NASA/SP–2016-09-100-LaRC

The Making of SOFIA

− The Stratospheric Observatory for Infrared Astronomy −

1985 to 2016

Nans Kunz, PE
NASA Ames Research Center, Moffett Field, CA 94035-1000

Cover: *SOFIA, the Stratospheric Observatory for Infrared Astronomy - SOFIA*

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Nans Kunz, PE

NASA Engineering and Safety Center
Chief Engineer at
NASA Ames Research Center

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199
September 2016

Available from:

NASA STI Program / Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199
Fax: 757-864-6500

Foreword

Nans Kunz was the lead Stratospheric Observatory for Infrared Astronomy (SOFIA) engineer for 22 years, starting 10 years before its official development began in December 1996. His technical and managerial skills and efforts were responsible in large part for the successful performance SOFIA now enjoys. This book describes SOFIA's development through 2007, when Nans resigned from the project, with some information updated to the current time (2016). His personal experiences, observations, and feelings are included, making this a unique account—a memoir—of the most extended and enjoyed professional activity of his career.

Initially, it was thought that SOFIA development could lead to beginning operations after 5 years, in 2001. In fact, from the official development start it took more than 10 years until the first test flights in 2007, with corresponding cost overrun. Being passionate about the project, Nans wanted not only to record the solutions to its unique engineering challenges and its history from his perspective, but also to describe "Lessons Noted" which relate to missteps that could have been avoided with better decision making. These he hoped could be "Lessons Learned" for future NASA projects.

We had the privilege and pleasure of working on the book with Nans for some months before his untimely death at age 59 in February 2016. Larry Caroff was the Infrared Program Chief at NASA Headquarters and subsequently the SOFIA Program Manager at NASA Ames for 2 years before his retirement. Ed Erickson was the SOFIA Project Scientist at Ames. Hence, both had worked with Nans and the project team for more than 2 decades. Desmond Chee helped Nans with writing and communicating as he became unable to do so. Most of the book was completed while Nans was still with us; our last meeting with him about this manuscript was a few days before he passed on. He was still intensely interested in its completion. We have attempted to fulfill his wishes, maintaining his views and intentions.

It was Nans' hope, as is ours that the book will be of interest and value to all who read it: the engineers, the managers, friends, and any interested in the development of this unique, world-class observatory.

Ed Erickson Desmond Chee Larry Caroff September 2016

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Preface

This book serves to document the history of the making of Stratospheric Observatory for Infrared Astronomy (SOFIA), primarily from the engineering perspective, or actually my perspective. My name is Nans Kunz and I was significantly involved in the development of SOFIA from the beginning; a time span of just prior to the establishment of the SOFIA Study Office (SSO) in 1985 to about half a year beyond the completion of the first test flight in 2007. During the pre-development phase, I was both the engineering manager, leading most of the technology development efforts, and the aircraft systems manager, serving as the Contracting Officers' Technical Representative for the many study contracts that investigated the feasibility of making a modification of this magnitude. In 1996, when SOFIA was approved for development, I applied and was selected for the position of Project/Program Chief Engineer. I maintained this position until I resigned from the Program in 2007. The combination of the depth and the duration of my involvement makes me uniquely suited to describe many aspects of the SOFIA history and the engineering development of SOFIA.

My many objectives for writing this book, include documenting the difficult development path that SOFIA followed to become a world-class observatory, documenting lessons learned (or that could be learned) from various decisions made along the way (looking at them from both remembering the objective at the time and in hindsight at what actually happened), providing background and perspective on key configuration decisions, and acknowledging key contributions by several people who had significant involvement. Of course, I also want this book to be entertaining or interesting to anyone interested in SOFIA.

Although the format of this book is primarily chronological, it is also organized by discipline or by area of interest so the reader will notice overlapping of some of the stories. Throughout this book, there are several people I am pleased to mention by name. I do apologize to those I may have missed. Special acknowledgements are due to some with over 20 years of participation beginning with the early planning: Dr. Bill Rose, Dr. Edwin Erickson, Dr. Hans Kaercher, Mr. Alois Himmes, Dr. Larry Caroff, Dr. Hans Peter Roeser, Dr. Jackie Davidson, Mr. Ted Brown, Mr. Paul Keas, and Mr. Rick Brewster. Also, I greatly appreciate the efforts of Mss. Dee Bullock, Erin Moran, Sandi Strickland, and Mr. Tim Wilson in the NESC Office at Langley Research Center for editing and arranging publication of the book.

1.0 INTRODUCTION

This book has been written and organized to serve multiple purposes. The intended audience is quite general, ranging from those who have never heard of the Stratospheric Observatory for Infrared Astronomy (SOFIA) to those who have been or are still intimately involved with the SOFIA Program. Hopefully this will include anyone with interests in project-management challenges and/or innovative engineering challenges in several engineering categories. In addition, there is a history timeline included to help readers better understand how a NASA Project development path can be altered and influenced by world events.

My hope is that this book can be read from beginning to end in a coherent and entertaining way, and that its organization allows you to navigate directly to topics of particular interest.

Section 2 provides an overview of what SOFIA is, while Section 3 provides a short explanation of why we (NASA) have undertaken this effort and expense to create SOFIA. Section 4 provides the background of SOFIA by describing some highlights of SOFIA's immediate predecessor: the Kuiper Airborne Observatory (KAO). Section 5 contains several sub-sections; each is focused on one or more engineering highlight or challenge addressed during the development of SOFIA. Where appropriate, each of these has its own chronology of events. Section 6 provides the timeline from 1985 to 1996 of pre-development milestones leading up to the beginning of the official program approval for development. Section 7 is the history of development, a period from the program approval to the completion of the first test flight. Section 8 gives a brief overview of the timeline from the aircraft's transfer to the Dryden Flight Research Center (DFRC) (now Armstrong Flight Research Center (AFRC)) to the beginning of science operations. Section 9 includes a brief overview of the current (through 2016) operations. Section 10 summarizes "lessons learned," the first of which is about keeping a log of progress:

Lesson 1:

Especially when working on a major project: record highlights, take photos as you go, and file them in chronological order. You may not realize from the start that you could be heavily involved in a project for over 20 years.

2.0 WHAT IS SOFIA?

Although the primary purpose of this book is to document the history of the SOFIA development, this section is included to provide a short overview of the facility. SOFIA is a highly modified Boeing 747SP aircraft that contains a large telescope within the fuselage in a cavity area that opens to the atmosphere while the plane flies at the upper edge of its flight envelope. Its purpose is scientific investigations of the universe at wavelengths of light and/or occurring during ephemeral events that are not accessible from the ground. Figure 2.0-1 is a photograph of SOFIA. Figure 2.0-2 shows a photograph of SOFIA with a cutaway computer-aided design (CAD) overlay showing the major interior sections of the observatory.

Figure 2.0-1. SOFIA flying with cavity door open (not usually done during daylight).

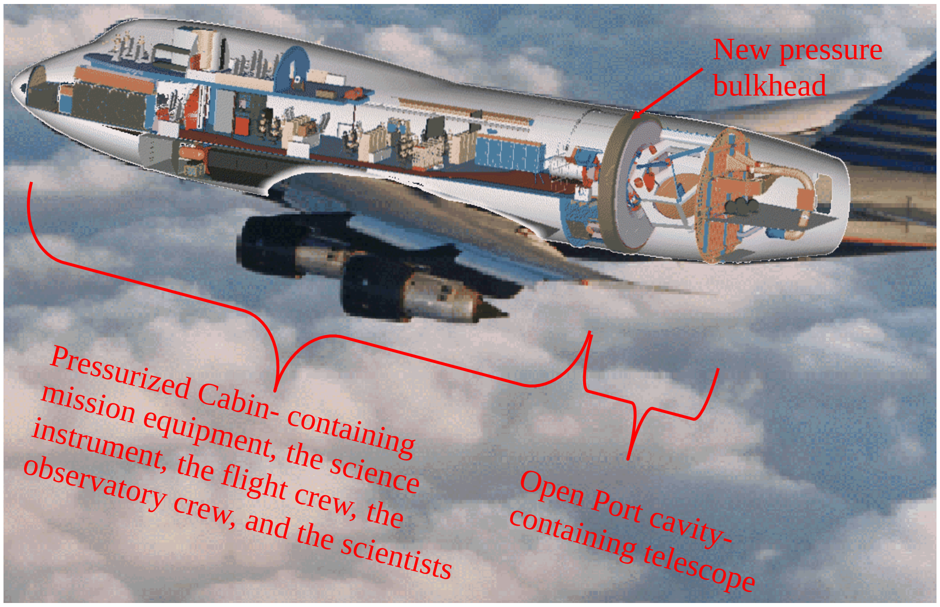

Figure 2.0-2. Cutaway CAD model overlaid on an actual photograph of the SOFIA airplane during a pre-modification test flight, showing major sections of the observatory.

The term, “SOFIA,” is an acronym for Stratospheric Observatory for Infrared Astronomy. The *Stratosphere* is the atmospheric layer above the troposphere, the atmospheric layer next to the surface of the Earth where we live. The tropopause is a shallow layer that separates the troposphere from the stratosphere. The elevation/altitude of the tropopause depends primarily on the latitude and the time of year, and is about 39,000 feet during the winter for latitudes equivalent with Northern California, where SOFIA was originally expected to be based. When in the stratosphere (above the tropopause), you are above about 98 percent or more of the atmospheric water vapor, thus allowing access to infrared wavelengths of light that do not reach the ground. The term *Observatory* within the acronym implies that SOFIA is a facility, not a particular single objective science experiment. Just like mountain-top astronomical facilities, SOFIA was designed to accommodate various types of science instruments (SIs) and to carry out a wide range of observing programs. SOFIA has a very broadband observing capability, including visible light, and is primarily optimized for the *Infrared* (IR) part of the electromagnetic spectrum, especially concentrating on wavelengths inaccessible to ground-based observatories. Figure 2.0-3 contains views of various CAD models showing more of the SOFIA-unique systems.

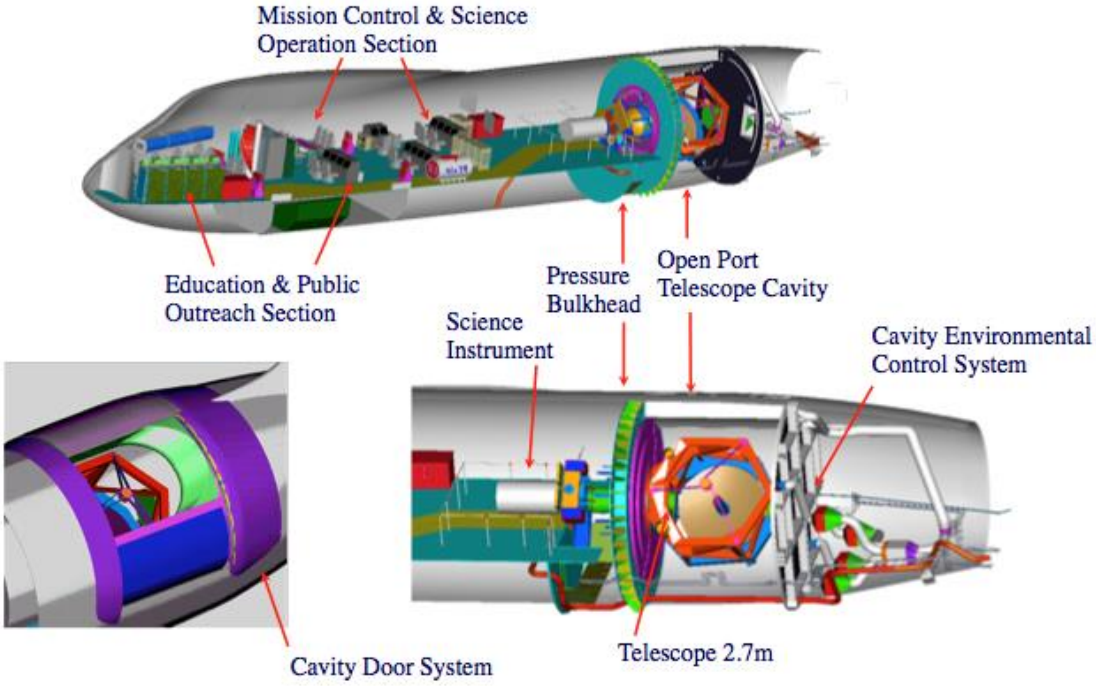

Figure 2.0-3. Views of various CAD models showing more of the SOFIA-unique systems.

2.1 Level 1 Requirements for Observatory.

The Level 1 requirements that were ultimately associated with the official approval of the development of SOFIA (see Section 6.16, 1996) were not direct transfers from KAO. They grew out of lessons learned from KAO operators and scientists regarding how the KAO specifications could have been improved. For example, Kuiper’s elevation range is higher (35° to 70°), but the history shows that the majority of usage was at the lower elevation angles, partly because of the desire to observe the area near the center of our galaxy soon after takeoff of the KAO from Ames; this resulted in the lower elevation angle for operation of SOFIA’s telescope.

The Level 1 Requirements (what the program promised to deliver for the cost and schedule given) at the time of approval of the SOFIA Program are listed here. Following the list is a brief description of how some of these requirements impacted the design.

SOFIA Level 1 requirements:

- Wavelength Range: 0.3−1600 microns
- Unvignetted Elevation Range: 20° to 60° above the horizon
- Configuration: Science Instrument access in cabin during flight
- Telescope Effective Aperture Diameter: 2.5 meters
- Time at ≥41,000 feet ≥6 hours
- Observing Hours per Year ≥960
- Lifetime ≥20 years
- Principal Investigator (PI) Teams per-year Capability ≥40
- Education Goals: NASA Office of Space Sciences (OSS) Guidelines
- Airworthiness: Federal Aviation Regulations (FAR) Federal Aviation Administration (FAA) Certification
- IR Functional Capabilities: chopping, nodding, & scanning
- Image Quality: 80 percent encircled energy within 1.5 arcseconds at visible wavelength
- Image Stability at Focal Plane: 0.2 arcseconds root mean square (RMS)

Wavelength Range: 0.3 to 1600 microns

Because there was no practical window material transparent to this broad band of wavelengths, the airplane needed an open port cavity. It follows that the aircraft needed a shear layer control (SLC) device. Furthermore, the telescope would be exposed to ambient temperatures, and to airflow, which creates static and dynamic torques and acoustic noise. To provide the open port cavity, the aircraft configuration required a new pressure bulkhead.

Unvignetted Elevation Range: 20° to 60° above the horizon

For the aircraft, this means it needed both a moving cavity door and SLC device, as well as a large structural opening. That led to an opening about 90° of the fuselage circumference. And since the airplane still needed to fly, a lot of standard aircraft systems needed to be rerouted, such as the control cables, auxiliary power unit duct, etc.

For the telescope, it meant that it needed a Course Drive function, in addition to the Rotation Isolation System (RIS). Of course, when the telescope is moving relative to the aircraft, the motion must be accommodated, which requires a large envelope for clearance and a cable drape system to relieve that load while staying connected to the power and control systems. Needless to say, the SI data must get to the data gathering computers.

Configuration: instrument access in cabin

Since the SI was to be in the cabin and connected to a telescope gathering photons from the astronomical object, the telescope needed to be mounted to the aircraft bulkhead and to be part of both the pressure boundary and thermal boundary. So despite the telescope being in the 41,000 feet altitude environment, which is typically about −70°F (for which the recovery temperature in the cavity is about −40°F) and is about 1/6th of atmospheric pressure at sea level, the Science Instrument would be located in a comfortable shirt sleeve cabin environment.

