PI Patch Panel, as well as distance information between the instrument mounting flange, Counterweight Rack, TA Patch Panels, and chopper junction box on the telescope assembly. Limited 3D CAD solid models of the forward side of the Telescope Assembly, which include the physical SI interfaces on the TA, are available from the SOFIA Program.

5.4.6 Power

Electrical power to the Science Instrument is supplied by the MCCS at panel U401 of the PI Patch Panel located near the PI racks. Power to the Counterweight Rack and Instrument Assembly on the telescope will be routed and supplied by the instrument team via jumper cables and connections to the U400 of the PI Patch Panel and the U402 TA Patch Panel interfaces described in Interface Control Document Principal Investigator Patch Panel to Principal Investigator Equipment Rack(s) MCCS_SI_05 (SOF-AR-ICD-SE03-2029) and Interface Control Document Cable Load Alleviator Device / Science Instrument Cable Interface TA_SI_01 (SOF-DA-ICD-SE03-036).

A total of 6.5 KVA is currently available for use by science instruments from MCCS, with the sub-allocations identified in Table 5.4.6-1.

Table 5.4.6-1: SI power allocation from SOFIA PI Patch Panel (U401)

Type of Power	Maximum SI Power
230 VAC, 50 Hz, Uninterruptible Power Supply	1 KVA
115 VAC, 60 Hz, Frequency Converter	3.5 KVA
115 VAC, 60 Hz, Uninterruptible Power Supply	2 KVA
28 VDC	85 W

5.4.7 Fluidic

The observatory recently added the capability to support instruments utilizing closed-cycle cryocooler (CCC) systems. The primary Cryocooler System interface to SIs is the U404 Quick Disconnect (QD) patch panel with two (2) pairs of Supply and Return pressurized He (gas) QDs. The *SOFIA Phase 2 Cryocooler System to Science Instrument (SI) ICD CRYO_SI_02* (SOF-NASA-ICD-SE03-2066) describes the electronic signaling, and fluidic interfaces between the Phase 2 Cryocooler System and the science instrument. Section 6.2.9 of this handbook provides additional information about the functional capability of the Phase 2 Cryocooler System.

5.4.8 Software

5.4.8.1 Mission Command and Control System

The observatory is controlled by the Mission Command and Control System (MCCS), which coordinates interactions between the aircraft, telescope, and science instrument. The Science Instrument issues commands to the observatory via the SOFIA Command Language (SCL). These SCL commands are then executed by the MCCS. The MCCS also provides, via subscription, the housekeeping data that the science instruments will use to reduce their data and populate their FITS headers. The software interface between the SI and the MCCS is described in *Interface Control Document MCCS to Science Instrument Software Interface (Functional) MCCS_SI_04* (SOF-DA-ICD-SE03-052). The *SOFIA Command Language (SCL) User's Manual* (SOF-DA-MAN-OP02-2181) is a supplemental resource useful for understanding commonly used SCL command constructs, housekeeping commands, reference frames and coordinate systems, and SI observing modes.

5.4.8.2 Data Cycle System

The SOFIA Data Cycle System (DCS) provides long-term archival and retrieval functions for raw and reduced science instrument data. The DCS stores the raw and reduced data in FITS files and utilizes the metadata keywords in FITS files to store the necessary parameters required to utilize the data for scientific investigations. The *Interface Control Document for the Data Cycle System, DCS_SI_01* (SCI-US-ICD-SE03-2023), describes the DCS and the interface for science instrument data products.

5.4.8.3 Data Reduction Pipelines

The SOFIA Data Processing System (DPS) provides data reduction capability for science instruments via instrument data reduction pipelines integrated with the DPS for all earlier facility science instruments and select Principal Investigator instruments, as well as for Next Generation SOFIA Instrumentation. Level 1 (raw, uncalibrated FITS) instrument data is processed by the DPS to produce higher level data products such as Level 2 (corrected for instrument artifacts), Level 3 (flux-calibrated), and Level 4 (higher order e.g., mosaics, spectral cubes) products. Data to be processed is handled by both the SOFIA DCS and DPS systems; the general process flow is Level 1 science data from an observing flight is ingested into the DCS Archive, followed by DPS performing data processing operations on the Level 1 science data to produce higher level data products which are then stored in the SOFIA Archive.

Requirements for data processing keywords in FITS metadata are described in the *Interface Control Document for the Data Cycle System, DCS_SI_01* (SCI-US-ICD-SE03-2023); these requirements apply to all SOFIA SI. Instrument teams which use the Science Mission Operations (SMO) DPS for pipeline data processing will develop and deliver data reduction pipeline algorithms, and will coordinate closely with the SOFIA DPS Group to develop a set of requirements for the instrument pipeline. Instrument developers will also deliver representative test data from the SI (e.g., on-sky data obtained during commissioning flight series) to ensure the objectives of the pipeline are met and to validate that the production pipeline code to be developed by the SOFIA Science Mission Operations (SSMO) can be successfully integrated with the DPS, and that the pipeline produces/outputs valid data products. The SI Developer's participation in the pipeline development and review processes are described in the *SOFIA Science Instrument Development Process and Deliverable* Requirements document (SOF-NASA-SOW-PM91-2094).

5.4.9 Ground Support Equipment

The SI Assembly installation cart is an important ground support equipment (GSE) item that is used to transport the instrument assembly within the SOFIA Science and Mission Operations ground facility, including transporting the instrument onto the aircraft and installing the instrument to the telescope instrument flange. The safety and interface requirements for SI installation carts are defined in the *Science Instrument System Specification* (SOF-AR-SPE-SE01-2028), the *Interface Control Document SI Handling Cart to Aircraft System SIC_AS_01* (SOF-AR-ICD-SE03-205), and the *Interface Control Document SI Handling Cart to SSMO Facility SIC_SSMO_01*, (SCI-AR-ICD-SE03-2017). Pertaining to interface requirements, instrument carts or stands used exclusively in the SI Labs are only required to meet the interface requirements of SE03-2017. Instrument installation carts however, which are used both in the SI Labs and on the aircraft, are required to meet the interface requirements of both SE03-2017 and SE03-205. These ICDs also contain dimension and geometry information of the ramps and incline surfaces for which an instrument cart will encounter at Armstrong Building 703. All instrument installation and lab carts, or stands, are required to meet the safety requirements defined in SE01-2028. Before the SI is transferred to NASA to maintain, the SI developer is responsible for performing proof and periodic load tests of SI GSE that have lifting devices that are used to structurally support the instrument assembly; SMO staff including Maintenance & Engineering (MandE) and SOFIA Quality Assurance (QA) will be available to assist with the coordination and execution of these load tests when the instrument is at AFRC B703. For non-lifting SI structural GSE the SI developer is responsible for performing an initial proof load test of the hardware before use, followed by performing inspections at periodic intervals (no periodic load testing is required).

The SOFIA Program supplies carts and dollies for the installation of the PI racks and the counterweight rack (see Section 4.3). The SOFIA Program is responsible for initial certification and periodic recertification (i.e., load test and/or inspection) of the PI rack dollies and CWR carts.

5.5 *Verification and Validation*

5.5.1 Purpose of Verification and Validation

From a process perspective, product (or science instrument) verification and validation (V&V) are similar in nature, but the objectives are fundamentally different. Verification shows proof of compliance with requirements—that the instrument meets each “shall” statement as proven through performance of a test, analysis, inspection, or demonstration. Validation shows that the instrument accomplishes the intended purpose in the intended environment—that it meets the expectations of the stakeholders. In essence, verification proves that “the system was built right,” and validation proves that “the right system was built”.

Verification relates back to the approved requirements set and can be performed at different times during the instrument life-cycle. Verification activities include: (1) testing used to assist in the development and maturation of products, product elements, or manufacturing or support processes; and/or (2) engineering-type testing, analysis, inspection, or demonstration used to verify the status of technical progress, verify that design risks are minimized, substantiate achievement of technical performance, and certify readiness for initial validation testing. Verification tests use instrumentation and measurements and are generally accomplished by engineers, technicians, or operator-maintainer test personnel in a controlled environment to facilitate failure analysis.

Validation relates back to the concept of operations. Validation testing is conducted under realistic conditions (or simulated conditions) to determine the effectiveness and suitability of the instrument for use in mission operations by typical users. Instrument validation will primarily occur during the commissioning flights.

5.5.2 Verification Process Overview

The verification process includes verification planning, preparation, execution, reporting, and NASA assessment. These elements of the process are described in further detail in the remainder of this section.

The approved requirements to be verified for instruments are contained within the following documents:

1. *SOFIA Science Instrument System Specification* (SOF-AR-SPE-SE01-2028)
2. *SOFIA Science Instrument ICDs (see list in Table 5.4.1-1)*
3. *SOFIA Science Instrument Development Process and Deliverable (P&D) Requirements* (SOF-NASA-SOW-PM91-2094)
4. The instrument science and performance requirements

A block diagram of the SOFIA SI ICDs and how they interrelate to the instrument system is shown in Figure 5.4.1-1.

Airworthiness design requirements are contained within the *SOFIA Science Instrument System Specification* and SOFIA SI ICDs. See Section 8 of this document for further details.

All airworthiness design requirements are verified prior to the instrument Pre-Shipment Evaluation (PSE). All ICD requirements are verified upon completion of the initial installation and checkout of the instrument on the Observatory. Performance requirements within the instrument science and performance specification are verified during the instrument's commissioning.

The NASA authorities for assessment of requirements compliance are as listed in Table 5.5.2-1.

Table 5.5.2-1: NASA verification compliance authorities

SOFIA Document	Requirements Type	NASA Compliance Authority
SI System Specification (SOF-AR-SPE-SE01-2028)	Airworthiness requirements	SOFIA Science Instrument Airworthiness Team (SIAT)
	All other requirements	Systems Engineering & Integration (SE&I)
SI ICDs	Airworthiness requirements	SIAT
	All other requirements	SE&I
P&D Requirements (SOF-NASA-SOW-PM91-2094)	All	Various
Instrument science and performance	All	SOFIA Science Instrument Development Manager and Project Scientist

5.5.3 Verification Planning

Verification planning includes establishing the verification activities to be performed in each life-cycle phase of the instrument. Verification activities are categorized as analysis (A), inspection (I), demonstration (D), or test (T).

5.5.3.1 SOFIA SI System Specification and SI ICDs

In the development phase of the instrument project life-cycle, the instrument team will begin planning verification activities with SOFIA Systems Engineering & Integration (SE&I). There are two general types of verification: (1) initial verification activities performed by the instrument team for risk mitigation purposes, typically performed before Initial Formulation Review (IFR) and Final Formulation Review (FFR), refer to the *SOFIA Science Instrument Development Process and Deliverable Requirements document* (SOF-NASA-SOW-PM91-2094) for more information on these reviews and (2) final verification activities witnessed by NASA for verification close-out.

SE&I will provide the instrument team with the *SOFIA Science Instrument System Specification and ICD Requirements Verification Matrix Template* (SOF-NASA-REP-SV05-2057) which contains all requirements from the SOFIA SI System Specification and SOFIA SI ICDs. The verification matrix template will be used to develop a verification compliance matrix specific to an instrument. The SI verification matrix serves as both a planning tool and a record of verification performed during the course of development of an SI. The five development phase verification planning columns—IFR, FFR, Pre-Ship, At AFRC prior to installation, and Installation and checkout—will be pre-populated in the template with the proposed verification method (A, I, D, T) for each of the prescribed development phases. The template contains a column describing the recommended verification activity for each applicable development phase for each requirement. The instrument developer may propose changes to verification phase, verification method, and verification activity based on the desired approach of the developer, however the proposed changes will need to be vetted with NASA to ensure that requirements are properly verified. Both NASA and the instrument developer are responsible for populating and maintaining certain fields of the verification matrix—for example, a set of columns is reserved for use by the SI team to self-identify compliance status while a similar set of columns is reserved for use by NASA to identify overall verification status based on a review of verification results recorded in the matrix.

At the instrument Step 2 Proposals Review, the instrument team will address all the requirements in the matrix and will identify the verification activities the team will perform for IFR and FFR. These initial verification activities serve to reduce risk; for example, drawings at FFR should be reviewed by the instrument team for compliance to ICD requirements, even though the definitive inspection by NASA of the as-built instrument will occur after fabrication.

Verification planning should be completed prior to IFR, and the verification matrix presented at IFR. Prior to each the IFR and FFR, the instrument team should record applicable compliance artifacts (e.g., analyses, drawings) and self-identify compliance (e.g., comply, do not comply) with each applicable requirement in the verification matrix.

The majority of SOFIA SI System Specification and SI ICD requirements compliance verification activities will be completed and closed-out before the instrument Pre-Shipment Evaluation. Several weeks before an instrument's shipment to Armstrong Building 703 for the first time, SE&I and SIAT will visit the SI Developer's site with a SOFIA QA Representative to conduct verification of SI hardware. The site visits by SE&I and SIAT are typically independent and may not necessarily be scheduled to coincide with one another. Verification procedures will be prepared prior to the visits and will serve as formal "as-run" records of inspection, demonstration, and tests when executed. The remaining verification activities to be performed after arrival at Building 703 will be limited to only those activities that cannot be definitively verified prior to shipment.

The SV05-2057 verification matrix template indicates the NASA compliance authority for each requirement (i.e., SIAT or SE&I). This identifies the NASA entity that is authorized to declare, after the final verification activity is performed, whether the requirement has been satisfied or not. The NASA compliance authority will usually witness the final verification inspection, demonstration, or test or will review the final verification analysis.

5.5.3.2 SI-Specific Science and Performance Specification

The instrument team will also create a similar verification matrix for the SI-specific science and performance requirements. For risk reduction purposes it is expected that verification activities will often span multiple development phases; for example, a supporting analysis for instrument science performance may be carried out prior to FFR but the definitive test may not occur until line operations or commissioning flights. The instrument developer will first produce a verification matrix for science and technical performance requirements at Step 2 Proposals Review, and will mature and update the document through subsequent life-cycle phases until all requirements are verified.

5.5.3.3 Process and Deliverables Verification

The instrument team should use the *SOFIA Science Instrument Development Process and Deliverable Requirements* (SOF-NASA-SOW-PM91-2094) document to keep track of all the required processes and deliverables for the successful delivery of the instrument. A verification matrix is not required to track the processes and deliverables.

5.5.4 Verification Preparation, Execution, and Close-Out

As described in the previous section, preparation for verification of requirements by inspection, demonstration, or test involves developing procedures, as well as facility preparation, equipment acquisition, and (if necessary) personnel certification.

Verification execution is the process of performing the verification procedures and having the NASA compliance authority review the results to determine whether the success criteria of the verification activity, as identified in the procedures, were met. The compliance authority will document the results ("Pass" or "Fail"), along with references to the documentation and associated compliance artifacts, in the verification matrix as verification activities are completed. As-run procedure records are submitted to SOFIA Configuration Management for archival.

As verification is performed during various phases of instrument development, noncompliance (or nonconformance) may be identified in which the instrument does not meet a requirement.

When noncompliance is identified during the design phase, before hardware fabrication or software coding has begun, SI Developers are strongly encouraged to explore design alternatives that would bring the instrument into compliance with the requirement unless there are compelling reasons why an instrument should be relieved of a requirement. In cases for which the NASA compliance authority believes that a deviation is warranted, a SOFIA team member from the functional group of the compliance authority will collect specific technical information about the instrument design to compose a deviation request to submit to the SOFIA Observatory Configuration Control Board (OCCB) for consideration, to release the instrument from its obligation to meet the requirement. It should be noted, pursuing a deviation request does not guarantee a deviation will be approved/granted, especially if the instrument is still in the design phase; each deviation request is individually evaluated to assess the specific noncompliance, justification, and potential impacts and risks of approving versus denying the deviation. In exceptions where a deviation is granted, verification of the as-built system will be performed against the specific design element which received the approved deviation (e.g., drawing) and not the requirement.

Instances in which the as-built instrument does not meet a requirement will be documented in the form of a discrepancy report filed with the SOFIA Program. Analogous to the deviation process but instead for instrument systems that have been built or fabricated, a waiver request may be submitted to release the instrument from its obligation to meet a requirement. As advised earlier, instrument developers are encouraged to explore design alternatives that would bring the instrument into compliance with the requirement, unless such design changes or modifications are deemed by the SOFIA Program to be technically unfeasible, cost prohibitive, or would significantly impact the instrument development schedule. Approved waivers will be documented in the instrument's verification compliance matrix. In certain cases, the Program may decide to grant a temporary waiver valid for a specific duration, by which time the instrument developer is responsible for bringing the instrument into compliance with the requirement per the terms agreed upon by the Program and instrument developer in the waiver.

All applicable SOFIA SI design requirements must be either passed or waived before the first installation of the instrument on the Observatory. Characterization of the science instrument to science requirements, documented in the ICS Report, must be completed during commissioning. All instrument-specific science and technical performance requirements must be either evaluated or re-baselined before the instrument may be fully commissioned or accepted.

5.5.5 Verification Activities

5.5.5.1 IFR Verification Activities

Verification activities for IFR will consist of the instrument developer delivering draft documentation and analyses based on the preliminary design of the instrument, and NASA reviewing the documentation to assess compliance of the design with SOFIA requirements. While the majority of design documentation will be delivered in the next phase of development (FFR), at IFR certain analyses are required to be delivered to show the requirements are understood in the preliminary design and the instrument developer is on track to satisfy the requirements in the next development phase.

Examples of verification activities performed for IFR include analysis of: instrument mass and c.g., cryostat vent pressure system, power budgets, physical/spatial envelopes). The results of the instrument team's IFR verification activities will be presented at the IFR.

5.5.5.2 FFR Verification Activities

Verification activities for FFR will consist of the instrument developer delivering updated and new documentation based on the detailed design of the instrument, and NASA reviewing the documentation to assess compliance of the design with SOFIA requirements. The primary method of verification used in this phase is analysis, whereas later development phases such as before shipment, will also include inspection, demonstration, and test.

Examples of verification activities performed for FFR include analysis of: instrument assembly drawings, rack configuration drawings, instrument mass and c.g., cryostat and vent system pressure stress analysis, power consumption, physical/spatial envelopes, cart design, and FITS data file header definition. In this phase, the instrument should submit deviation requests to the SOFIA Program for all identified non-compliance/discrepancies of the instrument with SOFIA requirements based on the results of verification at FFR, before proceeding to build the instrument (e.g., procure materials, fabricate parts, code software).

5.5.5.3 Pre-Ship Verification Activities

NASA will develop and provide a number of procedures for conducting SI verification close-out activities before an instrument ships to Armstrong Building 703. Examples of verification activities performed before instrument shipment are listed in Table 5.5.5.3-1 below.

Table 5.5.5.3-1: Examples of Pre-Ship verification activities grouped by verification method

Analyses	Airworthiness structural stress and loads analyses, SI center of gravity analysis, thermal analyses, alignment tolerance analysis, cryogen hazard analysis, failure modes and effects analyses, etc. Sensitivity performance models are developed prior to shipment, and updated throughout the test and commissioning program as instrument characterization improves.
Inspections	Airworthiness verification inspections, such as welding certifications, fastener specifications, etc. ICD verification inspections, such as envelope restrictions, connector types, wiring specifications, etc.
Tests	Detector characterization (dark noise, read noise, quantum efficiency, etc.), throughput characterization, image quality characterization, and mechanism characterization, at both room and operational temperatures. Measure power draw of the SI. Perform structural loads proof tests and pressure proof tests on flight hardware and SI handling equipment. Measure the mass of the flight hardware.
Demonstrations	Fit check of the SI flange to the TA instrument mounting flange. Functional testing of all operational modes and proper output format of science data, at both room and operational temperatures. Perform software tier tests on Systems Integration Lab (SIL).

5.5.5.3.1 Airworthiness Inspections

The SIAT will perform inspections of the as-built instrument at the instrument developer's site before shipment to verify the as-built instrument conforms to the design-to documentation (e.g., drawings) and to verify the instrument complies with airworthiness requirements. For this inspection the instrument hardware should be in its flight configuration. At the time of inspection, the instrument developer should communicate and identify to SIAT any parts of the instrument which are not in flight configuration, for which airworthiness inspection of those parts would need to be deferred to after instrument arrival at AFRC Building 703 when the instrument is fully assembled.

This inspection process includes verifying the as-built instrument hardware conforms to the instrument drawings, specifications, and other configuration-controlled design documentation delivered by the instrument developer to the SOFIA Program. Documentation such as certificates of conformance (CoCs) or certified material test reports (CMTRs) will also be inspected. Any noncompliance or nonconformance identified during in the inspection process will recorded in a discrepancy report for further review and possible action.

The SIAT will write the airworthiness inspection procedure and lead the airworthiness inspection activities. The SIAT also supports the final verification activities for compliance to SI System Specification and SI ICD requirements pertaining to airworthiness, reviews the results, and concurs on the compliance status. An SIAT representative will present their assessment of the readiness of the instrument to ship at the instrument Pre-Shipment Evaluation.

5.5.5.3.2 SE&I Verification (Non-Software)

A number of verification activities will be performed by the SOFIA SE&I Group before instrument shipment, to evaluate compliance of the as-built instrument system with SE&I requirements in the SE01-2028 SI System Specification and SOFIA ICDs. Verification performed by SE&I will first begin with review of updated analyses delivered by the instrument developer, analyses reflecting the as-built instrument system, followed by inspection, demonstration, and test verification activities.

For certain technical areas SE&I will interface directly with the instrument developer to conduct verification activities. Such activities have typically included mechanical verification (e.g., instrument mass measurement, instrument c.g. analysis inspection, instrument mounting flange inspection, instrument fit-check on TAAS, physical envelope inspections, cart load testing and inspections), electrical verification (e.g., power tests, ground tests, cable inspections & ring-out, UPS EPD response demonstration), and verification of various SE01-2028 functional, performance, safety, logistics, human factors, and material requirements. For other technical areas (e.g. software), the instrument developer may directly interface with other technical groups within the SOFIA Program to conduct verification activities but which SE&I will oversee the verification process and review verification results to assess final compliance of the instrument with SOFIA requirements in the instrument SE01-2028 and ICD requirements compliance matrix.

The instrument-specific SE01-2028 *SI System Specification* and SOFIA ICD requirements compliance matrix, developed from the SV05-2057 *SOFIA Science Instrument System Specification and ICD Requirements Verification Matrix Template* described in earlier Section 5.5.3.1 of this handbook, will be an important document which will be used by the instrument developer and NASA for verification planning and recording the verification compliance artifacts and results of all performed verification with SOFIA requirements.

SI conformance with the *SOFIA Science Instrument Development Process and Deliverable Requirements* (SOF-NASA-SOW-PM91-2094) document will be checked. The listed process requirements must be enforced during the instrument development, while the list of deliverables will be used as a check-list for hardware, software and documentation items, to be delivered as part of the contract agreement.

SE&I will write or oversee the development of verification procedures for evaluating instrument compliance with SE01-2028 and SOFIA ICD requirements, and lead or oversee these verification activities, for requirements which SE&I is the compliance authority. An SE&I representative will present their assessment of the readiness of an instrument to ship as an input to the instrument Pre-Shipment Evaluation. At this review SE&I will provide a summary of instrument verification status (e.g., number of requirements passed, failed, and deferred), open verification items, and status of approved deviations/waivers and any that are in pending.

5.5.5.3.3 Instrument Software-MCCS Testing

The instrument developer will perform pre-integration MCCS tests on the SIL before instrument shipment, to ensure the instrument can properly send commands to MCCS, handle responses from MCCS, execute scenarios, and demonstrate compliance with the MCCS_SI_04 ICD. The instrument team will conduct these verification activities with a team of SOFIA Mission Operations, Science Operations, and Software Systems personnel. The SOFIA Software Systems Group will lead and conduct the Tier 1-3 tests with the instrument developer. SOFIA Mission Operations (MOPS) will lead and conduct the Tier 4 tests, primarily by the Mission Director and Telescope Operator who have been assigned and dedicated to support Tier 4 tests of the new SI in the SIL and in-flight observations of the instrument onboard SOFIA. Tier 1-4 tests are described in the following subsections.

A prerequisite to performing Tier tests is the generation of an *<si>_data.xml* configuration file that establishes the SI’s interface with MCCS, containing the following SI information:

1. SCL commands and response items
2. Alerts and alarms
3. Housekeeping values
4. Description of SI modes: focus, scaling, boresight pixels, etc. (See Section 3.3.5 of ICD MCCS_SI_04 for a complete list of required data.)

The instrument developer should not need to create this configuration file from scratch; SOFIA Software Systems will provide a template for the instrument developer and the Instrument Scientist to fill in with the items listed above. Once the XML configuration file has been established, the team may proceed with conducting software Tier testing to establish SCL functionality. This testing verifies the interface and configuration definitions between the MCCS and SI, and proceeds through four incrementally increasing levels of complexity, Tier 1-4 tests.

Tier tests are performed with the SI team computer connecting remotely to a SIL located at either the SOFIA Science Center (ARC) or the SOFIA Operations Center (AFRC). Dry-run tests will generally be performed until the instrument team and SOFIA Tier test support team are confident the instrument is ready to officially perform the Tier tests “for the record”. SOFIA Software Systems will write the Tier 1-3 software test procedures; Mission Operations will write the Tier 4 test procedure. These procedures will be developed in close coordination with the instrument developer and Instrument Scientist, and will contain content specific to the instrument software system, operation, and observing mode(s). Once the instrument has officially completed Tier testing the instrument, from a MCCS software perspective, is ready to integrate with the observatory. The goal is for instruments to complete all tier tests before shipment. All Tier tests must be completed before the instrument flight series. A MOPS representative will present their assessment of the readiness of the instrument to ship at the instrument Pre-Shipment Evaluation.

5.5.5.3.3.1 Tier 1: Basic Connectivity

The purpose of the Tier 1 tests is to verify TCP/IP connectivity between the instrument and MCCS—that the instrument can create a connection(s) to the MCCS session and issue a successful "login" and "logout" command (as defined in the MCCS_SI_04 ICD) under nominal conditions, and handle errors under off-nominal conditions. The Tier 1 test cases are listed in Table 5.5.5.3.3.1-1 below.

Table 5.5.5.3.3.1-1: Tier 1 test cases

Test Case	Objective
Establishing a Session	Test that the SI can connect to the MCCS via TCP/IP, login, start a session(s) and logout
Establishing a Session with Errors	Test that the SI handle various basic error cases when creating a session

5.5.5.3.3.2 Tier 2: Mission Data Handling

The purpose of the Tier 2 tests is to verify the ability of the instrument to access MCCS housekeeping (HK) data of various types as necessary, via the "get" and "subscribe" commands (as defined in the MCCS_SI_04 ICD) and to verify the validity of the SI-provided data xml file. This Tier test also includes creation of a FITS data for inspection and ingestion into the DCS Archive. The Tier 2 test cases are listed in Table 5.5.5.3.3.2-1 below.

Table 5.5.5.3.3.2-1: Tier 2 test cases

Test Case	Objective
Establishing a Session SI Data Interface (XML Data Configuration File)	Verify that the SI-provided interface data is instantiated correctly in the MCCS
Accessing Housekeeping Data	Demonstrate that SI can access MCCS HK data in support of routine instrument use including: • display data to user via SI interface • create a data file correctly populated with the required FITS header keywords (including Mission ID) which can be ingested by the Data Cycle System (DCS)
Alerts/Alarms Handling	Demonstrate that SI can handle MCCS alert/alarm data in support of routine instrument use including: • display to user via SI interface • alarm confirmation
Science Data Archiving	Demonstrate that SI can write science data (e.g. FITS files) to the MCCS archive, based on the Mission ID, to the MCCS Redundant Array of Independent Disks (RAID).

5.5.5.3.3.3 Tier 3: Command Handling

The purpose of the Tier 3 tests is to verify basic SOFIA Command Language (SCL) command handling and to demonstrate that the SI can successfully construct, send, and parse responses of SCL commands. Whenever possible, the SI will send all commands relevant to their observing mode. The Tier 3 test cases are listed in Table 5.5.5.3.3.3-1 below.

Table 5.5.5.3.3.3-1: Tier 3 test cases

Test Case	Objective
SCL Command Handling	Demonstrate the SI can: • format SCL commands correctly • send SCL commands to the MCCS • handle success response • change state or display information to user as appropriate.
SCL Error Handling	Demonstrate that SI can handle SCL error responses and provide useful feedback to the user. This includes: • S: Syntax error: The command does not follow the proper syntax or the command name or given argument or attribute name are not valid. Command not processed. • E: Error in one or more data values: One or more command arguments or attributes have failed a limit check, failed unit conversion, or are of the wrong type. Command not processed. • F: A command failed at the destination. • #: Command aborted by the user. W: intermediate warning response (as appropriate)

5.5.5.3.3.4 Tier 4: Observing Scenarios

The purpose of the Tier 4 tests is to demonstrate that the SI can execute observing scenarios relevant to routine science operations as documented in relevant documentation (e.g., scenarios, test plans, etc.). MOPS and the SI team will agree on which Observing Examples are relevant to the SI and testing will be carried out only against those scenarios. The SI team will document the instrument behavior for each Observing Example and the test procedures for verification of that behavior.

5.5.5.3.4 Instrument Data Product-DCS Testing

The instrument developer will perform data file tests with the DCS before instrument shipment, to verify the delivered instrument FITS data files contain the required keywords and proper values for ingestion of data files into the DCS Archive, verify the data files contain the keywords and values required to support the DCS Archive search functionality, and verify the data files contain the conditionally required keywords which will depend on the specific operating mode and configuration of the instrument.

Before shipment, the instrument developer will also deliver an updated instrument-specific SI-to-DCS ICD to the DCS team for review, to ensure instrument astronomical observation templates (AOTs) are properly defined and that the SI FITS keyword list is complete and contains the required SOFIA DCS and DPS keywords/values as well definition of any instrument-unique FITS keywords. The SI-DCS ICD will be reviewed by the DCS team, and content agreed to, before any substantial data file testing with the DCS occurs.

The instrument data file ingestion tests consist of the DCS checking the FITS metadata header information to verify the required keywords for data file ingestion are present, as identified in DCS_SI_01 ICD, and that the keyword values are of the appropriate type. FITS header checks are also performed to verify the other keywords and values, identified in DCS_SI_01 and instrument SI-DCS ICD are present and appropriate. The DCS will generate a report identifying warnings for any missing keywords or values—the DCS team will work with the instrument team to fix issues with SI data files as well as identify which warnings may not require action at that time. Also, FITS keywords/values that are pipeline specific (i.e., are required by the pipeline to aid in data reduction) may be tested at this time.

The DCS team will write the test procedures and lead the SI-DCS test verification activities. A DCS representative will present their assessment of the readiness of the instrument to ship at the instrument Pre-Shipment Evaluation.

5.5.5.3.5 Instrument Data Reduction Pipeline-DPS Testing

Instrument developers are responsible for delivering algorithms and test data to support development and testing of a software data reduction pipeline by the SSMO. The SOFIA DPS team will write the procedures and lead formal verification of the instrument data reduction pipeline. A DPS representative will present the progress of development of the instrument data reduction pipeline at each major lifecycle review.

5.5.5.4 Post-Ship Verification Activities

Post-ship testing includes basic functional testing, at both room and operational temperatures, to verify that the baseline established at the Instrument Team's site has not changed. Final ICD verification activities are performed, such as electrical cable safe-to-mate checks and power tests if these were not performed during an earlier NASA site visit. Tests with the Pre-Flight Integration Facility (PIF) (see Section 6.2.2) using the Telescope Assembly Alignment Simulator (TAAS) are performed to verify the physical interface and optical alignment, and testing of the instrument software in the SIL and HIL (see Section 6.2.3) will demonstrate command and control functions. "For the record" SI software Tier Tests will be performed if they were not completed earlier.

5.5.5.5 EMI/EMC test

An electromagnetic interference and electromagnetic compatibility test (EMI/EMC) test will be performed with the instrument prior to flight. This test occurs on a taxiway or engine run-up area since it involves engine runs and radar use. This test ensures that the instrument systems do not cause adverse effects on the aircraft systems, characterizes any aircraft system impacts on the instrument performance (i.e. increased detector noise due to radio pick-up), and confirms the instrument shielding and grounding scheme is effective. Similarly, the test can be used identify instrument susceptibility to electromagnetic radiation emanated from any of the aircraft systems or other devices on board the aircraft (i.e. personal electronic devices and similar). The test does not include any more detailed quantitative measurements of the radiated or conducted electromagnetic spectrum.

5.5.5.6 Line Operations

Observatory line operations may provide the first end-to-end functional tests and performance characterizations of the integrated Instrument/Observatory. Line operations are the first major validation activity, yielding the first evaluation of how well the integrated Observatory system meets the operational and system-level objectives.

The aircraft is rolled out of the hangar onto the "flight line", where the telescope cavity door is opened and the telescope is "on-sky". Typical tests during line operations may include instrument optical alignment with the telescope, focus, chopper interface and characterization, image quality and plate scale measurements, MCCS command and control, and science data transfer.

Prior to the commissioning flight series, mission simulations are performed on the flight line, in the full flight configuration, in order to verify operational procedures and minimize risk to success of the flight series.

5.5.5.7 Instrument Commissioning Flight Series

The instrument will conduct commissioning flights to characterize all modes and operational parameters of the instrument. Two commissioning flight series campaigns are typically scheduled with each series consisting of hangar operations, line operations, and a number of flights. Commissioning flight series are typically scheduled a few months apart to provide time for the instrument team to analyze data and characterize instrument performance from the completed flights, as well as potentially provide the opportunity to make changes to the instrument to satisfy instrument requirements.

Tests conducted during commissioning flights are similar to those on line operations, but they are now in the flight environment. All instrument-specific science and performance requirements that cannot be verified on the ground will be verified during this flight series. All parameters necessary to provide the general scientific proposer with the quantitative information they need to propose to use the instrument aboard SOFIA will be characterized. A selection of science targets to provide a qualitative flavor for the capabilities of the instrument will be observed. Final verification of the instrument-specific science and performance requirements occurs during this flight series. The results of instrument performance verification will be presented by the instrument developer at the LSP Review.

5.5.5.8 Instrument Modifications and Upgrades

Modifications and upgrades to instruments may be expected periodically, following initial installation and use on the aircraft. Depending on the nature of the upgrade, some or all of the verification process is repeated to address verification of the upgraded configuration. Upgrades that impact compliance with airworthiness or SE&I requirements will require delta verification—prior to any changes being made to the instrument, the appropriate NASA compliance authority should be informed (see Section 9). Upgrades that impact interfaces between the instrument and the aircraft will require regression testing or analysis for ICD requirements. Depending on the nature of changes made to an instrument, the airworthiness recommendation letter issued by the SIAT may need to be updated.

5.5.5.9 Physical Configuration Audit

In addition to instrument requirements compliance verification, instruments must complete a Physical Configuration Audit (PCA) to confirm the configuration of the as-built instrument is accurate and complete. The outcome of the PCA also establishes a baseline configuration of the instrument before instrument acceptance.

The PCA examines the physical configuration of the product and verifies that the product corresponds to the build-to product baseline documentation previously approved at the FFR. PCAs are required to assure quality of safety critical items and will be conducted on hardware configured products.

The majority of the configuration inspection audit of the as-built instrument will be performed before first shipment of the instrument to Armstrong Building 703, or shortly after arrival, and at certain intervals during the instrument assembly process where accessibility of the part or subassembly that needs to be inspected is only available. For example, measurement and inspection of the dimensions of an instrument liquid helium reservoir may be performed early in the PCA process as the instrument is being built to confirm the as-built dimensions of the reservoir conform with its drawing, before the reservoir is integrated with the instrument with other structures being built around it. The timing of inspection of other parts may be more flexible, such as inspection of a cryostat vent pressure relief device on the outside of the instrument. The PCA is conducted by the SOFIA Safety & Mission Assurance (S&MA) team who will develop the audit inspection procedure. In addition to S&MA, development and scope of the PCA will be pre-coordinated with the SIAT, as many of these inspections will satisfy both SIAT and PCA inspections, to form a minimum essential set of inspections to be performed.

A prerequisite to the PCA is certain SI documentation for the as-built instrument must be approved, released, and made available to the SOFIA Program. This documentation typically includes: specifications, drawing trees, drawing lists, drawings, engineering change orders (ECOs), manufacturing and inspection "build" records, as-built discrepancy reports, SI Project-internal approved waivers and deviations.

6 Instrument Operations

The SOFIA operates out of the Armstrong Flight Research Center Building 703, located in Palmdale, CA, where the Science Instruments are integrated with the Telescope Assembly. Building 703 includes laboratory space for the storage, preparation, and maintenance of the science instruments. The observatory will fly several nights per week to achieve an average of 3 successful science flights per week during a flight campaign, returning to Palmdale each morning except in the case of a deployment.

SOFIA will occasionally be deployed to the southern hemisphere or other locations to accommodate the scientific objectives of the proposed science. All instruments should be capable of being deployed to remote sites. Any deployment of an instrument prior to instrument acceptance will be negotiated and coordinated between the Program and the instrument developer.

Instruments are prepared for the commissioning flights and operated during the commissioning flights by the instrument team. The documentation required for the SOFIA Program to maintain and operate the instrument will be delivered by the instrument developer prior to the instrument Operations Acceptance Review (OAR). Also prior to the OAR, the SI team will train SOFIA SMO personnel to independently maintain and operate the instrument to prepare for the transition of the instrument to the Program.

The instrument commissioning period will be scheduled by the SOFIA Program based on the instrument availability and Observatory availability. SOFIA science instrument observing time is allotted via the time allocation committee or SMO Director's discretionary time.

While the nominal configuration is for a single instrument to be mounted to the telescope, it is possible to support a dual-instrument configuration.

Further information on instrument operations can be obtained in the Excerpts from the SOFIA Operation Concept located in the document library.

6.1 *Telescope performance*

The performance requirements of the SOFIA Telescope Assembly are described in *SOFIA Telescope Assembly (TA) Requirements* (SOF-1011). Contact the SOFIA SI Development Manager for reference reports on measured telescope assembly performance.

6.2 *Observatory facilities*

6.2.1 Science Instrument Labs at AFRC Building 703

SOFIA Science Laboratories (SSLs), a.k.a. instrument readiness rooms (IRRs), are available at Building 703 for use by the Instrument Teams. Lab access will be limited to Instrument Teams, SMO support staff, and other key individuals authorized by the Lab Supervisor. General lab support times will be "day shift," 0700-1630, on weekdays. Additional support can be arranged upon request.

Electronics: Some labs have ESD workbenches but availability is limited. In addition, a shared stock of power supplies, signal generators, and oscilloscopes can be drawn upon as needed.

Vacuum: Vacuum pumping systems are available for SI use. "Roughing" pumps are available to reach ~10^{-3} Torr and turbo systems are available, capable of reaching 10^{-8} Torr. Furthermore, a He vacuum leak check system is available and is capable of diagnosing leaks from 10^{-2} Torr-Liter/sec down to 10^{-10} Torr-Liter/sec.

Cryocooler Compressors: Several of the SSLs can accommodate SIs that use the SOFIA closed-cycle cryocooler system for cooling to support the use of pulse-tube cold heads and cryostats. The *SOFIA Science Instrument Development Process and Deliverable Requirements* (SOF-NASA-SOW-PM91-2094) describes requirements for GSE cryocooler He compressors delivered to AFRC B703.

Storage: SI teams will be provided storage space equivalent to one 4'x8'x2' shelving unit and one 6'x3'x2' locking cabinet.

Cryogens: LN_2 and LHe will be available for SI use upon request. All capacity needs will be met with appropriate notification from the SI team as to instrument fill schedule and consumption. Personal protective equipment as required by NASA will be available in the labs. SI team members participating in instrument cryogen fills are first required to complete a short AFRC cryogen safety training course.

Other material including gases, solvents, and cleaners: Compressed He and N_2 will be available for SIs. Acetone and Isopropyl Alcohol will be available through the Building 703 tool crib. Other gases and solvents must be requested through the SMO contact for the SI team or directly through the Lab Supervisor.

Advanced Electronics diagnostic and fabrication: An electronics lab with an engineer qualified to make cables for the SIs is available. Cable fabrication requests should be pre-coordinated with the engineer and Maintenance and Engineering Manager to ensure any long lead-time items such as connectors, wiring, or tools needed can be procured to support cable fabrication in the time frame needed by the SI. Cable assembly drawings from the SI team should include the necessary information and detail for the engineer to fabricate the cable. Also, in the electronics lab a GHz oscilloscope and an advanced spectrum analyzer will be available.

Power: The lab wall power is sufficient for robust COTS systems to be plugged into. Both standard US 115V-60Hz and 3-phase are available on the wall. For any sensitive equipment, UPS power isolating systems are available both for standard US 115V-60Hz and for European connections at 50 Hz. To support V&V of SI power draw from each power interface, and to allow SIs to be operated and tested in the lab using flight cable harnesses, the SOFIA Program has developed three (3) Power Draw Test Fixture GSE racks which can be made available to SI teams on request. These racks do not have any integral power supplies, but accept power from various utility, UPS and DC power supply sources, and replicate the U401 J0, J1, J2 and J3 power interfaces, as well as the U400 / U402 J128, J129, J130, J131 and J132 patches between the PI Rack and "doghouse" to the SI assembly and CWR. These GSE racks are also capable of asserting the U401 J3 Emergency Power Disconnect (EPD) discrete signal, to support SI V&V of their UPS EPD circuitry, where applicable.

Network Access: NASA network ports are available in each lab. NASA Guest network on WiFi is available throughout the labs. Connections for instruments are available from the SIL, HIL, and Aircraft to the lab. A connection from the SI team's home institution to their lab can be authorized with at least a 60 day notice prior to the first date of usage.

Tools: A full tool set will be available to SI teams for general purposes. These tools will be inventoried and maintained per NASA AFRC tool control policy, to which SI teams must adhere. Specialty tools can be made available with prior notification. Calibrated wrenches, inclinometers, and other tools are available for check-out through the Building 703 Tool Crib and AFRC Calibration Lab.

Optics / Alignment Lab: An enclosed room connected to the Pre-Flight Integration Facility (PIF) with a double door, supports assembly and testing of SI optical bench components such as detector arrays, optical elements and mechanisms. Though not formally certified as a cleanroom facility, the HVAC system has been modified with HEPA filtration and door seals to maintain a positive pressure. With careful cleaning and the use of sticky mats and bunny suits, this lab can approximate a Class 5000 cleanroom facility.

Office Space and Break Areas: SI teams have access to a break room, with a coffee machine and microwave located near Lab 5. Unless your lab has an area specifically marked for food consumption no food and only beverages in spill proof containers (such as allowed on the aircraft) are allowed in the labs. Such areas will not be in every lab and cannot be negotiated. The break room may be used as an office space and desks will also be provided in the labs for such use. A public break room with refrigerator, microwave, tables, and seating is available on the first floor.

6.2.2 Pre-Flight Integration Facility

The Pre-Flight Integration Facility (PIF) is a laboratory located at Armstrong Building 703 containing simulations of certain Telescope Assembly (TA) interfaces (i.e. Telescope Assembly Alignment Simulator, or TAAS) with the science instrument (SI) and its related equipment. Its purpose is to facilitate the installation and integration process of an instrument onto the Airborne Observatory by testing interfaces between the instrument and Observatory.

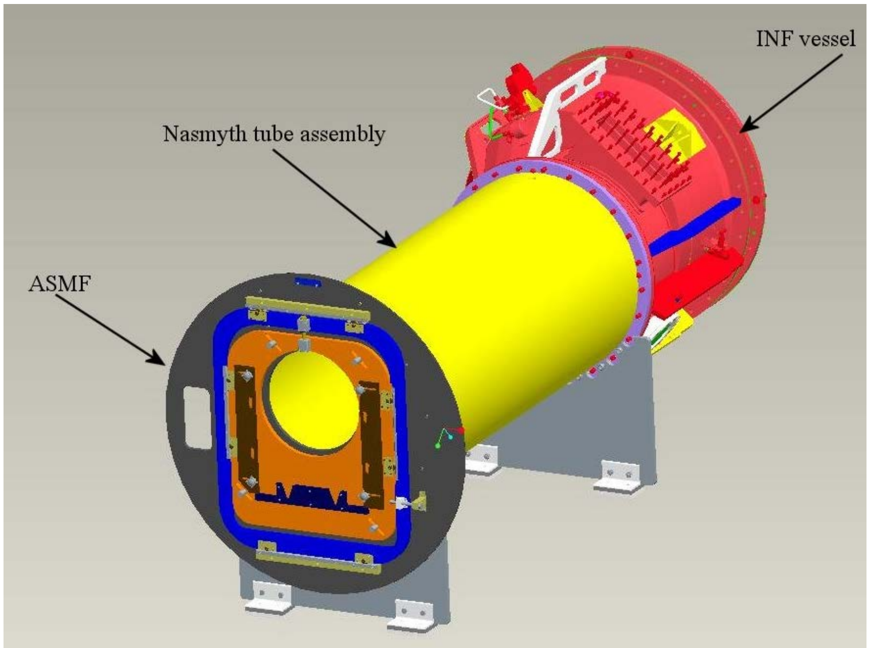

Figure 6.2.2-1: The basic structure of the telescope assembly alignment simulator

The Telescope Assembly Alignment Simulator (TAAS) consists of the following major components and associated software:

1) Telescope Assembly Alignment Unit (TAAU)
2) Large Chopped Hot Plate (LCHP)
3) Small Chopped Hot Plate (SCHP)
4) Focused Chopped Light Source (FCLS)
5) Alignment Camera (AC)

The TAAS is used to perform fit checks of SOFIA Science Instruments with the Telescope Assembly (TA) Flange Assembly and permits adjustment, checkout, test, and characterization of Science Instruments (SIs) prior to installation and use aboard the Observatory. The TAAU is the main physical structure of the TAAS, which allows the SI to be mounted at one end and the infrared sources at the other. The TAAU consists of the Instrument Flange (INF) vessel, Nasmyth tube, and Adjustable Source Mounting Flange (ASMF). The scale of the TAAU is designed so that the optical path length is 43% of the SOFIA Telescope Assembly's (TA) optical path length from the nominal focus to the TA secondary mirror.

The TAAS has three different infrared sources: the LCHP to simulate a "hot" secondary mirror for pupil imagers, a SCHP used mainly to map an SI's beam profile, and a FCLS which acts as a "point-like" source for focusing and alignment to the SI detector chip.

The TAAS also includes an Alignment Camera for purposes of maintaining the actual TA boresight transfer to the TAAS. This is accomplished by a first aligning an SI to the SOFIA TA boresight, the SI is then removed from the TA and installed onto the TAAS, and then the FCLS is then aligned to the SI-registered boresight pixel location. Herein, the TA boresight is transferred to the TAAS. The AC is installed and pixel registration of the FCLS beam on the AC is noted. In the event that the FCLS loses the boresight, the AC is reinstalled and the FCLS position is aligned to the AC boresight pixel registration.

The Alignment Camera is not used during normal operation of the TAAS and is only used to align the FCLS to the boresight.

Once an SI is mounted to the INF vessel, the INF vessel may be evacuated to check for leaks and proper mounting. The full optical path (SI to IR source) cannot be evacuated. However, the entire optical path may be purged with a dry air system in order to displace any water vapor inside the TAAS.

The TAAS is further described in the *Telescope Assembly Alignment Simulator Specification* (SCI-AR-SPE-SE01-040). Details of operation are provided in the *User's Manual for the Telescope Assembly Alignment Simulator* (SCI-AR-MAN-OP02-2068).

6.2.3 Systems Integration Laboratory

Multiple Systems Integration Laboratory (SIL) systems are located at NASA ARC and NASA AFRC B703 for development and testing of observatory and science instrument software. Two Hardware-in-the-Loop Simulator (HILS) labs, located at B703, contain flight hardware used for high fidelity simulation and testing of Observatory mission systems. Instrument software tier tests, are typically performed in the SIL.

A SIL is a self-contained simulation environment of the onboard SOFIA MCCS (Mission Controls and Communications System) computer systems. A SIL consists of several major components, some of which are identical to their flight-worthy counterparts and some of which are software simulations of other systems (the Telescope Assembly, for example).

The following is a general description of each of the components:

The Platform Interface Subsystem (PIS) consists of proxies for Session, Mission, Telescope Assembly, and Cavity Door Drive System.

The Telescope Assembly Image Processing Subsystem (TAIPS) connects to each of the imagers in the Telescope Assembly Simulator: Wide Field Imager (WFI), Fine Field Imager (FFI), and Focal Plane Imager (FPI).

The Workstation Subsystem consists of the Telescope Operator (TO) Workstation and Mission Director Workstation. The Mission Director Workstation has twin displays, while the TO Workstation has four.

The MCCS Network Subsystem manages three distinct subnets: PIS, TAIPS, and the Experimenter's Network. It is to this network that your Science Instrument software connects (physically).

The Simulators consist of several computers, which run a battery of software simulators, most notably including the aircraft (747) simulator and Telescope Assembly simulator.

6.2.4 Secondary Mirror Buttons

The secondary mirror can be outfitted with a selection of mirror "buttons" to either attenuate or redirect the optical path of the primary mirror central obscuration in the telescope exit pupil. The secondary-mirror button defines the central aperture stop for the telescope and prevents science instruments from imaging themselves. Specifically, the button ensures that the primary mirror hole and the edges of the tertiary mirror are not visible in the science instrument focal plane. The details of the button design depend on wavelength and other science-instrument specific considerations. For example, some buttons are reflectors ("scatter-cones"), deflecting cold sky emission into the focal plane, while others are flat, high-emissivity (black) absorbers.

Science instrument teams can select a suitable secondary mirror button from several provided by NASA or they can design and build their own.

6.2.5 Telescope Tertiary Mirror

The telescope has one tertiary mirror, a dichroic using a thin gold layer.

6.2.6 Vacuum

A vacuum pump system is available for use by the mission operations or instrument teams during flight. This vacuum system serves two purposes: to pump out the Nasmyth tub (volume between the science instrument flange and the gate valve) when needed and to support in-flight vacuum requirements of the Science Instruments. Pumping on the Nasmyth tub may after the gate valve is closed may be part of normal or off-nominal operations to reduce the pressure in the tub to protect an instrument window or instrument from condensation during descent. Some instruments may use the vacuum system to pump on liquid cryogen baths to reduce their temperature for normal operation. The observatory vacuum pump system is described in the *Vacuum Pump System Concept of Operations* (APP-DA-PLA-PM17-2074), *Vacuum Pump System (VPS) Specification* (APP-DA-SPE-SE01-2049) and *Vacuum Pump System to Science Instrument ICD VPS_SI_01* (SOF-DA-ICD-SE03-2022).

6.2.7 Cryocooler

Observatory infrastructure hardware was recently installed to support operation of closed-cycle cryocooler (CCC) systems. An advantage of using a closed-cycle cryocooler system is it eliminates the need to use expendable liquid cryogens, and can support steady-state operations for SIs that would otherwise not be capable of cryogenic hold times adequate to support a full ~10 hour flight.

The cryocooler system includes two (2) ruggedized Cryomech CP2870 liquid-cooled cryocooler compressors on vibration isolators, an accessible control system with both local and remote touchscreen GUI displays, an actively pumped liquid coolant loop with two in-series water/air heat exchangers to support both inflight and ground operations, and two (2) pairs of flexible helium supply/return lines that terminate at a quick disconnect (QD) panel U404 on the TA, to which an instrument may connect its own helium lines, as needed to service one or two pulse-tube cold head(s) and cryostat(s).

The capabilities and technical details of the SOFIA Cryocooler System are described in the *SOFIA Phase 2 Cryocooler System Specification* (SOF-NASA-SPE-SE01-2089) and *SOFIA Cryocooler System Concept of Operations* (APP-DA-PLA-PM17-2076). Cryocooler System interfaces to SIs are defined in the Phase 2 Cryocooler System-to-SI ICD CRYO_SI_02 (NASA-SOF-ICD-SE03-2066).

6.2.8 Workspace on aircraft

The *Layout of Personnel Accommodations (LOPA)* (APP-DF-DWG-SE02-2924) provides a graphical layout of the location of various SOFIA mission systems on the main deck of the aircraft, including the PI racks, conference tables, and seats, as well as the PI Patch Panel. A mission operations rack referred to as the Auxiliary or AUX rack, containing mission systems equipment in a rack frame structure identical to a PI rack, is typically installed in one of the PI rack locations available for use by the SI team.

The AUX rack contains the Mission Audio Distribution System (MADS) unit, a telescope status display, a slide-out workspace tray, and power strips available for use by the SI teams. The MADS unit enables SI team members to easily communicate with other SI team members, the Mission Director, Telescope Operators, Science Flight Planner, and other observatory personnel during flight, which is useful as personnel will oftentimes be seated in different areas on the aircraft and aircraft engine noise makes it especially difficult to directly communicate without the use of MADS. Installation of the AUX rack is optional; however, if the SI team elects not to have the AUX rack installed the SI team must reserve space in one of their PI racks for the MADS unit to be installed—the required space is defined in the *Principal Investigator Equipment to PI Rack to Aircraft System ICD*, SI_AS_01 (SOF-AR-ICD-SE03-2015). The SI Developer is responsible for providing any needed surface trays in their PI Racks for writing or using laptops. The SOFIA Program can provide recommendations for flight-qualified tray designs, as the AUX rack already takes advantage of two different flight-certified tray designs.

Two conference tables available for use by the SI team are located farther forward in the aircraft and are also equipped with power, MADS, and access to the experimenter's network. Each of these tables has four seats.

6.3 Instrument access during flight

SI equipment mounted in the PI rack(s) is readily accessible during flight, particularly equipment in the PI Rack bays facing the instrument team members seated at the PI rack(s) while wearing seat belts (i.e., during the take-off, ascent, descent and landing phases). Limited access to other portions of the science instrument (i.e., the SI assembly and items mounted in the CWR) is possible during flight.

The instrument counterweight rack (CWR) is especially difficult to access during flight. Only portions of the rack are within reach, and only when the telescope is caged at low elevation angles. It should be assumed in the instrument design and operations concept that the counterweight rack cannot be routinely accessed during flights.

To prevent personnel from falling into the Telescope Assembly "pit" as a result of unexpected turbulence, a TA barrier is installed forward of the science instrument across the width of the aircraft cabin. This TA barrier is a 4-foot tall net consisting of ~12"x12" square openings that extends the width of the aircraft cabin and is secured to hardpoints on the cabin floor. As an operational safety precaution, personnel must first receive permission from the Mission Director before approaching any area aft of the PI racks during flight.

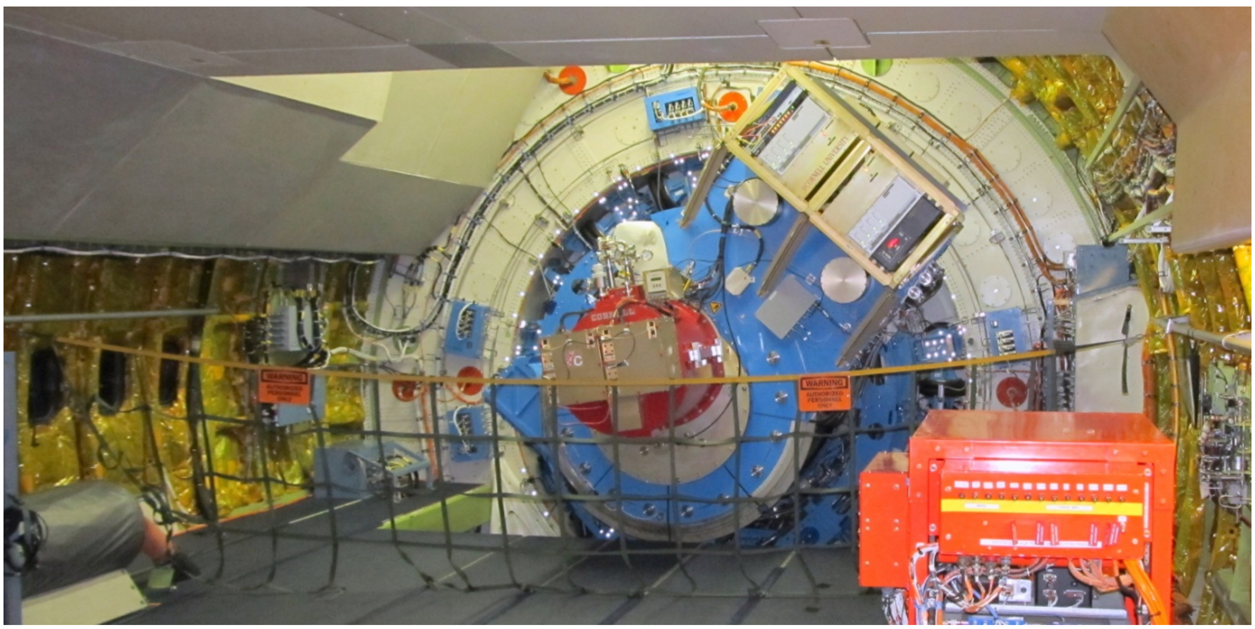

Figure 6.3-1: The telescope assembly barrier installed forward of the FORCAST instrument

The TA barrier will be installed during all flights and may also be installed during ground activities such as line operations to restrict access to the TA and instrument field of motion and to aid in simulating actual flight conditions.

Figure 6.3-2: Telescope assembly barrier floor rail mounting points

The TA barrier can be installed in a straight line across the aircraft cabin, or it can be routed around the instrument using the rail mounting system depending on the instrument design and needs for access during flight.

In-flight safety dictates that access to the Science Instrument behind the Telescope Assembly (TA) safety barrier be strictly controlled. Procedural details are specified in the *Procedure for Crossing the TA Barrier during Flight* (APP-DF-PRO-OP02-2043).

6.4 *Instrument status between flights*

It is the intent of the SOFIA Project to provide instruments with power and internet connectivity while the aircraft is in the hangar. This is to support instrument designs using cryocoolers, detector thermo-control systems, and maintenance of local oscillator stability, as well as provide the ability to remotely monitor the instrument's health and status. The operational details of providing this support have yet to be agreed to with aircraft operations. This section will be added to this document when an agreement is reached. This section will be updated in a future revision of this handbook.

6.5 *Commissioning and Guaranteed Observing Times*

The Instrument teams must develop a commissioning plan that minimizes the time required for testing on the aircraft and in flight, while fully characterizing instrument performance and testing all user-supported instrument modes. The commissioning plan should justify the number of commissioning hours requested and interval between flights. SI developers will operate the SI during commissioning, and should be prepared to make appropriate SI repairs or adjustments in between commissioning series, at the AFRC B703.

Guaranteed observing hours granted the instrument teams are described in *the Science Utilization Policies of SOFIA,* (SOF-1087). Guaranteed observing for instruments will be scheduled by the SMO Director. Instrument proposers should include the cost budget for guaranteed time observations (GTO) in their instrument proposal, if applicable.

6.6 *Data Archiving*

All raw science data taken in-flight from telescope-mounted science instruments on SOFIA is archived by the SMO at the SOFIA Science Center. Observers acquire their data as well as publicly available datasets through this data archive system. Pipeline-processed data from supported modes of instruments are also archived. The pipeline products involve standard data reductions including wavelength and flux calibrations.

The SOFIA Data Cycle System (DCS) provides off-aircraft data archiving and retrieval systems for raw and reduced instrument data. *Data Cycle System to Science Instrument ICD* (SCI-US-ICD-SE03-2023) describes system and interface for the science instruments.

The SOFIA Data Archive can be accessed online on the SOFIA Data Cycle System website at https://dcs.sofia.usra.edu/. In addition to providing access to the data archive and retrieval of science data, the website offers a number of other features and services pertaining to proposal development, observation planning, and user support. Access to data and services on the website is controlled, and individual user privileges and permissions are established by the SOFIA Program.

The MCCS provides on-aircraft data archiving during a flight, before the data is transferred to the SOFIA Ground Systems data facilities. The notes and rationale provided with SE01-2028 ParID 3.1.6 provide additional information about how instruments will interface and use the MCCS Archiver.

6.7 *Data Processing*

Information on the data processing system for science instruments is in *Data Processing Plan for SOFIA Science Instruments* (SCI-US-PLA-PM17-2010). The *Software Architectural Design Document for the Data Processing System (DPS) of the SOFIA Project* (SCI-US-SPE-SW02-2019) provides the high level architecture regarding pipeline data reduction with the Data Processing System.

7 Instrument Lifecycle

7.1 *Proposal Preparation and Selection*

7.1.1 US Provided Science Instruments

NASA solicits proposals for SOFIA instruments via the NASA Research Opportunities in Space and Earth Sciences (ROSES) research announcement. These solicitations define the key SI Project activities and timelines from development to instrument acceptance, and requirements for the selection process including requirements for the phases of the solicitation. As each solicitation may contain unique key information funding, schedule, and requirements, prospective instrument developers should refer to the specific solicitation.

7.1.2 German Provided Science Instruments

DLR and DSI will establish their own processes for selecting instruments.

7.2 *Science Instrument Advisory Group*

The charter of the Science Instrument Advisory Group (SIAG) is to review the current suite of instruments available to the general observing community, on a regular basis, and formulate a recommendation to either retire the instrument, or to continue operations, possibly under specific conditions.

7.3 *Instrument Development Lifecycle*

The reviews discussed below in the instrument development lifecycle, will be conducted or supported by the instrument team. The *SOFIA Science Instrument Development Process and Deliverable Requirements (*SOF-NASA-SOW-PM91-2094) document provides details for the review support requirements. Chart content guidelines for these reviews are contained in Appendix K of this document.

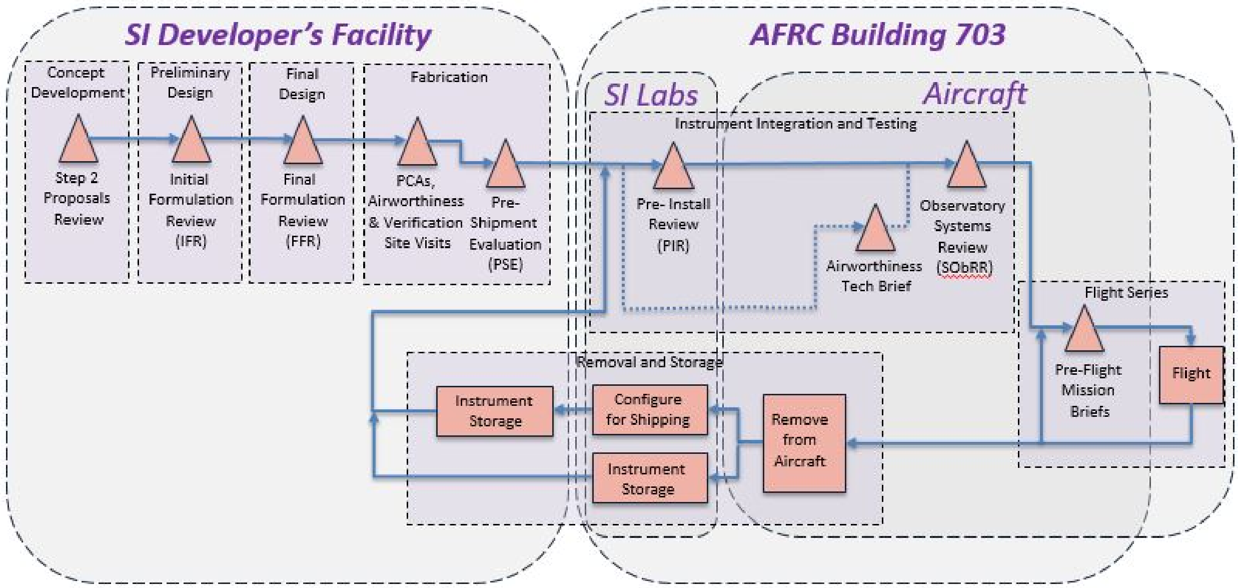

Figure 7.3-1: Instrument Development Lifecycle

Following instrument commissioning, additional pre-installation reviews and pre-flight reviews, will be held at the discretion of the mission operations plan manager. For programmatic planning purposes, the SI Developer should allocate resources to support these reviews should they occur.

7.4 *Instrument Integration and Testing at AFRC*

There are four parts to instrument integration following delivery to AFRC Building 703: laboratory tests, TAAS tests, aircraft integration tests, and flight tests. The testing philosophy is to test as early in the process as possible with the minimum number of subsystems required. SOFIA is a valuable asset with significant operations costs. No test should be performed during a flight that has not been practiced on the ground. No test should be performed on the aircraft that can be performed in the laboratory.

Laboratory tests occur in the Science Instrument readiness rooms located at Building 703. These tests are to verify that the instrument has been reassembled and no damage has occurred during shipment and the instrument is ready to be tested on the TAAS (refer to section 6.2.2) or installed on the aircraft. The instrument team determines what tests are performed depending on the instrument design and requirements. Generally, these consist of a leak check of the vacuum system, warm functional tests, and cold functional tests. The instrument team should confirm that the instrument has survived shipping, has been properly reassembled, is free of vacuum leaks and thermal shorts, and is ready for integration with the Observatory.

A Pre-Install Review is conducted prior to the scheduled installation date, to ensure the instrument is ready to install, to coordinate logistics of installation, ensure staff is ready to execute instrument installation, and to confirm the readiness of Observatory telescope and aircraft systems.

Following integration with the Observatory, aircraft integration tests are performed to confirm proper installation and cabling of the instrument. Aircraft integration tests include a warm functional test, if the instrument is installed warm, and a cold functional test. These tests verify the instrument is ready for hangar tests, EMI tests, and/or line operations.

Hangar tests are tests performed by the instrument on the aircraft while the aircraft is in the hangar (i.e., integrated tests for which sky sources are not required).

An electromagnetic interference and electromagnetic compatibility (EMI/EMC) test will be performed with the instrument prior to flight. Refer to Section 5.5.5.5 for additional details re: the EMI/EMC test.

Line operations are tests performed out on the flight line. In addition to instrument tests, mission simulations – observing flight rehearsals – are performed to familiarize the mission crew to the operation of the instrument and the instrument team with in-flight procedures.

Instrument control software integration testing should occur as early as possible. The instrument control software interface with the MCCS can be tested remotely or in person using the Systems Integration Laboratory (SIL). This testing should occur prior to the instrument Pre-Shipment Evaluation to ensure the software will be ready for instrument integration with the Observatory. Final testing of the instrument control software will occur on the Observatory in the hangar when possible and during line operations for those tests requiring sky targets.