Telescope Effective Aperture Diameter: 2.5 meters

The goal for SOFIA was to have the largest aperture telescope possible and to fly it as high and long as possible. The related trade study work done in the pre-development studies led to the obvious aircraft selection: a Boeing 747. During an early study, NASA and the German Test and Research Institute for Aviation and Space Flight (DFVLR) agreed on specifying an aperture of 2.5 meters, as you will read about in the timeline section. Because IR observing required the image to be "chopped," the scientists who originally wanted a bigger telescope (of course!) interpreted 2.5 meters to be the "effective" aperture. Chopping or oscillating the secondary mirror moves the images back and forth, thus requiring a 2.7-meter primary mirror. Because of the size of the primary mirror and the limited diameter of the airplane, the mirror had to be fast (meaning highly curved) to keep the secondary mirror within the fuselage. This drove the alignment and stiffness requirements of the telescope.

Time at ≥41,000 feet ≥6 hours

Again, the goal of SOFIA was to have the largest aperture telescope possible and to fly it above the troposphere as long as possible, and into the stratosphere as high as possible, within some reasonable cost envelope. So again, the primary factor was aircraft selection: the combination of fuselage diameter and high-altitude performance. To maximize time at the highest altitude, the weight of everything in the aircraft needed to be minimized. That included all of the telescope and observatory equipment and the supporting infrastructure. With the aircraft we selected, the 747SP, the fuel burn rate at the end of the mission is about 16,000 lbs/hr. So, saving 16,000 lbs of telescope weight or modification weight would yield an additional hour of observation time every flight for the life of SOFIA. Unfortunately, for the aircraft to fly safely, the location of the center of gravity (CG) has a limited range. With the entire weight of the telescope mounted to a new bulkhead installed aft of the wing, ballast weight had to be added near the front of the airplane. Using the same technology as the KAO, the SOFIA telescope would have weighed about 300,000 lbs. Instead, the weight budget was 20 metric tons or 44,000 lbs for all telescope systems including support equipment. Of course, we had done multiple feasibility studies prior to program approval to show that it could be done. This drove the requirement to have Carbon-Fiber Reinforced Plastic (CFRP) for the metering structure, instead of Invar[1] that was used for the KAO telescope. And of course, the very large primary mirror required a light-weighted design. As you will read later, our German partners met this weight requirement.

Observing hours per year ≥960

The purpose of this requirement was to maximize science productivity, achieved in large part by maximizing observing hours per flight, plus the number of flights per year. This required multiple factors including reliability of the unique telescope, the highly modified airplane, and all associated infrastructure; and of course, maintainability and productivity (automation of functions) of the same systems. To make the best use of the flight time, pre-cooling the telescope and cavity was required so that the telescope was ready to operate stably immediately after opening the cavity door at altitude. Once observations would begin, the telescope needed to be tolerant of aircraft motion to maintain the desired pointing stability. Of course, with the open door cavity, the telescope also needed to be tolerant to the normal temperature environment variations.

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[1] Invar, also known generically as FeNi36 (64FeNi in the US), is a nickel–iron alloy notable for its uniquely low coefficient of thermal expansion.

Lifetime ≥20 years

As an observatory that represents a substantial investment by both NASA and DLR (Deutsche Zentrum für Luft und Raumfahrt – German Center for Aviation and Space Flight), SOFIA needed to be able to support operations for at least 20 years, accommodating new state-of-the-art SIs, updates to existing SIs, and improved computer technology.

PI teams per-year capability ≥40

As an observatory and not an individual experiment, SOFIA needed to accommodate a wide variety of SIs and quick change-outs from one to another, and to provide for numerous general/guest investigators to make use of those SIs.

Education Goals: NASA OSS Guidelines

As you might expect, while bringing in new knowledge to humankind about our universe, there are goals not only to share the new information but also to share how it is obtained.

Airworthiness: FAR FAA Certification

This was a late addition to the requirements added by NASA Headquarters (HQ) as part of the privatization approach. As you might expect, there are no sections or chapters in the FAR about open port cavities and operating telescopes during flight! The FAA Certification process does cover qualification of materials and processes, documentation, aircraft loads, and aircraft safety standards. Note: this late addition to requirements was dropped prior to first flight after much effort and many resources had been expended in meeting it!

IR Functional Capabilities: chopping, nodding, & scanning

As an observatory that is primarily designed for IR, SOFIA needed to have the appropriate IR observatory functionality, as provided by an articulating secondary mirror.

Image Quality: 80 percent encircled energy within 1.5 arcseconds at visible wavelength

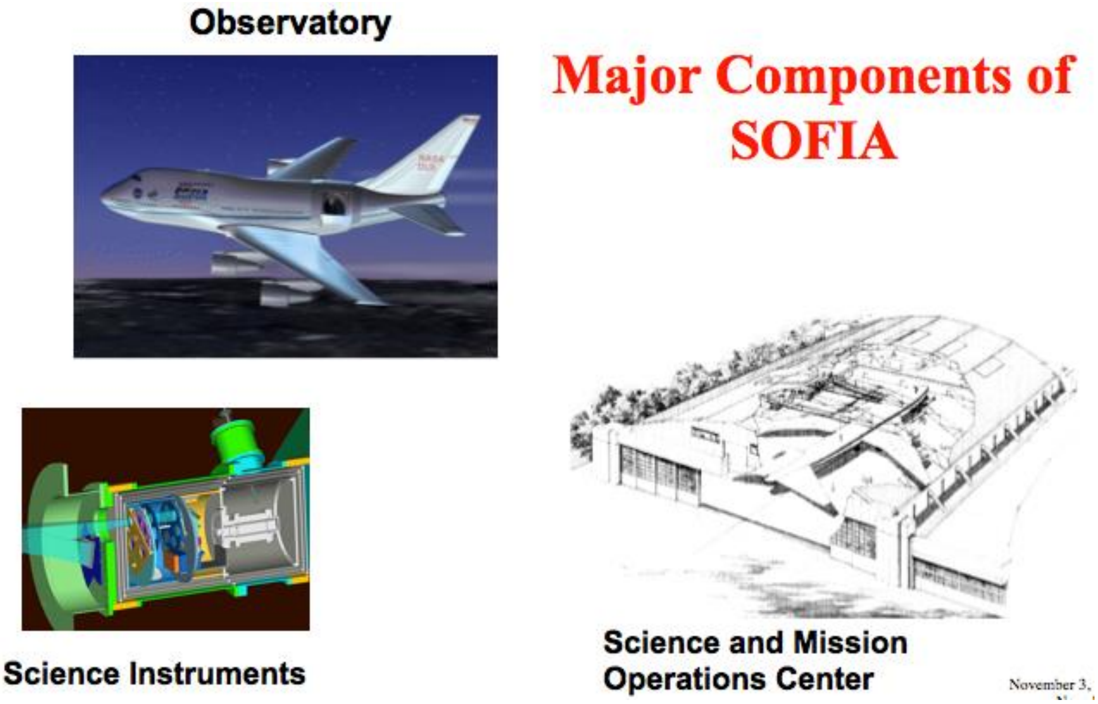
To take maximum scientific advantage of the large mirror, one of the most important factors was the quality of the image delivered to the SI. Image quality is affected by several factors including quality of the optics, alignment of the optics, motion of the optics, and "seeing" disturbances of shorter wavelength light passing through the shear layer over the cavity opening and through the air within the cavity.

Image Stability at Focal Plane: 0.2 arcseconds RMS

The pointing stability (jitter and drift) of the telescope should be so small that it would not contribute significantly to the other limits on angular resolution. If the stability contributes less than about 20 percent of the diffraction-limited resolution, it permits achieving "super resolution": a technique that actually enables surpassing the diffraction limit. There is an important niche of science applications for SOFIA that can benefit from this technique. These applications justify the stringent pointing stability requirement of 0.2 arcseconds RMS.

To achieve this requires serious attention to a lot of details including: telescope isolation from aircraft rotational and vibrational motions, in turn requiring the telescope system to attenuate aircraft motion by factor >1000. This is primarily done by the RIS. And of course, a lot of other supporting systems, many of which are covered later in this book. These include: RIS seals, cable drape, Vibration Isolation System (VIS) to attenuate aircraft translation motion, VIS seals, a stiff telescope structure, systems and controls to reject or compensate for disturbances which include gyros, strain gauges, pressure sensors, control system, and torque motors.

Rationale for the 0.2-arcsecond RMS pointing stability requirement is described in a paper by Drs. Erickson and Dunham (ref. 1). It is my understanding that there are some types of science that actually gain as the 4th power of the primary mirror diameter. To achieve the benefit for super resolution applications at the shorter IR wavelengths mentioned above, the telescope needed this kind of pointing stability. So for these applications, SOFIA has the potential of ~80 times more powerful science than the KAO, if this pointing stability can be achieved. At longer wavelengths, the benefit accrues for poorer image stability because of the increasing diffraction-limited image size.



Observatory

Major Components of SOFIA

Science Instruments

Science and Mission Operations Center

November 3,

Figure 2.1-1. Copy of an early PowerPoint® slide showing the three major components required for SOFIA operations and the objectives of this program.

3.0 WHY

3.1 Advantages Over Ground-based Observatories

So why go through all this trouble to modify an airplane to mount a telescope enabling observations during flight? The primary reason is that we gain access to wavelengths not available to ground. This is illustrated in Figures 3.1-1 through Figures 3.1-3, which include the Orion region in just visible light compared to a far-IR image measured from the Infrared Astronomical Satellite (IRAS). In addition, an airborne facility has mobility that allows for optimum placement of the telescope to observe time-sensitive astronomical events, such as an occultation of Pluto that allows us to see the characteristics or even to discover the atmosphere as was done using the KAO.

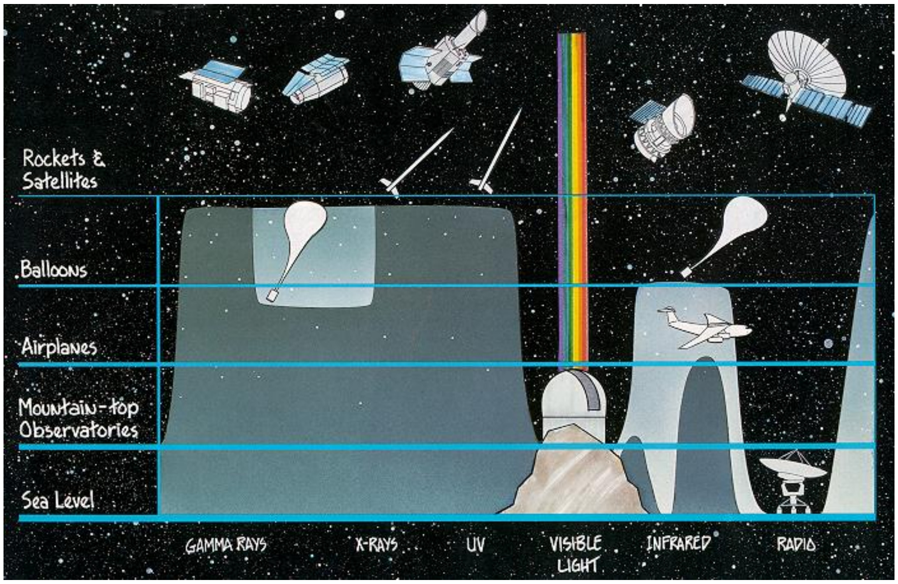


Figure 3.1-1. Shows in symbolic/iconic method what wavelengths of electromagnetic radiation reach the ground or upper elevations.

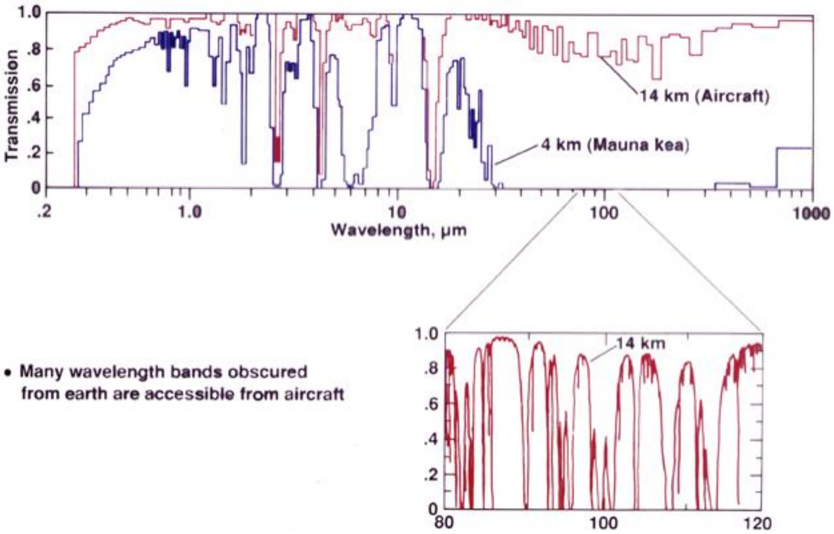


Figure 3.1-2. Graphic comparison of how much more electromagnetic radiation of different wavelengths reach a detector placed at 14 km (airborne flight altitude) versus 4 km (the top of Mauna Kea).

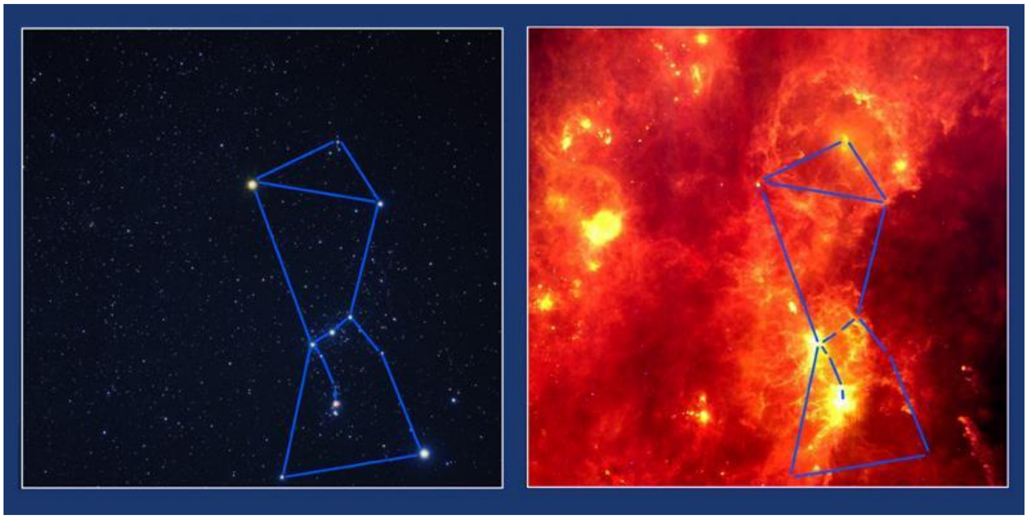


Figure 3.1-3. Photographic comparison of the Orion region, between visible light and IR light, demonstrating how much more information about how our universe works is available in different wavelengths.

3.2 Advantages over space-based observatories

Because it lands after every observation flight, an airborne SI can be updated, modified, or swapped out very easily as opposed to an instrument on a satellite. In fact, SOFIA's instruments can be adjusted or tuned up in real time during observations because they are located in the cabin with the scientists. This allows the use of state-of-the-art instruments with a worst-case consequence of a wasted take-off and landing of a 747SP as opposed to a wasted launch of a satellite. And because the complexity of some of the SIs required to observe these wavelengths means they are not suitable for satellites, SOFIA can achieve science that no other facility in the world can. Again, an airborne facility allows mobility of observation such as observing planetary occultations, that typically cannot be done with satellite-based instruments. This is actually how the rings around Uranus were discovered with the KAO.