7.5 *SOFIA Observatory Readiness Review*

The SOFIA Observatory Readiness Review (SObRR) is held prior to each Observatory flight series. The objective of this review is to confirm that the Observatory, which includes the science instrument, is ready to fly. In preparation for this review, the instrument team's representative should confirm that any open issues are being worked, that the instrument team believes they have had enough practice and simulations, and that they believe the Observatory is prepared to support their observing plan. The instrument team's representative should communicate any changes made to the instrument configuration since the Pre-Install Review and deliver an update to the instrument configuration sheet to the SOFIA Program. The first SObRR, or a SObRR held following a major instrument modification, will be a more extensive review covering the instrument modification and overall instrument readiness for flight. As operation becomes routine, this will become a shorter review, and can often occur just after the Pre-Install Review on the same day.

Prior to each individual flight there will be a Mission Brief held ~2 hours prior to the scheduled take-off time. Instrument teams will be asked to report the instrument status at the Mission Crew brief and report any issues or risks that may have developed since the SObRR and status any science instrument actions from the SObRR.

7.6 *Commissioning*

All SOFIA next generation instruments will undergo commissioning. Each new SI must be commissioned prior to making the SI available to the general science community. The commissioning process characterizes the core performance of the SI and includes, but is not limited to, completion of a commissioning plan, completion of the commissioning flight tests per the commissioning plan, and documenting the results of the commissioning in an SI commissioning report. Commissioning results will be reviewed at the LSP Review.

7.7 *Post-Commissioning / Pre-Acceptance Support*

There is an approximately 2-year period between successful completion of SI commissioning and acceptance of the instrument as a facility science instrument. During this period the SI team will conduct science flights to complete their Legacy Science Program as well as conduct and support science flights for science proposals, selected through a competitive process, for use of the instrument by the general science community. During this period the SI team will also train SMO personnel on how to independently maintain and operate the instrument in preparation for the transition of the instrument from the instrument developer to NASA.

7.8 *SI Acceptance Process*

After the successful completion of the instrument Operations Acceptance Review (OAR), all actions from the OAR that are identified as being required for formal acceptance must be resolved and closed out. Once this is accomplished, the OAR Chair must then inform and obtain concurrence from the OAR Panel that the actions have been successfully closed.

The SOFIA SI Development Manager will coordinate signoff of NASA and SOFIA level acceptance documentation. Once this documentation is signed, the SOFIA Mission Operations team takes full responsibility for the operation and maintenance of the instrument. This entire process should be completed within 45 days after the OAR.

Review of Operations Acceptance Review documentation/presentation, instrument science and technical performance verification matrix, instrument ICD requirement verification matrix, software deliverables, and the commissioning report by NASA Quality Assurance will act as the Functional Configuration Audit (FCA) per SOF-NASA-PLA-PM21-2090, SOFIA Quality Plan [SQP] and SOF-DF-PLA-PM03-1054, SOFIA Program Configuration Management Plan (CMP).

7.9 *SI Retirement*

Each science instrument should reliably contribute high quality science observations that maximize the scientific return of flight opportunities and the unique capabilities of SOFIA. Instruments that do not demonstrate sufficient science productivity will be removed from the suite of instruments available to the general observing community.

The retirement of Science Instruments is necessary in order to keep the number of supported instruments available to the SOFIA observer community at a manageable level and to make way for new instrumentation by freeing up resources including funding, personnel, and flight hours. Instruments owned by NASA will be retired after a time at which the cost of their maintenance and support is no longer commensurate with their ability to competitively deliver science.

On a regular basis, the Science Instrument Advisory Group (SIAG) will review the suite of instruments available to the general observing community, and formulate a recommendation to either retire the instrument, or to continue operations, possibly under specific conditions.

If the review results in the recommendation to permanently retire an instrument from SOFIA service, the SMO Director and NASA Project Scientist will communicate this recommendation to the NASA Program Scientist and the SMD Astrophysics Director and recommend the final disposition of the instrument and supporting hardware (e.g., to be returned to the developing institution, made available to new developers, placed in storage at NASA). The NASA SMD Director of Astrophysics has final authority to decide on retirement or replacement of a science instrument.

8 Airworthiness Process

The primary purpose of SOFIA science instrument airworthiness certification is safety. Receiving airworthiness certification will significantly reduce the likelihood that either the aircraft or the personnel onboard will be harmed. The guidelines presented in this handbook follow those of the NASA Armstrong Flight Research Center Flight Safety and Review Process as outlined in AFOP-7900.3-023. The S&MA and Airworthiness Certification requirements that are verifiable (i.e., those for which specific objective evidence of verification closure are required) will be found within the *SOFIA Science Instrument System Specification*, SOF-AR-SPE-SE01-2028.

The following are topics that pertain to the airworthiness of a science instrument:

- Anything that can cause injury to personnel
- Anything that can cause a fire
- Commands by one system to others that result in hazardous conditions
- Anything that affects the aircraft pressure boundaries
- Foreign Object Damage (FOD) and equipment security
- Pressure systems
- Cryogens
- Toxic substances
- Radiation, both ionizing and non-ionizing

The purpose of this airworthiness and certification procedures chapter is to lead a SOFIA science instrument builder through the certification process with information and examples of all aspects of an instrument design that are required to comply with NASA airworthiness regulations. These requirements include mechanical and electrical design and analysis, instrument construction, testing, hazard identification and analysis, operations, and instrument maintenance.

Certification is not difficult, but it does require following specific steps from preliminary design through instrument construction, installation, operations, and maintenance for the purpose of maintaining a safe environment aboard the Observatory.

8.1 Science Instrument Certification: General Process & Overview

8.1.1 Science Instrument Airworthiness Team

The Science Instrument Airworthiness Team (SIAT) is a group of engineers within the SOFIA Program that review the instrument for airworthiness. The Science Instrument Airworthiness Team (SIAT) is the verification authority for airworthiness requirements. The SIAT members consist of specialists from NASA and include: flight operations engineers, structural engineers, system safety personnel, and quality assurance representatives.

Science Instrument airworthiness is established by the verification of the SIAT requirements in the *Science Instrument System Specification* (SOF-AR-SPE-SE01-2028) and the ICDs called out in section 3.11 of the specification. The SIAT is the verification authority for a subset of these requirements, the complete set of which comprises the airworthiness requirements. The verification of these requirements will result in the SIAT releasing an airworthiness letter to the chair of the Airworthiness & Flight Safety Review Board (AFSRB) endorsing the airworthiness of the instrument and representing the instrument at the AFSRB meetings. The criteria the SIAT uses to determine if the SI is airworthy is listed in Appendix C of the *SOFIA Science Instrument Development Process and Deliverable Requirement* (SOF-NASA-SOW-PM91-2094) document. The risks specifically associated with operating the science instrument onboard SOFIA will be incorporated with the risks of the observatory as one entity. Final airworthiness approval of a science instrument as part of the SOFIA platform will be determined by the AFSRB.

8.1.2 Flight Readiness Review

The Flight Readiness Review Board is a group of AFRC engineers that conduct an independent review and assessment of the entire SOFIA aircraft configuration and operation and assure that proper, adequate planning and preparation have been accomplished, resulting in the project being conducted in an acceptable, safe manner. This review should include, where applicable, the design, fabrication, performance, and documentation of all software and hardware associated with the project as well as ground and flight operational procedures. The SIAT was established as a subcommittee of the FRR to focus on evaluating the airworthiness and safety aspects of the science instrument designs. This assessment is revisited whenever the SI configuration is changed, to ensure that the airworthiness approval granted by the FRR Board is still valid in the current flight configuration.

8.1.3 Airworthiness and Flight Safety Review Board

The Airworthiness and Flight Safety Review Board (AFSRB) is tasked with ensuring the flight safety of all projects conducted at Armstrong Flight Research Center. The AFRC Center Director appoints the chairperson and the members of the AFSRB. The AFSRB members are the line organizational Directors, ex Officio members, the Chief Pilot, and the Chief of the Safety Office. Other US Government personnel may be appointed to the AFSRB as necessary to provide a thorough review. The AFSRB will declare the airworthiness of the SOFIA aircraft configuration for a given flight series—with an instrument or instruments installed—following a Technical Briefing (a.k.a. Tech Brief) on that configuration. Once SOFIA has received the airworthiness approval for an instrument from the AFSRB, it is unlikely the program will need to re-present on that instrument unless changes that affect airworthiness are made to the instrument configuration.

8.2 SOFIA Contacts

As a Science Instrument Team pursues airworthiness certification, inquiries to SOFIA team members can be made at any time. Contact the SOFIA SI Development team at Ames Research Center or your Contracting Officer Representative (COR) with technical questions. Those technical questions will be forwarded to the appropriate technical expert.

9 Instrument Change Control

The SI developer should work all changes through the SOFIA SI Development Manager. After the instrument team has submitted their airworthiness documentation and completed SOFIA SI System Specification & ICD verification, the SIAT and SE&I need to be alerted to any changes to the instrument that could impact airworthiness, SI System specification, or ICD compliance. The Program also needs to be alerted to any changes that could change the scientific performance or characteristics of the instrument.

9.1 *Instrument Maintenance Logbook*

In order to ensure that the instrument team does not unwittingly make changes that impact airworthiness, once the initial airworthiness data package has been submitted, the instrument team will maintain an Instrument Maintenance Logbook. Whenever an instrument component that is part of the flight system (i.e., opto-cryo assembly, counterweight rack, PI rack, and associated harnesses) is modified, the instrument team will make an entry into the notebook indicating the date of the change, the reason for the change, and a description of the change made.

The Instrument Maintenance Logbook will be available for review by the SIAT at their request at any time. The SIAT will review the notebook several weeks prior to instrument pre-install reviews and report to the SOFIA SI Development Team whether they have any concerns about the instrument history since the previous review so those issues can be addressed prior to or at the pre-install review.

While it would be convenient for the notebook to be electronically available for project review, for practical matters a physical notebook that remains with the instrument is acceptable.

9.2 *Instrument Configuration Sheet*

The Instrument Configuration Sheet establishes, for each installation, a record of the instrument hardware and software configuration on the aircraft. The instrument configuration sheet will be included in Observatory Configuration Change Requests for the aircraft, serving as documentation for the instrument configuration for a particular installation. The SMO may use these instrument configuration records for instrument anomaly investigation and science data processing.

The Instrument Configuration Sheet is updated by the Instrument Team (or Instrument Scientist for accepted instruments) and submitted to the SOFIA Program prior to each pre-installation review. A description of the content for the Instrument Configuration Sheet is in *the SOFIA Science Instrument Development Process and Deliverable Requirements* document (SOF-NASA-SOW-PM91-2094).

9.3 *Document Configuration Management*

Systematic document configuration management ensures that there are no differences between the configuration of the “as-built” product and the configuration defined in design documents. Product configuration documents include:

- The currently authorized revisions of all applicable drawings and referenced specifications, plus any unincorporated “redlines” and any approved but unincorporated engineering change orders
- As-run procedures for production, assembly, inspection and test, including any “redlines”
- Waivers, deviations and other nonconformity documents.

Instrument documents delivered to the SOFIA program will be assigned SOFIA document numbers and entered into the SOFIA configuration control system when delivered.

10 Environments and Design Guidelines

This section presents definition of the environments to which SIs will be exposed and related design considerations and guidelines. These are offered as design guidance, not verifiable requirements, and are intended to support and dovetail with those in the *Science Instrument System Specification* (SOF-AR-SPE-SE01-2028).

10.1 *Cabin Environmental conditions*

10.1.1 Temperature and Humidity

Generally speaking, the SOFIA 747-SP cabin environmental conditions during flight provide a comfortable shirt-sleeve environment characteristic of commercial airliners, with the cabin temperature maintained at around +20°C ± 4°C. It should be noted that the pressurization and air conditioning systems for a 747-SP aircraft do not provide stable conditions such as in typical office or laboratory spaces, and air temperature shifts may occur on timescales of a few minutes.

Typically, the humidity of the SOFIA 747-SP aircraft cabin air is quite low during stratospheric flight.

It should also be noted that SI equipment in the SOFIA 747-SP aircraft cabin may at times be subject to significantly more extreme temperature and humidity environments. The nominal base of operations in Palmdale, CA experiences wide variations in ambient temperature characteristic of the California high desert. While the SOFIA aircraft is nominally housed in an enclosed hangar, there are situations that result in the aircraft being left unpowered on the tarmac during the daylight hours, and this can lead to high cabin temperatures. Also, for tropical deployment sites, high ambient temperatures combined with relative humidity approaching 100% should be anticipated on a routine basis.

In an effort to better characterize the operating temperature environments for observatory systems in various locations aboard the SOFIA aircraft, temperature recording instrumentation was flown during 2016, including operations based out of both Palmdale, CA and Christchurch, NZ. Based on the range of operational temperatures recorded in the aft cabin area documented within System Test Report SOF-NASA-REP-SV03-2115, 2016 Cabin Temperature Characterization Results, an SI operating temperature environment of 55° F (12.8° C) to 85° F (29.4° C) has been specified within SE01-2028.

For transportation of SIs in the SOFIA cargo hold using an SI Shipping Assembly, a somewhat less benign non-operating temperature range should be anticipated and considered in the instrument design and transportation plan. SI designs that have known susceptibilities to storage at elevated temperatures (e.g., detectors, ADR salt pills, etc.) may need to assess and mitigate the potential for warm-up of internal components due to heat-soak.

Modifications to the aircraft Environmental Control System (ECS) ducts implemented in early CY2018 do provide tighter control of the operational temperature environment in the aft cabin area, but this has not yet been well characterized. The results of these efforts will be captured in a future release of this handbook.

10.1.2 Pressure

The SOFIA cabin is pressurized in flight and generally maintains a pressure altitude of less than approximately 8,000 ft. The actual cabin pressure is settable by the flight crew at the flight engineer station. The telescope Nasmyth tube Gate Valve assembly, when closed, acts as the pressure barrier between the pressurized cabin and the unpressurized telescope cavity. When this Gate Valve assembly is open for observations, the instrument flange or instrument pressure coupler mounted in the interface flange forms the pressure barrier between the pressurized cabin and the unpressurized telescope cavity.

The pressure differential is generally maintained at 8.9 psid or less, with an emergency pressure relief valve setting of 9.4 psid (maximum emergency relief pressure is 9.75 psid).

10.1.2.1 Arcing and Coronal Discharge, and design considerations

Though the SOFIA 747-SP cabin is pressurized and generally maintains a pressure altitude of approximately 8,000 ft., reduced atmospheric pressure, combined with typically low relative humidity, increases the possibility of coronal discharge and arcing between high voltage components and ground potential.

High voltage leads should be sufficiently insulated to prevent flashover. Normal cabin pressure is equal to 7,500 ~ 8,000 ft, and for a given voltage the break down distance is ~1.3 x greater than at sea level pressure. For equipment exposed to the stratospheric conditions outside at 41,000 ft altitude (i.e., in those portions of the SI assembly that are exposed to stratospheric atmosphere when the gate valve is open), the equivalent distance is greater by a factor of 5 x greater than at sea level.

These conditions should guide SI equipment design with respect to lead separation, insulation for high voltage components, avoiding sharp bends, solder peaks, and other best practices. High voltage components and cables should be clearly marked and, where practical, electrical and mechanical interlocks should also be used. Contacts on terminals carrying 50 volts or more to the ground should have guards to prevent accidental contact by personnel.

The SOFIA Electrical Power Distribution Subsystem (EPDS) includes an Emergency Power Disconnect (EPD) relay, which removes all power from the SI power buses (including UPS-protected buses) in the event of a cabin decompression. This EPD relay will open when the pressure altitude of the SOFIA cabin gets to 20,000 ft.

All SI equipment with internal high voltages, including COTS items such as oscilloscopes, spectrum analyzers, etc., should be assessed for ability to withstand the reduced atmospheric pressures associated with pressure altitudes of up to 20,000 ft. without arcing or corona discharge (many COTS items are only certified up to pressure altitudes of ~10,000 ft., and modifications such as additional insulation or potting with dielectric materials may be indicated).

10.2 Nasmyth Tube environmental conditions

Once the telescope Gate Valve is open for in-flight observatory operations, the telescope Nasmyth tube and SI mounting interface tub are in communication with the very cold, stratospheric in the telescope cavity, though the temperatures are likely to be somewhat higher due to radiative, conductive and convective heat transfer from the TA electronics, cabin environment and attached instrument assemblies, and the absence of significant air circulation (e.g., forced convection). Temperature gradients may also exist, and to the extent that these may affect image quality, efforts will be made to characterize and if necessary minimize such gradients using fans or blowers.

Unsteady Computational Fluid Dynamics (CFD) flow simulations and acoustic models of the TA cavity and Nasmyth tube have predicted acoustic resonance patterns (“organ pipe” modes) at 28 Hz and 84 Hz, which could lead to an amplification of acoustic energy at the SI mounting flange with respect to the pressure fluctuations within the SOFIA TA cavity.

To address concerns regarding microphonic pickup by sensitive SI receivers, measurements of Nasmyth tube acoustic energy were made by DSI during SOFIA Flight 046. Figure 10.2-1 shows the installed location of two 1 psid microphones that were installed within the TA Nasmyth tube, while

Figure 10.2-2 defines the aligned “Reference Configuration” and the misaligned “Configuration B” Figures 10.2-3 and 10.2-4 present the measured Power Spectral Densities (PSDs) from the two microphones in both the aligned TA “Reference Configuration” and the misaligned “Configuration B” as a function of frequency, at a typical observing altitude of 43,000 ft. and at a lower altitude of 37,000 ft., respectively. Figure 10.2-5 presents the Sound Pressure Levels (SPLs) measured by the microphones during flight at 43,000 ft., and also shows the SPL at the 37,000 ft. altitude (aligned TA “Reference Configuration” only), as well as CFD simulation results for both TA configurations at 41,000 ft.

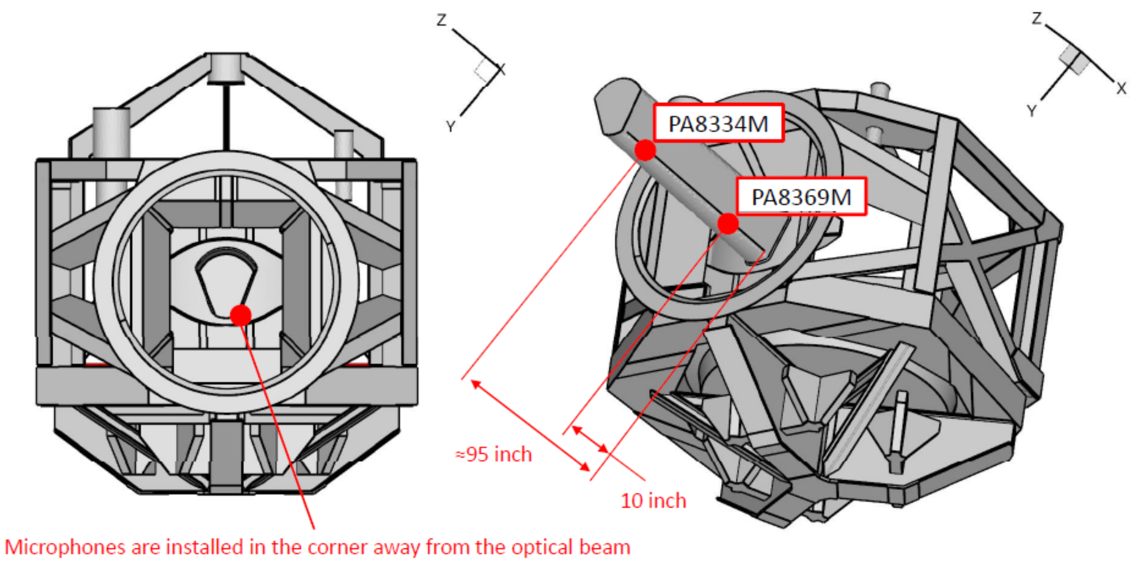

Figure 10.2-1: Positioning of two 1 psid range microphones within Nasmyth tube during Flight 046

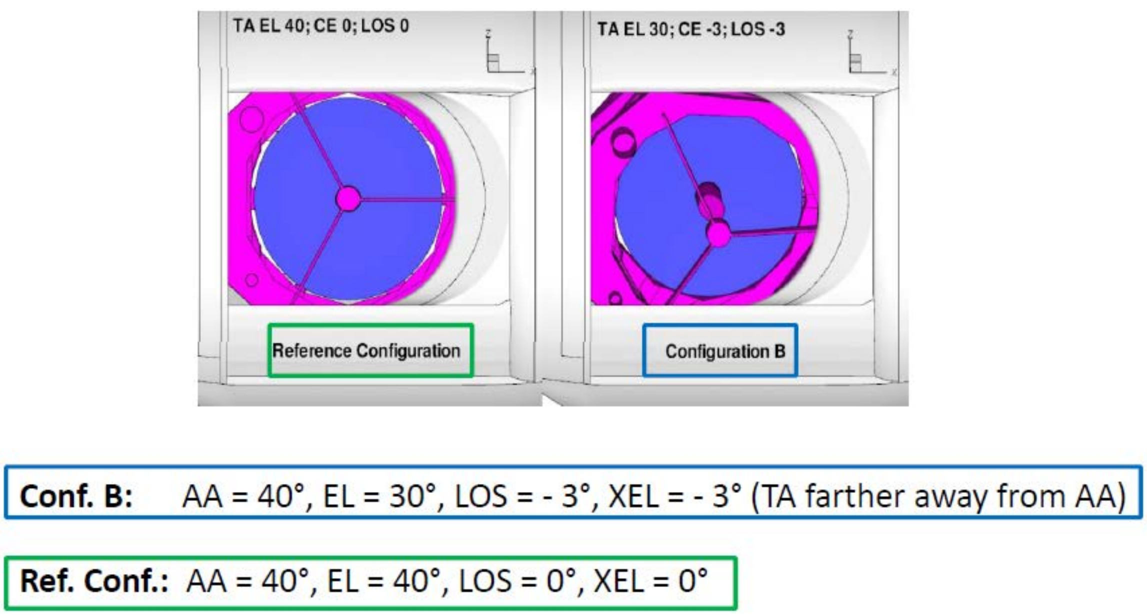

Figure 10.2-2: Aligned “Reference Configuration” and misaligned “Configuration B” considered in DSI study

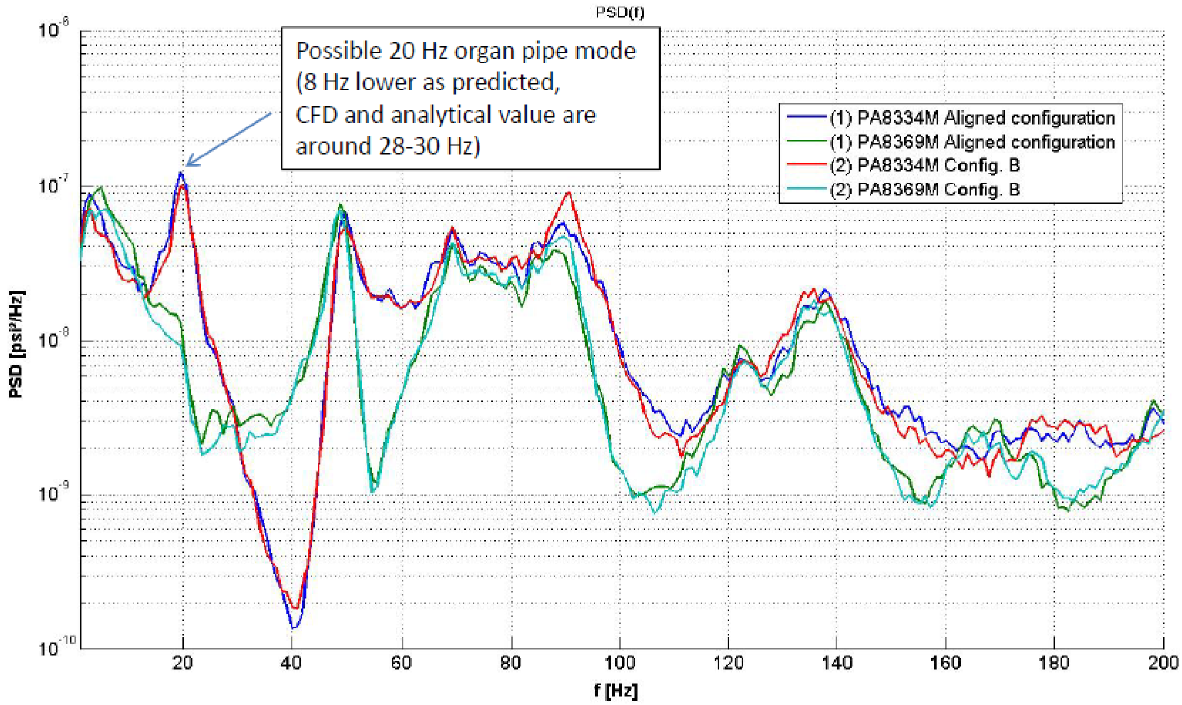

Figure 10.2-3: Power Spectral Density (PSD) from microphones during flight at 43,000 ft.

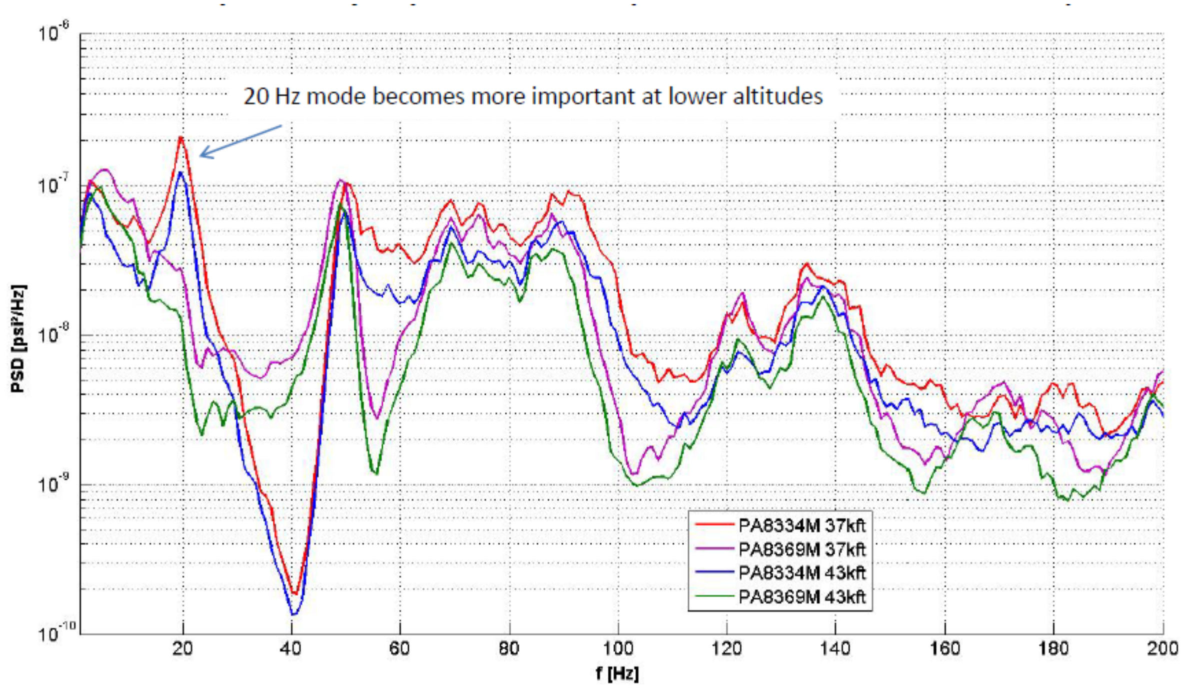

Figure 10.2-4: Power Spectral Density (PSD) from microphones during flight at 37,000 ft.

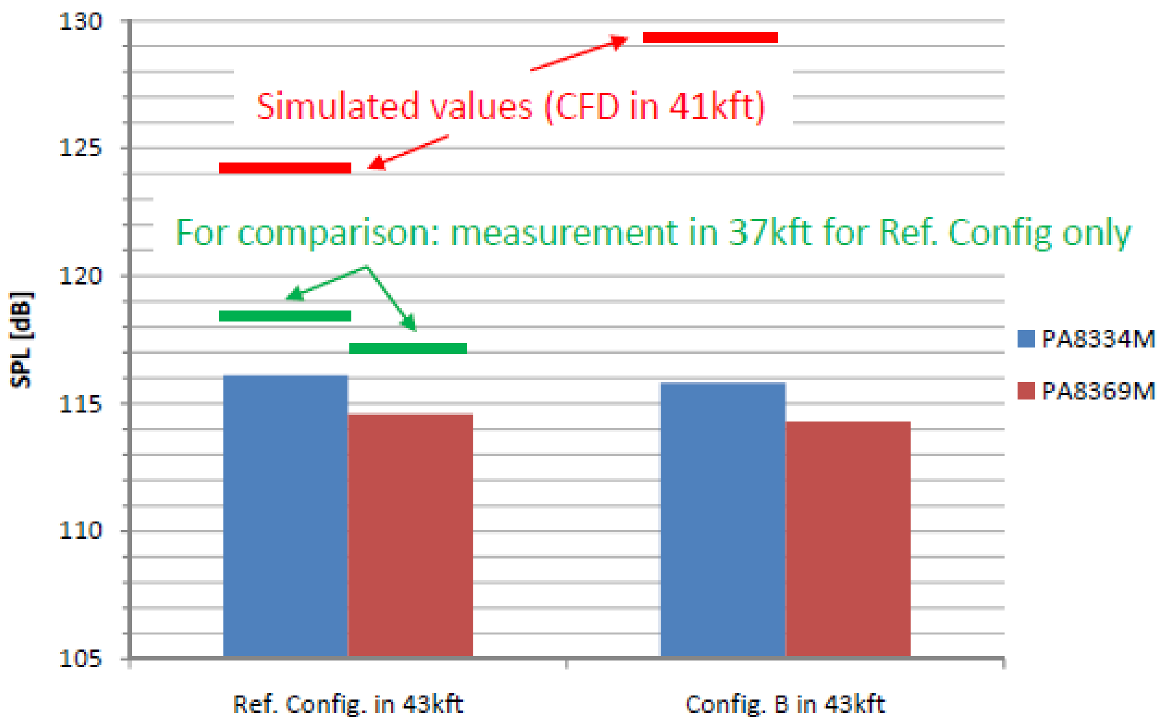

Figure 10.2-5: Flight test data Sound Pressure Level (SPL) from microphones during flight at 43,000 ft.

The results of these measurements were quite encouraging, as they showed that the SPLs and the amplitudes of the "organ pipe" modes were ~2 orders of magnitude lower than had been predicted by CFD simulations and also indicated very little sensitivity to TA alignment configuration. The 1st mode (predicted at 28 Hz) was observed at 20 Hz, and while it was far lower than predicted by the CFD simulations and acoustic models, the results did reflect the expected result that it becomes more significant at lower altitudes due to the higher atmospheric density.

The SPL of 116 dB close to the Nasmyth tube gate valve at 43,000 ft. corresponds to a pressure fluctuation of 13 Pa (RMS), while the SPL of 118.5 dB at 37,000 ft. corresponds to a pressure fluctuation of 17 Pa (RMS).

10.3 *Vibration and Dynamic Environment*

The SOFIA 747-SP aircraft exhibits a low level of vibration characteristic of large jet aircraft. In addition, the instrument assembly mounted on the TA flange is isolated from the airframe vibrations during observing integration periods by the telescope Vibration Isolation Subsystem (VIS). The most severe vibration environment an instrument will experience is when the telescope assembly is caged and braked, which occurs during aircraft taxi, takeoff, landing, and maximum reverse thrust events. Caging and braking the telescope is a safety measure for the telescope assembly and aircraft that happens to result in a more severe vibration environment for instruments during these three specific phases of a flight.

Because of the relatively "benign" shirtsleeve environment of SOFIA's pressurized jetliner cabin, SE01-2028 does not require that SOFIA SIs or SI equipment be subjected to vibration and/or "thermo-vac" environmental acceptance testing (colloquially known as "Shake & Bake") in favor of a risk-tailored approach in which SOFIA environmental conditions are characterized and published, so that SI developers may make informed assessments and decisions to optimize mission success.

Developers of SIs with subsystems with known or suspected susceptibilities to vibrational resonances (e.g., optical bench stability, ADR suspension vibrational heating, etc.) are encouraged to review the measurements reported herein for use as inputs to dynamic modeling efforts, constraints or tuning of structure natural frequencies, and potentially random vibration testing.

In-flight vibration measurements have been made using a triaxial accelerometer during various phases of typical flights at the telescope flange with the telescope in caged and braked, locally and inertially stabilized and tracking configurations. Measurements were also taken at the Counterweight Rack (CWR), PI rack, on the SI Shipping Assembly in the SOFIA cargo bay, and on the aircraft floor seat track in the vicinity of the telescope “pit” and aft MCCS rack. These are provided within the captioned figures in this section as representative of the worst-case vibration environmental conditions to which instruments will be routinely subjected in flight.

10.3.1 Quasi-Steady Load Factors

Measurements taken at the aft seat track indicate that continuous accelerations during turns can be as high as 1.2g in Z for several minutes; shorter transients of 1.7g in Z due to turbulence (one “bump”), and even 3g in the Y (lateral) axis during takeoff have also been measured, however these are generally too short in duration to be considered quasi-steady load factors, and better quantified with the vibration characterization in subsection 10.3.2.