4.0 PREDECESSOR – THE KAO

As you might expect, you cannot start from zero or with no previous experience to create a 747-sized airborne observatory. Modern history of airborne IR astronomy starts in the 1960s with an idea from Dr. Gerard Kuiper. He used the NASA Ames Convair 990 aircraft to show—unexpectedly—that the clouds of Venus are not made of water droplets.

Figure 4.0-1. SOFIA's predecessor: a modified C-141, the KAO. Based at NASA Ames Research Center, it operated from 1974 to 1995.

Figure 4.0-2. View looking down on the open port cavity of the KAO in flight.

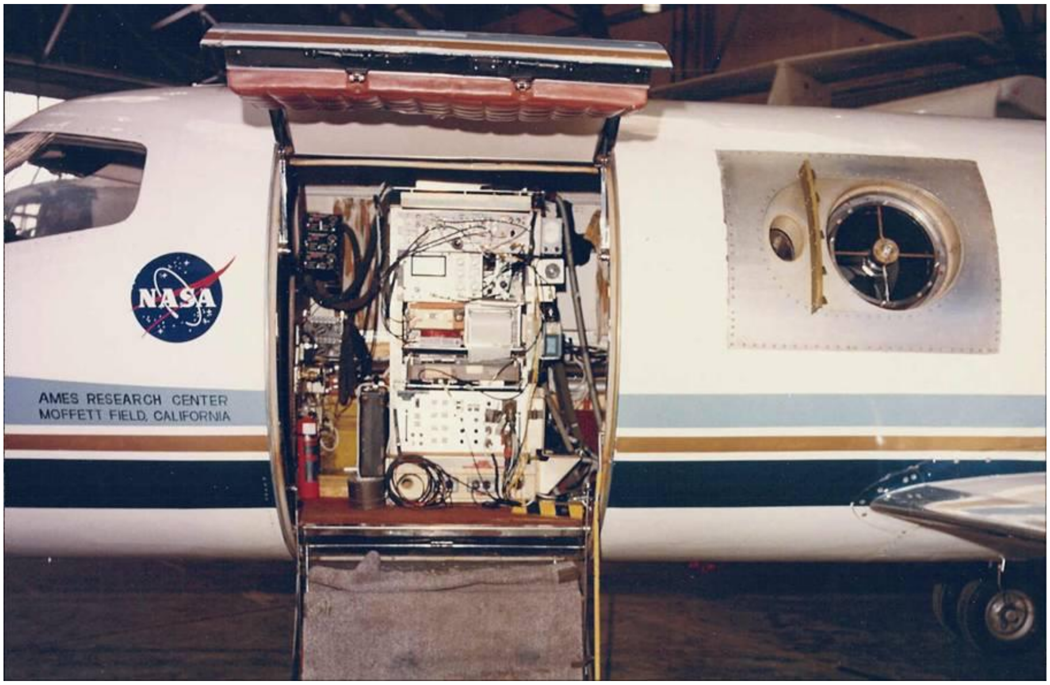


Figure 4.0-3. KAO's predecessor: Ames' Lear jet with the 12-inch telescope.

Kuiper's insight was succeeded by a 12-inch telescope mounted in the NASA Ames Lear jet, followed by SOFIA's immediate predecessor, the Kuiper Airborne Observatory, or KAO, a Lockheed C-141 aircraft with a 36-inch diameter telescope. For further details on the history of airborne astronomy, you can refer to a paper by Ms. Wendy Dolci (ref. 2). For a detailed description of KAO operations and a brief history of SOFIA, you can read the Special Publication by Dr. Ed Erickson and Mr. Allan Meyer (ref. 3). The KAO started operations in 1974; it had about 10 years of overlap with the pre-development activities of SOFIA by the time the KAO was decommissioned in 1995. It should be noted that when the KAO was decommissioned it was not due to obsolescence. Actually, it was the opposite. With advancement of technology (computer speed/memory, charge-coupled device (CCD) imagers for star tracking, IR detector arrays, etc.) and continuous operations improvements, the KAO was at its best at the time of decommissioning. However, as with many things in life, bigger is better and this is especially true with regard to astronomy and telescope size. Some methods of astronomical science actually improve by the ratio of the diameter of the telescope to the 4th power. Even as just a "light bucket," the increase in productivity for the same science is proportional to the square of the diameter of the telescope (area). With good optics, the gain is even higher because of improvement in diffraction-limited angular resolution. So the reason that KAO operations were ceased was primarily related to the IR science community agreeing to suspend airborne astronomy to use the KAO operations funding to help provide some of the funding needed for the development of SOFIA—the more capable replacement for the KAO. The initial plan was to have only a 5-year time span without airborne astronomy capabilities—but more about that in later sections. So in summary, SOFIA was/is the next step in this evolution of airborne astronomy—the largest telescope possible in the largest aircraft capable of flying at these altitudes for extended periods of time.

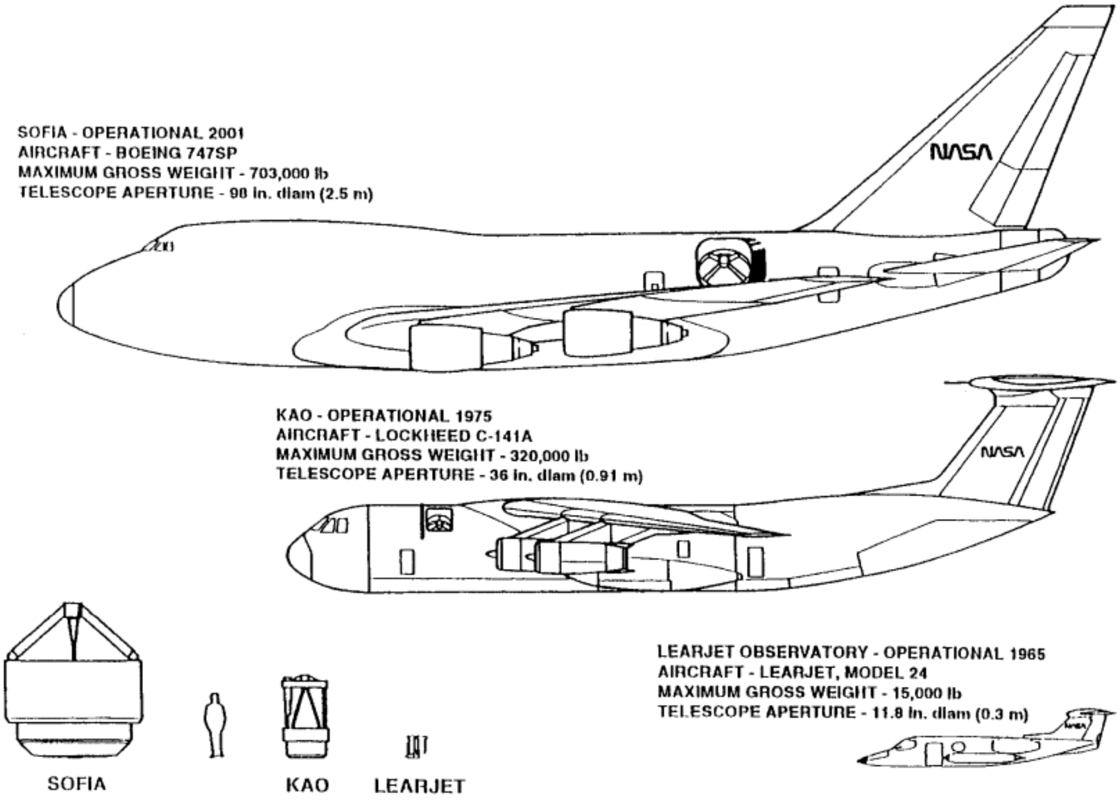


Figure 4.0-4. Illustration showing the relative sizes of the airborne observatories and their respective telescopes.

Note: for SOFIA, the telescope and associated cavity opening are proportionally larger despite the much larger aircraft.

5.0 SELECTED ENGINEERING HIGHLIGHTS

This section provides brief descriptions of some of the unique features of SOFIA and associated modifications.

5.1 Aircraft Selection

The objective of SOFIA was to create an observatory with the largest possible telescope that could fly for the longest possible time above the tropopause. Therefore, in selecting the aircraft, the obvious factors were the fuselage diameter and high-altitude performance. In fact, it was the development of the 747 that fostered the idea of SOFIA in the first place. To verify that the 747 was the ideal choice, we did a study of available aircraft comparing the factors of fuselage diameter and cruise altitude characteristics. We quickly confirmed that a 747 was the right choice and that left us choosing between the 747SP, a standard 747-100, or 747-200. The SP was a special version of the 747 that was created for Pan Am to be able to fly non-stop between selected major city pairs, such as from San Francisco to Tokyo. The SP has the same wingspan and engines as a regular 747, but the fuselage is about 48 feet shorter, which means that it weighs less and therefore has a much greater range than either the 747-100 or 747-200. However, during the pre-development phase, aircraft engines became a lot more fuel-efficient so the new model of the 747, which was the 747-400, also had a longer range. This meant that Boeing only built a limited number of 747SPs. The official number was 44, although we heard that a Middle Eastern country head-of-state or royalty had Boeing make a special 45th 747SP for his personal use. Since the volume required to fit the telescope, crew, and mission systems was not too large, the 747SP seemed like the ideal aircraft, the primary concerns being associated with the modification required for the cavity and the potential disturbance to the airflow affecting the flight characteristics. As you'll read in the upcoming sections, these were addressed by the second wind-tunnel test. The analysis showed that even with a potential modest increase in drag, the 747SP would be able to provide more than 6 hours at or above 41,000 feet with a reasonable estimate for the mass increase required for the structural modifications, for the telescope, and for the necessary observatory infrastructure.

5.2 Open Port Cavity – SLC Objectives

Clearly one of the biggest challenges where we were pushing the state-of-the-art for the SOFIA development was to design an open port cavity of the desired size that would not adversely affect the flight characteristics while flying at high altitudes and cruising speeds. There were many goals for the open port cavity and SLC design, including the following: minimal impact on the stability and control of the aircraft, and a robust and non-resonating cavity for structural safety. The latter requirement was extended to include non-observing flight conditions in case the cavity door failed and the aircraft was required to descend and land with the door open. Since the precision optical telescope had a demanding requirement on pointing stability, another objective was to provide the quietest cavity possible. Maximizing the time at altitude meant the SLC should have minimum drag increase to maintain the aircraft performance. Finally, since the light coming from the astronomical targets passes through the shear layer on the way to the telescope, another objective was to optimize the aero-optic performance, otherwise known as "seeing," especially for short wavelength image quality performance.

I describe below various activities necessary to achieve these design objectives. The key person involved with essentially all of these activities was Dr. Bill Rose. Dr. Rose was involved from the very beginning through the completion of the final flight test; in fact, he was involved with the KAO prior to the start of SOFIA. This book will contain only very top-level descriptions of what we did; if you would like to know more, I highly recommend reading Rose's "SOFIA TA Cavity Aerodynamics: Wind Tunnel to Flight," (ref. 4); additional references regarding Aerodynamics, Aeroacoustics and Aero-optics (refs. 5−26) are listed in Section 14.0.

5.2.1 KAO is Direct Predecessor to SOFIA

Of course, as mentioned before, you don't start a project of this size without having some idea of how it was done before. In this case, the immediate predecessor to SOFIA was the KAO, which was a modified C-141 with a 36-inch-diameter telescope; it successfully flew with an open port cavity from 1974 to 1995. There are still some major differences between the KAO approach and SOFIA. First, as you can see in Figure 4.0-4, even though the 747 is substantially larger than the C-141, proportionally the SOFIA telescope is still larger relative to the 747 than the KAO telescope was to the C-141. Also, the C-141 is a high-wing aircraft and the cavity was in the forward fuselage in front of the wing. The SLC device for the majority of the life of the KAO was a deployable upstream porous fence.

5.2.2 AOA Test Results

Another program that was also trying to develop open port cavity technology that we heard about, was called the Airborne Optical Adjunct (AOA), which consisted of a Boeing 767 with a cupola mounted on top of the forward fuselage with two open port cavities, one right behind the other. As you might expect, this was a military-based research program, so it didn't provide a lot of detail about the planned usage of the open port cavities. We suspected that they might be for outgoing photons instead of incoming photons. In any case, their idea for SLC was having a forward-facing scoop on another part of the aircraft and then ducting the air to the forward edge of the cavity opening to stabilize the shear layer and cavity acoustics. As it turns out, on one of the flight tests, the valve in this air duct didn't open, but the resulting cavity acoustics were the best compared to the other test results. We used this information to avoid that approach for open port cavity SLC on SOFIA!

5.2.3 Wind Tunnel Testing

The best solution to address the open port cavity design was to start wind tunnel testing as soon as possible. Of course, with this type of issue, you want to have the largest model possible and the wind tunnel needs to be capable of providing the appropriate wind speed to represent the desired flight conditions for the planned open port cavity usage. We also needed the appropriate experts to help or lead this effort, and we, the SOFIA Program, were lucky to get Dr. Bill Rose to fulfill this role. Dr. Rose was a former NASA Ames employee who had been intimately involved with the KAO open port cavity SLC, but had since left NASA and started his own company. So I started working with Bill to determine the parameters that we would use for the wind tunnel model. We chose the Ames 14-ft wind tunnel as the appropriate facility to conduct the SOFIA wind tunnel testing. The next parameter was to choose the scale size for the wind tunnel model. We wanted it as big as possible, but it had to fit in the 14-ft wind tunnel test section. We ended up choosing 7 percent, which was still pushing the limits a little bit, since 7 percent of a 747 is still a pretty large model. The wingspan alone of this scale model is 14-ft, but since our area of interest was centered on the fuselage, the idea was that the airflow over the ends of the wings had a negligible effect on our area of interest, and we verified this with some analysis.

The typical way a wind tunnel model is mounted in a wind tunnel test section is at the end of a forward cantilevered beam, also called a stinger, that is mounted to a vertical support system that sits well behind the model so that the model being tested gets clean, undisturbed airflow. The stinger support system typically has the capability to move the model during testing to vary the angle of attack or pitch and also the yaw. In the case of the SOFIA wind tunnel tests, the model was so big that the weight of the model was too much for the support system to lift, and the lift of the SOFIA model while the test was running was too high a load for the stinger. Plus, the lateral forces of the model when being tested at the desired yaw limits would also exceed the allowable side forces of the stinger. So we ended up having to modify the wind tunnel to provide a counterweight system to allow movement of the model while it was being tested, by adding vertical and lateral restraints to counteract the lift of the model.

5.2.4 SOFIA I

Making the model was not a trivial task; that was true, even for the first wind tunnel test model with the cavity in the forward fuselage, leading to a model with only the front half of the airplane and with clipped wings. By the way, the SOFIA wind tunnel test numbering system did not start until the second SOFIA wind tunnel test; I came up with the system based on the “Rocky” movie series. Also, for the very first SOFIA wind tunnel test, I was able to recruit Dr. Ralph Haslund, who was the open port cavity expert/researcher for Boeing. So Dr. Bill Rose was the primary PI and Dr. Ralph Haslund was the co-PI.

One of the parameters associated with open port cavities in flight is the ratio of the boundary layer thickness to the streamwise length of the cavity opening. For the geometry of the SOFIA cavity, especially with the thinner boundary layer in front of the aircraft, we were far beyond any previous cavity that had been implemented or even tested at model scale. Also, to complicate things even farther, the section of the forward fuselage where we were putting the cavity was getting wider in width, but shorter in height in the streamwise direction so the aft edge of the cavity opening was not parallel to the front edge of the cavity opening. This wind tunnel test was clearly a development/exploratory test. Going into this test, we had several ideas that we were going to try, especially the concept of an aft ramp extending forward from the aft edge of the cavity opening and downward into the cavity. Many of the parameters associated with the SLC concepts to be tested had to do with the length and slope of the aft ramp.