Table 10.3.1-1 presents 1 Hz flight dynamic load factor and angle data acquired during 9 flights of a Spring 2011 observing campaign, broken down by flight phase. Note that while these measurements capture airframe rather than TA-mounted dynamics, the load factors are quasi-steady and will be fairly representative of load factors for TA- and CWR-mounted SI equipment, in aircraft coordinates. The Max Nz value recorded for each flight is highlighted in blue text.

Figures 10.3.1-1 and 10.3.1-2 present these data graphically. Table 10.3.1-2 is a composite summary of the Min / Max values from this suite of 9 flights, also broken down by flight phase. Note that these 1 Hz data indicate that turbulence events during the cruise phase (i.e., during observations) yield higher load factors than runway taxi and even ascent operations, and confirms that lateral loads remain generally quite small.

Table 10.3.1-1: Flight Acceleration Data (1 Hz) by Flight Phases

Flight Data by Flight Phase, 1 Hz										
Flight	Phase	Alt A	Alt B	Nz	Ny	Nx	Pitch	Nxyz	Nxy	Nxyz Angle
54	Taxi	2275	2236	1.19	-0.07	0.22	-2.0	1.20	0.22	13.3
	Takeoff	2275	37503	**1.27**	-0.07	0.29	18.6	1.29	0.29	17.3
	Cruise	37506	43050	1.19	0.08	0.08	3.9	1.19	0.09	5.2
	Descent	43045	2280	**1.27**	0.10	-0.16	7.3	1.28	0.17	-9.8
55	Taxi									
	Takeoff	2924	38004	0.91	-0.03	0.27	13.4	1.09	0.27	14.8
	Cruise	38010	42912	0.83	0.06	0.07	3.6	1.17	0.07	4.1
	Descent	42896	2511	**1.28**	0.10	0.20	7.9	1.28	0.20	11.3
56	Taxi	2569	2537	0.85	0.07	0.22	-2.1	1.11	0.22	13.0
	Takeoff	2569	38001	0.82	0.07	0.28	15.8	1.18	0.29	15.9
	Cruise	37998	41023	0.84	-0.05	0.08	4.0	1.14	0.08	4.7
	Descent									
57	Taxi	2448	2413	**1.23**	-0.07	0.22	-2.1	1.25	0.22	12.8
	Takeoff	2448	37930	1.23	-0.07	0.28	16.1	1.25	0.28	16.7
	Cruise	37933	43041	1.16	-0.04	0.07	4.4	1.16	0.07	4.2
	Descent	43022	2454	0.78	-0.10	-0.18	8.8	1.19	0.18	-10.6
58	Taxi	2537	2539	1.18	-0.06	0.23	-2.0	1.20	0.23	13.1
	Takeoff	2537	38003	**1.19**	-0.06	0.32	14.1	1.21	0.33	17.3
	Cruise	38006	41037	1.17	0.03	0.08	3.9	1.17	0.08	4.3
	Descent									
59	Taxi	2462	2460	0.86	-0.10	0.25	-2.1	1.14	0.25	13.7
	Takeoff	2462	37004	**1.33**	-0.10	0.30	16.9	1.36	0.30	16.0
	Cruise	37007	43017	1.21	-0.06	0.09	4.9	1.21	0.09	5.4
	Descent	43008	2508	1.20	-0.07	-0.22	7.5	1.20	0.22	-12.1
60	Taxi	2486	2447	1.29	-0.10	0.22	-2.0	1.30	0.22	13.5
	Takeoff	2486	38008	1.29	-0.10	0.32	15.3	1.30	0.32	17.6
	Cruise	38008	42950	**1.52**	-0.05	0.08	6.3	1.52	0.08	4.6
	Descent	42946	2479	1.25	0.13	-0.19	8.1	1.26	0.19	-11.6
62	Taxi	2468	2436	**0.78**	-0.09	0.22	-2.0	1.23	0.22	12.7
	Takeoff	2468	38050	0.78	0.21	0.35	13.8	1.26	0.41	18.9
	Cruise	38054	43050	0.74	-0.07	0.08	4.2	1.21	0.09	5.1
	Descent	43049	2414	0.75	-0.11	-0.16	7.0	1.18	0.16	-9.6
63	Taxi	2625	2575	1.15	-0.10	0.21	-2.0	1.01	0.22	12.9
	Takeoff	2625	38863	0.79	-0.10	0.29	14.1	1.21	0.29	15.3
	Cruise	38863	43101	**1.22**	0.05	0.10	6.3	1.23	0.10	5.8
	Descent	43089	2553	1.22	-0.07	-0.17	7.5	1.22	0.17	-9.7

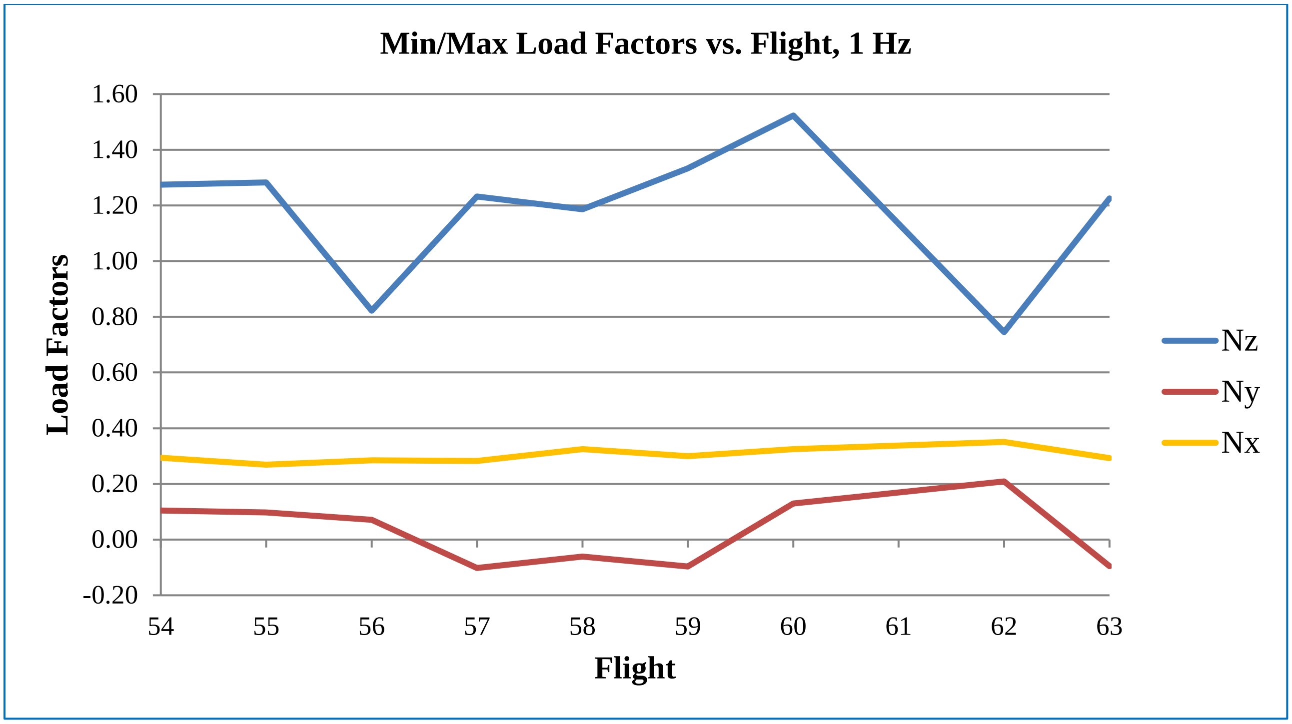

Figure 10.3.1-1: Graphical Summary of Flight 54 through 63 Min / Max Accelerations (1 Hz)

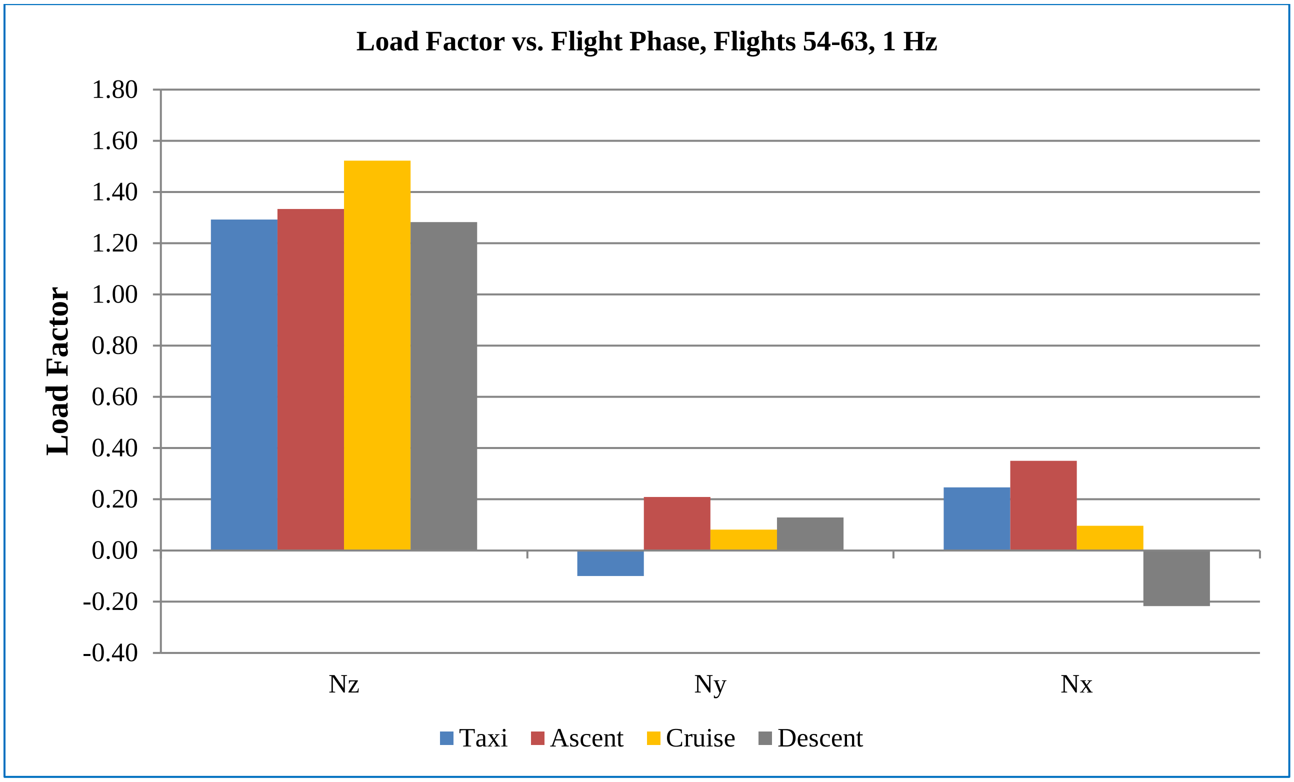

Figure 10.3.1-2: Graphical Summary of Flight 54 through 63 Min / Max Accelerations (1 Hz) broken down by Flight Phase

Table 10.3.1-2: Summary of Flight 54 through 63 Min / Max Accelerations (1 Hz) broken down by Flight Phase

Flight 54-63 Min / Max Values by Flight Phase, 1 Hz							
	Nz	Ny	Nx	Pitch	Nxyz	Nxy	Nxyz Angle
Taxi	1.29	-0.10	0.25	-2.10	1.30	0.25	13.70
Ascent	1.33	0.21	0.35	**18.63**	1.36	0.41	**18.90**
Cruise	**1.52**	0.08	0.10	6.30	**1.52**	0.10	5.84
Descent	1.28	0.13	-0.22	8.83	1.28	0.22	-12.06

10.3.2 Vibrations

In addition to the quasi-steady dynamic load factor measurements characterized above, a triaxial accelerometer head and "tattletale" vibration logger were flown on multiple SOFIA missions in order to characterize the vibration environment in three SI equipment locations: the TA IMF / SI Flange, a PI Rack, and a CWR. Earlier measurements have also been made with the accelerometer head mounted to seat track at the aft portion of the SOFIA main deck (near the TA pit), an aft MCCS rack, an upper bay of the MD Console, and the TA Balancing Plate Assembly (BPA), behind the CWR mounting location.

Detailed reports from each of these flights were produced by the AFRC Instrumentation group, and are available from the SOFIA SI Development group upon request. These reports generally include a summary of the data logger start and stop times, with a description of the flight phase and any notable conditions (e.g., turbulence, climb to new FL, etc.), and a variety of plots for the Longitudinal (X), Lateral (Y), and Normal (Z) axes: PSD plots (and corresponding composite G_{rms} levels) for the worst-case vibration levels encountered during the flight, time-series plot of Min / Max load factors, and time-series plot of G_{rms} vibration levels.

In addition to the primarily graphical information presented in the aforementioned summary reports and excerpted in the subsections below), the SOFIA SI Development group also has files that capture numeric frequency-domain 3 axis average vibration PSDs from 1 to 2000 Hz, as measured in level cruise at the TA IMF / SI Flange during 2 SOFIA flights. These data will also be made available upon request to support analyses by SI development teams (e.g., propagation to SI cryostat cold plate, optical bench, and focal plane).

Rather than attempt to include all of these charts and summaries in this document, we have opted to "cherry pick" a subset of these that are representative of both typical / nominal operating conditions in the three (3) SI equipment locations aboard SOFIA, as well as for routine events such as turbulence, landings and high-speed ground maneuvers, etc.

The authors would like to thank Phil Hamory of AFRC-RD for providing and operating the accelerometer and tattletale recorder, as well as the post-flight processing and reporting of the vibration data. We would also like to thank Tim Krall of AFRC-OE for his assistance with integration of the hardware and coordination with the Instrumentation group to obtain these measurements.

10.3.2.1 Aft Seat Track

The triaxial accelerometer head was placed in the Brownline seat track on the starboard side of the aft main deck, just forward of the R/H CLA Disconnect Panel U2 during SOFIA Flight 55 (take-off on 5/5/2011). The worst-case vibrations during this flight were observed during the take-off phase. Figure 10.3.2.1-1 shows the time history of the G levels recorded by the accelerometer during this phase.

It is worth noting that the +3 G lateral axis load factor picked up by this accelerometer and recorder is a very short-lived transient (< 1 millisecond) and as a result is not represented in the 1 Hz flight data set reported for the take-off phase from this same flight in the quasi-steady load factors section 10.3.1, above.

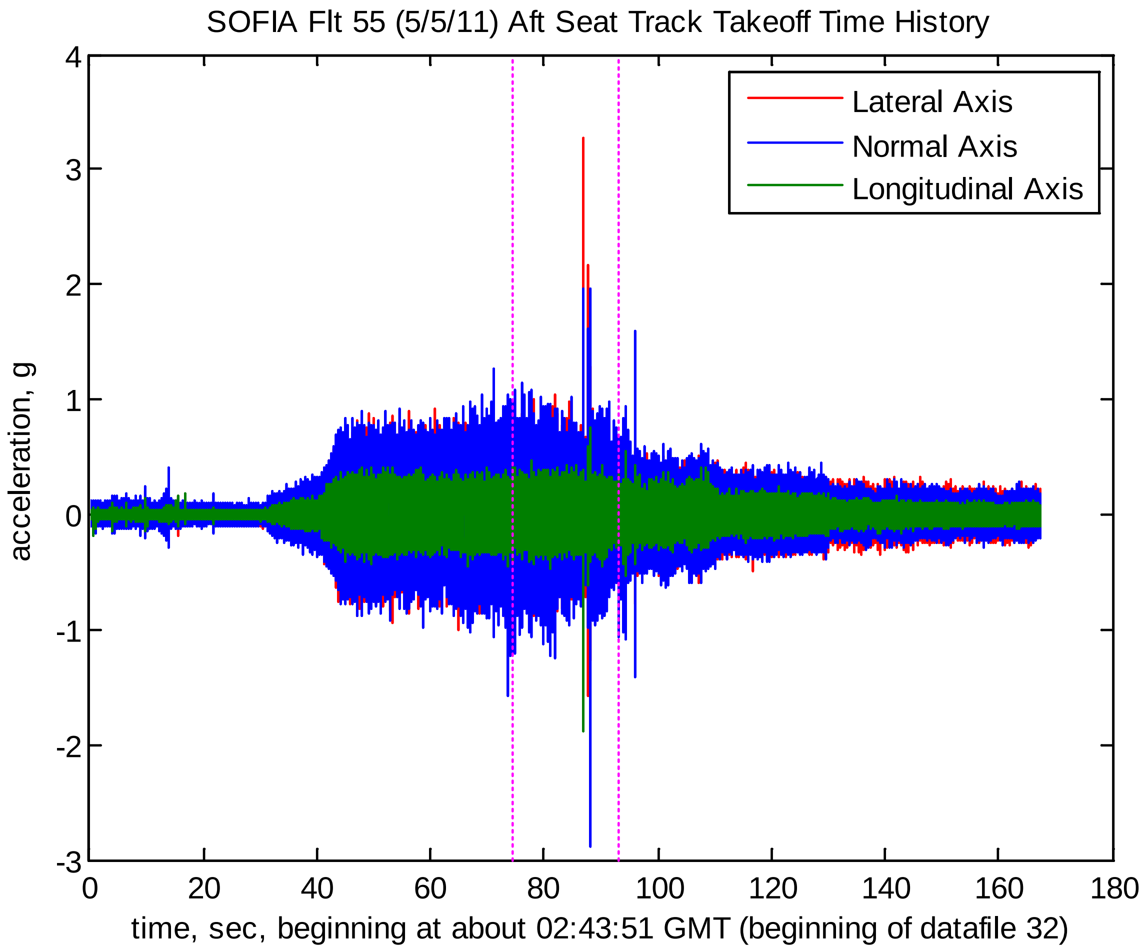

Figure 10.3.2.1-1: Time history of loads measured at aft seat track on SOFIA main deck during take-off flight phase

The dashed vertical lines define the start and end of datafile 36, which is the 18.6 second period which includes the worst-case loads. Figure 10.3.2.1-2 shows the Power Spectral Density (PSD) content of the vibrations measured in each axis during this 18.6 second period.

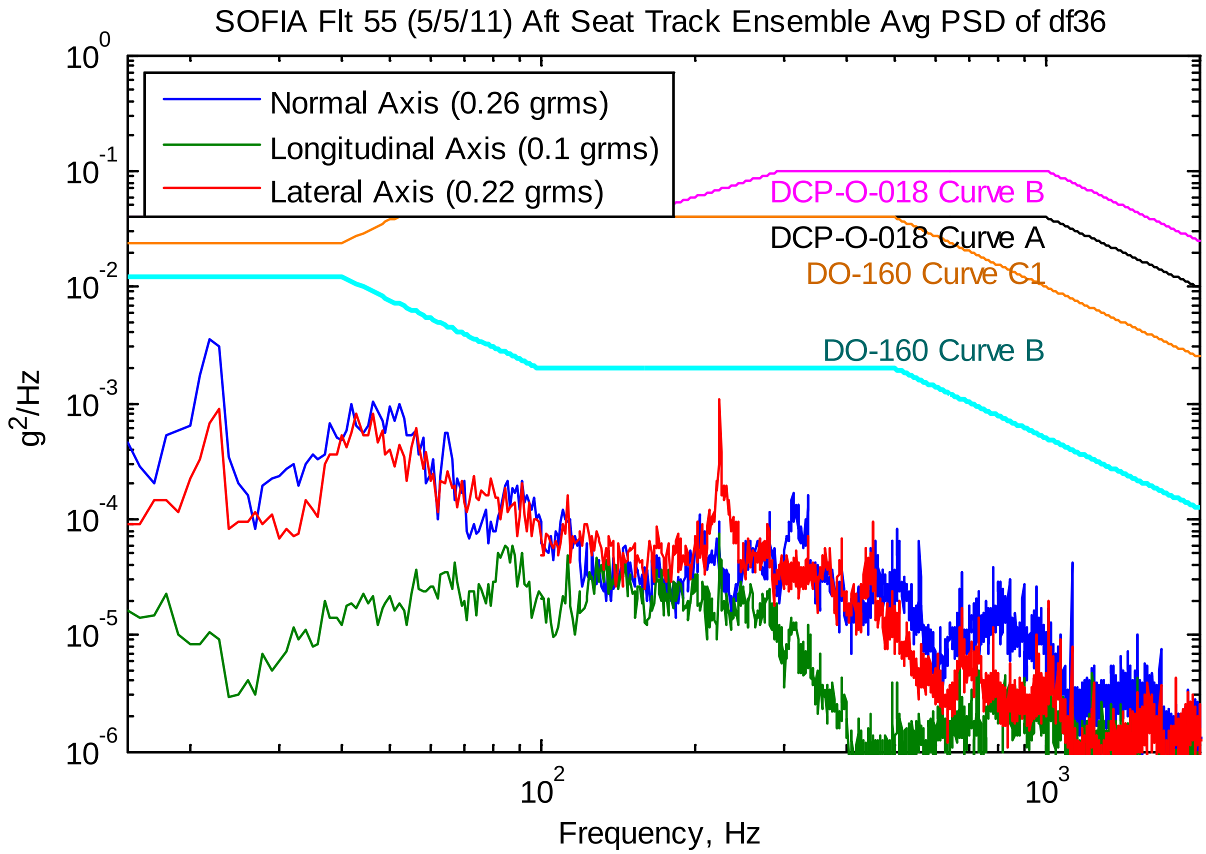

Figure 10.3.2.1-2: PSD of vibrations measured at aft seat track on SOFIA main deck during worst-case 18.6 seconds of take-off flight phase

Note that even measurements obtained from this non-isolated location of the SOFIA airframe during worst-case take-off flight phase exhibit low composite vibration levels of 0.1 G_{rms} in the Longitudinal (X) axis, 0.22 G_{rms} in the Lateral (Y) axis, and 0.26 G_{rms} in the Normal (Z) axis.

As expected, the vibrations recorded during observations in level flight at 38,000 ft, as shown in Figure 10.3.2.1-3, below, are even lower, with composite vibration levels of 0.06 G_{rms} in the Longitudinal (X) axis, 0.13 G_{rms} in the Lateral (Y) axis, and 0.18 G_{rms} in the Normal (Z) axis.

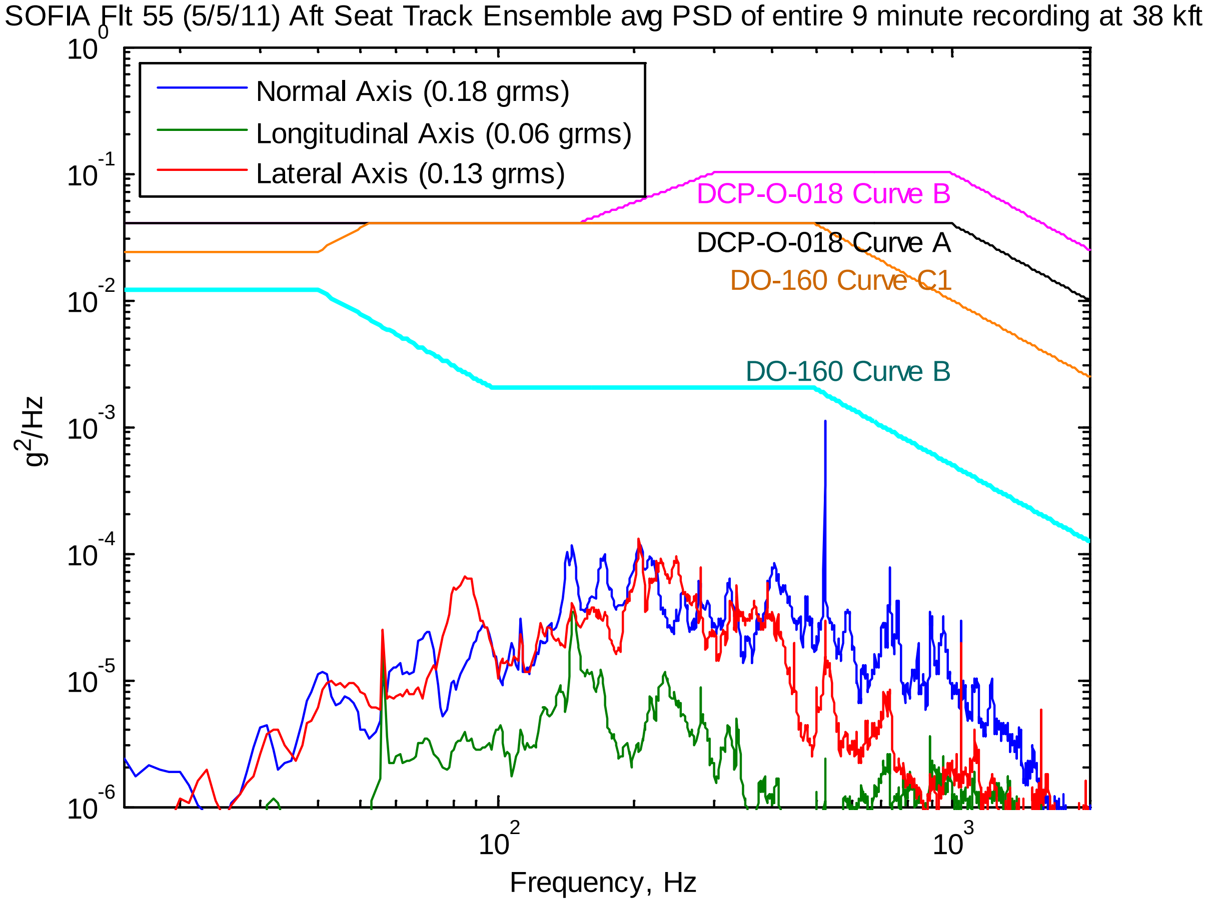

Figure 10.3.2.1-3: PSD of vibrations measured at aft seat track on SOFIA main deck during 9 minutes of recording in level flight at 38,000 ft.

Finally, measurements made during the descent flight phase, shown below in Figure 10.3.2.1-4, exhibit slightly higher vibration levels in the Longitudinal (X) axis, while the vibration levels in the Lateral (Y) and Normal (Z) axes are slightly lower.

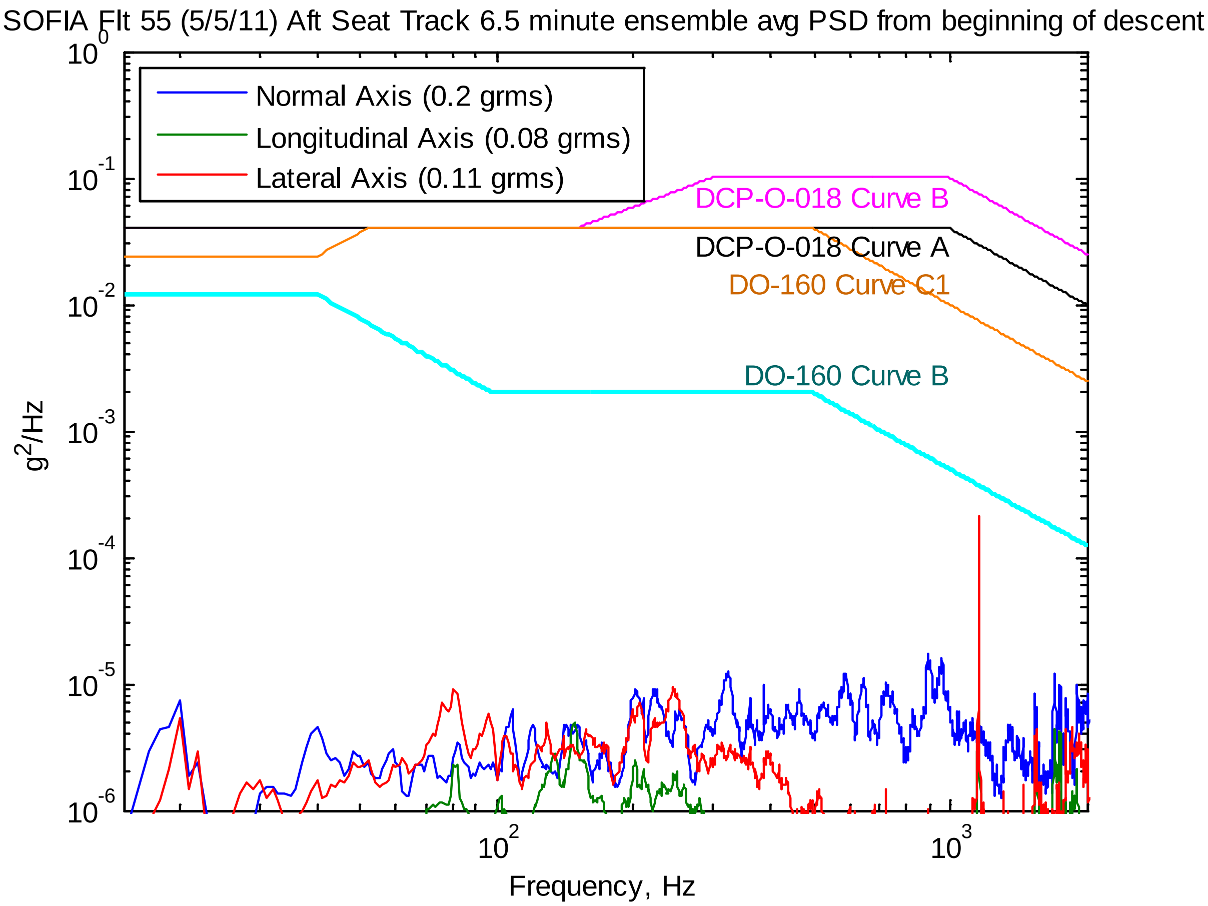

Figure 10.3.2.1-4: PSD of vibrations measured at aft seat track on SOFIA main deck during 6.5 minutes of recording starting with descent from observing altitude

10.3.2.2 TA IMF / SI Flange (FORCAST)

Vibration measurements made at the TA IMF / SI Flange are expected to be of most interest to SI developers, as this is the structure to which the SI assembly, with the SI cryostat, optics, and focal plane detectors are rigidly mounted. Accordingly, measurements using the accelerometer and "tattletale" datalogger were made over 6 SOFIA flights, resulting in a very rich dataset.

In the interest of keeping this section concise and on point, we are publishing herein just a fairly tidy subset of these measurements, with a focus on those that characterize both typical / nominal operating conditions, as well as routine bumps and "knocks" that should be anticipated due to the dynamic nature of this observatory.

For these measurements, the triaxial accelerometer head was affixed to the "top" of the TA IMF, just aft of the FORCAST SI flange. See Figure 10.3.2.2-1 for an overview and detailed view of the accelerometer placement.

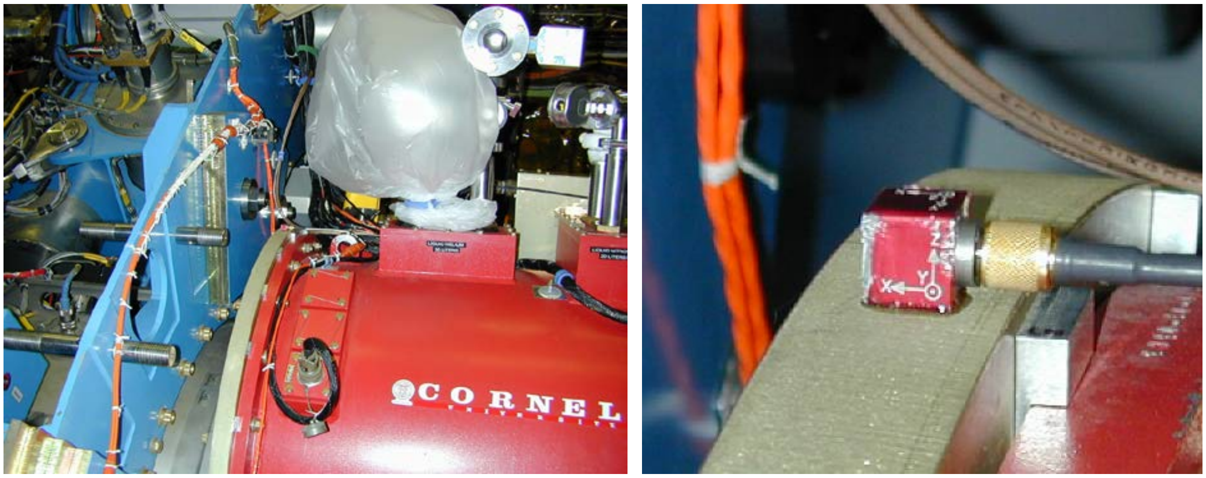

Figure 10.3.2.2-1: Overview and detailed view of the placement of the triaxial accelerometer head on "top" of the TA IMF, just aft of the FORCAST SI flange (red)

Note that these for measurements, the reported Aircraft Longitudinal, Lateral and Normal coordinate axes (X, Y, Z) should be interpreted as representing the corresponding TA coordinate axes u, v, w, due to the rotation of the TA w/ respect to the airframe in the Elevation (EL), and to a lesser extent, the Line of Sight (LOS) and Cross-Elevation (XEL) axes.

For SOFIA Flight 56 (take-off on 5/10/2011), the datafile with the worst-case composite G_{rms} levels was recorded during take-off (see Figure 10.3.2.2-2), while the datafile with the largest amplitude PSD component was recorded during ground taxi operations (see Figure 10.3.2.2-3).