The testing finally got underway in March 1990 and as it turned out, none of the ideas that went into this first SOFIA wind tunnel test worked. Part of this testing involved putting colored oil drops onto the fuselage, then running the test to see where the wind would push them. From this, you could see that the airflow was not parallel to the axis of the fuselage, but instead, because the cavity was not far in front of the wing, the airflow was diagonally upwards. So up to that point, all the SLC concepts were based on more of a 2-dimensional concept where it was assumed that the airflow was perpendicular to both the forward and aft edges of the cavity opening. So as we were sitting there brainstorming on what to do next, it occurred to me that not all the airflow leaving the leading edge of the cavity opening was reaching the aft ramp, and not all the airflow hitting the aft ramp came from the leading edge. So I came up with the idea of curving the aft ramp around to the top and bottom edges of the cavity opening. At that point, we clearly didn’t have a curved aft-ramp concept made, so I remember sweeping my hand with my thumb and forefinger in a way to show John Wallace, the lead wind tunnel mechanic, my idea and perhaps how he could make it with Bondo® (an autobody dent-repair filler).

It worked! The curved aft-ramp concept worked very well, providing a very robust SLC that yielded a very quiet cavity. We tested it through the flight parameters planned and completed the testing in July 1990.

5.2.5 KAO Aft Ramp Augmentation

Immediately following the SOFIA I wind tunnel test, Bill Rose conducted more wind tunnel testing on the SOFIA model where it was slightly modified to try to represent the front of the KAO (a C-141). Bill had been awarded a NASA Small Business Innovative Research (SBIR) grant to see if he could improve the open port cavity SLC for the KAO, the idea being that an aft-ramp concept would help the shear layer reattach better aft of the cavity. This one short wind tunnel test showed positive results so he was able to convince the KAO project to implement the aft-ramp approach on the aircraft. This was done in 1993, and was flight tested for one or two flights. Even though the aft-ramp design concept had to be compromised, to not interfere with the existing cavity door system, the results showed that the flow attachment was significantly improved with the aft ramp, and that allowed the fence position to be lowered from 30° to 10°. This in turn led to many improvements, including: significantly reduced internal cabin noise during open-door flight, reduced aircraft vibration, and reduced drag, thus improving flight performance. This led to better science observations because the cavity acoustic environment was significantly improved resulting in less vibration for the telescope and optics. Also, the shear layer was significantly thinner, resulting in improved “seeing.”

Of course, with lower acoustic levels there is less structural fatigue all around, including the aircraft structure. The acoustic levels with the door open had been reduced so much that the pilots were only able to detect whether the door was open or closed by the indicator light on the cockpit control panel.

Figure 5.2-1. KAO with the newly added aft ramp in flight testing.

Figure 5.2-2. Outside of the cavity area of the KAO after implementation of the aft ramp developed during the first SOFIA wind tunnel test.

5.2.6 SOFIA II – June–August 1994

Almost immediately after the first SOFIA wind tunnel test was completed, planning for the second wind tunnel test started. The original SOFIA II wind tunnel test plan had the cavity in the front, but due to other events to be talked about later, this wind tunnel test was aborted because the cavity was moved to the rear behind the wings.

Once we decided to move the cavity to the aft fuselage, behind the wing, the SOFIA I wind tunnel model had to be significantly modified to include the aft fuselage, empennage/tail, and more of the wingspan out to the outboard engines. In addition, one of the open questions at that time was whether we should use a 747SP or 747-100 or 747-200 configuration. So, the model was made to be convertible between the three configurations. One of the objectives of this test included assessment of stability and control and which 747 configuration would work better with the open port cavity in front of the tail, with the concern that the open port cavity might adversely affect the airflow over the empennage control surfaces. The SOFIA II model included several measurement techniques, one of which was an innovative balance mount, which just measured the forces on the tail. Also, it was one of the first times that pressure-sensitive paint was used in the wind tunnel test.

The results showed that the well-behaved cavity had negligible impact on stability and control. It also verified that the 747SP was our primary choice.

5.2.7 SOFIA III – February 1995

The SOFIA III wind tunnel test was primarily to fine-tune some of the aperture geometry and it used only the 747SP configuration. In addition, we had a detailed model of a telescope in the cavity with a bunch of Kulite high-frequency pressure sensors mounted all over it to measure the loads on the telescope.

Figure 5.2-3. Dr. Bill Rose with the SOFIA 7 percent wind tunnel model used to develop SLC design technology and determine cavity acoustic environment and resultant loads on the telescope in the test section of Ames' 14-ft Transonic Wind Tunnel.

5.2.8 SOFIA IV - September–December 1995

The SOFIA IV wind tunnel test was primarily used to evaluate the different door mechanism design concepts involving gaps, steps, partial ramps, etc. The issue was this: with the curved aft ramp, moving the aperture to follow the telescope when it changes elevation angle is more complicated than with the KAO cavity door concept. Thus, the tests included additional variables such as which parts move as opposed to being stationary, where the smooth aft-ramp design concept had to be broken up with associated discontinuities to make a viable moving door concept.

5.2.9 SOFIA V (post start of official development) – November 1997

The SOFIA V wind tunnel test was performed as a sub-contract to the official prime contractor (Universities Space Research Association (USRA)); this was part of the privatization development approach, which will be covered later in this book. Fortunately, it still involved most of the same people and the same 7-percent model and Ames' 14-ft Transonic wind tunnel. At this point, SOFIA V was primarily a verification test of the final design which we called the Partial External Door (PED) design. Also, since we at that time had an actual boundary layer profile measurements from the flight tests of the 747SP, the boundary layer of the 7-percent wind tunnel model was adjusted accordingly. We also had the final design of the telescope from our German partner so the model of the telescope in the cavity was modified accordingly and instrumentation was added to measure the loads on the telescope primarily to help us with the pointing performance analysis. Measurements from these tests of telescope disturbance loads were incorporated into the infamous Document Change Request 12 (DCR12), the big specification update. The SOFIA V wind tunnel test was also used to measure loads for use in the PED design.

Figure 5.2-4. The cavity area of the model during SOFIA V showing the telescope details.

5.2.9.1 SOFIA I through V Summary

As mentioned above, the details of these wind tunnel tests are included in the references listed in Section 14.0. To give a very brief summary: these tests involved the use of a 7-percent scale model of a 747SP in the NASA Ames Research Center 14-ft Transonic wind tunnel. The test conditions included Mach 0.3 to Mach 0.92, with the aircraft yaw between −4.5° and 4.5° and the aircraft pitch or angle of attack between 2° and 5° with the telescope elevation angle (cavity-door aperture position) between 25° and 60°. The measurements included aero-acoustics, telescope torque, and pressure loads (both static and dynamic) as well as the assessment of the impact on the stability and control of the aircraft.

In summary, SLC technology was developed successfully and results from the last test indicated that SLC was robust and provided the quietest cavity known for an aircraft-based open port cavity. They also indicated that the effect of the cavity on aircraft stability and control characteristics would be negligible. Later on, you will read that actual experience in flight supports these conclusions.

5.2.10 3-percent Scale Model – Stability and Control Tests

Figure 5.2-5. The 3-percent SOFIA Model in Kirsten Wind Tunnel.

The 3-percent wind tunnel tests were sponsored directly by Raytheon/L3 to verify the flight characteristics from the pilots' perspectives and had little to do with the cavity environment. These tests were done in two different wind tunnels in the state of Washington, the same two wind tunnels at the same scale that the original 747SP testing was done for Boeing in the 1970s. The purpose of these tests was to measure the changes in aero-coefficients between a baseline 747SP and the SOFIA-configured 747SP as well as to provide substantiation for a reduced flight test program.

The low-speed tests were done in the University of Washington Kirsten Wind Tunnel and they were done in two parts to accommodate the availability schedule of Boeing's Wind Tunnel. Part 1 occurred from September to October 1998 while part 2 occurred from January to February 1999. The highest speed of this tunnel is Mach 0.24 and on completion, a total of 2,484 runs were conducted.

The high-speed tests were done in the Boeing Transonic Wind Tunnel in November 1998. The Mach range tested in this tunnel is Mach 0.24 to 0.975 for a total of 1,032 runs completed.

For both the high-speed and low-speed tests, there were five different configurations tested: the baseline 747SP, and then four different configurations of SOFIA, including with the cavity door closed and with the door open and the telescope/aperture elevation angles at 20°, 40°, and 60°. What was measured included the total aircraft forces and moments, over 300 static pressure locations, and cavity acoustics.

The 3-percent wind tunnel testing results showed that there was no measurable change in lift, and yawing and rolling moments, small changes in pitching moment and side force depending on the door position, and a very small increase in drag ($\Delta CD = 0.0008$). So, the 3-percent wind tunnel tests confirmed and validated the 7-percent stability and control assessment that the SOFIA cavity door/SLC design had negligible impact on the aircraft handling characteristics.

5.2.11 Computational Fluid Dynamics (CFD)

The early pre-development phase of SOFIA coincided with early development of computational fluid dynamics (CFD). NASA Ames Research Center was one of the world leaders in development of CFD, so we decided early on to try to help SOFIA using our in-house expertise. At the time, early 1990s, the model and tool developments were moving along in parallel. With an open port cavity, the problem involved both internal and external flows interacting with each other. This was very difficult for the CFD tools/computer programs. At that time, a single solution took hundreds of Cray Supercomputer central processing unit (CPU) hours, which actually took months of calendar time. The results did augment wind tunnel test data, but they were very limited. Essentially, the wind tunnel data were used to calibrate the CFD model, of course at wind tunnel scale, and then the CFD was used to help extrapolate the results to full scale.

Once we were in the development phase, CFD analysis programs were commercially available. They were primarily used for external flow, so Raytheon/L3 used these to help with the design, analysis, and verification of the SOFIA modifications. A couple of the CFD programs used included TranAir (inviscid, adaptive grid) and OVERFLOW (viscous, Navier-Stokes). As you can see from Figure 5.2-6, the final versions of the CFD results are compared to wind tunnel results with a pretty good correlation.

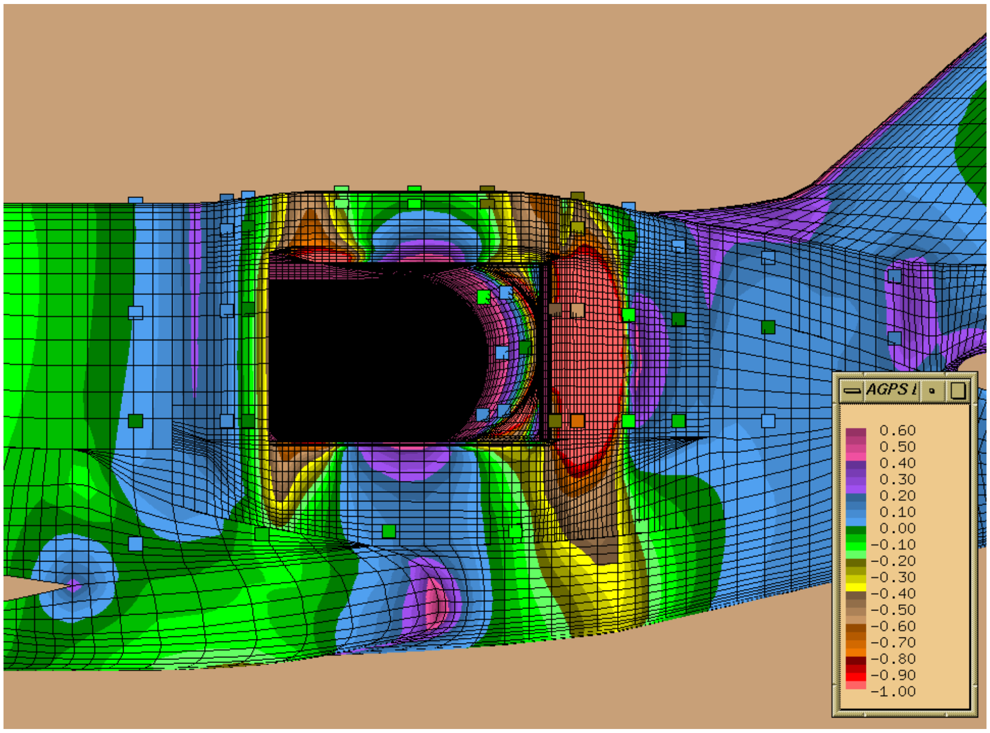


Figure 5.2-6. TranAir CFD comparison with wind tunnel data at: door 20°, Mach = .85, alpha = 2°, and beta = 0°.

In summary, multiple CFD models were developed and the analyses completed. The results concurred with the wind tunnel results and provided more detail on the center of pressure (Cp) distribution. They also concurred with the assessment of the stability and control. CFD results also provided additional data for load distributions used in component structural analyses.

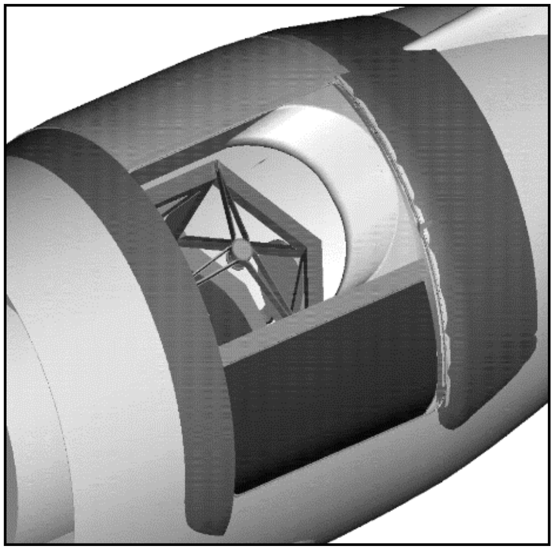


Figure 5.2-7. 3-D CAD drawing showing PED concept

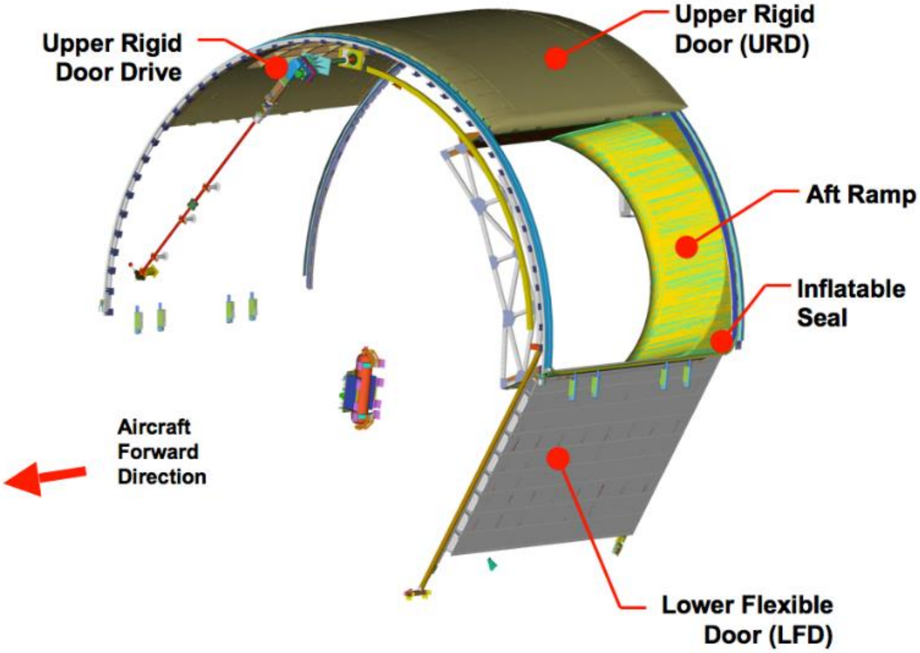


Figure 5.2-8. Open port cavity – aero-SLC summary.

5.2.12 Open Port Cavity SLC Modification Summary

The data from all the tests and analyses indicated that all the objectives were met, including minimal impact on stability and control of the aircraft, a robust non-resonating cavity, a "quiet" cavity for optimum telescope pointing performance, minimal drag increase to maintain aircraft performance, and minimum disturbance to the shear layer over the cavity opening to optimize aero-optic performance "seeing" for short wavelength image quality performance. The open port cavity SLC was identified very early in the SOFIA pre-development (1980s) as a risk area, so we planned and completed risk reduction activities accordingly. Of course, SLC development began with KAO heritage, and even prior to flight testing, as described above, we had completed eight separate wind tunnel test series and multiple CFD analyses. Multiple independent reviews concurred with both the approach and the results, including a very extensive NASA Engineering and Safety Center (NESC) review that examined the test and analysis data and planned program approach and recommended proceeding to flight test.

At this time, as you will read later, the completed flight tests verified that SOFIA flies like an unmodified 747SP!

5.3 Aircraft Modification

As you might imagine, making a modification of this magnitude on a 747SP is not a trivial task. Although early in the pre-development phase we actually had Boeing involved with the feasibility and configuration studies, when we finally got to the official development phase, Boeing was no longer involved. Since air carriers do need to perform significant maintenance on the aircraft that they operate, they have extensive manuals, drawings, and other information about the aircraft. But they do not have information about load distribution, stresses, allowable stresses and loads, etc. required to design and verify the structural integrity. Given that our goal was to install the largest telescope possible into an open port cavity with an unvignetted elevation range of 20° to 60°, the modification was significant. In addition to the telescope size and elevation movement, the telescope is also rotationally isolated from the other two rotational axes for a small amount of angular motion, but it still requires an envelope size larger than the telescope to avoid collision contact between the telescope and the aircraft structure. The required large structural opening wraps around about one-fourth of the fuselage circumference and is a little under 20 feet long. When I used to give talks about SOFIA in the early phases, I would mention that the structural opening was large enough to drive two 18-wheeler trucks through side-by-side, so people could appreciate that the cavity door was even larger in size than a 2-car garage door! As described above, the aperture opening with the aft ramp that follows the telescope elevation is much smaller.

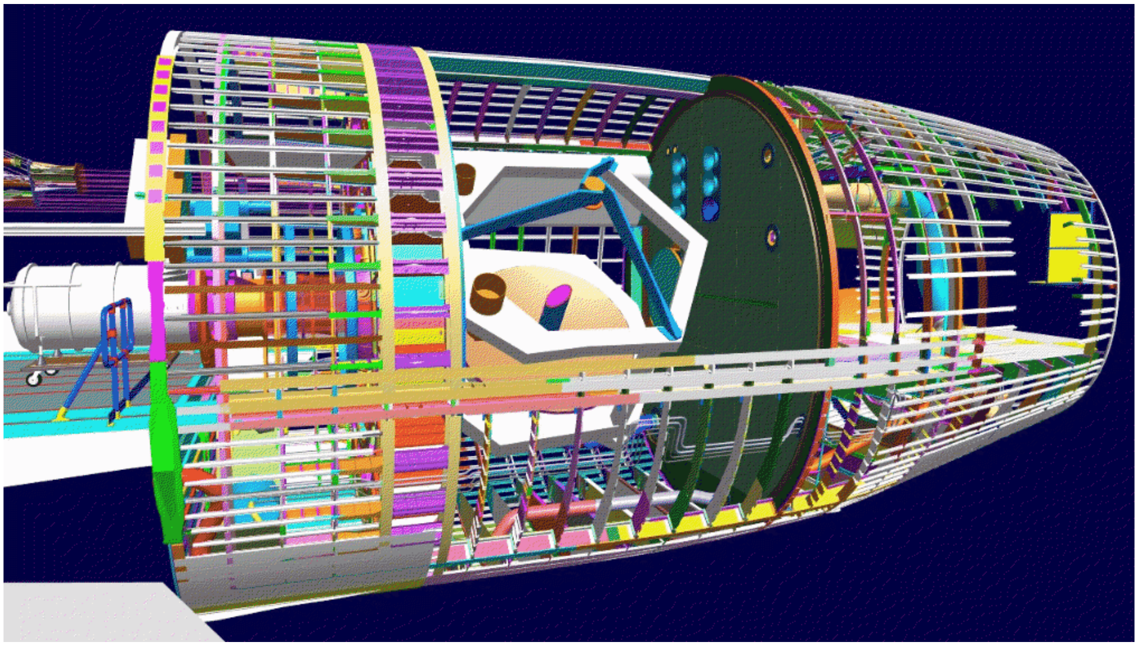


Figure 5.3-1. 3D CAD model of the aft fuselage area with the telescope installed.

From just a structural perspective, the modification was significant with both the structural opening and the new pressure bulkhead, and since we didn't have either the load envelopes or Boeing's design manuals letting us know the allowable stresses and loads in the various parts of the structure, we had to reverse engineer our 747SP. Note that one of the concerns that we had when we moved the cavity to the aft fuselage area was that we would be putting this modification in the area of the fuselage that carries all the loads from the empennage. Also, for a little background and more appreciation, the 747 fuselage structure, like most modern aircraft, is called a monocoque structure where the skin actually carries the loads as opposed to just being a fairing attached to a structural backbone. So in the area where the cavity was being installed, there are roughly three major loads to deal with: vertical loads (lift), side loads (yaw forces), and torsion loads all from the empennage plus internal cabin pressure.

The reverse-engineering process started out by making a very-high-fidelity Finite Element Model (FEM) of the unmodified 747SP as shown in Figure 5.3-2. This FEM was then run through hundreds, if not thousands, of different load cases with different mass distributions and flight maneuvers to predict the loads and stresses in various parts of the aircraft structure. The next step was to verify this FEM by flight testing the unmodified 747SP and flying it through the same maneuvers as analyzed. Of course, this was a back-and-forth process in that the pilots couldn't always exactly duplicate the desired flight maneuvers, so measurements were also taken for what the actual flight maneuver was, so that the actual tested flight maneuver could then be run on the FEM. A typical result is shown in Figures 5.3-3 and 5.3-4. Another verification of the FEM is what is called a ground vibration test, where various shakers are distributed on the aircraft structure to determine the natural frequencies of various structural modes, and this too is compared to the predictions of the FEM.

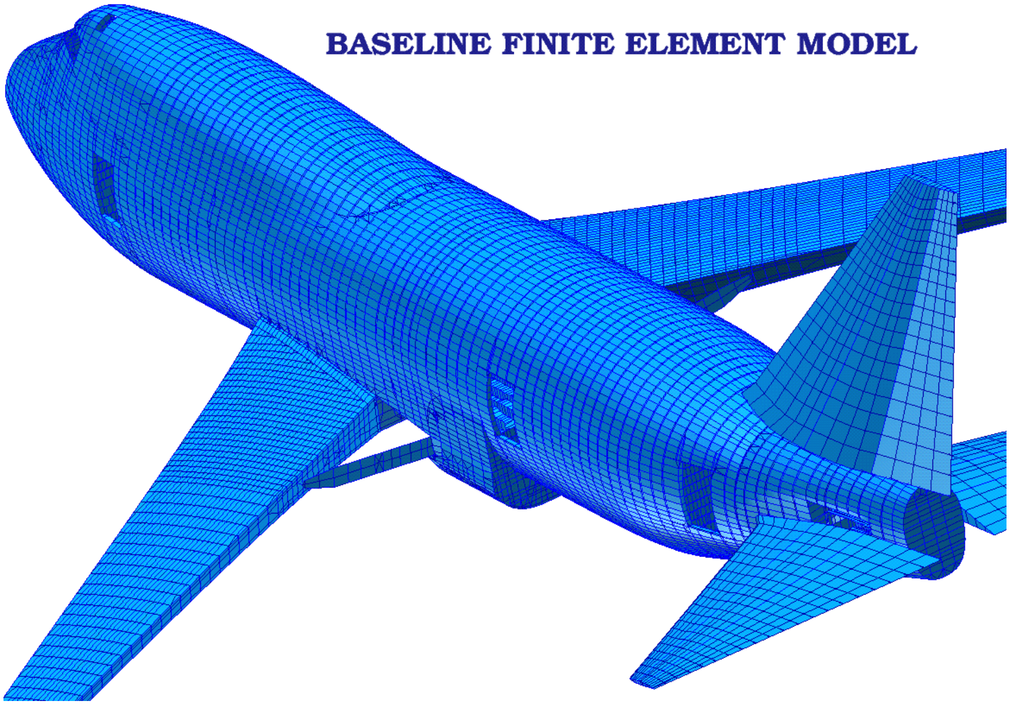


Figure 5.3-2. FEM of un-modified 747SP.

After the FEM was verified, the modeling of the SOFIA modification ideas could be implemented on the FEM to start the iterative process of coming up with a good design. And because of the monocoque structure as mentioned earlier, it truly was an iterative process. For example, if the results of the FEM analysis showed a high-stress area, you could not just put in a thicker or larger structural element since this new structural element would actually attract more loads and would likely affect the adjacent structure as well, in addition to adding more mass which in turn would add to and change the load distribution. To further complicate the modification, the new cavity required a new pressure bulkhead, which, in addition to having to be designed to take almost a million pounds of axial force (from the design cabin pressure load), also had to carry the weight of the telescope with all the appropriate design loads including emergency landing loads. In addition, one of the requirements was to minimize the weight of the modifications to maintain the aircraft's high-altitude performance to meet the time at altitude requirement of more than 6 hours at or above 41,000 ft. And to make it even more difficult, due to the location of the cavity and the telescope to maintain the correct aircraft CG/balance required the use of ballast such that when weight was added to the cavity area or telescope, additional weight had to be added to the front of the aircraft. The end result being a big steel plate added to the floor of the main deck in the very front of the aircraft. To cover all the different possible flight conditions/maneuvers with all the possible mass distributions required analyzing over 20,000 load cases. Near the end, prior to the start of flight testing, the modified SOFIA FEM was verified using another ground vibration test. In addition to the structural modification, several aircraft systems also had to be rerouted, the most complicated being the 11 control cables that run along the top of the inside of the fuselage from the cockpit through the cavity to the tail.

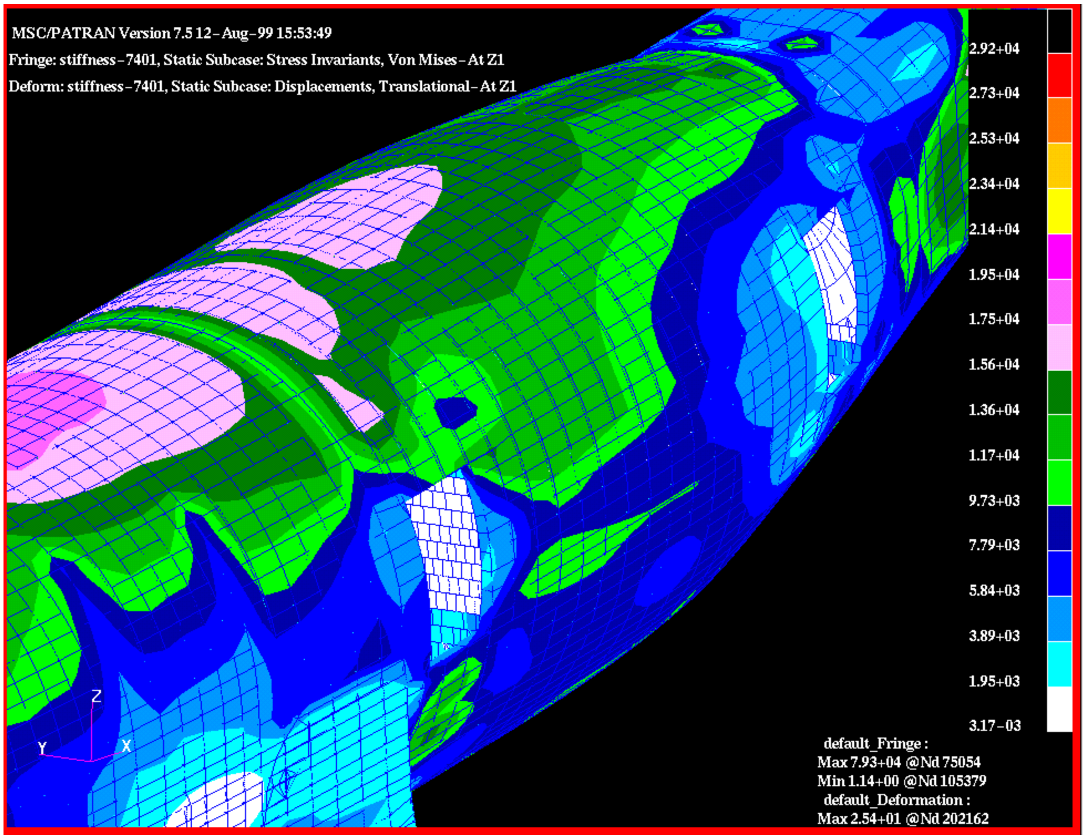


Figure 5.3-3. One sample of baseline stress contour plots.

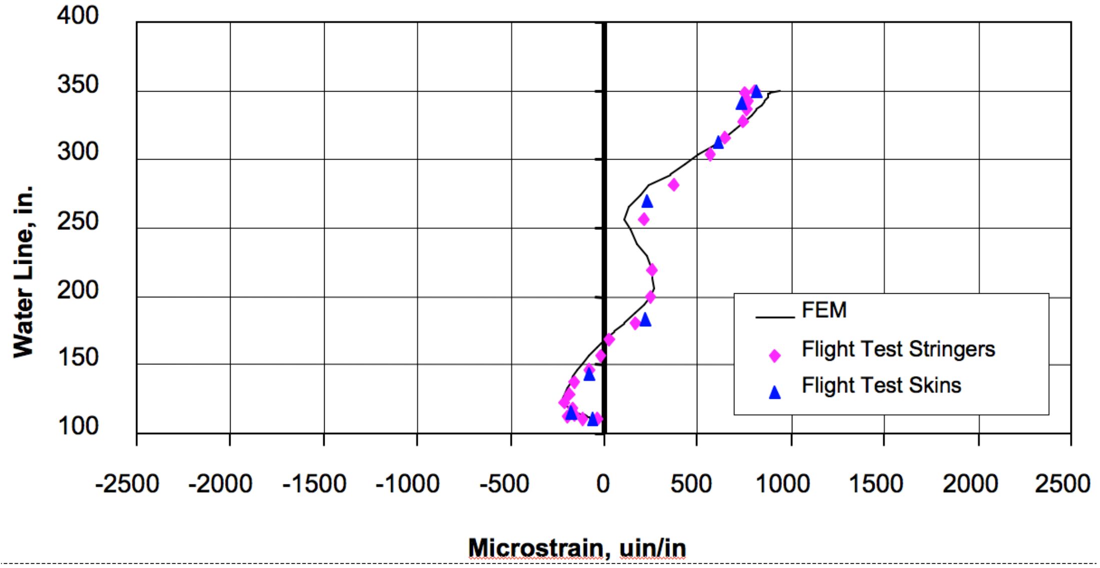


Figure 5.3-4. FEM predicted longitudinal strain and flight-test calibrated strain vs. water line at FEM station 1990 (left-hand side)

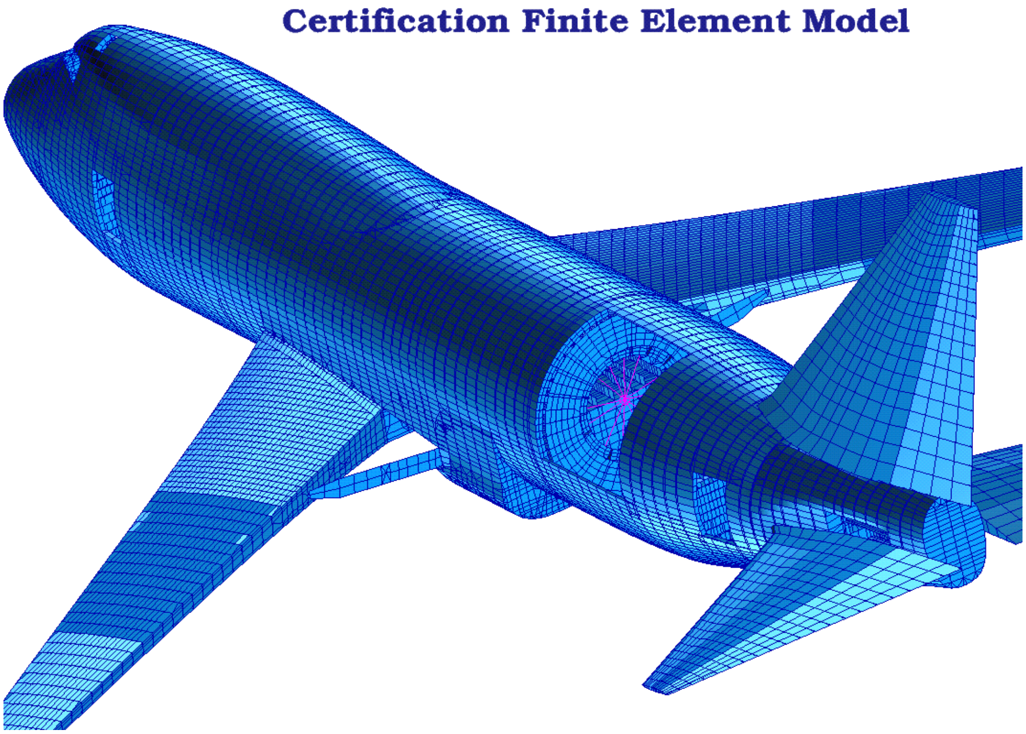


Figure 5.3-5. FEM of 747SP with modification for SOFIA.