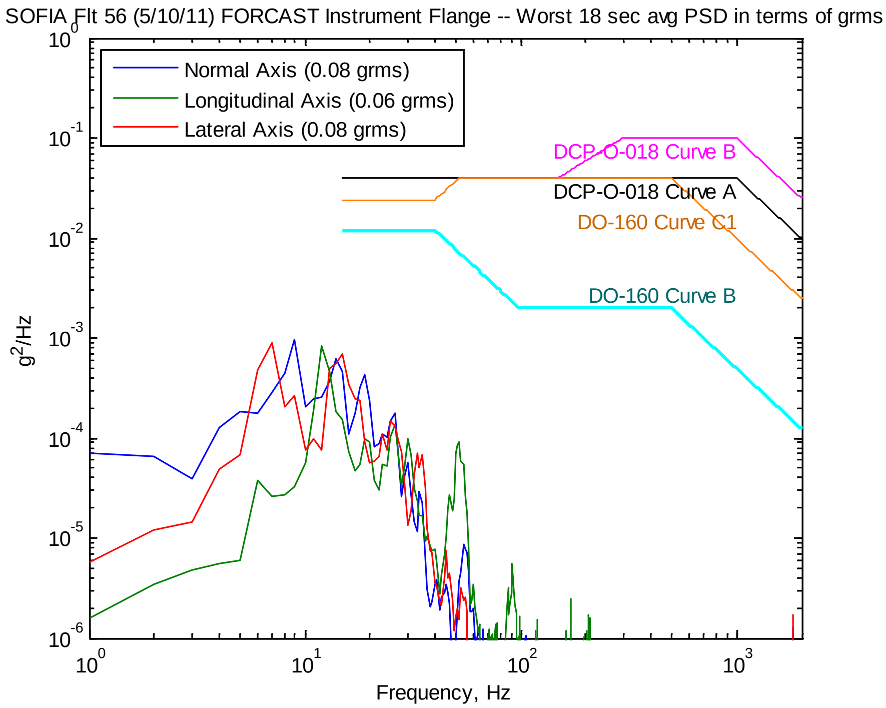

Figure 10.3.2.2-2: PSD of datafile reflecting worst-case composite G_{rms} vibration levels (take-off)

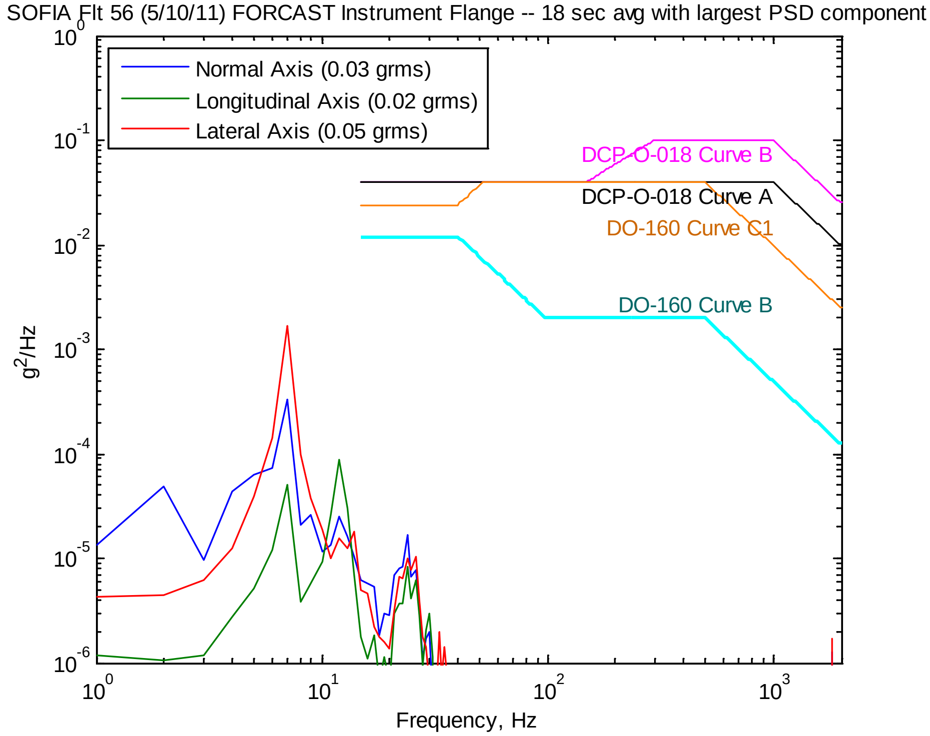

Figure 10.3.2.2-3: PSD of datafile reflecting largest amplitude PSD component (taxi)

To characterize a good range of flight conditions, we have selected and presented 3 datasets, below (these also represent the flight segments for which we have available the numeric frequency-domain 3 axis average vibration PSDs from 1 to 2000 Hz from the datalogger).

Figure 10.3.2.2-4 represents the PSD averaged over a 7 minute segment acquired during level flight at 38,000 ft., with light turbulence and the TA uncaged / unbraked and on the vibration isolation system, but in inertial stabilization mode (not tracking an object).

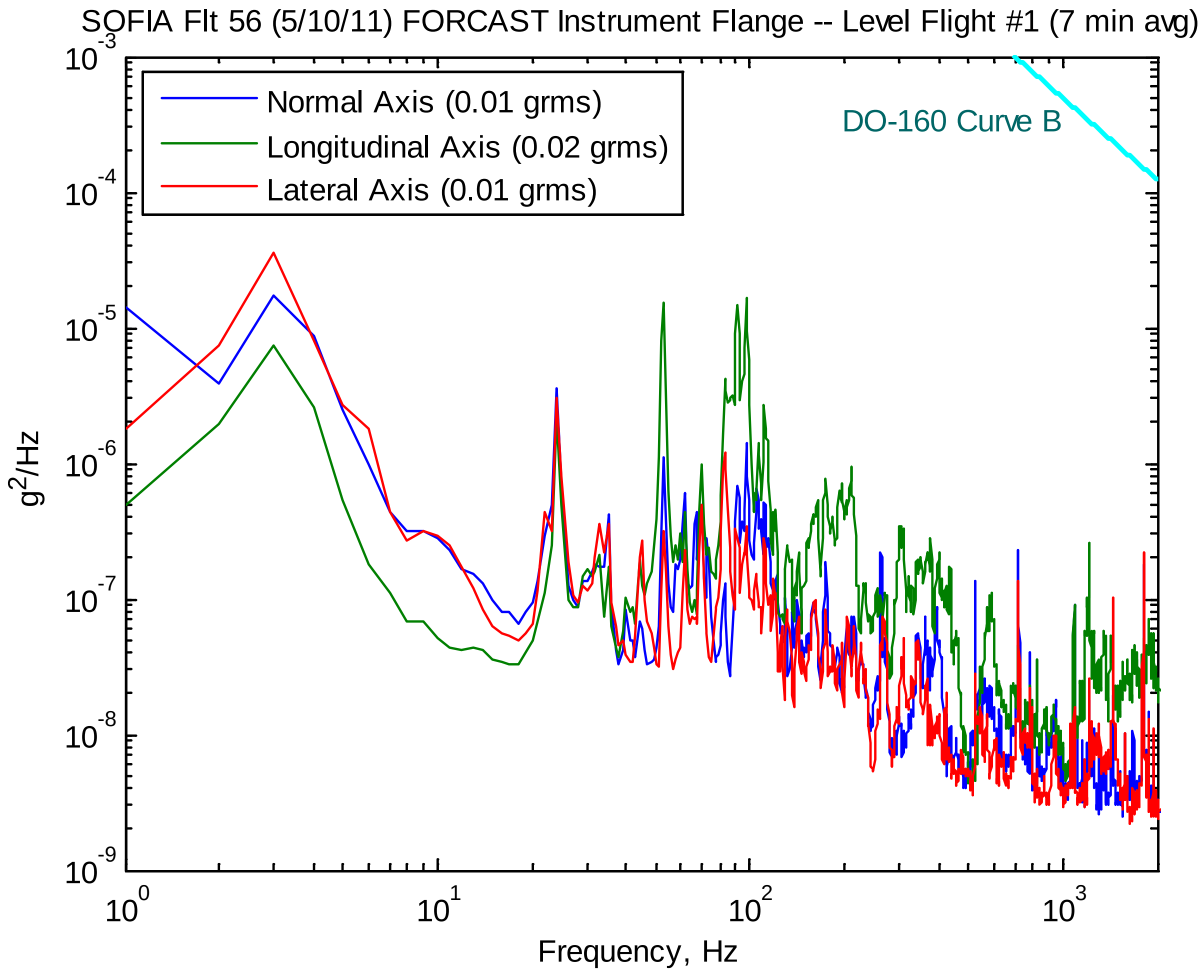

Figure 10.3.2.2-4: PSD of 7 minute datafile recorded in level flight at FL380 in light chop turbulence with TA uncaged / unbraked and in inertial stabilization mode (not tracking)

Figure 10.3.2.2-5 is the PSD from an 8 minute segment, also in level flight at 38,000 ft., but in smooth air and with the TA now tracking an object.

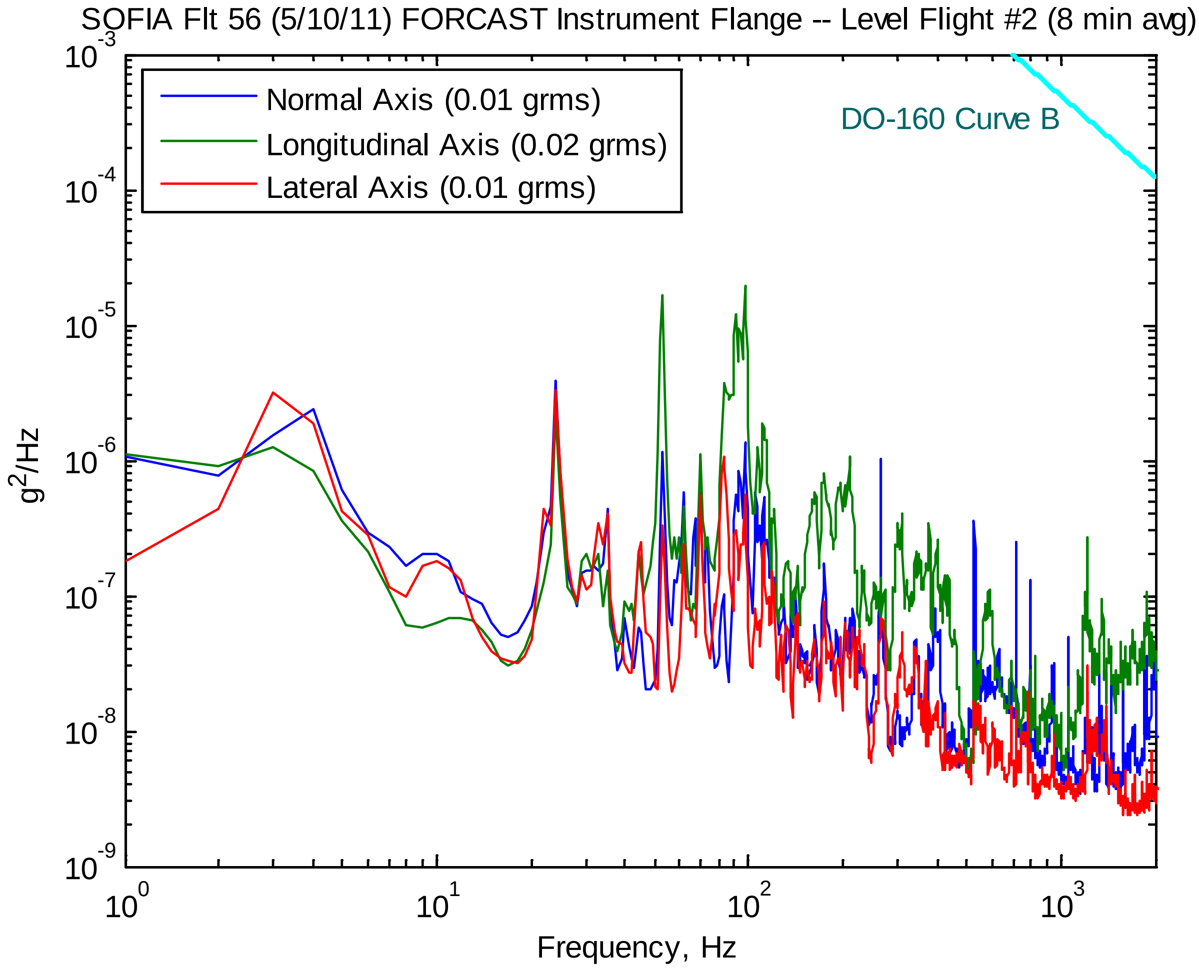

Figure 10.3.2.2-5: PSD of 8 minute datafile recorded in level flight at FL380 in smooth air with TA uncaged / unbraked and tracking object

Figure 10.3.2.2-6 is from SOFIA Flight 59 (take-off on 5/20/2011), and represents the PSD from a 4.3 minute segment acquired in level flight at 43,000 ft., in moderate turbulence with the TA uncaged / unbraked. As expected the low frequency content is a bit enhanced here due to the moderate turbulence.

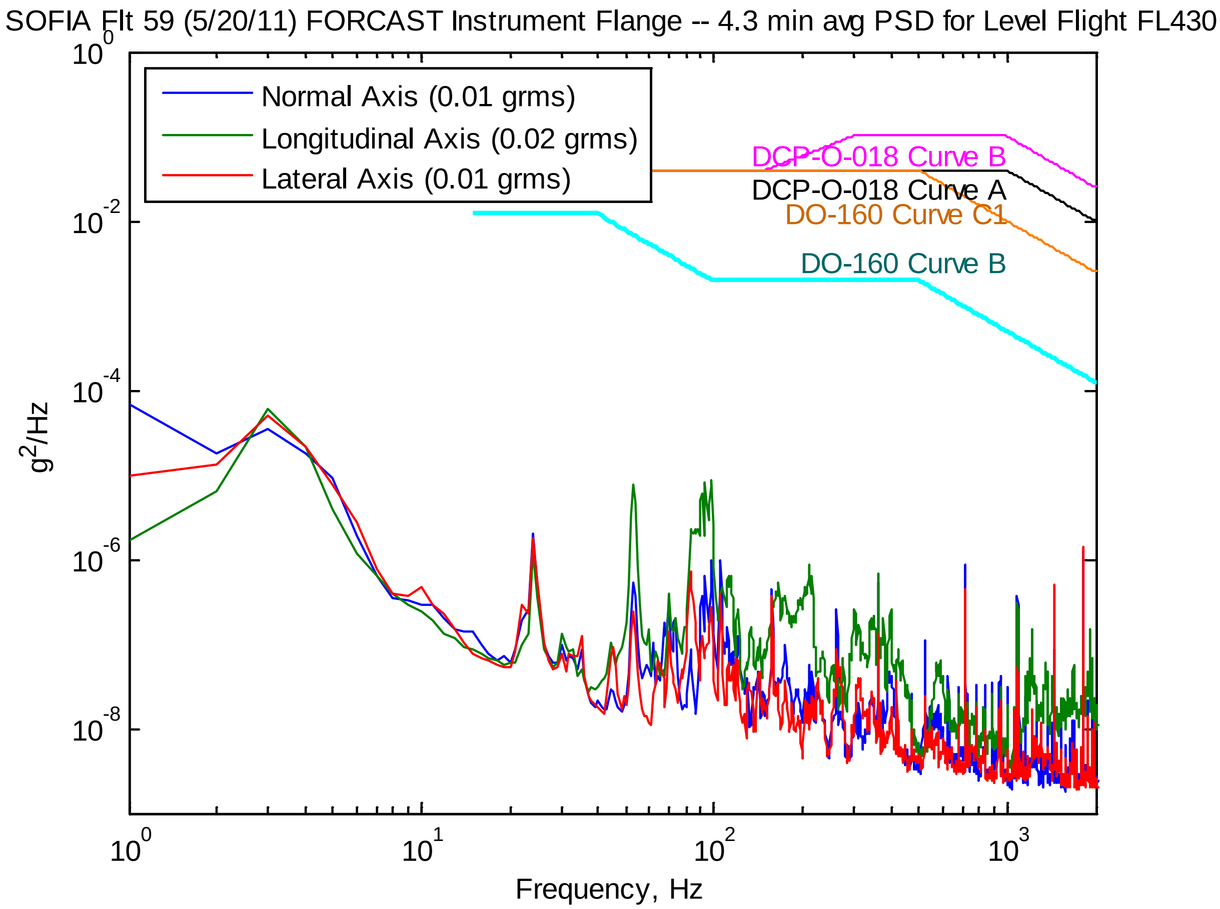

Figure 10.3.2.2-6: PSD of 4.3 minute datafile recorded in level flight at FL430 in moderate turbulence with TA uncaged / unbraked

As you can see, the SOFIA TA provides a fairly smooth ride to the SI during typical observing conditions, with these data providing some insight into certain frequency ranges where natural frequencies should be avoided to ensure these are not excited by transmitted vibrations.

10.3.2.3 PI Rack

To obtain vibration measurements representative of the PI Rack, the triaxial accelerometer head was attached to the aft center post of the Aux PI Rack, and the datalogger was operated during SOFIA Flight 64 (take-off on 6/7/2011). The worst-case vibrations for this location were observed during the landing phase. Figure 10.3.2.3-1 shows the PSD of the data file including this largest PSD component.

Though the vibration levels are still relatively low, the Lateral (Y) axis does reflect a largest frequency component “spike” at 19 Hz.

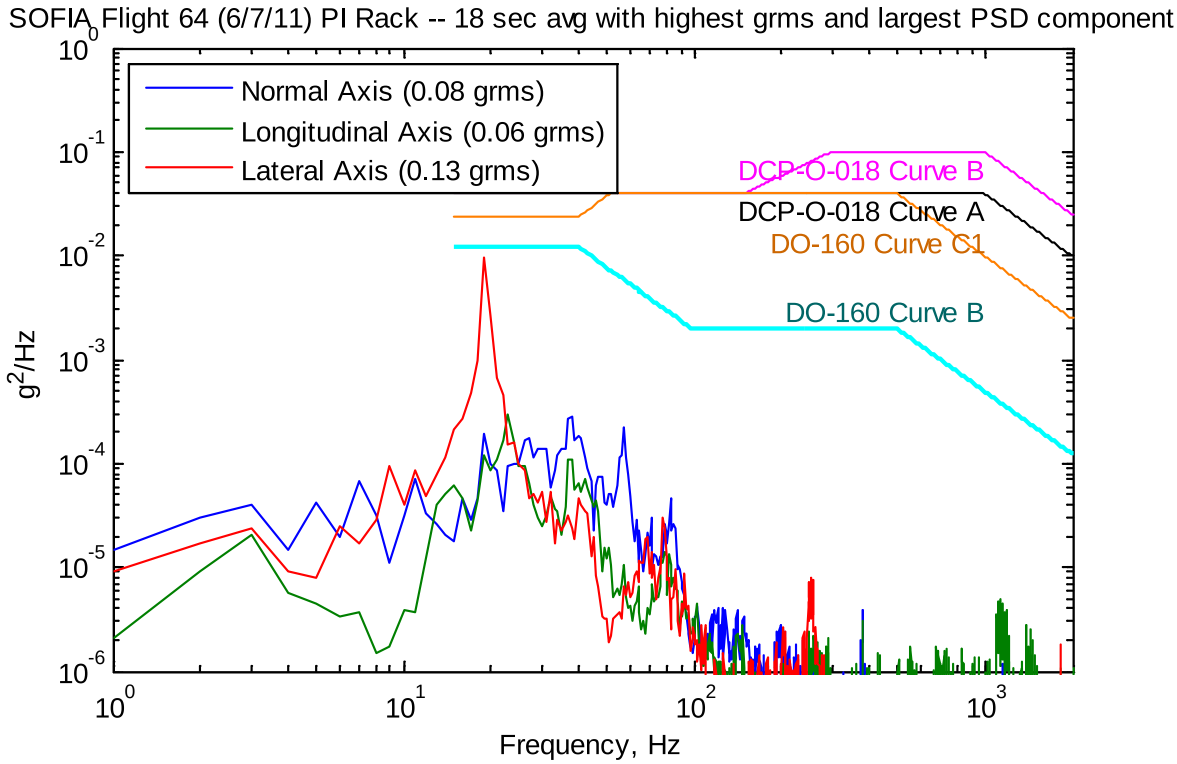

Figure 10.3.2.3-1: PSD of vibrations measured at aft center post of Aux PI Rack during landing

10.3.2.4 Counterweight Rack (CWR)

To obtain vibration measurements representative of the CWR, the triaxial accelerometer head was attached to one of the fore-aft equipment mounting extrusions in the CWR, and the datalogger was operated during SOFIA Flight 66 (take-off on 6/22/2011). The worst-case vibrations for this location were observed during the take-off phase. Figure 10.3.2.4-1 shows the PSD of the data file including this largest PSD component.

Note that these are correctly reported using the TA coordinate axes u, v, w, in lieu of Aircraft coordinate axes X, Y, Z.

The vibration levels measured here are somewhat higher than those recorded in the Aux PI Rack during landing, with the largest frequency component "spike" at 22 Hz.

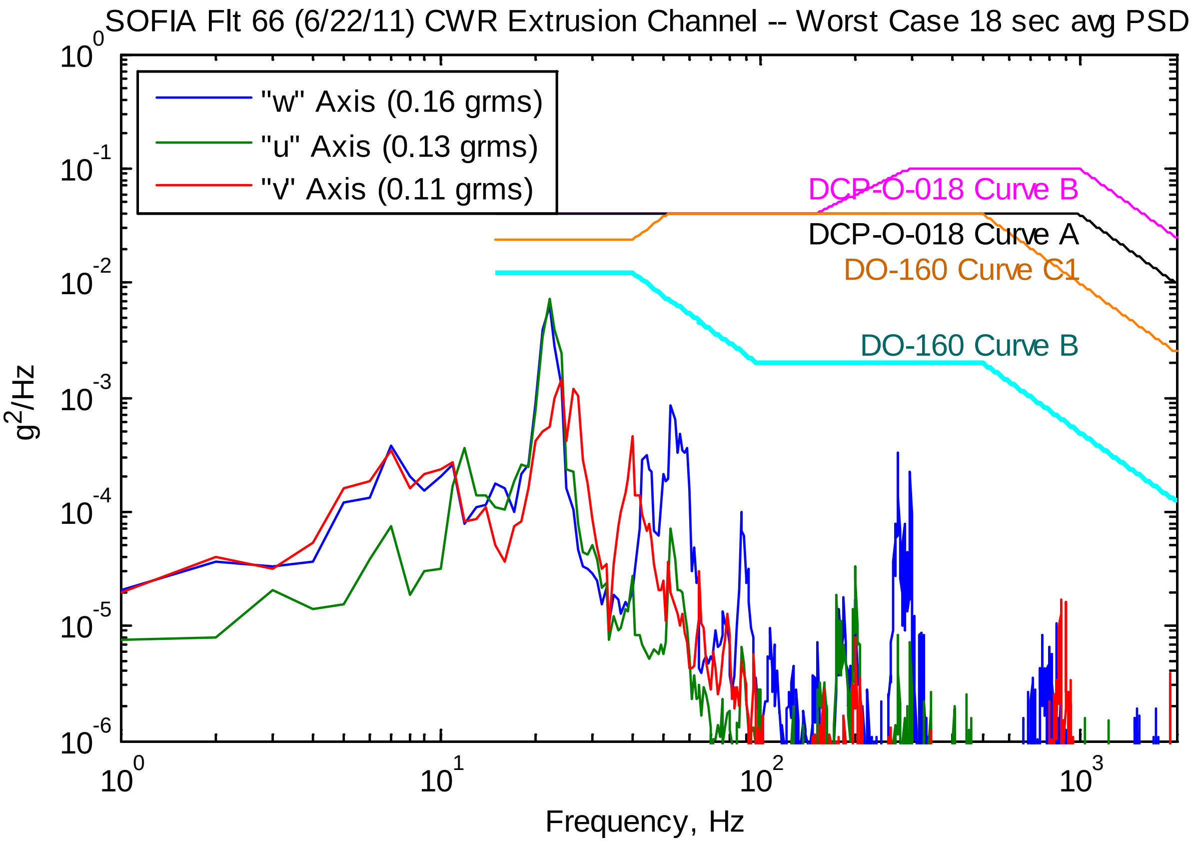

Figure 10.3.2.4-1: PSD of vibrations measured in CWR during take-off (worst-case)

Figure 10.3.2.4-2 presents the vibrational PSD measured in this same CWR location in flight, over a 12.5 minute period spanning cruise at 40,000 ft. and climb to 41,000 ft. with the TA caged and braked and the URD closed, with some measurements continuing with the TA uncaged and unbraked with the URD open. Note that while these PSD levels may appear to be similar to those from the worst-case take-off phase, the low end of the g^2/Hz scale is 2 orders of magnitude lower, and the composite G_{rms} values are also significantly lower.

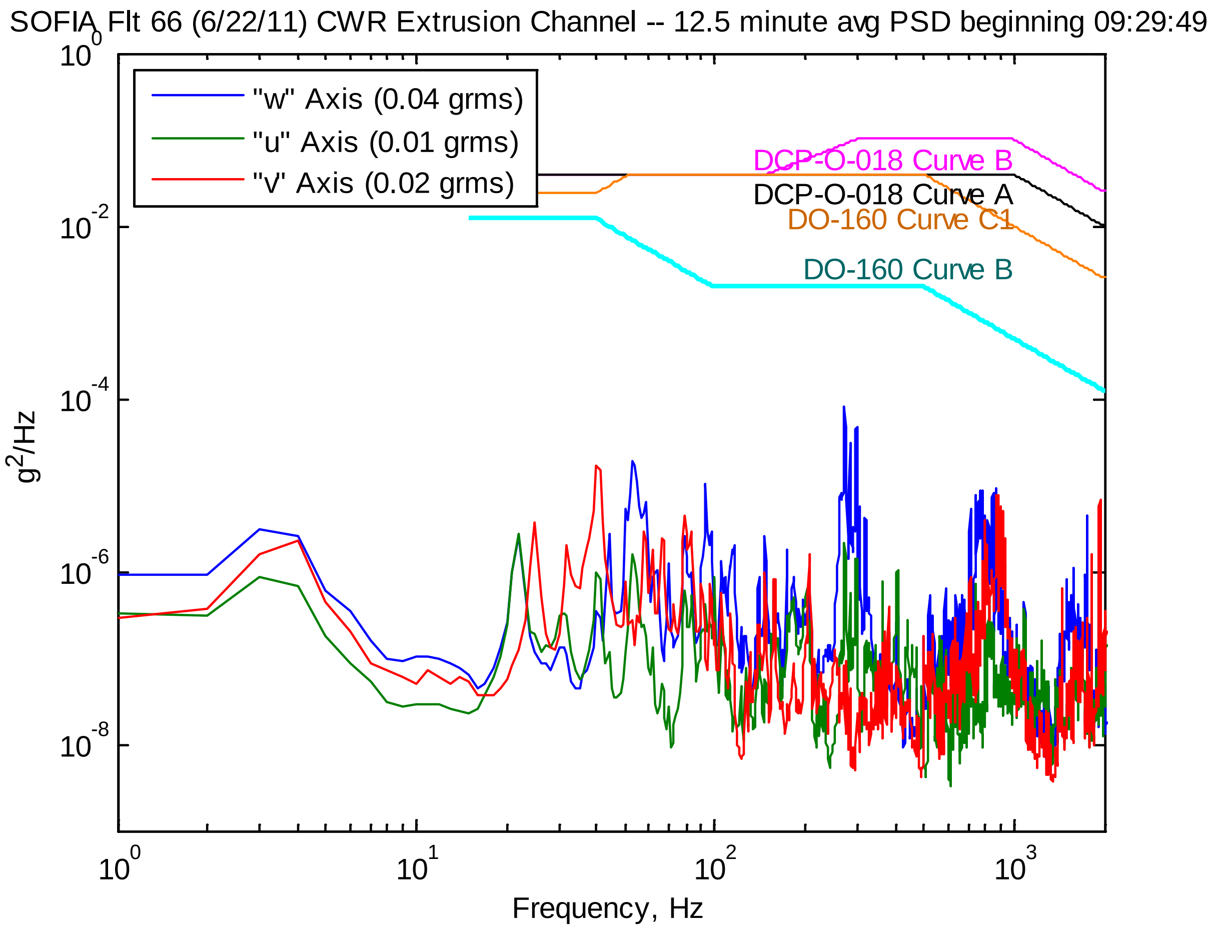

Figure 10.3.2.4-2: PSD of vibrations measured in CWR during 12.5 minute period during level flight at FL400 and climbout to FL410

As previously mentioned, the PSDs excerpted in this section are just intended to be exemplar of the range of vibration environmental conditions; the SOFIA SI Development group has a set of reports spanning 13 flights (9 from May ~ June 2011 period are presented in a comprehensive and consistent format, and will be made available to SI developers along with the accompanying numeric frequency-domain 3 axis average vibration PSDs from 1 to 2000 Hz files).

10.3.2.5 SI Shipping Assembly

To support the SI transportation logistics associated with multi-instrument deployments, the SOFIA program has developed two (2) SI Shipping Assemblies, shock-mounted and vibration-isolated structures that allow SIs to be transported in the SOFIA cargo bay, structurally supported solely via the SI mounting flange, for a very flight-like ride. This provides a convenient, low-risk, and cost-effective alternative to commercial freight shipment.

That said, the isolators used for these assemblies are known to be not particularly effective at attenuating lower frequency vibrations, such as those typically associated with inflight turbulence, and also exhibit natural frequencies in the 5 ~ 15 Hz range that can lead to amplification (resonance) with excitation frequencies.

A series of vibration measurements using triaxial accelerometer heads and vibration loggers were conducted on flights 208 and 211 in May 2015 to characterize the vibration and load environment for SIs being transported using this SI Shipping Assembly. During these flights, an SI mass dummy was supported on the SI Shipping Assembly in the cargo hold, and both the isolated and unisolated structures of the SI Shipping Assembly were instrumented with triaxial accelerometers. Simultaneous measurements were also acquired using a third triax accelerometer placed on the flange of the SI on the telescope (GREAT on Flight 208, and FORCAST on Flight 211) resulting in side-by-side comparisons of the vibrations during the various phases and dynamic events considered representative of a mission.

These measurements have been collected and published within SOF-NASA-REP-SE07-2165, *SOFIA SI Shipping Assembly Structure Dynamic Analysis*, so rather than attempting to excerpt and summarize these here, we invite interested parties to reference this analysis report.

It is worth mentioning that the vibration environment for SIs installed in the cargo bay are dependent on the orientation of the SI Shipping Assembly, and to a lesser extent, the specific location of the Shipping Assembly's pallet, and which tie-down "uplocks" are engaged.

10.3.2.6 Contextual comparison of measured vibrations with AFOP-7900.3-004 Environmental Acceptance Test levels

It is worthwhile to consider these typical SOFIA flight vibration measurements in the context of the environmental acceptance test levels that per AFOP-7900.3-004 are generally required of observatory mission system developments aboard SOFIA. Note that AFOP-7900.3-004 was formerly released as DCP-O-018B, and references to this earlier document number are still found in several figures within this section.

The figures showing vibration energy PSDs in previous subsections include several curves that define environmental acceptance vibration test levels from both AFOP-7900.3-004 and DO-160. However, these figures do not yet include Curve PA (1.55 G_{rms}), which was only available for NASA Transport Category V research aircraft via a Center Waiver process prior to Aug. 2014 when AFOP-7900.3-004 was released.

Figure 10.3.2.6-1 presents Z-axis vibration data PSD levels recorded over several flights, with an overlay of the applicable 1.55 G_{rms} Curve PA levels.

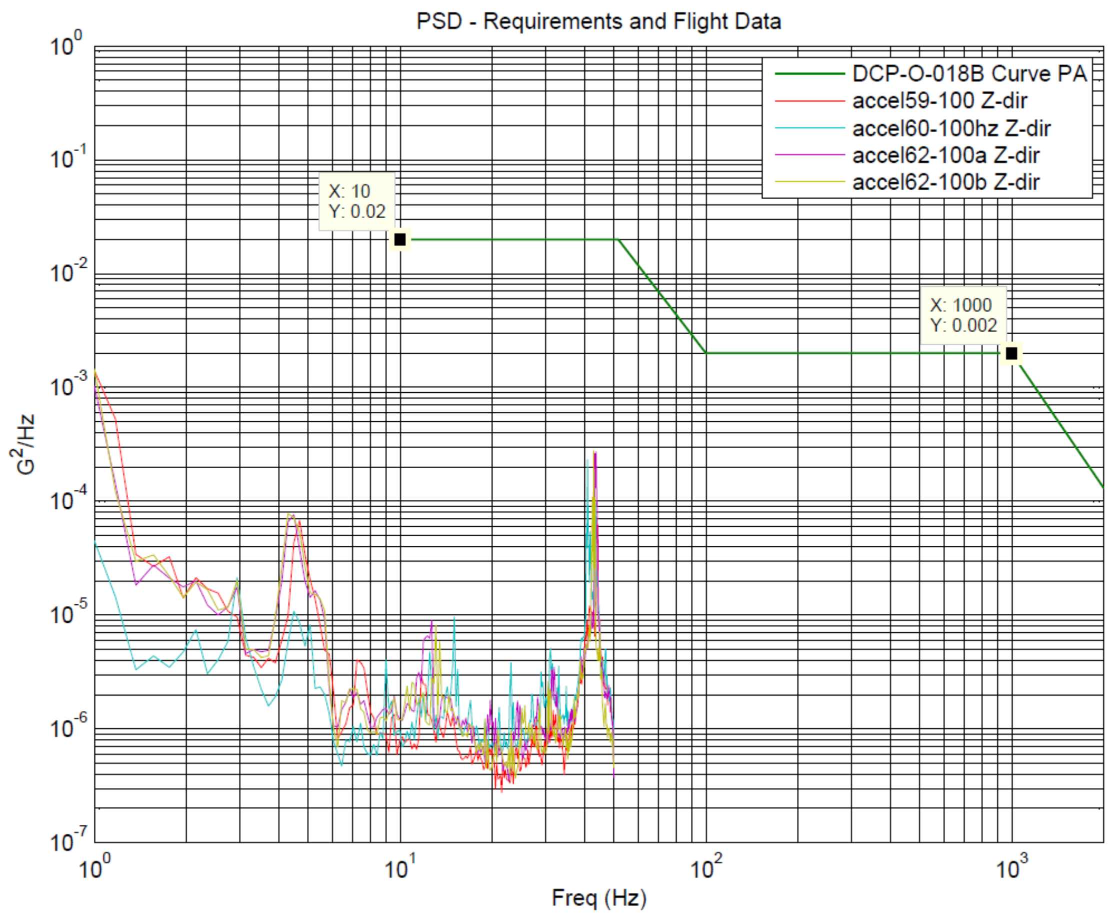

Figure 10.3.2.6-1: Typical Z-axis Vibrational PSDs with Overlay of AFOP-7900.3-004 Curve PA Environmental Acceptance Vibration Level

AFOP-7900.3-004 does include mass loading reduction factor provisions that allow for attenuation of the environmental acceptance test levels for heavier items of equipment (e.g., a typical SOFIA Science Instrument). For example, environmental acceptance vibration test levels for an assembly that weighs 160 lb or more are reduced from 1.55 G_{rms} to 0.78 G_{rms}, as depicted in Table 10.3.2.6-1 and Figure 10.3.2.6-2, below.