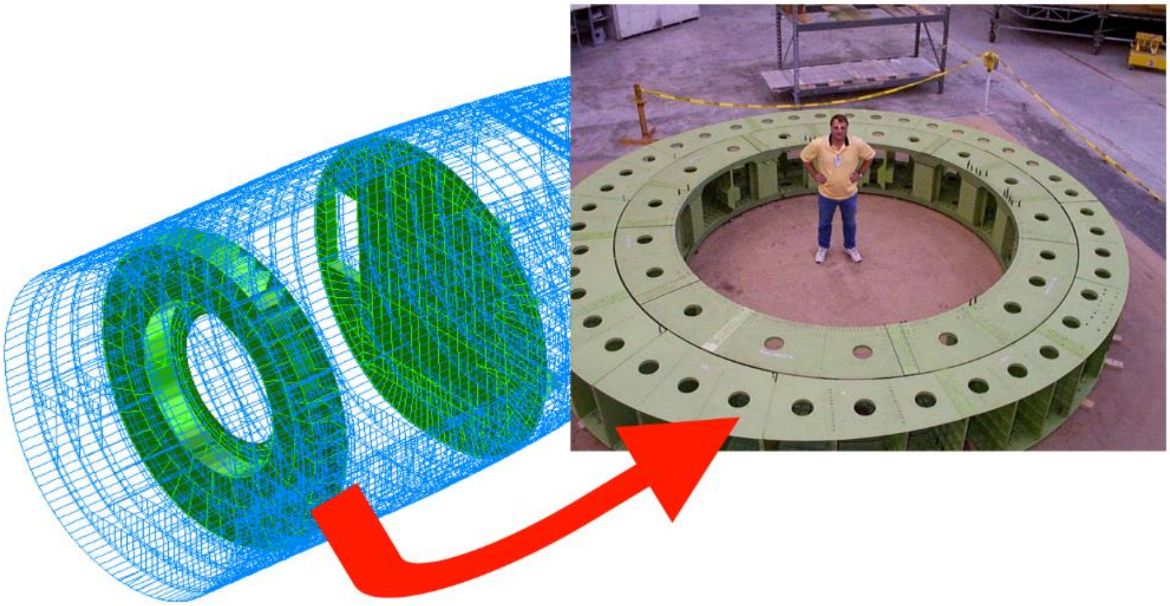


Figure 5.3-6. Illustration and photo showing the FEM and the fabricated new pressure bulkhead.

Figure 5.3-7. Cliff Imprescia, Hans Kaercher, John Fitch and Eric Becklin in the bulkhead simulator used to build up the telescope assembly (TA).
Note: this photo shows the size of the opening to be built into the new aircraft bulkhead, which is the same as the hole in the bulkhead in the previous figure. (Three of these fellows are over 6 feet tall).

Figure 5.3-8. Looking out of cavity opening from cabin area.

Figure 5.3-9. Looking into cavity opening from outside the aircraft.

Of course, implementing the modifications on a structure as large and complex as the 747SP was not trivial. Again, this was complicated by the monocoque structure plus we didn't have 747SP manufacturing fixtures, so we couldn't just remove all of the old skin, stringers, and frames and replace them with the modified design components. We had to transform the structure gradually by removing some of the old components and replacing them with the new components and iterating back-and-forth to maintain the shape of the 747SP aft fuselage. During this process, which took a long time, the fuselage was supported as well as possible to try to assure that no change would occur in its shape.

The results and current operations indicate that the SOFIA modifications, both design and implementation, were entirely successful.

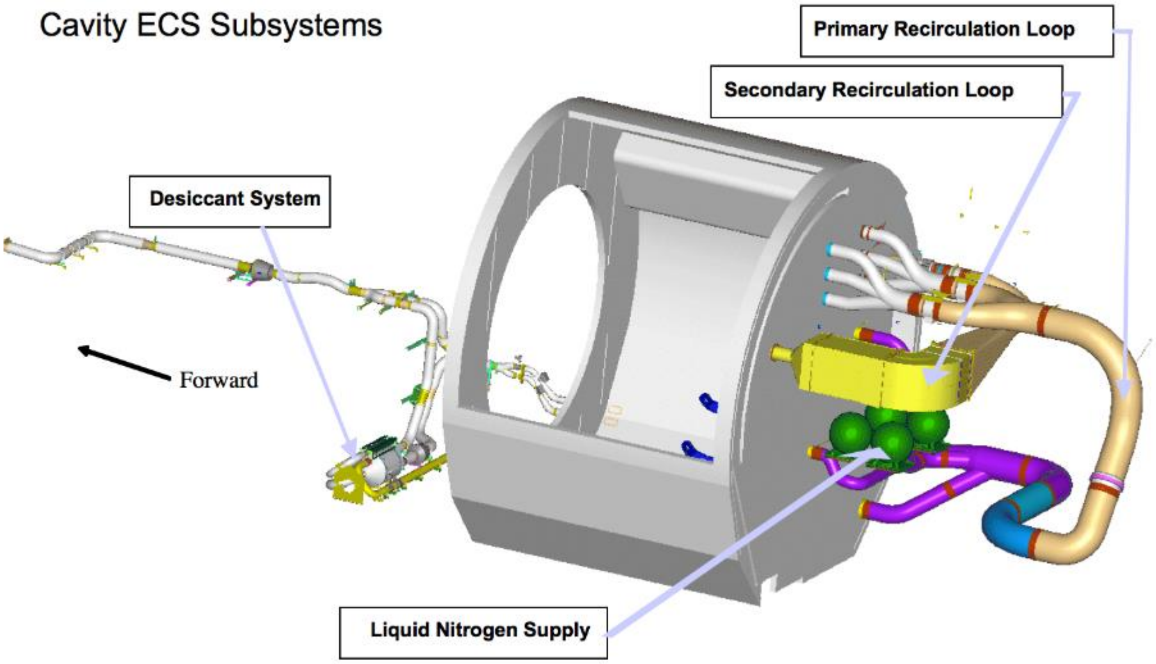


Figure 5.3-10. The CAD model of the design concept for the cavity cooling and desiccant dryer systems.

5.4 Telescope Assembly (TA)

An airplane is not the typical place for which you design and build a telescope, so in addition to all normal challenges associated with a high-quality telescope of this size, the design has to accommodate the aircraft environment as well as, per the requirement at the beginning of the official development, meet FAA certification requirements. As you can read in other parts of this book, the telescope was provided by our German partners under a fixed-price contract. Some of these additional challenges arose from the need to provide SI access in the cabin while the telescope is operating in an open port cavity; this requires the telescope to be part of the aircraft pressure and thermal boundary, as you can see in Figures 5.4-5, 5.4-9, and 5.4-10.

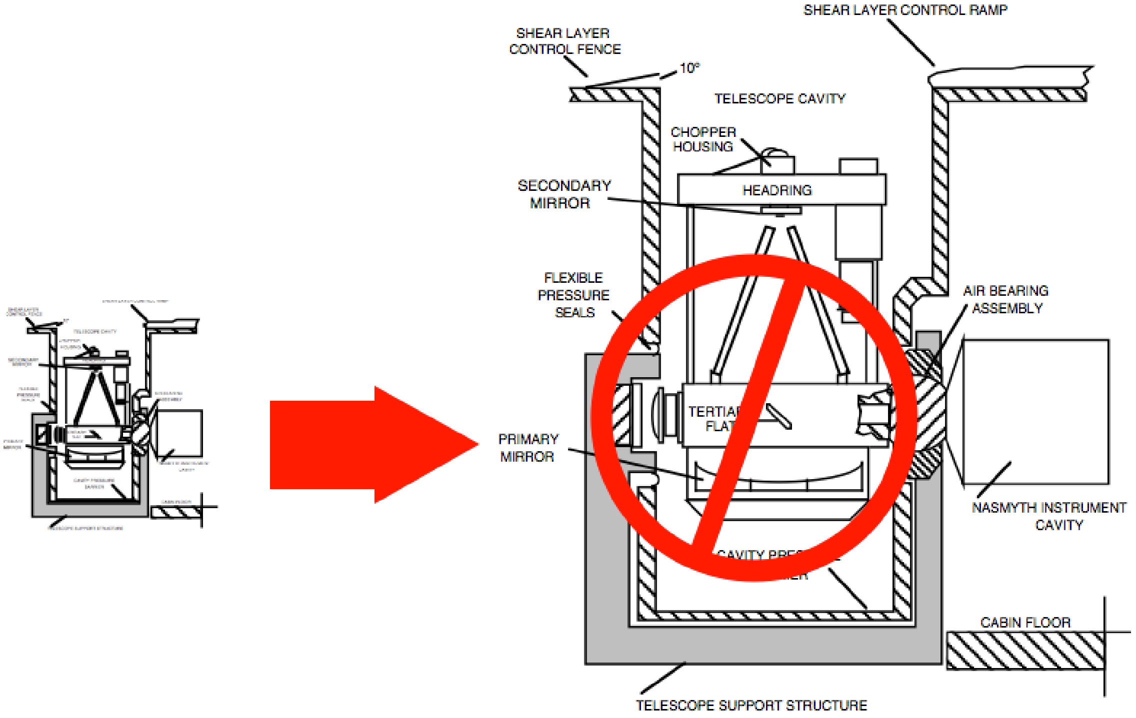


Figure 5.4-1. Illustration showing the KAO telescope configuration and the same design scaled up by a factor of 3 to be the size required for SOFIA.

Of course, again the starting point was the existing KAO telescope design, but as shown in multiple figures, even though the 747SP is larger than the C-141, the SOFIA telescope is still proportionally larger, and simply upscaling the KAO telescope design by a factor of 3 would have led to a telescope that weighed 300,000 lbs as seen in Figure 5.4-1, which clearly would not meet the performance requirements. Instead, the weight budget given to the telescope system including all the control consoles was 20 metric tons or 44,000 lbs, so significant light-weighting was required. The two primary features carried over from the KAO design were the general configuration where the light path is turned 90° to align with the axis of the fuselage by the Nasmyth mirror, and the spherical bearing that isolates the telescope from the aircraft rotations. This second feature for the KAO was accomplished by a spherical air bearing such that the entire weight of the telescope would be carried by a thin layer of air so it was essentially frictionless. This feature was recognized early on as a challenge to be scaled up for SOFIA, so multiple studies were done and it was determined that the monolithic approach used for the KAO did not look feasible for SOFIA because the gap tolerances required were just too tight for the size and weight to be carried to use air as the fluid. At the start of development, it appeared that our approach was going to be articulated air pads to help with the precision gap requirements, but our German partners pursued another approach, which used oil as the fluid. Very high precision was still required and there were some concerns involving the use of oil around the telescope optics and SIs, but the final design turned out great and worked spectacularly well. So, we did end up with a monolithic approach similar to the KAO, but just used oil as the fluid. The high-precision spherical bearing can be seen in Figure 5.4-2. The paper by Dr. Hans Kaercher *et al.* describes the design history of the telescope (ref. 27).

Figure 5.4-2. That's me standing behind the 1.2-meter diameter RIS sphere that supports the floating part of the telescope and is the key component that isolates the telescope from aircraft rotations.

Figure 5.4-3. Dr. Jackie Davidson checking out the inner suspension assembly (SUA) where the RIS sphere will soon be installed.

As you might expect, there were many more issues and stories involved with the development of this RIS, including, because it needed to be FAA certified, the material used for the sphere, GGG nodular (ductile) cast-iron, had to go through a gauntlet to get approved because it was not a material typically used on airplanes.

The general layout/schematic of the telescope is shown in Figure 5.4-4, which shows the telescope mounted to the center of the new pressure bulkhead with the primary telescope structure (metering structure) being mounted in the open port cavity. Light from the observed object hitting the concave primary mirror is reflected up, converging toward the secondary mirror, which reflects it back down until it hits the tertiary mirror where it is then reflected 90°

axially through the Nasmyth tube towards the SI located in the pressurized cabin. So even from this quick explanation you can see that important parts of the telescope are also part of the aircraft cabin pressure barrier, and depending on the SI, the SI itself can be part of this pressure boundary. As you can see from these figures, the “floated” part of the telescope is roughly shaped like a dumbbell weight with the primary mirror and metering structure at one end and the SI attached to the SI flange/counterweight assembly at the other end. The Nasmyth tube, as shown in Figure 5.4-5, acts as the dumbbell bar, with the RIS holding up the middle. The purpose of the counterweight on the cabin side, which has both a passive and an active portion, is to maintain the center of mass of the “floated” part of the telescope in the very center of the RIS. Of course, this schematic is overly simplified so a more realistic installation/layout of the telescope is shown in Figure 5.4-6.