Table 10.3.2.6-1: AFOP-7900.3-004 Mass Loading Reduction Factor for Equipment weighing 160 lb or more

Test Curve Break Points						G_{rms}
Hz	**10**	**31**	**100**	**500**	**2000**	
Curve PA	0.02	0.02	0.002	0.002	0.00013	1.55
Curve PA,	0.005	0.005	0.0005	0.0005	0.000033	0.78

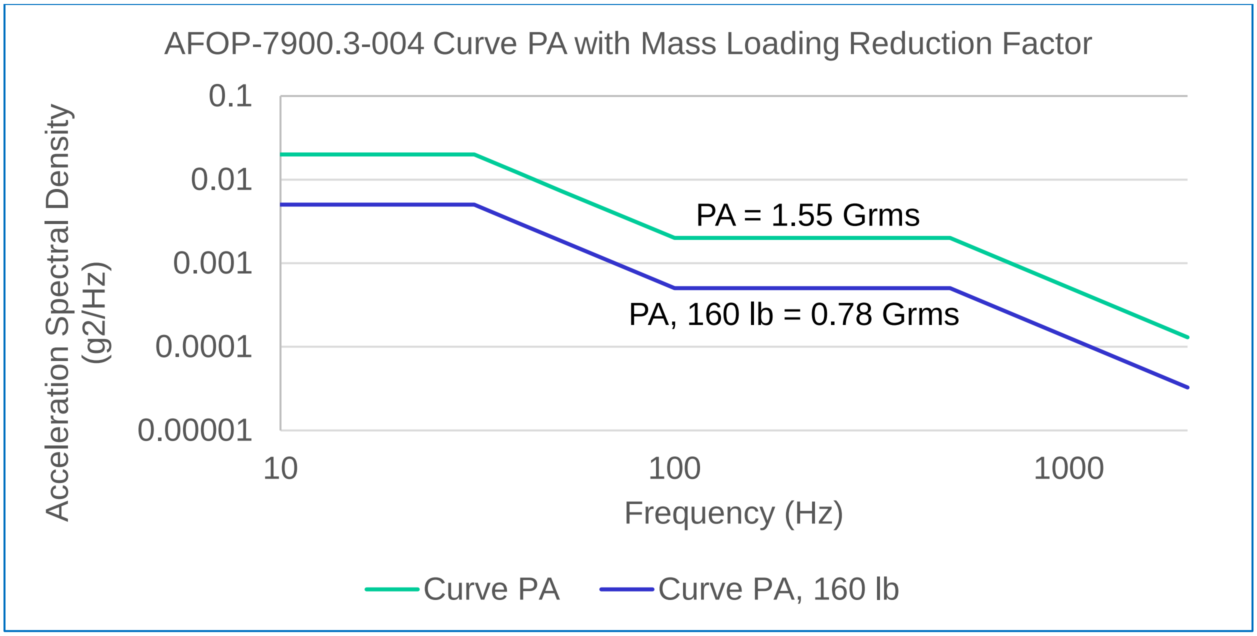

Figure 10.3.2.6-2: Typical Z-axis Vibrational PSDs with AFOP-7900.3-004 Curve PA Environmental Acceptance Level Overlay

It should be noted that even the attenuated 0.78 G_{rms} composite vibration level using this Mass Loading Reduction Factor is significantly higher than any of the measured environment vibration levels to which SOFIA SI equipment is subjected aboard SOFIA.

10.4 *Electromagnetic Interference / Compatibility*

SOFIA has an electromagnetic environment that might impact the performance of some instrument concepts. The aircraft is equipped with radios operating at a variety of frequencies as well as radar. The telescope uses a system of strong fine and course positioning torquer motors to position and stabilize the telescope. There are also various electrically actuated solenoid valves, a chopping Secondary Mirror Assembly (SMA) and associated drive circuitry. While the selected torquer motors are quite efficient and therefore have relatively weak magnetic stray fields, possible magnetic interference to the SI is a concern.

Prior to the initial flight with an instrument or following instrument modifications for which it is deemed necessary either by the Instrument Team or aircraft operations, an EMI test is performed. The EMI test is a ground test to ensure that the science instrument creates no interference with the aircraft electrical systems and that it is operating as designed. Likewise, this examination will determine if any of the aircraft or observatory systems create electrical interference with the science instrument. Successful EMI testing is finished by approval of the documented results of the Science Instrument Airworthiness Team.

The radiated EMI environments in the SOFIA aircraft cabin and telescope cavity are not well characterized as a fully integrated system. The Instrument Team is advised that there are several active telescope and MCCS subsystems operating in close proximity to the instrument and instrument racks.

SOFIA Science Instruments should of course be designed and fabricated using accepted astronomical and/or aerospace industry best practices with respect to susceptibility to radiated Electromagnetic Interference (EMI) environments, notably electromagnetic fields and Radio Frequency Interference (RFI).

The frequency ranges of aircraft avionics are listed in Table 10.4-1. The instrument should be designed to avoid spurious response, and to limit electromagnetic radiation to the lowest practical level (preferably under 100 milliwatts), at these frequencies.

Table 10.4-1: Aircraft systems frequencies

Aircraft Systems	Frequency (Range)	Rx	Tx	Power Output	Comments
HF Radio	3.0 ~ 29.999 MHz	☑	☑	125 W carrier SSB 400 W peak	28000 channels available Commonly used frequencies: HF1: 10.0 MHz HF2: 13.339 MHz
VHF Radio	118 ~ 137 MHz	☑	☑	25 W carrier	760 channels available for VOX com Commonly used frequencies: VHF1: 121.5 MHz Guard / Emergency com VHF2: 133.65 MHz
VHF Omni-Range (VOR) Instrument Landing System (ILS) Navigation	108 ~ 117.975 MHz	☑			200 channels narrow band for VOR / ILS
UHF Radio	220.0 ~ 399.95 MHz	☑	☑	30 W carrier	7000 channels for Air-to-Air and Air-to-Ground com, including Air Traffic Control (ATC) com Commonly used frequencies: 348.6 MHz 243.0 MHz Guard / Emergency channel
Automatic Direction Finding (ADF)	190 ~ 415 kHz 510 ~ 535 kHz	☑			Non-directional beacon
DME	960 ~ 1213 MHz		☑	300 W (min) 600 W (max)	
DME interrogator	1025 ~ 1150 MHz	☑	☑	500 W	Pulsed
Glideslope Receiver (GS)	329.3 ~ 335.0 MHz	☑			
ALT-4000 Radar Altimeter 1 & 2	4.3 GHz	☑	☑	1 W (max)	Used below 2500 feet AGL
XM Weather	2332.5 ~ 2345.0 MHz	☑			
Weather Radar 1 & 2 (X-Band)	8 ~ 12 GHz	☑	☑	12 kW (max)	Predictive windshear and forward turbulence sensing (smoother flightpath)
ATC Transponders 1 & 2 / Traffic Alert and Collision Avoidance System (TCAS II)	1030 MHz	☑			
ATC Transponder / Traffic Alert and Collision Avoidance System (TCAS II)	1090 (+/- 3) MHz		☑	500 W (max)	Pulse 235/sec
Iridium Satellite (SATCOM) Telephone	1626.4 MHz	☑	☑	5 W	
InmarsatC (SATCOM)	1626.4 ~ 1645.5 MHz	☑	☑		Inflight internet, long range communication, high rate data transfer (a.k.a. "SkyNet") Alternative to UHF and/or HF for Data / VOX Installed: Activation anticipated Spring 2015
Global Positioning System (GPS)	1.57542 GHz (L1 signal) 1.2276 GHz (L2 signal)	☑			
Compass 1 & 2		☑			
CMA-3024 GNSSU MkII GPS Sensor	1.57542 GHz	☑			Crash Locator

Many instruments are expected to be fairly insensitive to low frequency magnetic interference, whereas others may exhibit significant susceptibility to it. In particular, superconductor-insulator-superconductor (SIS) heterodyne receivers may be susceptible to an unstable magnetic environment. The same is true for various instruments using squid amplifiers as low noise amplifiers in their readout circuits.

The magnetic stray field environment of the telescope was measured in the vicinity of the interface flange prior to the telescope installation in the aircraft using portable Hall sensor flux meters. The results of this study were documented in a July 2002 publication *Measuring Magnetic Interference Caused by the SOFIA Telescope Drive System* and are summarized below.

The dominant effect, as in any ground-based telescope, is the change of the magnetic field vector when rotating an instrument in azimuth or elevation. The maximum possible change of the field will be twice the earth's field strength (for reference, -479 mG to 479 mG in Augsburg, where the test was conducted at a MAN facility).

The next weaker effect is the residual magnetization of telescope parts like stator magnets, yoke parts and other magnetized items. In SOFIA, their magnitude is no larger than 25 mG (5% of the earth's field) and should not be an issue for an SI at all if the SI is rigidly attached to the SI flange, as the orientation with respect to the telescope, and hence the field will not change (the orientation with respect to the geomagnetic field will change, though).

The measurements of the magnetic stray fields of the torquer motors confirmed the magnetic field signatures at a maximum of ~10 mG at the Hall sensor.

Hydraulic brake release and fastening pulses are the next in line: Their magnitude is no larger than 3.2 mG (0.7% of the geomagnetic field) and even less (< 1.2 mG) within the SI assembly envelope.

Fine drive nominal torques were not detectable at all with the sensitivity of about 0.3 mG. This should thus be negligible for any instrument.

Based on this study, it was concluded that an instrument that can operate on a ground-based observatory will not be affected or degraded by telescope magnetic stray fields. The measurements did detect a 10 kHz component to the electromagnetic stray field signature from the fine drive torquer motor control circuits, and this should be considered by the SI designer as this can be picked up by any high impedance electronics and not only by devices sensitive to magnetic fields.

As integrated into SOFIA such TA control circuits will be somewhat enclosed by MCCS rack structures and it is expected that the 10 kHz signature will be more effectively shielded as compared with the test setup at MAN, where no special measures were undertaken to suppress it.

11 Safety and Mission Assurance

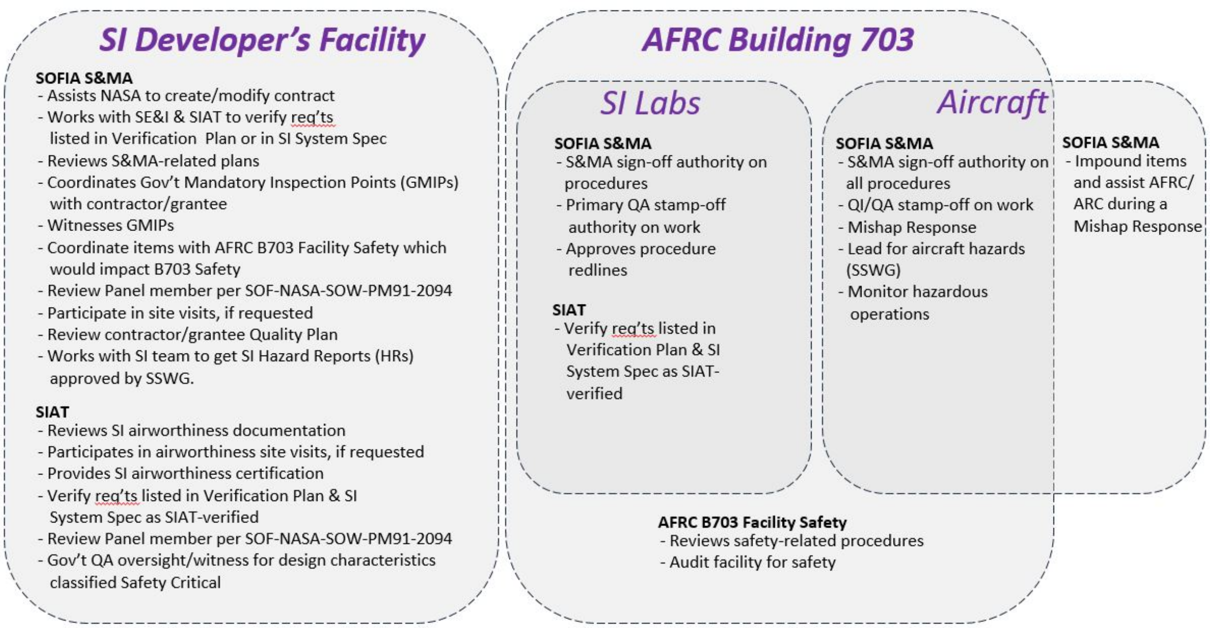

Figure 11-1: S&MA Responsibilities

The Science Instrument development team is required to develop a Quality Plan that defines the developer's Quality Assurance process. This plan is provided to NASA for review.

11.1 Risk-tailored Assurance Approach

Certain design characteristics of SOFIA Science Instruments are classified as Safety Critical. Such instrument design characteristics are required to follow additional configuration management and change controls, including the usage of special identification markings on drawings of Safety Critical design characteristics and the written approval from the SOFIA Science Instrument Airworthiness Team before changes can be made to Safety Critical instrument design characteristics. These controls are to ensure the information pertaining to instrument Safety Critical design characteristics available to the SOFIA Program is accurate and proposed changes to these items receive proper review and concurrence from SIAT. A part or assembly constituting a Safety Critical design characteristic may also be referred to as a Critical Safety Item (CSI).

Note:

Design characteristics considered **Safety Critical** typically include the following:

1. The instrument assembly structure mounted to the telescope, consisting of instrument mounting flange, outer structure, fasteners, and externally mounted components of the instrument assembly.
2. Equipment inside the PI Rack and Counterweight Rack, emphasis on equipment mounting to rack, equipment structure, and containment of internal components.
3. All components and parts that contact liquid helium.
4. All pressure relief devices and burst disks associated with venting of cryogen reservoirs.
5. Any window subassembly forming part of the instrument pressure boundary with the telescope Nasmyth Tube or forming part of the pressure boundary of the vacuum annulus/jacket surrounding liquid helium reservoirs.
6. Overcurrent protection devices in PI Rack, Counterweight Rack, and instrument assembly.
7. Electrical safety ground jumper cables or straps.
8. Additional items as required by the SIAT Lead.

Safety critical items should have high reliability. High reliability is verified by reliability analysis using accepted modeling techniques and data in which uncertainties are incorporated. Where this cannot be accomplished with a specified confidence level, the design of safety critical operations should have fail-safe and safety margins in which critical operability and functionality are ensured. Fail-safe is the ability of a system to perform its function(s) or maintain control of a hazard in the presence of failures of its subsystems. Safety margins are the difference between as-built factor of safety and the ratio of actual operating conditions to the maximum operating conditions specified during design.

The SI developer will deliver a Critical Safety Items List to the Program, per Appendix A of the SOF-NASA-SOW-PM91-2094; SOFIA Science Instrument Development Process and Deliverable Requirement document.

11.2 *Mishap Reporting*

The Instrument Team will report “mishaps” where injuries or significant costs are incurred, or had the potential to injure of cause significant costs as described in their contract. If the instrument just stops working, this is not considered a mishap. The *SOFIA Program Mishap Preparedness and Contingency* Plan (SOF-DF-PLA-OP05-2000) defines the classification categories of a mishap, how to respond to a mishap, and how to report a mishap event. In addition, NPR 8621.1, *NASA Procedural Requirements for Mishap and Close Call Reporting, Investigating, and Recordkeeping* provides requirements to report, investigate, and document mishaps, close calls, and other unidentified serious workplace hazards to prevent recurring accidents.

11.3 *System Safety*

All hazards associated with the operation of SI end items on the SOFIA Observatory or at NASA Installations will be communicated by the Instrument Team to NASA during Safety coordination meetings, and documented in a System Safety Assessment (SSA) and Hazard Reports (HRs).

Completion of the SSA is done by systematically assessing the components of a science instrument system to determine if the design and construction of parts and assemblies will survive expected operational circumstances both in flight and on the ground. The SSA is designed to identify, eliminate or mitigate all safety risks posed by a science instrument system.

The hazard assessments include "Integrated Hazards" (i.e., hazards that can cross the boundary between systems). This would include any hazards that the aircraft systems can induce into the SI and the SI can induce into the aircraft systems.

The risk of asphyxiation or hypoxia to personnel due to the rapid dilution/displacement of oxygen within the SOFIA cabin environment will be assessed for each instrument. Each SI Developer will be asked to submit the volume of LHe and LN2 cryogens contained within their instrument. Depending on the volume of cryogens, hazard mitigations may be defined and implemented to reduce this risk. The worst case scenario considered is the event in which all liquid cryogen rapidly boils off into the gas phase inside the aircraft cabin. The loss of vacuum surrounding a LHe reservoir is one example of a functional failure that would result in a rapid boil-off of LHe. The volume of LHe (as opposed to LN2) is the primary cryogen of concern given its low heat of vaporization, low boiling temperature, and high liquid-to-gas phase expansion ratio. The rapid boil-off event is considered for both the flight and ground operational environments of SOFIA.

Because the possibility of a rapid boil-off event exists, the behavior and effect of such an event must be analyzed, understood, and have hazard mitigations implemented as necessary. Scenarios that could contribute to the onset of accelerated cryogen boiling will be reviewed as part of the system safety assessment and hazard analysis performed with written assessment of science instrument design features that minimize risk if such an event occurs.

Despite constantly venting the aircraft cabin with outside air and the partial pressure of O_2 inside the aircraft cabin it is still necessary to evaluate oxygen displacement that results from the sudden introduction of He or N gas inside the cabin. No specific mitigations are generally required by the instrument team during flight.

In the ground operational environment, hazard mitigations may need to be implemented to ensure the safety of personnel, depending on the volume of cryogens within an instrument. Unlike in flight, the aircraft provides limited or no active ventilation of cabin air when on the ground. The entry doors to the aircraft are also routinely closed during periods of no personnel activity on the aircraft—the worst case scenario considered is significant oxygen displacement from the cabin resulting from a rapid cryogen boil-off event. The SOFIA Program may define and implement procedural and operational mitigations for instruments carrying a large volume of cryogens, such as requiring a certain number of aircraft doors be opened and the use of portable fans to increase ventilation whenever an instrument is onboard, and use of additional oxygen sensing monitors during normal ground operations as well as first re-entry into the aircraft following closure of the aircraft cabin.

Contact the SOFIA SI Development team at Ames Research Center or your COR with technical questions. Those technical questions will be forwarded to the appropriate technical expert. Further guidance can be found in the *SOFIA Safety Plan (SSP)* (SOF-NASA-PLA-PM21-2089).

Table 11.3-1: Definitions of the human hazard severity categories

Description	Class	Definition
Catastrophic	I	A condition that may cause death or permanently disabling/life-threatening injury
Critical	II	A condition that may cause severe/lost time injury or occupational illness.

Moderate	III	A condition that may cause medical treatment for a minor injury or occupational illness (no lost time).
Negligible	IV	A condition that could cause the need for minor first aid treatment (though would not adversely affect personal safety or health).

Table 11.3-2: Definitions of the loss of asset/mission hazard severity categories

Description	Class	Definition
Catastrophic	I	• Total direct cost of mission failure and property damage of $2M or more, OR • Crewed aircraft hull loss, OR • Unexpected aircraft departure from controlled flight for all aircraft except when departure from controlled flight has been pre-briefed (e.g., upset recovery training, high Angle of Attack (AOA) envelope testing, aerobatics, or Operational Check Flight (OCF) for training) or mitigated through the flight test process inherent at each Center.
Critical	II	Total direct cost of mission failure and property damage of at least $500k, but less than $2M.
Moderate	III	Total direct cost of mission failure and property damage of at least $50k, but less than $500k.
Negligible	IV	Total direct cost of mission failure and property damage of at least $20k, but less than $50k.

The result of the assessment is a collection of documented potential hazards, which are classified according to the probability of the event occurring and the severity of the event if it occurs. Tables 11.3-1 and 11.3-2 provide guidance for assigning the hazard severity category for a hazard and Table 11.3-3 provides guidance for assigning the probability category for a hazard. Note that the hazard categories for human safety are different than for assets.

Table 11.3-3: Definition of the hazard probability categories

Class	Approximate Numerical Probability (P)	Description
A	Frequent $P > 10^{-1}$	• Likely to occur immediately OR expected to occur often in the life of the project/item. Expected to be experienced continuously in on-going projects. • Controls cannot be established to mitigate the risk
B	Probable $10^{-1} \geq P > 10^{-2}$	• Probably will occur OR will occur several times in the life of a project/item. • Controls have significant limitations or uncertainties.
C	Occasional $10^{-2} \geq P > 10^{-3}$	• May occur OR expected to occur sometime in the life of a project/item, but multiple occurrences are unlikely. • Controls have moderate limitations or uncertainties.
D	Remote $10^{-3} \geq P > 10^{-6}$	• Unlikely but possible to occur OR unlikely to occur in the life of the project/item, but still possible. • Controls have minor limitations or uncertainties.

E	Improbable $P \leq 10^{-6}$	Improbable to occur OR occurrence theoretically possible, but such an occurrence is far outside the operational envelope. • Typically robust hardware/software, operational safeguards, and/or strong controls are put in place with mitigation actions to reduce risk from a higher level to an improbable state.

11.4 Shipment

11.4.1 Packaging, Packing and Containers

Articles will be packaged to prevent deterioration, corrosion, damage, and contamination using appropriate materials (e.g., ESD bags, shrink film, desiccant). For small shipments, dunnage such as Styrofoam peanuts, foam sheets, bubble wrap, and foam end/corner blocks should be used within the container.

Special packaging, packing and containers will be used to protect critical, sensitive, dangerous, or high-value articles. When necessary, engineered shipping containers should be used including cushion materials, blocking, and/or bracing to reduce the effect of sudden impact, movement within the container, vibration, etc. As appropriate, environmental and handling requirements should be marked on the exterior of the packaging and/or container.

For high-value equipment like the SI or PI rack electronic equipment, shipping containers should contain shock monitors with data loggers.

11.4.2 Handling and Transportation

The Instrument Team will ensure handling devices and transportation vehicles are suitable for the articles and materials being shipped to prevent damage.

Road transportation can subject shipments to high-G acceleration loads from potholes, expansion joints, frost heaves and low-G, high-frequency, continuous vibration that could cause significant contact fretting wear over long distances.

For high-value items, shipping containers should be secured from movement within transportation vehicles. Loading methods, personnel and equipment should also be selected and controlled to minimize the chance of damage. A shock measuring instrument should be used to log significant shock loads during transportation. Shock stickers or shock recorders should be used. Shock recorders are available from the NASA procuring S&MA organization if requested by the Instrument Team approximately three weeks prior to the planned transportation of the instrument.

To prevent any scratches or damage to the mating surface of the instrument flange to ensure a proper mating seal when the instrument is installed, it is recommended the mating surface of the instrument flange be protected by a cover, such as Plexiglas or similar, prior to shipment as well as after shipment whenever the instrument is not mounting to SOFIA or the TAAS.

11.5 At AFRC Building 703

General information related to the Instrument Team's activities at the Armstrong Flight Research Center Building 703 defined in USRA-DAL-SSMOC-MOPS-PRO-0130, *SOFIA Science Investigator Information for DAOF* (DAOF was the former name of AFRC Building 703).

11.5.1 Receiving Inspection

A packing list identifying shipment contents will be present upon delivery to the Armstrong Building 703. When the instrument arrives at Building 703, a visual inspection will be performed to verify that there is no visible damage to the container, its packing and packaging materials or the contained articles. Shock measuring instruments, if employed, will be downloaded and their data reviewed for excessive shock loads. NASA ARC and/or AFRC QA will be present during receiving inspection.

11.5.2 In the SOFIA Science Laboratories

Safety and Mission Assurance (S&MA) is performed in the SI Labs per the *SOFIA Program Safety and Mission Assurance Plan*, SOF-DA-PLA-PM21-1086. The SMO operates the SI laboratories and has created generic SI Lab procedures based on flow down of these S&MA requirements. A NASA QA Representative or designee will monitor work in the SI Labs.

Some recurring tasks such as cryogen servicing and lifts that have safety implications are performed in accordance with written procedures. Lab procedures are developed by the Instrument Team in coordination with the SMO team. Most SI Lab documents are prepared by the SMO team as part of their SI Lab activities (e.g. non-conformance reports, metrology, travel sheet, as-run procedures, etc.).

11.5.3 On the Aircraft

On the aircraft, NASA may impose Government witness requirements it deems necessary to ensure the SI is ready to fly safely. These witness points will be part of the task procedure.

Some recurring tasks, such as cryogen servicing, that have safety implications are performed in accordance with written procedures. On-aircraft procedures are developed by the Instrument Team in coordination with the SMO team. Most SI aircraft documents are prepared by the SMO team as part of their mission operations activities (e.g. non-conformance reports, metrology, travel sheet, as-run procedures, etc.).

12 Roles and Responsibilities

12.1 Instrument team/SI developer

The science instrument principal investigator is responsible for the conception, design, and development of the instrument. The SI PI provides all facilities necessary to design, develop, and build the instrument prior to delivery. The instrument team defines the SI-specific science and technical performance required to achieve the scientific investigation proposed and develops the verification matrix for the performance requirements. The instrument team reviews the SI requirements verification matrix template provided by SSP SE&I that contains the instrument requirements from the SI System Specification and the SI ICDs, identifies which requirements are applicable to the instrument, and identifies the preliminary instrument verification activities to be performed prior to FFR. The instrument team is responsible for planning, performing, and documenting the pre-FFR verification activities. The instrument team assists in planning, performing, and documenting post-FFR verification activities and waiver requests.

The Principal Investigator (PI) will designate a person within the SI staff who is responsible for the Quality Assurance (QA) functions for the SI development team. In this document, this person will be referred to as the QA Lead. The QA Lead should have the freedom to flow quality issues up to the Principal Investigator (PI). The QA Lead is responsible for creating and maintaining an effective quality assurance system for all items procured and produced for a Science Instrument development. All procedures or instructions developed for the procurement, production, assembly, inspection, test, or evaluation of SI items should be reviewed and approved by the QA Lead. The QA Lead is also responsible for verification of conformity to requirements. While the QA Lead could also have other responsibilities, enough time should be allotted to adequately perform the QA functions. No team member should ever act as a QA check for their own work. If this might occur, the PI should temporarily assign QA duties to another person.

12.2 *SOFIA SI Development Manager*

The Science Instrument Development Manager is the cost account manager and principal engineer for the SOFIA Instrument Development WBS (1.05), thus is responsible for the cost, schedule, and technical performance of all US Science Instruments in development.

The Science Instrument Development Manager is the compliance authority for the requirements contained in the instrument-specific science and technical performance specification. As compliance authority for these requirements, the Science Instrument Development Manager submits deviation and waiver requests to the SOFIA Program where warranted.

12.3 *SOFIA Systems Engineering and Integration*

SE&I is responsible for providing to the instrument team an SI requirements verification matrix template that contains the SI requirements from the SI System Specification and the SI ICDs, and is pre-populated with recommended, post-FFR final verification activities. SE&I will provide most of the procedures for final verification of the SI System Specification and SI ICD requirements. SE&I is the compliance authority for the requirements contained in the SI System Specification and SI ICDs other than airworthiness requirements. As compliance authority for these requirements, SE&I submits deviation and waiver requests to the SOFIA Program where warranted.

12.4 *SOFIA Safety and Mission Assurance*

SOFIA S&MA supports the final verification activities for compliance to SI System Specification and SI ICD requirements other than airworthiness requirements and reviews and concurs on the compliance results.

The operations and work of the Instrument Team and their suppliers are subject to evaluation, review, audit, survey, and inspection by Government QA Representatives as defined in the *SOFIA Science Instrument Development Process and Deliverable Requirements* (SOF-NASA-SOW-PM91-2094) document.

12.5 *SOFIA Science Instrument Airworthiness Team*

The SIAT is the compliance authority for the airworthiness requirements contained in the SI Development Process and Deliverable Requirements, SI System Specification and SI ICDs. As compliance authority for these requirements, the SIAT submits deviation and waiver requests to the SOFIA Program where warranted. Prior to flight of a science instrument, the SIAT will provide a written letter indicating that a science instrument is accepted as an airworthy article for the SOFIA aircraft.

12.6 *Instrument Scientists*

For each science instrument, a member of the Science Mission Operations (SMO) staff is assigned as an instrument scientist. The instrument scientist performs the following roles:

a) Serve as the point of contact between the SMO and the instrument team for the science operations of the instrument
b) Participate in the development of the instrument, with a primary focus on understanding instrument performance, capabilities, operating modes, and limitations
c) Responsible for operating the instrument following acceptance by the SOFIA program
d) Report to the SMO and the SOFIA program on updates to the instrument capabilities for inclusion on the website, in observing proposal calls, and other documentation
e) Assist the instrument teams in the design of the Astronomical Observing Templates (AOTs), serve as point of contact to the Information Systems Development group, and participate in the Working Group on AOTs
f) Understand, operate, and validate the data reduction pipeline for the instrument
g) Oversee calibration of the science data
h) Assist in flight planning, selecting calibrations observations for flights, making calibration Astronomical Observing Requests (AORs), and ensuring calibrations are appropriately assigned and the products are validated before insertion into the archive for release to the observers
i) Monitor and report the performance of the instrument, such as sensitivity, dark current, bad pixels, etc.

12.7 *Mission Operations*

Mission Operations is responsible for several areas in support of overall SOFIA operations. For flight operations Mission Operations is responsible for pre-flight planning, in-flight operations of mission systems by the telescope operator, mission director, and in-flight planner, and post-flight aircraft mission system checks.

In direct support of Science Instruments on the ground, Mission Operations is responsible for the management of five SOFIA Science Laboratories (SSLs) at the Armstrong Building 703 used for pre-flight preparation of Science Instruments. Management of the SSLs includes the following;

- Supplying Cryogens and compressed gases for each Science Instrument

- Technician support, if requested, to Science Instrument teams for cryogen fills (both in SSLs and on aircraft)

- Technician support to Science Instrument teams for installation of Science Instrument, Counterweight racks and PI racks on the aircraft

- Providing Counterweight Rack dolly/lift device and PI rack dolly

- Providing standard laboratory instrumentation (i.e., multimeters, oscilloscopes, vacuum pumps, leak detector, etc.) in each SSL

- Providing a selection of hand tools (i.e., metric and SAE wrenches, sockets, and Allen wrenches)

Note: For the purpose of tool control, all Mission Operations provided tools for SSL use will be engraved. Also, any tools intended for use on the aircraft should be permanently marked and inventoried on form D-WK324-7 prior to aircraft entry and reviewed again upon exit.

- Providing a gantry crane capable of lifting 1 ton for use in the SSLs

In addition, Mission Operations will provide a single point of contact for Science Instrument team needs to include information for shipping/receiving, training required, SSL operations/procedures, etc. Mission Operations ground support will be negotiated with the Maintenance and Engineering Manager.

Appendix A.1 – {Deleted}

This earlier appendix section has been deleted in this revision of the handbook; this section has however been retained to maintain consistency in the appendix numbering / designations across revisions.

Appendix A.2 – {Deleted}

This earlier appendix section has been deleted in this revision of the handbook; this section has however been retained to maintain consistency in the appendix numbering / designations across revisions.

Appendix B – Acronyms

Acronyms and abbreviations are listed in alphabetical order.

A, I, D, T	Analysis, Inspection, Demonstration, Test
a.k.a.	Also Known As
AC	Alignment Camera
AC	Alternating Current
ADR	Adiabatic Demagnetization Refrigerator
AFRC	NASA Armstrong Flight Research Center
AFSRB	Airworthiness & Flight Safety Review Board
ANSI	American National Standards Institute
AO	Announcement of Opportunity
AOR	Astronomical Observing Requests
AOT	Astronomical Observing Templates
API	Application Program Interface
APP	Airborne Platform Project
AR	Acceptance Review
ARC	NASA Ames Research Center
arcmin	arc minute
arcsec	arc second
AS	Aircraft System
ASTM	American Society for Testing & Materials
AUX	Auxiliary
AWS	American Welding Society
B703	Building 703 (AFRC)
BPA	Balancing Plate Assembly
C	Celsius
CA	California
CAD	Computer Aided Design
CAR	Corrective Action Request
CCC	Closed-Cycle Cryocooler
CDR	Critical Design Review

Cert	Certificate of Conformance or Certification
CFD	Computational Fluid Dynamics
CG	Center of Gravity
CLA	Cable Load Alleviator
cm	centimeter
CMTR	Certified Material Test Report
CoC	Certificate of Conformance
COR	Contracting Officer Representative
COTS	Commercial Off-The-Shelf
CPU	Central Processing Unit
CSCI	Computer Software Configuration Item
CSI	Critical Safety Item
CWP	Counterweight Plate
CWR	Counterweight Rack
DAOF	Dryden Aircraft Operations Facility
dB	decibel
DCS	Data Cycle System
DCS	Direct Current
deg	Degree
DIL	Deliverable Item List
DLR	German Aerospace Center, Deutsches Zentrum für Luft- und Raumfahrt
DOT	Department of Transportation
DFRC	Dryden Flight Research Center (now AFRC)
DSI	Deutsches SOFIA Institut
ECO	Engineering Change Order
EL	Elevation
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EPD	Emergency Power Disconnect
EPO	Education & Public Outreach
ESD	Electrostatic Discharge
F	Fahrenheit
FCLS	Focused Chopped Light Source
FFI	Fine Field Imager
FITS	Flexible Image Transport System
FLITECAM	First-Light Infrared Test Experiment Camera (SI)
FMO	Focused Mission of Opportunity
FOD	Foreign Object Debris
FORCAST	Faint Object InfraRed CAmera for the SOFIA Telescope
FPI	Focal Plane Imager
FRR	Flight Readiness Review
FSC	Federal Stock Code
FSI	Facility Science Instrument
ft	Feet
FY	Fiscal Year

GFE	Government Furnished Equipment
GHz	Gigahertz
GI	General Investigator
GPS	Global Positioning Subsystem
GREAT	German Receiver for Astronomy at Terahertz Frequencies
GSE	Ground Support Equipment
GTO	Guaranteed Time Observation
GUI	Graphical User Interface
GVPP	Gate Valve Pressure Plate
He	Helium Gas
HF	High Frequency
HIL	Hardware-in-the-Loop
HILS	Hardware-in-the-Loop Simulator
HIPO	High Speed Imaging Photometer for Occultations (SI)
HK	Housekeeping
hr	Hour
Hz	Hertz
I&T	Integration & Test
ICD	Interface Control Document
IMF	Instrument Mounting Flange
IMS	Integrated Master Schedule
in	Inch
INF	Instrument Flange
IR	Infrared
IRIG-B	Inter Range Instrumentation Group – B
IRR	Instrument Readiness Room
kHz	kilohertz
ksi	kilopound per square inch
KVA	kilovolt-ampere
L/H	Left-hand
L3	L-3 Communications
LCHP	Large Chopped Hot Plate
LFA	Low Frequency Array (GREAT SI)
LHe	Liquid Helium
LN2	Liquid Nitrogen
LOPA	Layout of Personnel Accommodations
LOS	Line Of Sight
LSP	Legacy Science Program
MADS	Mission Audio Distribution System
MAN	MAN Technology
MCCS	Mission
mG	milligauss
MHz	Megahertz
MIL	Military Standard
MIL-STD	Military Standard

µm	micrometer; micron
min	Minute
mm	millimeter
MNOP	Maximum Normal Operating Pressure
MOPS	Mission Operations
MOU	Memorandum of Understanding
MS	Military Standard
MS	Margin of Safety
msec	millisecond
N/A	Not Applicable
N2	Nitrogen Gas
NAS	National Aerospace Standards
NASA	National Aeronautics and Space Administration
NASA-STD	NASA Standard
NDE	Non-Destructive Examination
NGSI	Next-Generation Science Instrument
NPR	NASA Procedural Requirement
NRA	NASA Research Announcement
NSPIRES	NASA Solicitation and Proposal Integrated Review and Evaluation System
OCCB	Observatory Configuration Control Board
PCA	Physical Configuration Audit
PDR	Preliminary Design Review
PDS	Power Distribution System
PEA	Program Element Appendix
PI	Principal Investigator
PIF	Pre-Flight Integration Facility
PIR	Pre-Install Review
PIS	Platform Interface System
PMP	Project Management Plan
PPBE	Planning, Programming, Budgeting, and Execution
PRD	Pressure Review Device
PSD	Power Spectral Density
PSI	Principal Investigator Science Instrument
psi	pounds per square inch
psid	pounds per square inch differential
PSR	Pre-Shipment Review
PTFE	Polytetrafluoroethylene
PVC	Polyvinyl chloride
PVS	Pressure Vessel Systems
QA	Quality Assurance
QA	Quality Assurance
QD	Quick Disconnect
R/H	Right-hand
RAID	Redundant Array of Independent Disks
Rev	Revision

RFA	Request for Action
RFI	Request for Information
RMS	Root-Mean-Square
ROSES	Research Opportunities in Space and Earth Sciences
S&MA	Safety & Mission Assurance
SAE	Society of Automotive Engineers
SALMON	Stand-Alone Mission of Opportunity Notice
SCHP	Small Chopped Hot Plate
SCL	SOFIA Command Language
SE&I	Systems Engineering & Integration
sec	Second
SI	Science Instrument
SIAT	Science Instrument Airworthiness Team
SIC	Science Instrument Cart
SICCR	Science Instrument Configuration Change Request
SIDAG	Science Instrument Development Advisory Group
SIL	Systems Integration Laboratory
SIS	Superconductor-Insulator-Superconductor
SMA	Secondary Mirror Assembly
SMD	Science Mission Directorate
SMO	Science Mission Operations
SObRR	SOFIA Observatory Readiness Review
SOFIA	Stratospheric Observatory For Infrared Astronomy
SOW	Statement of Work
SP	Special Performance
SPARC	Scalable Processor Architecture
SPL	Sound Pressure Levels
SRR	System Requirements Review
SSA	System Safety Assessment
SSL	SOFIA Science Laboratory
SSMO	SOFIA Science and Mission Operations
SSP	SOFIA Science Project
SSWG	System Safety Working Group
STD	Standard
TA	Telescope Assembly
TA	Telescope Assembly
TAAS	Telescope Assembly Alignment Simulator
TAAU	Telescope Assembly Alignment Unit
TAIPS	Telescope Assembly Image Processing Subsystem
TBD	To Be Determined
TBR	To Be Reviewed
TCP/IP	Transmission Control Protocol/Internet Protocol
TDSI	Technology Demonstration Science Instrument
TRR	Test Readiness Review
TTL	Transistor–Transistor Logic

UPS	Uninterruptible Power Supply
US	United States
USRA	Universities Space Research Association
V	Volt
V&V	Verification & Validation
VAC	AC Voltage
VDC	DC Voltage
VDD	Version Description Document
VIS	Vibration Isolation Subsystem
VME	Versa Module-Europe
VPN	Virtual Private Network
VPS	Vacuum Pump System
W	Watts
WBS	Work Breakdown Structure
WFI	Wide Field Imager
XEL	Cross-Elevation
XML	Extensible Markup Language

Appendix C – Rack & Patch Panel Distances

The following graphics are intended to be serve as guidance to SI Developers for approximating and determining lengths of needed cables. It is generally recommended that cables be longer than needed to accommodate the routing and securing of cables to tie-down locations that is performed during instrument hardware and cable installation. SI Developers are encouraged to contact the SOFIA SI Development Team for any specific questions about instrument, rack, and patch panel distances or cable fabrication.

Figure C-1 shows a top view of the three PI rack locations and PI Patch Panel. The direction of aircraft “forward” is the bottom of the graphic. Although not explicitly shown in the graphic, the U401 panel (aircraft portside) is the right side of the PI Patch Panel in the graphic; similarly, the U400 panel (aircraft starboard) is the left side of the PI Patch Panel in the graphic.

Figure C-2 shows a side view of the PI rack locations and PI Patch Panel. The direction of aircraft “forward” is the left side of the graphic. The view is from aircraft portside looking starboard.

Figure C-3 shows three views of the telescope assembly, in respect to the counterweight plate. The features and locations shown are the instrument mounting flange, Counterweight Rack, TA/SI Patch Panels U402 & U403, and chopper junction box. Note not all telescope components are shown in the graphic—only select components to more clearly show the physical SI interface locations.

Note: The U404 patch panel is installed on SOFIA and The U404 He patch panel is not shown in this figure, location information for the U404 panel on the telescope assembly is contained within the Cryocooler to Science Instrument CRYO_SI_02 ICD (SOF-NASA-ICD-SE03-2066.

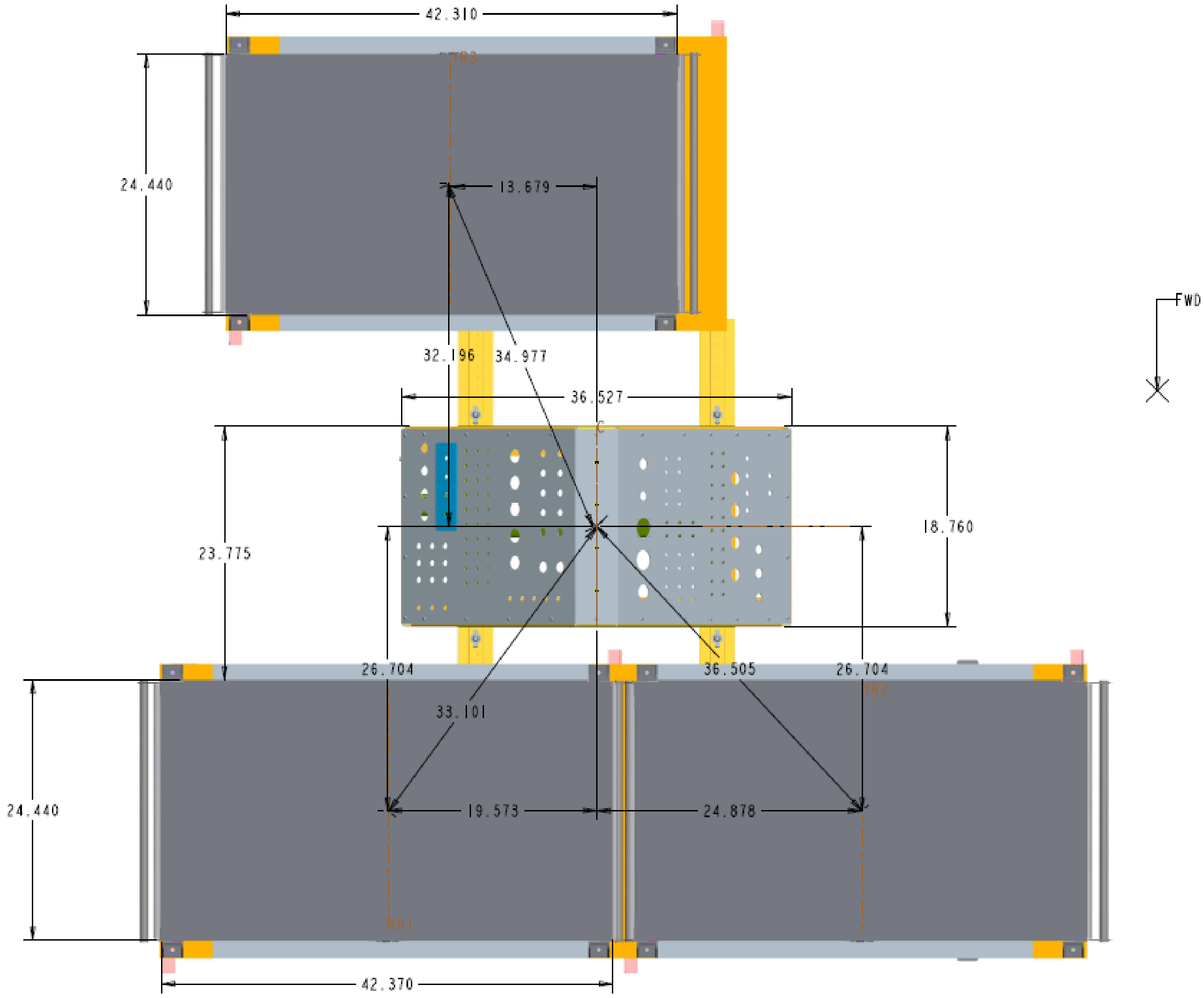

Figure C-1: Top view of PI racks and PI Patch Panel (panels U400 & U401)

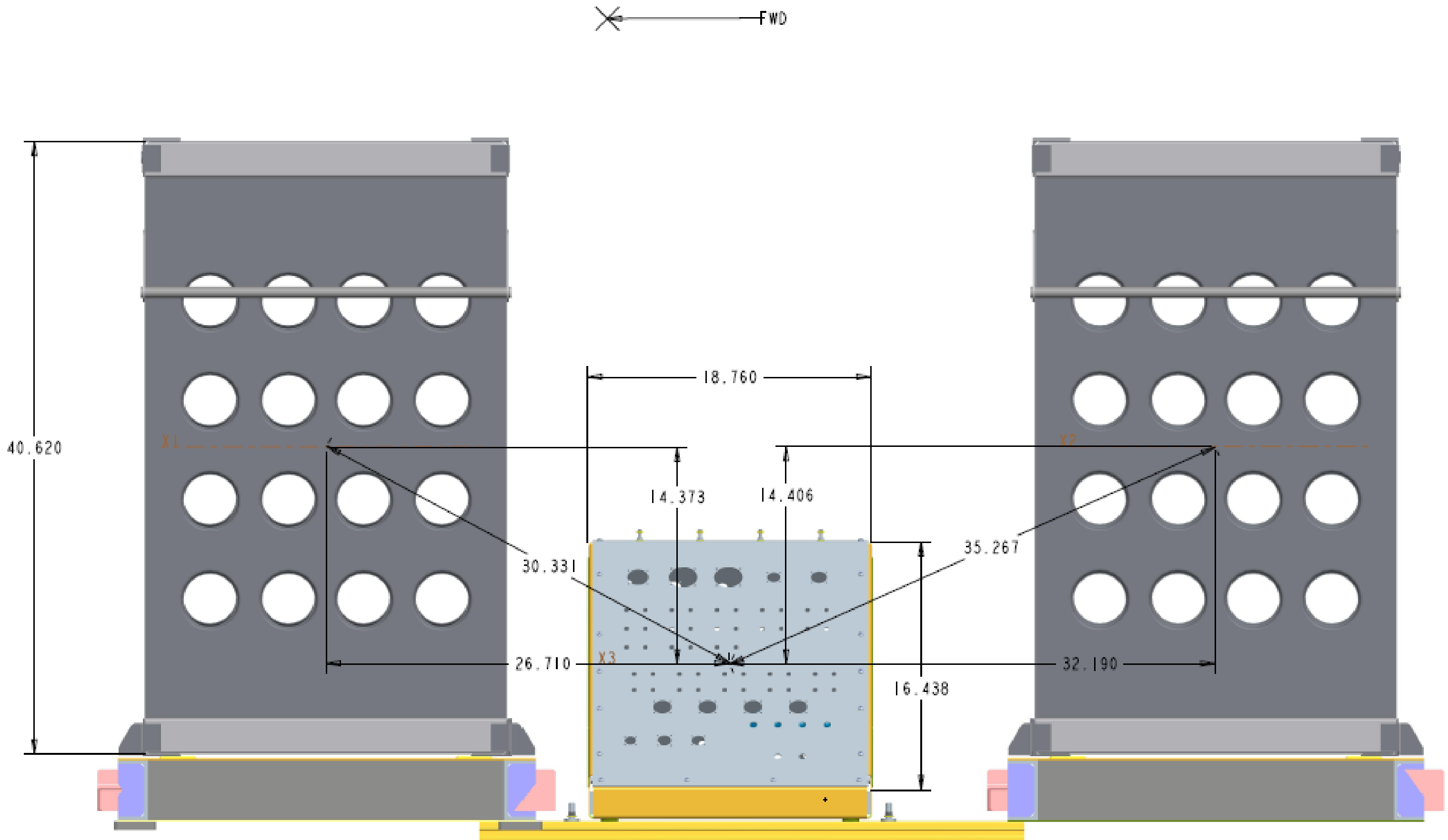

Figure C-2: Side view of PI racks and PI Patch Panel (View looking starboard)

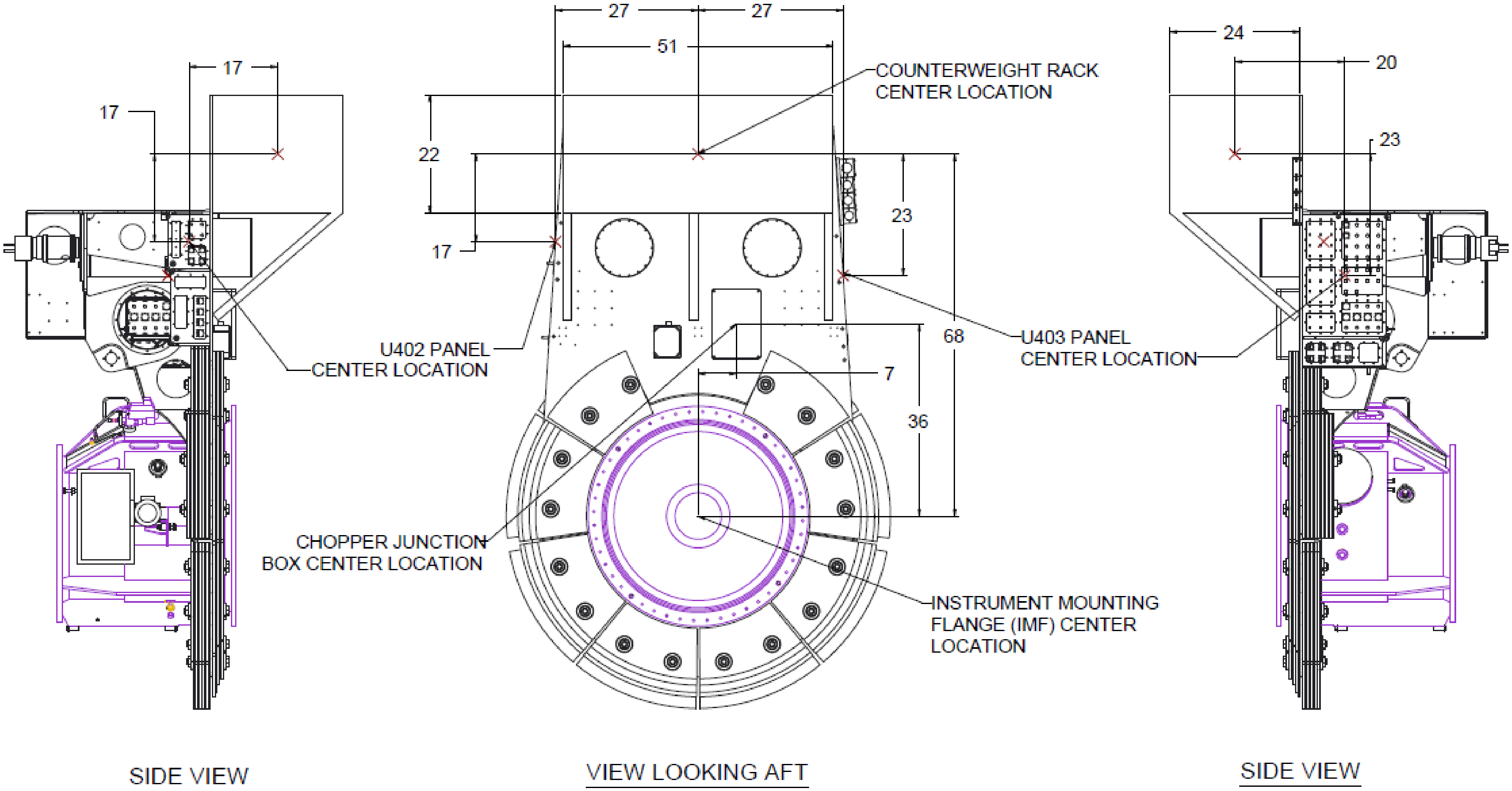

Figure C-3: Views of Telescope Assembly Counterweight Plate and Instrument Mounting Flange

Appendix D – {Deleted}

This earlier appendix section has been deleted in this revision of the handbook; this section has however been retained to maintain consistency in the appendix numbering / designations across revisions.

Appendix E – {Deleted}

This earlier appendix section has been deleted in this revision of the handbook; this section has however been retained to maintain consistency in the appendix numbering / designations across revisions.

Appendix F – SI Developer's Handbook, Rev. – to A Change Details

Administrative changes:
- Updated cover page and signature page.
- Made global replacements in handbook of Dryden references to Armstrong; DAOF to Armstrong Building 703.
- Removed references to SOFIA Science Project (SSP) and Airborne Platform Project (APP) in handbook.
- Renumbered all figure and table numbers to include specific subsection number.

Specific changes (Rev. - paragraph numbers cited below):
1.3: Removed reference to Windchill User's Manual (manual never written). Added reference to Windchill ./Help library.
2: Added information about SOFIA Program transition and dissolution of Science Project and Platform Project. Added reference to SOFIA Concept of Operations (SOF-DA-PLA-PM17-2000).
3: Removed reference to Special Purpose Instrument class—current suite of instrument classes are: Facility, PI, Technology Demonstration. Converted Table 1 image to text.
3.3: Removed Special Purpose Science Instrument section; baseline version of handbook already acknowledged this instrument classification is obsolete.
4.2: Added optional pressure coupler or optical window assembly to system list for instruments. Replaced existing Figure 2 photograph with a new similar photograph showing PI Patch Panel Guard.
4.4: Added Auxiliary (AUX) Rack and Shipping Assembly to Government Furnished Equipment list.
5: Revised ICD count from 14 to 15, accounting for CRYO_SI_01. Removed reference to Synopsis of SOFIA Concept of Operations (SCI-US-PLA-PM17-2016) since it has been by SOFIA ConOps (SOF-DA-PLA-PM17-2000).
5.3.1: Created new Figure 3 ICD context block diagram. Converted Table 2 image to text and added CRYO_SI_01 to the list.
5.3.3: Added vacuum pump system to section.
5.3.4: Added pressure coupler and optical window assembly to section.
5.3.5: Added statement SI Developers will provide their own jumper cables to interface/connect to SOFIA patch panels.
5.3.6: Updated total SI power budget from 5 to 6.5 KVA to reflect current available SI power budget. Added table showing available power types and amounts.
5.3.7: Inserted new section 5.3.7 to address fluidic interface of Phase 1 SOFIA Cryocooler System.
5.3.7.1: Added reference to SOFIA Command Language (SCL) User's Manual (SOF-DA-MAN-OP02-2181). Removed Appendix B SOFIA Command Language Tutorial.
5.3.8: Added more information about specific applicability of cart ICDs to installation vs. lab carts.
5.4.2: Converted Table 3 from image to text.
5.4.3: Revised SI verification section to align with present process used by SE&I and SIAT. Removed out-of-date Table 4.
5.4.4: Added details about deviation and waiver process for SI nonconformance/non-compliance.
(5.4.5.8) Added new section describing Functional & Physical Configuration Audits.
5.4.5.2: Converted Table 4 from image to text and added tier tests to table. Added description of each Tier Test level.

6.2.1: Added cryocooler compressor to Science Lab provisions list. Added statement about cryogen training for SI members participating in cryogen servicing at AFRC.
(6.2.9): Added new section and description about Observatory cryocooler system.
6.2.9: Replaced SOF-DA-ICD-SE03-005 Layout of Personnel Accommodations (LOPA) with APP-DF-DWG-SE02-2924 LOPA. Added new details about workspace on aircraft, including trays in the AUX Rack and two conference tables on the main deck
6.6: Added statement that instrument proposers should include cost of guaranteed time observations (GTO) in proposal budget.
7.1.1: Added statement that this section is out-of-date and will be updated in the next revision of this handbook. Added statement about instrument proposal single-step or two-step selection process.
7.3: Clarified phases referenced in section correspond to NASA project life-cycle phases. Removed Post-Flight Mission Briefs from Figure 8 since these are not performed.
7.4.1.2: Clarified SRR subsections in handbook are guidelines for the content and subject areas to be addressed in the SRR by instrument team.
7.5.1.2: Clarified PDR subsections in handbook are guidelines for the content and subject areas to be addressed in the PDR by instrument team. Added instrument science & technical performance, SOFIA SI System Specification, and SOFIA SI ICD verification matrix deliverables.
7.5.1.7: Changed “waiver” to “deviation” for PDR. Added hazard reports to section.
7.6.1.2: Clarified CDR subsections in handbook are guidelines for the content and subject areas to be addressed in the CDR by instrument team. Added instrument science & technical performance, SOFIA SI System Specification, and SOFIA SI ICD verification matrix deliverables.
7.6.1.2.6: Added hazard reports to section. Added identification of safety critical items.
7.6.1.2.7: Added physical configuration audit (PCA) plan and schedule.
7.6.1.2.9: Change “waivers” to “deviations”. Added applicability of SOFIA SI System Specification to section.
7.6.2.2: Clarified PSR subsections in handbook are guidelines for the content and subject areas to be addressed in the PSR by instrument team. Added instrument science & technical performance, SOFIA SI System Specification, and SOFIA SI ICD verification matrix deliverables.
7.6.2.2.5: Added PCA has been completed. Added certification of proof load tests for instrument carts or stands have been completed. Added certification of pressure relief devices (PRDs) for instrument cryogen vent systems has been completed.
7.7.1: Added details about Pre-Install Review success criteria.
7.7.2: Added entrance and success criteria for Test Readiness Review; section was previously empty.
7.7.3: Changed acronym “SobRR” to “SObRR” for consistency.
7.4.4: Added entrance and success criteria for Acceptance Review.
7.7.5: Added entrance and success criteria for Commissioning Review.
8.1.5: Removed airworthiness deliverables list; it is already contained in Appendix A.
8.3: Removed Quality Assurance section since quality is already covered in detail in section 11, Safety & Mission Assurance.
8.6.1.1.2: Changed polyvinylchloride (PVC) insulation statement from “should be avoided” to “prohibited”.
8.9: Converted Table 7 image to text.
9.4: Added statement specifying delivered CAD models and drawings (facility instruments) should be created from the Professional version of the CAD programs, and not the Student or Academic versions.
11: Revised Figure 19 per input from SOFIA S&MA Lead. Corrected figure title from “S&SM” to “S&MA”.
11.1: Per input from SOFIA S&MA Lead, removed Critical/Major/Minor design characteristics classification from entire section 11 and subsections and replaced it with Critical Safety Item classification. Added list describing design characteristics of CSI items.
11.7: Removed statement that Inspection and Test section “only applies to tests for technology demonstration instruments”.

11.7.3: Removed statement that all calibrated instruments "will be traceable to National Institute of Standards and Technology (NIST)".
11.8: Removed statement that section does not apply to technology demonstration instruments.
11.9: Deleted Waivers & Deviations section—it will now be covered in section 4 (verification) of the handbook.
11.10: Removed reference to NPR 6000.1 for instruments shipping from instrument developer's site.
11.10.2: Added statement recommending instrument protect SI flange mating surface with Plexiglas or similar material.
11.14: Added description of asphyxiation and hypoxia risk due to rapid dilution/displacement of oxygen resulting from a rapid cryogen boil-off event, stating mitigations may be defined and implemented depending on amount of liquid cryogens (LHe) contained within an instrument.

Appendix A: Removed statement "This list applies to US Facility Instruments procured under NASA contract"; this statement is redundant as this appendix applies to all classes of instruments and identifies deliverable items specific to facility instruments. Revised Airworthiness Data Package item list and due dates per inputs from SIAT. Changed due date for Instrument Configuration Sheet from PDR to Pre-Install Review to match review specified in section 9.3.

Appendix B: Removed entire SOFIA Command Language tutorial, this has now been replaced by the SOFIA Command Language User's Manual, which is referenced in Software interface section of this handbook.

Added Appendix C: Added graphics showing distances between interfaces including PI Racks and PI Patch Panel, and telescope assembly instrument mounting flange, Counterweight Rack, TA/SI Patch Panels, and chopper junction box.

Added Appendix D: Added an excerpt from the SOFIA SI System Specification & ICD Requirements Verification Matrix Template.

Added Appendix E: Added a table identifying SI Acceptance/Commissioning Data Package Content.

Added Appendix F: SI Developer's Handbook OP03-2000, Rev. A Change Log: Changes made to Rev. - (June 2011 version)

Appendix G.1 – {Deleted}

This earlier appendix section has been deleted in this revision of the handbook; this section has however been retained to maintain consistency in the appendix numbering / designations across revisions.

Appendix G.2 – {Deleted}

This earlier appendix section has been deleted in this revision of the handbook; this section has however been retained to maintain consistency in the appendix numbering / designations across revisions.

Appendix G.3 – {Deleted}

This earlier appendix section has been deleted in this revision of the handbook; this section has however been retained to maintain consistency in the appendix numbering / designations across revisions.

Appendix G.4 – {Deleted}

This earlier appendix section has been deleted in this revision of the handbook; this section has however been retained to maintain consistency in the appendix numbering / designations across revisions.

Appendix H – SI Developer's Handbook, Rev. A to B Change Details

Administrative changes:
- Updated signature page.
- Made global editorial revisions throughout document; correcting typos and making minor changes to style and grammar usage to improve readability.

Specific changes (Rev. A paragraph numbers cited below):
1.1: Added DLR to first introductory sentence. Added OP03-001 document number to SOFIA Experimenter's Handbook reference. Added USRA-DAL-SSMOC-SCIN-PLAN-4100 document number to Guidelines for SOFIA SI Integration and Commissioning Plans reference.
2: Added USRA-DAL-SSMOC-SCIN-REP-1018 document number to Science Vision for the Stratospheric Observatory for Infrared Astronomy reference.
4.1 & 4.2: Consolidated these sections into one section to eliminate redundancy. The remaining 4.x subsections were renumbered to reflect this change (e.g., "Other equipment" subsection 4.3 has been renumbered to 4.2).
Figure 5.3.1-1: Added data interface type to figure; pertaining to the DCS_SI_01 interface.
Table 5.3.1-1: Corrected scope description within table for SI_CWR_01 and SI_AS_01 ICDs; changed description from "guidelines" to "requirements". Clarified that scope of SIC_SSMO_01 ICD covers both instrument lab carts and stands.
5.3.2: Added details about the various methods for driving the chopper.
5.3.6: Added U401 panel reference designator to description—the panel at which MCCS supplies power to science instruments.
5.3.7: Added references to Phase 1 SOFIA (upGREAT) Cryocooler System Specification APP-DA-SPE-SE01-2076 and (upGREAT) Cryocooler Concept of Operation APP-DA-PLA-PM17-2076.
5.3.8.3: Added summary description of the Level 1-4 data product levels. Added reference to SCI-US-PLA-SW09-2000 SI Pipeline Acceptance Plan.
5.3.9: Added clarifying statement that initial certification and periodic recertification of the SOFIA PI Rack dollies and CWR carts is performed by NASA.
5.4 & 5.4.x subsections: Updated the number of major verification phases to align with the verification process defined in the SOFIA Science Instrument System Specification and ICD Requirements Verification Matrix Template (SOF-NASA-REP-SV05-2057) approved by the OCCB 4 Nov 2015, which defines the five major verification phases of instrument development: PDR, CDR, Pre-Ship, At AFRC prior to installation, and Installation and checkout.
5.4.2: Added pipeline software requirements to the list of approved requirements (documents) to be verified for instruments.
5.4.4: Added clarifying statement that the parts or elements of the instrument which receive an approved deviation or waiver against a SOFIA requirement will still undergo verification—but will be performed against the design element which received the approved deviation/waiver (e.g., design drawing) to verify the as-built part conforms with the design.
5.4.5.1: Changed section title from "Pre-CDR Verification Activities" to "PDR Verification Activities".
- Added new section "CDR Verification Activities"; subsequent 5.4.5.x sections have been renumbered to reflect the newly added/inserted section (e.g., Pre-Ship Verification Activities section number changed from 5.4.5.2 to 5.4.5.3).
5.4.5.2: Pre-Ship Verification Activities section number changed from 5.4.5.2 to 5.4.5.3.
- Added new 5.4.5.3.1 Airworthiness Inspections section describing the airworthiness verification inspection process.

- Added new 5.4.5.3.2 SE&I Verification (Non-Software) section describing the roles and scope of SE&I verification activities.
- Added new 5.4.5.3.3 Instrument Software-MCCS Testing section describing the roles and scope of SI-MCCS Tier tests. The tier test cases are defined in the 5.4.5.3.3.x subsections.
- Added new 5.4.5.3.4 Instrument Data Product-DCS Testing section describing the roles and scope of SI-DCS testing.
- Added new 5.4.5.3.5 Instrument Data Reduction Pipeline-DPS Testing section describing the roles and scope of SI-DPS testing.