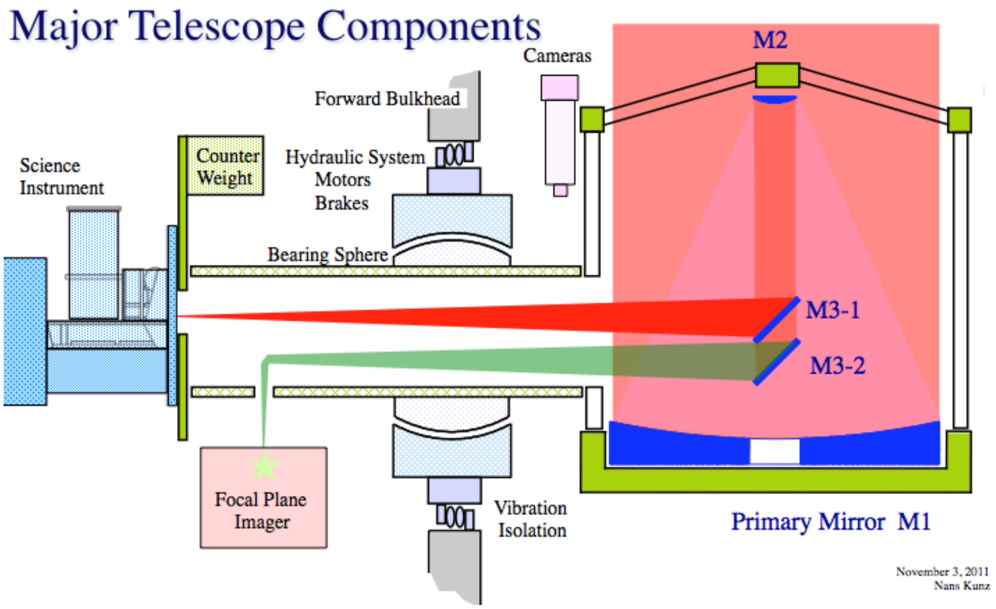


Figure 5.4-4. Illustration showing operational schematic of the telescope.

Figure 5.4-5. The carbon fiber filament-wound Nasmyth tube that connects the telescope metering structure in the cavity to the SI in cabin supports both sides on the RIS.

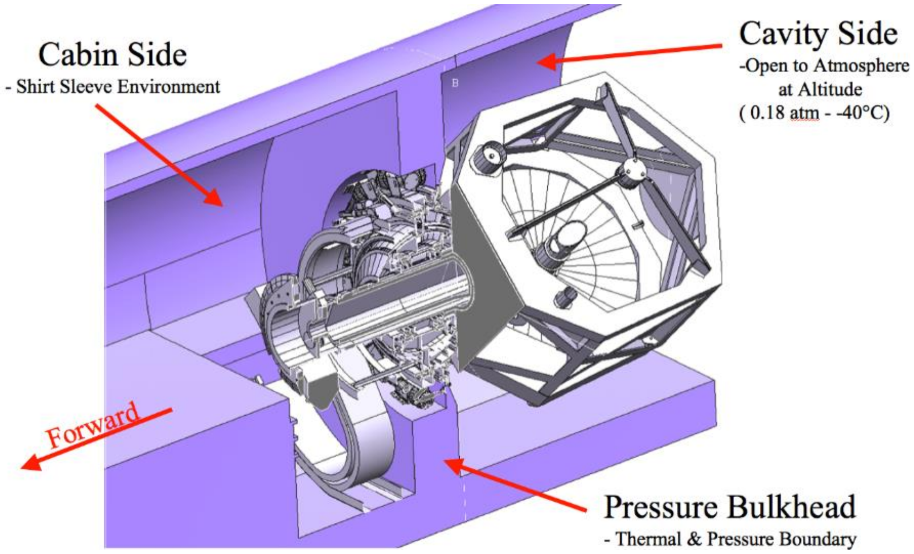


Figure 5.4-6. A 3-D cutaway CAD model showing the design of the overall telescope installation in the aircraft.

As you can see from the multiple figures in this section, the interface between the telescope and the aircraft bulkhead is not simple. It consists of multiple layers of different systems, which we called the suspension assembly (SUA). Starting with the RIS sphere, the next layer is of course the socket which has the very-high-precision (about a 10-micrometer, same as the sphere) spherical socket that maintains about a 25-micrometer (0.001-inch) gap from the sphere while the hydraulic fluid is under pressure as well as having the appropriate oil supply and retraction systems. This is of course in addition to having a sealed system for the oil as well as being part of the pressure boundary between the cabin and the cavity. The next spherical layer is the fine drive system which has a spherical shell attached to the “floating” part of the telescope sandwiched between two other spherical shells attached to the SUA. With the combination of multiple permanent magnets, armature segments, brakes, and associated brake friction pads, the fine drive system can control the motion of the “floating” part of the telescope with a range of motion of plus or minus 3° along any axis. To get the range of motion in the telescope elevation/airplane roll direction needed to support both observation operations and maintenance operations, the next layer in the SUA is the coarse drive system. This is a large diameter roller bearing in parallel with a large diameter gear driven by pinion gears that can move the telescope as far as necessary. This was the connection between what we called the inner SUA and outer SUA. You can see a portion of the outer SUA in Figure 5.4-7 and will see many more details in the timeline section.

Then there is the connection between the TA and the aircraft bulkhead. To minimize the transmission of aircraft motions and vibrations into the precision telescope operations, it is desirable to have this connection as soft as possible, but again the pressure difference between the cabin and cavity comes into play. The solution that our German partners came up with we called the VIS, as you can see in Figure 5.4-7, which has two sets of air bladders, twelve axial and twelve radial. These air bladders are similar to what you see on truck suspensions. As the cabin pressure increases, the axial bladders are inflated to compensate and keep the telescope in the center of the VIS travel range. In parallel with the bladders, there are also a few custom-made 3-D dampers. This combination works quite well to minimize the aircraft motions/vibrations that get transmitted to the telescope.

Figure 5.4-7. VIS.

The most important part of a telescope is of course the primary mirror, which is the first thing within the SOFIA observatory that the photons hit after traveling (sometimes for many light years) from the object of interest. The primary mirror surface needs to maintain its shape within fractions of the wavelength of light being observed. This requires both special materials for the primary mirror and a good support system that maintains the shape of the primary mirror while observing at different elevation angles. In addition, because of the variable thermal environment, the primary mirror material needs to have a very low coefficient of thermal expansion (CTE). The material used for the SOFIA primary mirror was ZERODUR®, a proprietary material from SCHOTT, which is a glass-like material that has an ultra-low CTE.

For normal ground-based telescopes, primarily just the front surface would be figured into the desired shape, and for a mirror of this size, it would weigh about 4.5 tons, but as mentioned above, since time at altitude is important, the weight of the mirror is also very important. The weight of the metering structure is roughly proportional to the weight of the primary mirror. The CG of the telescope must be at the center of the RIS, so weight/ballast must be added to the cabin side of the telescope to balance the weight of the primary mirror plus metering structure. Then of course, to maintain the CG of the airplane within the required envelope requires ballast in the front of the airplane for all this weight. And obviously all this weight is payload that the airplane has to carry, reducing the time at altitude. So the weight of the primary mirror turned out to be leveraged by a pretty high factor. Therefore, light-weighting the primary mirror was very important. The light-weighting was done by machining a honeycomb-like structure out of the back primary mirror slab as shown in Figures 5.4-8 and 5.4-9 with the end result that the primary mirror weighed only 880 kg, light-weighted by about 80 percent. Another feature of the primary mirror that pushed the limits a little bit is that because the diameter of the mirror is relatively large compared to the diameter of the fuselage, the f/ ratio is a fast f/1.2 to be able to keep a reasonably sized secondary mirror within the cavity/diameter of the fuselage. The final numbers on the SOFIA primary mirror are as follows:

Diameter 2.7 meter
Thickness 35 cm
f/1.2 parabolic surface geometry
Depth of vertex 14 cm
Back side wall thickness 7 mm
Weight 880 kg

Figure 5.4-8. The SOFIA primary mirror nearing completion at REOSC in France, with members of several SOFIA teams.

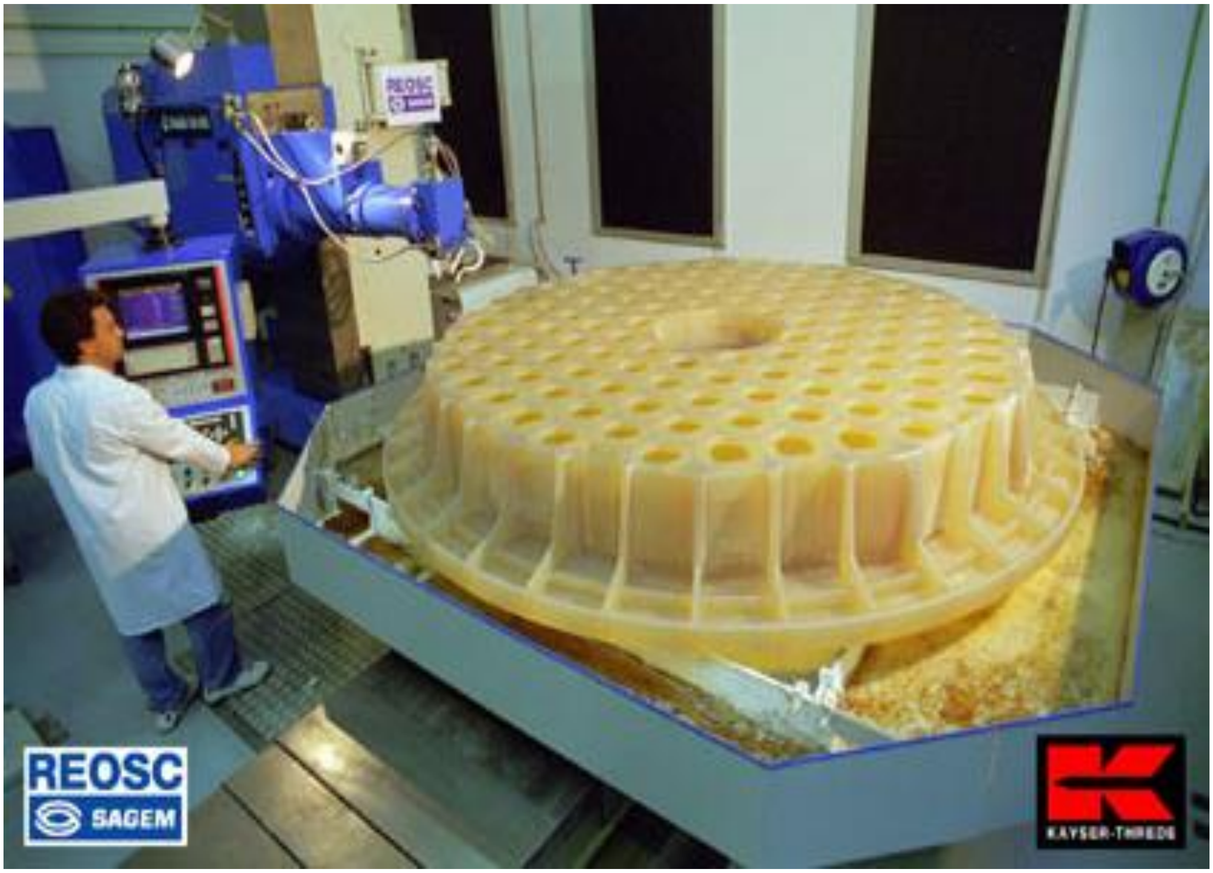


Figure 5.4-9. Largest light-weighted mirror with milled honeycomb structure.

Another engineering highlight of the SOFIA telescope is the metering structure, the structure that holds the optical components of the primary mirror, the secondary mirror, and the tertiary mirror in the telescope cavity. The metering structure, while exposed to the extreme cavity environment, must hold all the mirrors accurately with respect to each other through the entire operating elevation range of the telescope. Again, as mentioned above, the weight of the metering structure is leveraged with balanced weight on the cabin side plus ballast weight in the front of the airplane. Therefore, CFRP was the material of choice for the metering structure because it is lightweight, stiff, and has high breaking strength. The FAA certification requirement added an additional gauntlet for this development because the composite material fabrication process needed to be certified and approved. The nice thing about telescope structure is that it is primarily driven by stiffness requirements to maintain optical tolerances. The result for SOFIA was that when the air-worthiness stress analysis was done for the telescope, even with the superposition of multiple load cases that normally don't occur at the same time, the telescope design passed with flying colors.

Another important part of the metering structure is the primary mirror cell, whose job is to support the primary mirror with a kinematic mount that does not over-constrain the primary mirror, maintaining its proper shape while it is being held at various elevation angles.

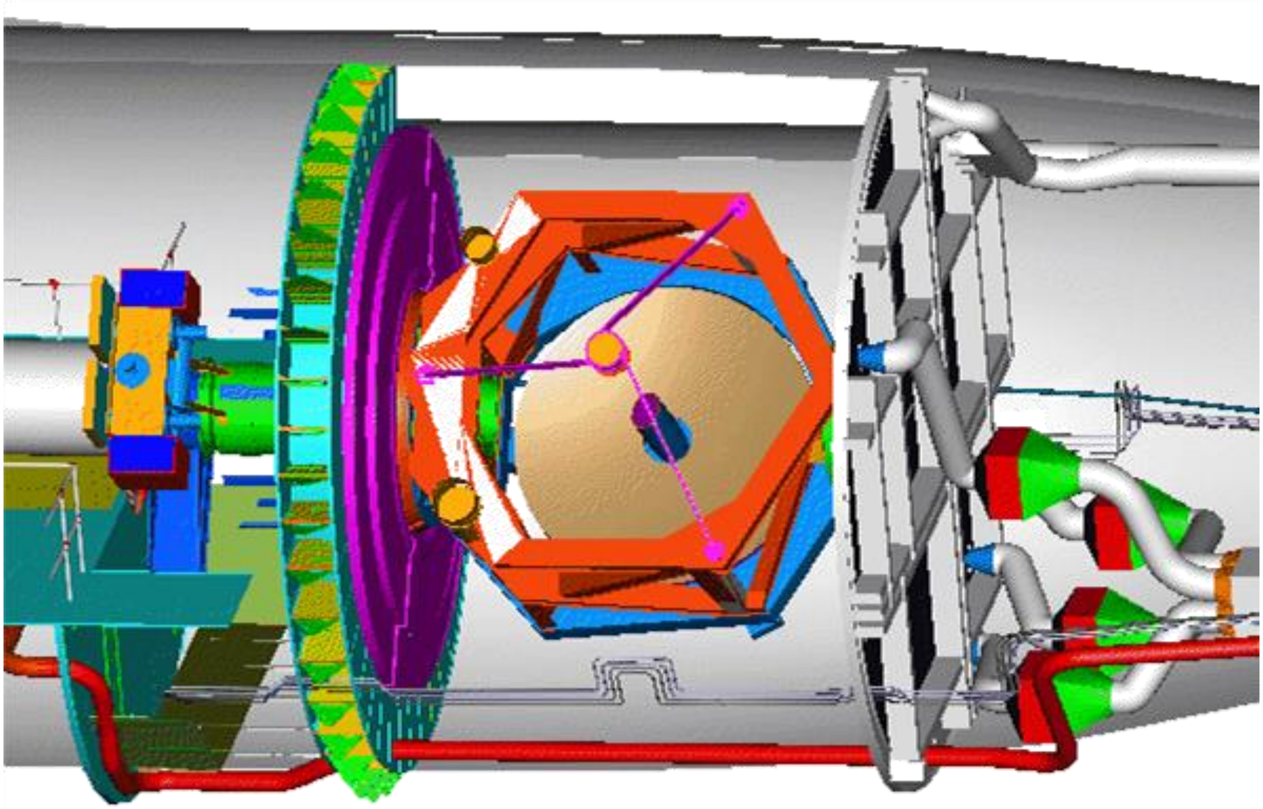


Figure 5.4-10. Configuration: instrument access in cabin.