5.4.5.3: Post-Ship Verification Activities section number changed to 5.4.5.4.
5.4.5.4: EMI test section number changed to 5.4.5.5.
5.4.5.5: Line Operations section number changed to 5.4.5.6.
5.4.5.6: Instrument Commissioning Flight Series section number changed to 5.4.5.7.
5.4.5.7: Instrument Modifications and Upgrades section number changed to 5.4.5.8.
5.4.5.8: Functional & Physical Configuration Audit section number changed to 5.4.5.9.
6.2.7: Added citation to Vacuum Pump System Concept of Operations, APP-DA-PLA-PM17-2074.
6.8: Added citation to Software Architectural Design Document for the Data Processing System (DPS) of the SOFIA Project (SCI-US-SPE-SW02-2019).
7.4.1: Inserted and added new SRR Entrance Criteria section before SRR Success Criteria section; the entrance criteria section becoming the new 7.4.1.2 section. All existing 7.4.1.2.x subsections have been renumbered to 7.4.1.3.x.
7.5.1: Inserted and added new PDR Entrance Criteria section before PDR Success Criteria section; the entrance criteria section becoming the new 7.5.1.2 section. All existing 7.5.1.2.x subsections have been renumbered to 7.5.1.3.x.
7.5.1.11: Removed text “Transportation container requirements have been identified.”
7.6.1: Inserted and added new CDR Entrance Criteria section before CDR Success Criteria section; the entrance criteria section becoming the new 7.6.1.2 section. All existing 7.6.1.2.x subsections have been renumbered to 7.6.1.3.x.
7.6.2: Inserted and added new PSR Entrance Criteria section before PSR Success Criteria section; the entrance criteria section becoming the new 7.6.2.2 section. The criteria was adapted from the SOFIA SE&I Technical Review Entrance and Success Criteria Confluence page which has been vetted by the SOFIA Integration Office. All existing 7.6.2.2.x subsections have been renumbered to 7.6.2.3.x.
7.7.1: Added details about delta airworthiness and ICD verification process for subsequent installations of an instrument on SOFIA.

- Added new 7.7.1.1 PIR Entrance Criteria section; criteria was adapted from the SOFIA SE&I Technical Review Entrance and Success Criteria Confluence page which has been vetted by the SOFIA Integration Office.
- Added new 7.7.1.2 PIR Success Criteria section.

7.7.2: Added general reference to TRR checklist used to determine readiness of a project to start formal test.
7.7.4: Removed redundant statement about applicability of Acceptance Review to only facility instruments.
7.7.4.1: Made correction clarifying AR Entrance Criteria for pipeline is not only the data reduction pipeline algorithms but are all the deliverables defined in the SI Pipeline Acceptance Plan SCI-US-PLA-SW09-2000

- Added new 7.7.4.3 SI Acceptance Process section describing the instrument acceptance process, including participant stakeholders and action timeline.

7.7.5.1: Corrected CR Entrance Criteria for pipeline, pertaining applicable PI instruments for which delivery of a pipeline is required, is not only the data reduction pipeline algorithms but are all the deliverables defined in the SI Pipeline Acceptance Plan SCI-US-PLA-SW09-2000.

8.2: Revised System Safety section per inputs received from SOFIA Safety. Introduces use of hazard reports and hazard action matrices to identify hazards, establish mitigations, and characterize residual risk.
8.4.2.1: Revised description of cryostat internal pressure structural analysis to align with pressure requirements of SOFIA Science Instrument System Specification SOF-AR-SPE-SE01-2028 Rev. A, which was approved 15 July 2015.
10.3: Made minor revisions to vibration description pertaining to caging and braking of the telescope. Revised in-flight acceleration value to 1.7g in Z (normal) based on feedback from DSI.
11.2: Added guidance reference to SOFIA Quality Plan, SOF-NASA-PLA-PM21-2090.
11.10: Replaced Software Assurance guidance statements from: “1. Reviewing the SOFIA Science Project Software Management Plan, SCI-AR-PLA-PM20-2004 first,” to “1. Reviewing the SOF-DA-PLA-PM20-201, SOFIA Software Management Plan (SMP) first,”; and “2. Reviewing the SOFIA Science Project Software Assurance Plan, SCI-AR-PLA-PM21-2014,” to “2.Reviewing the SOF-NASA-PLA-PM21-2091, SOFIA Software Assurance Plan (SSAP),”.
Table 11.10-1: Reconstructed software assurance deliverables table to be editable.
11.12: Added guidance reference to SOFIA Program Mishap Preparedness and Contingency Plan, SOF-DF-PLA-OP05-2000.
11.14: Revised System Safety section pertaining to oxygen deprivation/asphyxiation hazard per inputs from SOFIA Safety. Added guidance reference to SOFIA Safety Plan, SOF-NASA-PLA-PM21-2089.
Table 11.14-1: Reconstructed hazard severity classification table to be editable.
Table 11.14-2: Reconstructed hazards probability classifications table to be editable; an issue with not all text being visible (rows for Class A & C) with the previous table has been corrected in this new version.
Table 11.14-3: Reconstructed hazards action matrix table to be editable; typos that existed within the previous table has been corrected in this new version.
Appendix A: Appendix renamed to “Appendix A.1 Deliverable Items List”. Formalized the following items as deliverables: Software requirements verification matrix, SI mass and C.G. ICD analysis report, Instrument ICD envelope analysis report, Instrument cart/stand ICD analysis report(s), Instrument cart/stand structural analysis report(s), Cryogen fill procedure. Renumbered deliverable items to account for the new entries added to the list. Revised deliverable due dates to align with proposed Appendix A.2 Documentation Delivery Schedule.
- Added Appendix A.2 Documentation Delivery Schedule summarizing document deliverables due by milestone/technical review.
Appendix D: Added document number SOF-NASA-REP-SV05-2057 to appendix title. Replaced previous matrix template excerpt with layout/format established in the recently approved and baselined SOF-NASA-REP-SV05-2057.
Appendix E: Added informational statement content of table originates from SOFIA Science Project Data Requirements, SCI-AR-SOW-PM91-2001. Added annotations for items which apply to “FSI only”.
- Added Appendix G.1 Hazard Report: Generic SI and SI-provided GSE Structural Hazards.
- Added Appendix G.2 Hazard Report: Generic SI Cryostat Overpressure and Habitable Atmosphere Hazards.
- Added Appendix G.3 Hazard Report: Generic SI - Aircraft Platform Pressure Boundary Hazards.
- Added Appendix G.4 Hazard Report: Generic SI and SI-provided EGSE Electrical Hazards.
- Added Appendix H SI Developer’s Handbook OP03-2000, Rev. B Change Log: Changes made to Rev. A (June 2015 version).

Appendix I – SI Developer's Handbook, Rev. B to C Change Details

Administrative changes:
- Updated signature page.

Specific changes (Rev. B paragraph numbers cited below):
Global changes: Made revisions throughout document to make handbook consistent with 2017 ROSES NRA solicitation NNH17ZDA001N-SFNXGNI for SOFIA Next Generation Instrumentation, notably removal of instrument class types (i.e., facility-, PI-, tech demo-) to align with a single development approach for Next Gen SI, and
1.2: Added explicit statement that handbook is not a source of requirements; handbook is only for guidance. Also added clarifying description for "shall / should / will" terminology.
3: Updated section to reference 2017 ROSES solicitation and simplification of instrument development approach for NGSI. Deleted Table 3-1. Shortened sections 3.1, 3.2, and 3.3 to focus on primary characteristic of each instrument class.
3: Replaced section 3, 3.1, 3.2, and 3.3 text with summary instrument development lifecycle and process laid out in ROSES solicitation.
Figure 5.3.1-1: Replaced CRYO_SI_01 ICD reference to CRYO_SI_02.
Table 5.3.1-1: Replaced CRYO_SI_01 (APP-DA-ICD-SE03-2059) ICD reference to CRYO_SI_02 (SOF-NASA-ICD-SE03-2066).
5.3.7: Updated section to reflect SOFIA Phase 2 cryocooler system from the earlier Phase 1 cryocooler system information.
5.3.8: Updated section to reflect pipeline development organizational roles and responsibilities as defined in the ROSES solicitation, notably that SI team is responsible for delivering algorithms and data; SOFIA Program will develop data reduction pipeline software. Also removed out of date data processing and pipeline document references.
5.4.2: Removed pipeline software requirements from the responsibilities of the SI team to align with ROSES solicitation.
5.4.3.1: Revised SI SE01-2028 and SOFIA ICDs V&V matrix formulation and first delivery of draft from Phase B to Phase A.
5.4.3.2: Revised SI science and technical performance V&V matrix formulation and first delivery of draft from Phase B (PDR) to Phase A (SRR).
5.4.4: Provided clarification that the context of the term "commissioned" used is intended to mean "fully commissioned".
5.4.5.2: Deleted CDR responsibility of SI team for "data reduction pipeline design".
5.4.5.3.5: Updated section to reflect pipeline development organizational roles and responsibilities as defined in the ROSES solicitation.
5.4.5.7: Added information that instrument commissioning typically is accomplished through two separate commissioning flight series.
5.4.5.8: Added information statement that changes made to an instrument may require an updated airworthiness recommendation letter from SIAT.
6: Eliminated specific reference to required capability just for facility science instruments to instead science instruments in general (Next Gen instruments). Also added explicit statement that SI team will train SOFIA SMO staff on operating the instrument, since the instrument will transition from the instrument developer to NASA after the instrument Legacy Science Program is completed.
6.2.1: Renamed Instrument Readiness Rooms (IRRs) to SOFIA Science Laboratories (SSLs).
6.2.8: Made minor editorial changes to blower system historical description.

6.2.9: Updated section to describe Phase 2 cryocooler system; added reference to Phase 2 cryocooler spec SOF-NASA-SPE-SE01-2089 and Cryocooler System ConOps APP-DA-PLA-PM17-2076.
6.6: Deleted reference to PI and Tech-demonstration instruments.
6.7: Added reference to SE01-2028 ParID 3.1.6 for additional information about MCCS Archiver.
7.1.1: Updated section providing an overview of the solicitation process as described in the ROSES solicitation.
Figure 7.1.1-1: Deleted; multiple aspects of figure are inconsistent with ROSES solicitation.
7.4.1: Added explicit statement that SOFIA SE01-2028 and SOFIA SI ICD requirements also apply to the instrument SRR.
7.6.2.2: Clarified and revised PSR criteria for demonstrating pipeline development version functionality to be a responsibility of SOFIA SMO.
Figure 7.7-1: Deleted figure; no longer accurate
7.7.4: Established scope of Commissioning Review; instituted as a review which will be conducted by all Next-Gen SOFIA SI. Revised criteria "SI performance and limitations have been determined and documented." to "SI has been verified to meet instrument science and technical performance requirements, and SOFIA SI design requirements."
7.7.5: Revised scope and criteria of Acceptance Review, given an earlier Commissioning Review will be held for all instruments.
(Earlier section 7.7.5 for Commissioning Review has been deleted; and instead created as section 7.7.4 since the Commissioning Review occurs before the Acceptance Review in the instrument lifecycle.)
7.8.1: Inserted new first section titled "Post-Commissioning / Pre-Acceptance Support" to cover the period between commissioning and acceptance in which the instrument is still under the control of the instrument developer, similar to a PI-class instrument. Moved existing 7.8.1 to a new 7.8.2.
8.3.4: Added the specific applicability of ANSI / AWS D17.1 to SI welds, and typical minimum class (Class B) for GSE cart / stand structural welds.
8.5.1.1.2: Moved PVC prohibition statement from section 8.5.1.1.2 to 8.5.1.1.1 for reading clarity.
10.1.1: Added information about operating temperature environments for observatory systems onboard SOFIA, including reference to STR SOF-NASA-REP-SV03-2115, 2016 Cabin Temperature Characterization Results. Deleted reference to SOF-AR-ICD-SOF-1030 since it is an out of date document for operational temperature information.
10.2: Added Nasmyth Tube acoustic information from empirical data, including power spectral density data from characterization measurements.
10.3: Provided clarifying language that SE01-2028 does not require SIs or SI equipment to undergo vibration and/or "thermo-vac" environmental acceptance testing.
10.3.1: Added new section presenting quasi-steady state load factors for flight phases (taxi, takeoff, cruise, descent) with flight acceleration data.
10.3.2: Added new section and subsections providing measured vibration data for locations on SOFIA including aft seat track (section 10.3.2.1), TA IMF / SI Flange (section 10.3.2.2), PI Rack (section 10.3.2.3), Counterweight Rack (section 10.3.2.4), and SI Shipping Assembly (section 10.3.2.5). Also added new section 10.3.2.6 providing contextual comparison between vibration measurements presented in 10.3.2.x subsections and the Environmental Acceptance Test levels defined in DCP-O-018B.
11.1: Extracted Critical Safety Items List as a data requirement of the System Safety Assessment, and made the Critical Safety Items List a separate deliverable.
11.2: Added statement that SOFIA Program will provide a SI QA Plan template to the instrument developer.
11.5.2: Deleted section since identification list is being removed as a data requirement
11.10: Updated table to reflect changes to software documentation deliverables required for Next-Gen SI developments; deleted software user's guide, software analysis report, and software verification & validation plan. Scope and intent of these documents will be covered in other SI documentation.
11.16.2: Replaced Science Project System Safety and Mission Assurance Plan (SCI-AR-PLA-PM21-2000) reference with SOFIA Program Safety and Mission Assurance Plan (SOF-DA-PLA-PM21-1086).

12.6: Deleted section since this WBS information isn't relevant to instrument developers. Subsequent 12.x sections have been renumbered as a result of this section deletion
Appendix A.1: Added subsection numbers to categories: Hardware (A.1.1), Software (A.1.2), Documentation (A.1.3), and Instrument Team Inputs to Documents Developed by SOFIA Program (A.1.4).
Appendix A.1.2: Replaced "Instrument data analysis/pipeline software" with "Data reduction algorithms and test data"; added "check cases and/or scripts to support regression testing" to Instrument control software deliverable.
Appendix A.1.3: (Sub-bullets below)
- Refined scope of Drawing Package for Airworthiness data package to "Flight Hardware Drawing Package"
- Deleted the following documentation items as formal deliverables; scope and intent of these deliverables will be incorporated into other SI documentation deliverables: software user's guide, software verification and validation plan, instrument control software manual, instrument optical alignment plan
- Deleted documentation items from responsibility of SI developer: software analysis report, pipeline developer's manual, pipeline user's manual, instrument identification list, commissioning data package
- Changed form of expected deliverable from "documentation deliverable" to "SI technical input to SOFIA team": SI Electromagnetic Interference (EMI) Test Plan, SI Installation Procedure, SI Removal Procedure, and SI Acceptance Data Package
- Added the following documentation deliverable items: Critical safety items list, Ground support equipment drawing package, Ground support equipment load test procedure, Calibration Plan
Appendix A.2: Updated documentation delivery schedule table to reflect the deliverable item changes made to Appendix A.1; shifted baseline release of Electrical systems report, Instrument assembly structural analysis report, Counterweight rack report, PI rack report, System safety assessment, Instrument assembly mass and c.g. ICD analysis report, Instrument ICD envelope analysis report, Instrument cart/stand ICD analysis report(s), Instrument cart/stand structural analysis report(s) earlier to CDR instead of PSR, and specified typical update and delivery of these documents at PSR.
Appendix B: Updated acronyms list.
Appendix E: Deleted this appendix, reflecting changes made to commissioning data package and acceptance data package in Appendix A.1.

Appendix J – SI Developer's Handbook, Rev. C to D Change Details

Administrative changes:
- Updated signature page.

Specific changes (Rev. C paragraph numbers cited below):
Global changes: Made revisions throughout document to make handbook consistent with the new *SOFIA Science Instrument Development Process and Deliverable Requirements* (SOF-NASA-SOW-PM91-2094) document.

1.1 – Deleted sections pertaining to SOW and previous old reference to documents before the Handbook.
1.2 Deleted sentences pertaining to "Shall" and "Should" classifications, there are no shall statement in this document.. Added SI developer and Safety critical to terminology
2- Updated public outreach link
3.3- Deleted sentence referring the 2017 solicitation.
4.1 – moved figure 4.1-2 sentence
4.2 - second sentence revised
5.1-5.2- updated to reflect 2094
Fig. 5.3.1-1 – revised
5.3.5 – added sentence about limited 3D CAD to end.
5.3.9 – Added Sentences about Load tests.
5.4 - updated to reflect 2094
6.0 – removed reference to FLITECAM and HIPO
6.2.1 – added some detail to cryocooler compressor section, power revised Network access Electronics, Office space sections and added a section on Optics.
6.2.3 – Minor name change revisions.
6.2.9 – added reference to new document 2066
6.5 – deleted and some content moved to 6.7
6.6 – modified reference to GTO
7 - updated to reflect 2094, also created App K and moved chart content guidelines.
8.- updated to reflect 2094, Airworthiness requirements now in 2094.
9.- updated to reflect 2094
10.1.1 –added cargo hold environment info
10.3.2.6- updated references to AFOP-7900.3-004 instead of DCP_0-018B
11.-updated to reflect 2094
12.1.-updated to reflect 2094, FFR reference
12.3.-updated to reflect 2094, FFR reference
12.4, 12.5- updated to reflect 2094
12.7 - IRR references changed to SSL, last sentence revised and references deleted

Appendix A.1 – deleted, content moved to 2094
Appendix A.2 – deleted, content moved to 2094
Appendix B- added acronyms for RAID, HILS, and deleted redundant COR acronym and GIMP (GMIP)
Appendix E—deleted, templates will be provided elsewhere.
All Appendix Gs – Deleted, templates will be provided instead.
Appendix J - added to capture changes between Rev C and Rev D
Appendix K – added to capture Chart Content Guidelines for Reviews

Appendix K – Chart Content Guidelines for Reviews

1. Initial Formulation Review (IFR)

The following subsections contain guidelines for the chart content and subject areas to be addressed in the IFR by the instrument team.

Design Description (including Requirements, Evolution and Heritage):

a) A complete and comprehensive definition of the entire design exists to the component level.
b) Results of trade studies and rationale for selected alternatives are defined.
c) Remaining trade studies are identified and potential impacts are understood.
d) Requirements flow-down and traceability to the appropriate subsystem of each system element, and, to the extent practical, to the component, has been completed.
e) Verification compliance matrices for instrument science & technical performance, SOFIA SI System specification, and SOFIA ICD requirements have been updated with results of verification; and verification planned for next development phase has been identified.
f) Requirements and design changes since the ICS report and their rationale are documented.
g) Appropriate descopes have been identified.
    a. Plans and trigger points have been identified.
    b. Impact to science objectives and deliverables has been defined.
    c. Potential impacts to mass, power, software and other resources have been quantified.
    d. Budget and schedule impacts have been estimated.
h) Long-lead items and their acquisition plans have been identified. Any fabrication needed prior to FFR has been identified.
i) Software Considerations:
    a. Preliminary requirements are identified, including language, structure, logic flow, CPU throughput and memory loading, re-use, safety, and security.
    b. Nominal operating scenarios are identified, along with fault detection, isolation, and recovery strategies.
    c. Design and development plans are defined.
    d. Verification strategies are defined including test environments.

Total System Performance (budgets/projections/margins for combined optical, thermal, mechanical, control, etc.):

a) Budgets and margins for system performance (pointing, throughput, etc.) are defined.
b) Preliminary system performance estimates are complete.
c) Estimates of critical resource margins (e.g., mass, power) have been delineated based on design maturity.
    a. Sufficient margin exists based on applicable standards. Risk mitigation strategies are defined for margins below guidelines.

Design Analyses:

a) Preliminary analyses critical to proof of design are complete.
b) Analyses required to enable detailed design should be complete.
c) Rationale and risk assessment exists for outstanding analyses that may, at completion, impact the design baseline, i.e., mass, power, volume, interfaces.
d) Status and schedule of final analyses are defined.

Development Test Activities:

a) Breadboard and engineering model development activities have been defined.
b) Test objectives and criteria have been identified.
c) Completed breadboard and engineering model test results have been iterated into the design.

Risk Management:

a) All significant risks, problems, and open items are identified and tracked (including programmatic, development and flight performance related items). Risk mitigation plans are appropriate and credible.
b) Lessons learned have been appropriately researched and adapted.
c) Reliability and maintainability considerations have been factored into the design.

Safety and Airworthiness:

a) An updated system safety assessment identifies all requirements as well as any planned tailoring approaches or planned deviation requests.
b) Preliminary hazards, controls, and verification methods are identified and documented. Drafts of hazard reports have been completed.
c) Any open safety issues are identified with plans for resolution.
d) Plans and schedules for all required safety submittals are defined and documented.

Assurance Activities:

a) Quality Assurance plans are complete including the problem reporting system.
b) Preliminary production planning and process controls (including strategy for control/verification of units of measurement) have been identified. Applicable workmanship standards have been defined.
c) Special materials considerations have been identified.

Implementation Plans:

a) Equipment and facilities for the development and test of hardware and software have been identified.
b) Preliminary planning for Systems Integration and Test activities, including science validation and calibration, as well as operations compatibility testing, has been defined. Facilities are available and, if needed, utilization agreements are in work.
c) Risks associated with I&T have been characterized and preliminary mitigations have been defined.
d) Contamination requirements and preliminary control plans are defined.

Interface Control Documents:

a) ICDs with the Observatory are understood and any preliminary ICDs needed between instrument elements are complete.
b) TBD and TBR items are clearly identified. Plans and schedules exist for their definition.

Logistics:

a) Transportation methods are identified including environmental control and monitoring considerations.
b) Preliminary identification of all GSE has been completed including instrument installation carts and instrument laboratory stands.

Ground and Mission Operations:

a) Science and mission operations concepts are defined.
b) Mission operations unique ground systems have been defined.
c) Preliminary plans are defined for test activities at Armstrong Building 703, integration with the Observatory, commissioning, and operations.
d) Preliminary planning for involvement and training of SOFIA instrument scientists and mission operations teams are defined.

Programmatic:

a) Organization and staffing plans delineate clear responsibilities and adequate assignment of current and future staff.
b) Appropriate processes and metrics are in place to track and control cost, schedule, and technical activities throughout the remaining life-cycle.
c) Preliminary configuration management plan has been defined.
d) Appropriately detailed schedules show realistic event times as well as appropriate funded slack and are compatible with approved commissioning dates.
e) Updated cost and Integrated Master Schedule (IMS) schedule inputs are ready to submit after review comments are incorporated.
f) Cost to complete shows adequate spending profiles and financial reserves, and is compatible with allocations.

Project Review Activity:

a) Timely response to actions and liens from previous reviews has occurred. Resultant actions have been implemented effectively. Schedule for completion of any outstanding actions is defined.
b) An appropriate set of engineering peer reviews has been conducted and documented. Resultant actions have been effectively dispositioned and executed. Appropriate additional reviews are planned.
c) Recommendations from other project or external review activity that is applicable to the subject matter of the IFR have been adequately implemented.

2. Final Formulation Review (FFR)

The following subsections contain guidelines for the chart content and subject areas that should be addressed in the FFR by the instrument team.

Design Description (including Requirements, Evolution and Heritage):

a) A complete and comprehensive definition of the entire design exists to the piece-part level.
b) Trade studies and rationale for selected alternatives are complete. Impacts of trade decision have been fully integrated into systems requirements, design, verification, operations, etc.
c) Requirements flow-down and traceability has been completed.
d) Verification compliance matrices for instrument science & technical performance, SOFIA SI System specification, and SOFIA ICD requirements have been updated with results of verification; and verification planned for next development phase has been identified.
e) Requirements and design changes since IFR and attendant rationale are documented.
f) Potential de-scopes have been identified.
    a. Plans and trigger points have been identified.
    b. Impact to science objectives and deliverables has been defined.
    c. Impacts to mass, power, software and other resources have been quantified.
    d. Budget and schedule impacts have been determined.

g) A high percentage of drawings (> 80 %) are completed:
    a. Number and title of all drawings have been identified,
    b. Status and schedule of drawing completion (e.g.: draft/preliminary/under review/final) have been defined.
    c. Rationale for outstanding drawings is defined and impact understood.
h) Software Considerations:
    a. Requirements changes since IFR are identified, including those to language, structure, logic flow, CPU throughput and memory loading, re-use, safety, and security.
    b. Current operating scenarios are identified, along with fault detection, isolation, and recovery strategies.
    c. Current software performance estimates exist. Results meet requirements.
    d. Software Requirements Document is approved. Document includes verification matrix mapping requirements to subsystems or CSCIs.
    e. Software Development Plan is approved and includes lines of code estimate, number of builds, tools, and procedures to be utilized, and the verification strategy including planned test environments.

Total System Performance (budgets/projections/margins for combined optical, thermal, mechanical, control, etc.):

a) Budgets and margins for system level performance (pointing, throughput, etc.) are fully defined.
b) System performance estimates are complete. Margins are adequate or viable corrective actions are in work.
c) Current estimates of critical resource margins (e.g., mass, power) are regularly updated based on design maturity.

Design Analyses:

a) All analyses critical to proof of design are complete.
b) Additional outstanding analyses have acceptable completion dates and potential impacts are understood and can be reasonably accommodated.
c) Schedules for required updates of analyses are defined.

Development Test Activities:

a) Breadboard and engineering model development activities have been completed. Results are understood and have been iterated into the final design.
b) Viable rationale exists for any outstanding testing that may at completion impact the design baseline, i.e., mass, power, volume, interfaces.
c) Potential impact of other outstanding activity is understood and can be reasonably accommodated.

Risk Management:

a) All significant risks, problems, and open items are defined and tracked (including programmatic, development, and flight performance related items). Risk mitigation plans are credible and will retire risks in a timely fashion.
b) Lessons learned have been appropriately researched and adapted.

Safety and Airworthiness:

a) An updated system safety assessment identifies all requirements as well as any planned tailoring approaches and accepted deviations.

b) Analysis of system hazards, identification of control methods, and definition of verification methods is complete. Documentation has been approved. Updated hazard reports have been completed.
c) Verification of hazard controls is on-track.
d) Safety critical items have been identified. Preliminary schedule for fabrication of safety critical items is established, and NASA inspection points identified.
e) Airworthiness data package has been submitted to the SIAT and approved.
f) Hazardous integration and test procedures and appropriate controls have been identified.

Assurance Activities:

a) The Instrument Quality Plan is complete, including the problem reporting system.
b) Preliminary production planning and process controls (including strategy for control/verification of units of measurement) have been identified. Applicable workmanship standards have been defined.
c) Physical Configuration Audit plan has been completed, and schedule for NASA inspection points established.

Implementation Plans:

a) Equipment and facilities for the development and test of hardware and software have been identified.
b) Planning for instrument integration and commissioning, including science validation and calibration, as well as EMI/EMC testing, is defined.
c) Risks associated with I&T have been characterized and mitigations are on track for timely closure.
d) Contamination requirements and control plans are defined. Required implementation activities are complete.

Interface Control Documents:

a) Up-to-date ICDs, with external systems as well as between system elements, are approved. No TBDs exist.
b) Deviations have been approved for known noncompliance(s) with SOFIA SI System Specification or SOFIA ICD requirements.

Logistics:

a) Transportation considerations have been fully defined including environmental control and monitoring requirements.
b) Preliminary design of all GSE has been completed including instrument installation carts and instrument laboratory stands.
c) Preliminary transportation container design has been completed.

Ground Operations, Mission Operations:

a) Science and mission operations concepts are fully defined.
b) Plans are defined for test activities at Armstrong Building 703, integration with the Observatory, commissioning, and operations.
c) Planning for involvement and training of instrument scientists and of mission operations teams are defined.

Programmatic:

a) Organization and staffing plans delineate clear responsibilities and adequate assignment of current and future staff.

b) Appropriate processes and metrics are in place to track and control cost, schedule, and technical activities throughout the remaining life-cycle.
c) Final configuration management plan has been defined.
d) Appropriately detailed schedules show realistic event times as well as appropriate funded slack and are compatible with approved launch dates.
e) Cost to complete shows adequate spending profiles and financial reserves, and is compatible with allocations.

Project Review Activity:

a) Timely response to actions from previous reviews has occurred. Resultant actions have been implemented effectively. Schedule for completion of any outstanding actions is defined.
b) An appropriate set of engineering peer reviews has been conducted and documented. Resultant actions have been effectively dispositioned and executed. Appropriate additional reviews are planned.
c) Recommendations from other project or external review activity that is applicable to the subject matter of the FFR have been adequately implemented.

3. Pre-Shipment Evaluation (PSE)

Although there is no formal chart package deliverable required of the instrument team, the following subsections contain guidelines for the subject areas that should be addressed prior to or in the PSE by the instrument team.

Requirements / Design Update:

a) Requirements and design changes to hardware or software since FFR and attendant rationale are documented. Mission implications and interface compatibility have been considered, and verification updates (analyses and tests) have been completed.
b) Current calculations of all critical resource margins remain adequate and based on actual measured values.
c) Analyses of the current design are complete and demonstrate adequate margin.

Completed Verification Results:

a) All laboratory-based verification activities at the instrument developer's institution have been successfully completed.
b) Verification compliance matrices for instrument science & technical performance, SOFIA SI System specification, and SOFIA ICD requirements have been updated with results of verification; and planned verification to be performed before instrument installation/integration with SOFIA has been identified.
c) Software interface testing in the SIL or HIL have been successfully completed.
d) Current calculations for systems performance have been updated as appropriate with system test results and continue to demonstrate full compliance with system requirements.
e) All discrepancies (nonconformances, anomalies, failures, "cannot duplicates," etc.) are fully understood. Corrective actions are completed, and plans and preparations for any required follow-on actions are completed. All noncompliances and nonconformances have approved waivers.

Safety and Airworthiness:

a) System Safety Assessment has been updated and approved, reflecting any changes from FFR.

b) Hazard reports have been updated and approved by the SSWG. Hazard mitigations have been implemented or schedule for implementation has been established.
c) Airworthiness approval status is adequate for shipment.

Risk Management:

a) All significant risks, problems, and open items are defined and tracked (including programmatic, development, and flight performance related items). Risk mitigation plans are credible and will retire risks in a timely fashion.

Assurance Activities:

a) Physical configuration audit (PCA) has been completed.
b) All discrepancies have been reviewed for acceptable closure. Any items requiring special attention or monitoring during subsequent activity, including during mission operations, have been identified and appropriate action planned.
c) Proof load tests of instrument carts or stands have been completed.
d) Tests for pressure relief devices (PRDs) of instrument cryogen vent systems have been completed.

Logistics:

a) Transportation plans are fully defined. Shipping containers, handling equipment, environmental control and monitoring equipment are verified and available.
b) Armstrong Building 703 facilities are available and have been verified to meet requirements.
c) Laboratory check-out procedures are approved and include appropriate system performance testing.

Mission Operations:

a) Required team training to support laboratory and Observatory operations have been identified and scheduled.

Review Activity:

a) All actions from all previous reviews are closed. Resultant actions have been implemented effectively.

4. Pre-Install Review (PIR)

The following subsections contain guidelines for the chart content and subject areas that should be addressed in the PIR by the instrument team. The PIR is a high level meeting and charts should summarized in a few charts the readiness of the SI to be flown onboard SOFIA.

Completed Verification Results:

a) All laboratory-based verification activities and testing at AFRC Building 703 have been successfully completed.
b) Verification compliance matrices for instrument science & technical performance, SOFIA SI System specification, and SOFIA ICD requirements have been updated with results of verification; For the first installation of an instrument onto SOFIA, the verification status of all requirements will be presented. With the exception of requirements that will be verified after installation or during commissioning, all applicable requirements must be declared pass (complies) or have approved deviations or waivers.

c) All noncompliances and nonconformances have approved waivers.

Safety and Airworthiness:

a) Instrument has received airworthiness approval from the SIAT.
b) SI cart qualification (load testing) has been completed.
c) A physical inspection of the safety/airworthiness related external features of the instrument has been successfully completed. All discrepancies have been reviewed for acceptable closure. Any items requiring special attention or monitoring during subsequent activity, including during mission operations, have been identified and appropriate action planned

Risk Management:

a) Any remaining risks have been identified. All significant risks, problems, and open items are defined and tracked (including programmatic, development, and flight performance related items). Risk mitigation plans are credible and will retire risks in a timely fashion.

Assurance Activities:

a) The Instrument Configuration sheet describing the current configuration of the instrument and any instrument software changes from the prior flight series of the instrument, is current and complete.

Mission Operations:

a) Installation procedures are approved.
b) Required team training to support instrument installation onboard SOFIA aircraft has been completed
c) An installation schedule has been developed and coordinated with the SOFIA operation team.

Review Activity:

a) All actions from all previous reviews are closed. Resultant actions have been implemented effectively.
b) Clearly state the instrument is ready for installation.

5. Operations Acceptance Review (OAR)

The following subsections contain guidelines for the chart content and subject areas that should be addressed in the OAR by the instrument team.

Completed Verification Results:

a) Verification compliance matrices for instrument science & technical performance, SOFIA SI System specification, and SOFIA ICD requirements have been updated with results of those requirements that were verified after installation or during commissioning, all applicable requirements must be declared pass (complies) or have approved deviations or waivers.
b) All noncompliances and nonconformances have approved waivers.

Risk Management:

a) Risks are known and manageable.

Assurance Activities:

a) Instrument commissioning is complete, and performance of the instrument is well understood.
b) Data reduction pipeline for the instrument is complete.

Mission Operations:

a) Operations procedures are approved.
b) SSMO staff are trained in the operation and maintenance of the instrument.
c) Associated documentation deliverables are complete and reflect the delivered system

Review Activity:

a) All actions from all previous reviews are closed. Resultant actions have been implemented effectively.
b) Clearly state if the science performance is acceptable.