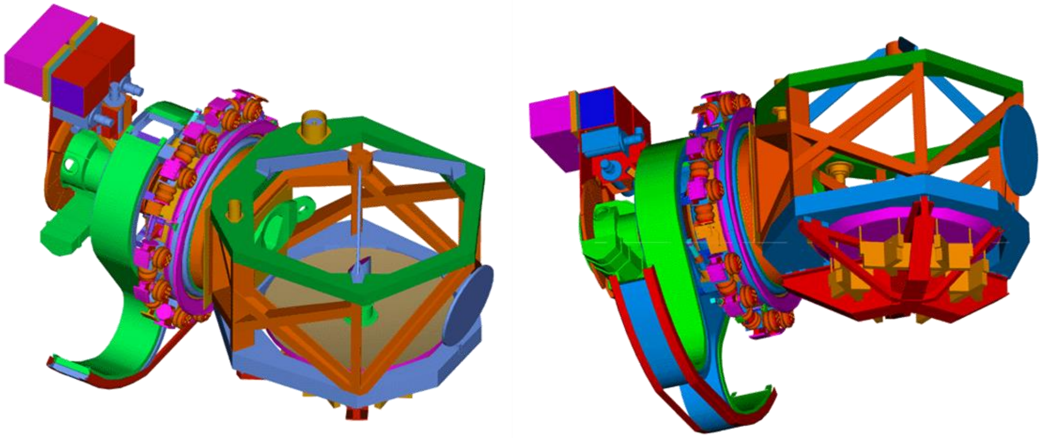


Figure 5.4-11. Two views of the 3D CAD models of the telescope showing both sides and attachment to bulkhead.

Figure 5.4-12. The TA in the assembly hall at MAN in Augsburg, Germany where all systems were integrated and tested for the first time.

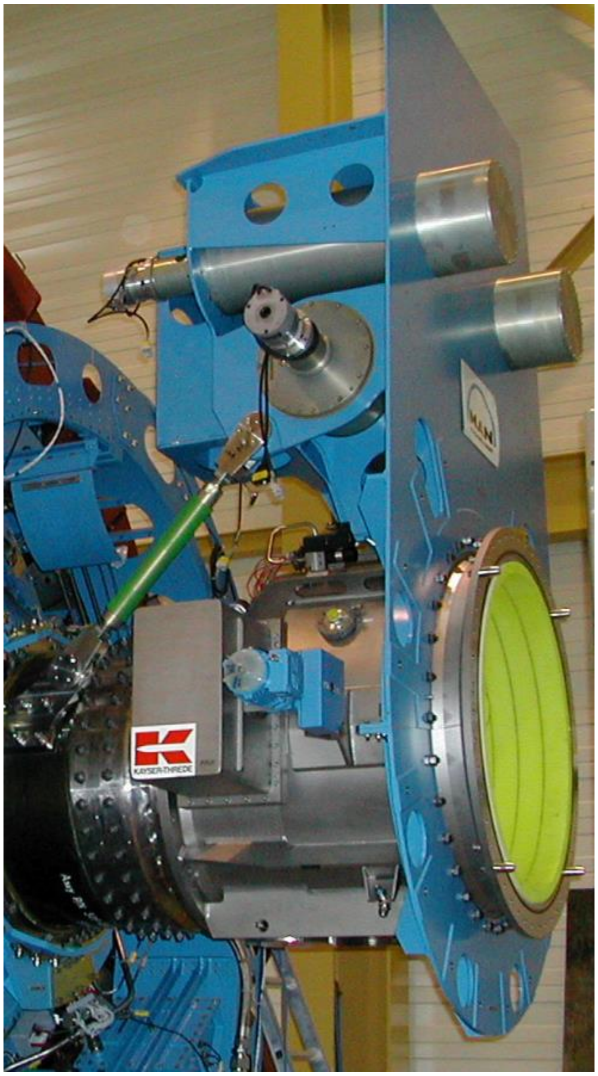


Figure 5.4-13. Instrument flange assembly − counter-weight system. Photons exit here and enter the SI that would be mounted onto this flange.

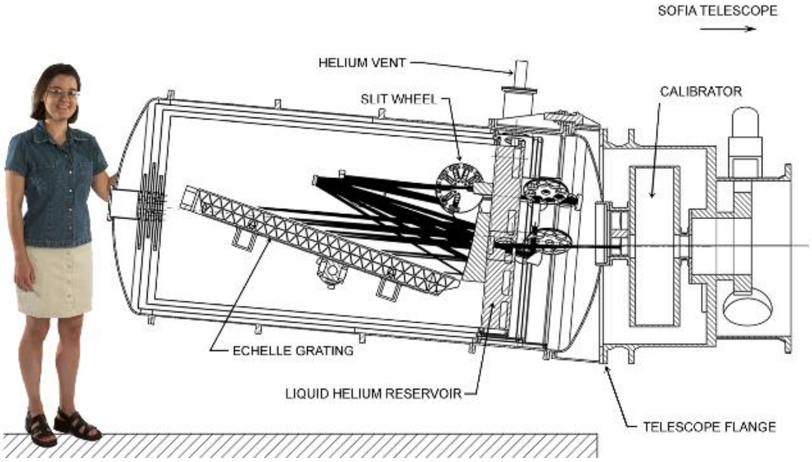


Figure 5.4-14. Illustration of instrument access in the pressurized shirt-sleeve cabin environment.

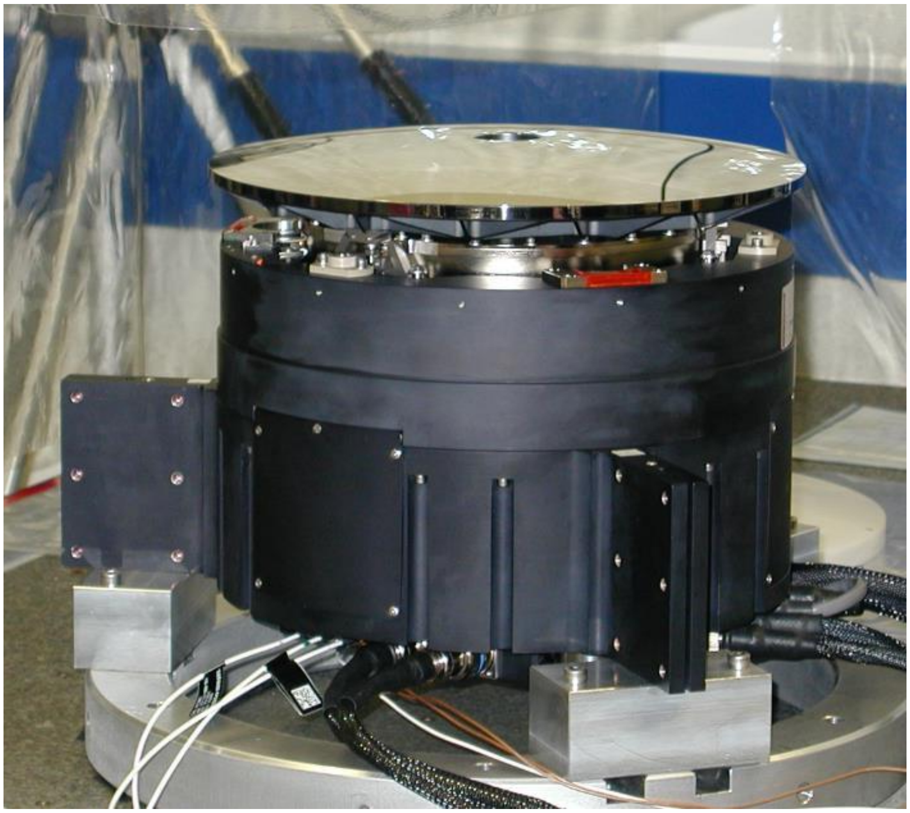


Figure 5.4-15. Secondary mirror assembly.

Another key feature of an infrared telescope is the Secondary Mirror Assembly (SMA). It provides multiple features necessary for quality IR astronomy including focusing, optical alignment, and beam movement including “chopping.” Chopping is a method by which astronomers can extract valuable science from an object that has a very low signal to noise ratio, such as 1:10,000. It is done by tilting the secondary mirror to move the observation area from the object of interest to the background area beside the object of interest then alternating back to the object of interest at a defined frequency such as 20 Hz (chopping), then moving to the background area on the other side of the object of interest. The signals from the two background areas are then averaged and subtracted from the signal from the object of interest in a process called “synchronous demodulation” to yield the signal of interest. As you might expect, the desire is to collect as much data as possible by maximizing the dwell time at the endpoints of the motion and to minimize the transition time, so the goal of the chopping mechanism is to tilt the secondary mirror back and forth in essentially a square wave between two angular positions, which is always difficult with objects that have mass. Also, given where the SMA is mounted, on the spider assembly in front of the primary mirror, it also is required to be a compact design with low energy consumption and have a momentum compensation feature so that no reaction forces are imposed onto the spider assembly. To move the secondary mirror, the secondary mirror mechanism has a slow drive that can move the mirror in all 6 degrees of freedom; for the chopping or other fast motions, there is a fast drive system with 3 degrees of freedom that is momentum compensated. These are all contained within the cylinder shown in Figure 5.4-15. The SMA was developed by a company called CSEM, the Swiss Center for Electronics and Microtechnology, in Neuchatel, Switzerland, and if you would like to learn more, there has been at least one paper written about it (ref. 28).

For the mirror itself, because of the square wave motion dynamics, it was desirable to make the mirror out of very lightweight and stiff material. Matra Marconi, a French company, was developing new technology to make things out of solid silicon carbide (SiC), a very hard material that is typically only used on the tips of machining tools. They had a proprietary process that they used to make the SOFIA secondary mirror which is shown in Figure 5.4-16, which at that time was the largest secondary mirror ever made from SiC. The final numbers on the SOFIA secondary mirror are as follows:

Diameter 35 cm
Thickness 4 cm
Weight <2.2 kg
Back side wall thickness 2 mm
Hyperbolic geometry
Height at vertex 15 mm
Eigen frequency ~1.1 kHz

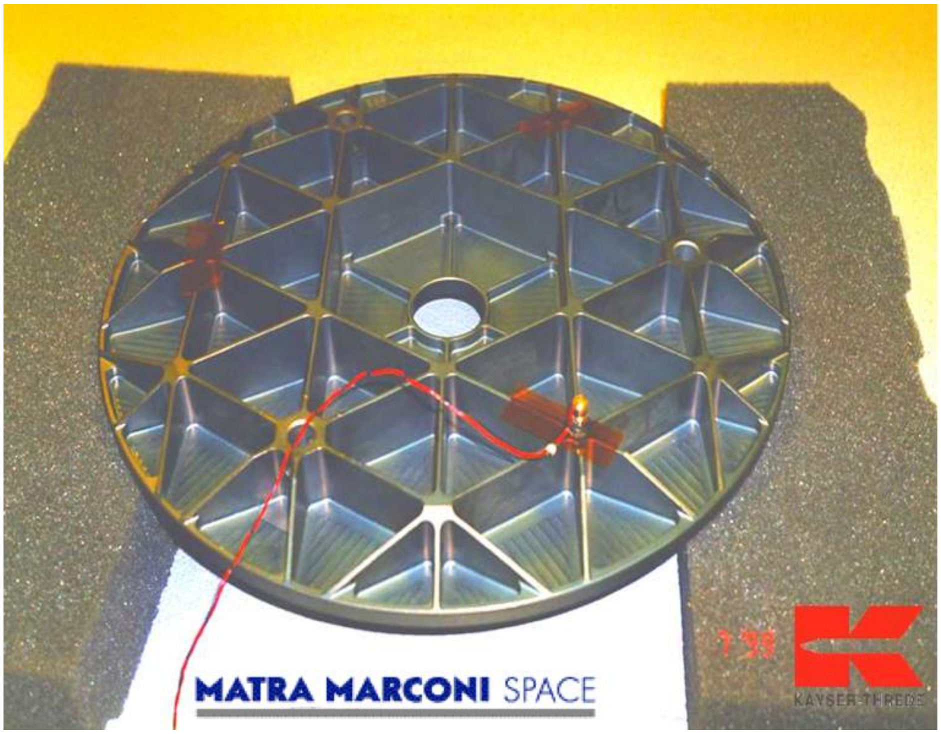


Figure 5.4-16. The backside of the secondary mirror made from SiC.

For SOFIA, the nominal aperture diameter is limited by the secondary mirror to 2.5 meters and the diameter of the primary mirror is 2.7 meters, which allows the secondary mirror projection to move or be chopped and still maintain an effective aperture of 2.5 meters.

The first mirror seen by the SI, or the last mirror the photons hit in the cavity, is the tertiary mirror as seen in Figure 5.4-17. This mirror assembly actually consists of two mirrors, the first being a dichroic mirror that reflects the IR light to the SI and transmits the visible light through to the second mirror that reflects this visible light to the focal plane imager (FPI) to help with the telescope tracking.

Figure 5.4-17. Dichroic tertiary mirror on tower with visible light reflecting mirror.

There were many subsystems on the telescope that were pushing the state-of-the-art to meet the requirements in the aircraft environment, in addition to having to be FAA certified. Fortunately, our German partners were outstanding. This section has covered just a few of these technical highlights and if you would like to learn more, there are multiple papers written, *e.g.* ref. 27, and other papers presented at SPIE conferences such as the 2000 conference in Munich, Germany; the 2002 conference in Glasgow, Scotland; and the 2004 conference in Kona, Hawaii (ref. 29).

5.5 Pointing

Achieving 0.2-arcsecond pointing stability for a ground-based telescope is difficult enough, trying to achieve this same level of performance for a large telescope mounted in an aircraft that is flying in the stratosphere adds significant additional challenges. With the aircraft motion and vibration, plus the airflow over the cavity, it is somewhat analogous to simultaneously having a mild earthquake and a Mach 0.84 hurricane outside the dome of a ground based telescope, while trying to achieve this level of pointing stability. In addition, being an integral part of an aircraft results in further design constraints including weight limitation and structural airworthiness requirements for the telescope system to be airworthy throughout the flight envelope of a 747SP, including severe turbulence and limit emergency maneuvers.

First, to get a little more appreciation of the magnitude of 0.2 arcseconds, I'll share how I have described it at various talks I've given. First, as you can see in Figure 5.5-1, even 10 miles out from the vertex, the separation of two lines diverging by 0.2 arcseconds is still within the diameter of a dime. Another way to get a feel for it: if you remember your protractor from high school, typically the finest resolution has the marks at 1° spacing. So, with 60 arcminutes in 1° and 60 arcseconds in 1 arcminute, within that 1° spacing, there are 3600 arcseconds, so at 0.2 arcseconds, the angular pointing stability requirement is equal to that smallest increment on your old protractor divided by 18,000. Finally, to get an appreciation of why it would even be difficult for a ground-based telescope, remember that the Earth rotates about 360° in 24 hours, or 15° per hour, or in arcseconds, 15 arcseconds per second, meaning that even a rock-solid, ground-based telescope without active tracking would exceed this requirement by a factor of 75 in 1 second of time.

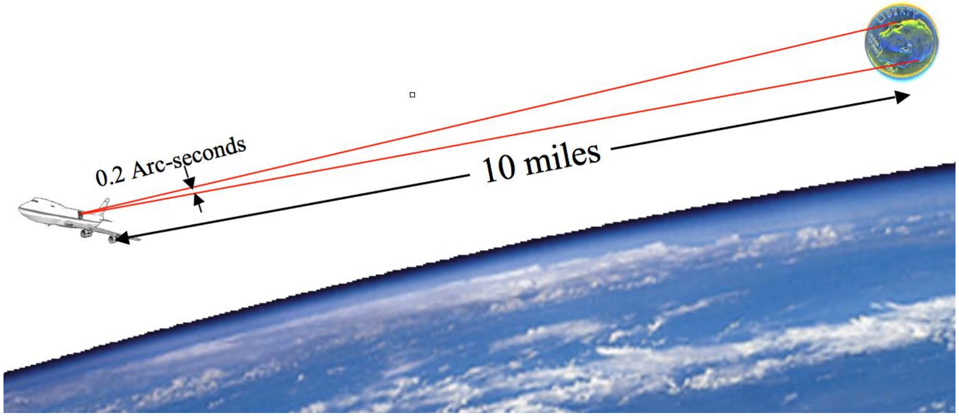


Figure 5.5-1. A schematic to show a small angle 0.2 arcseconds.

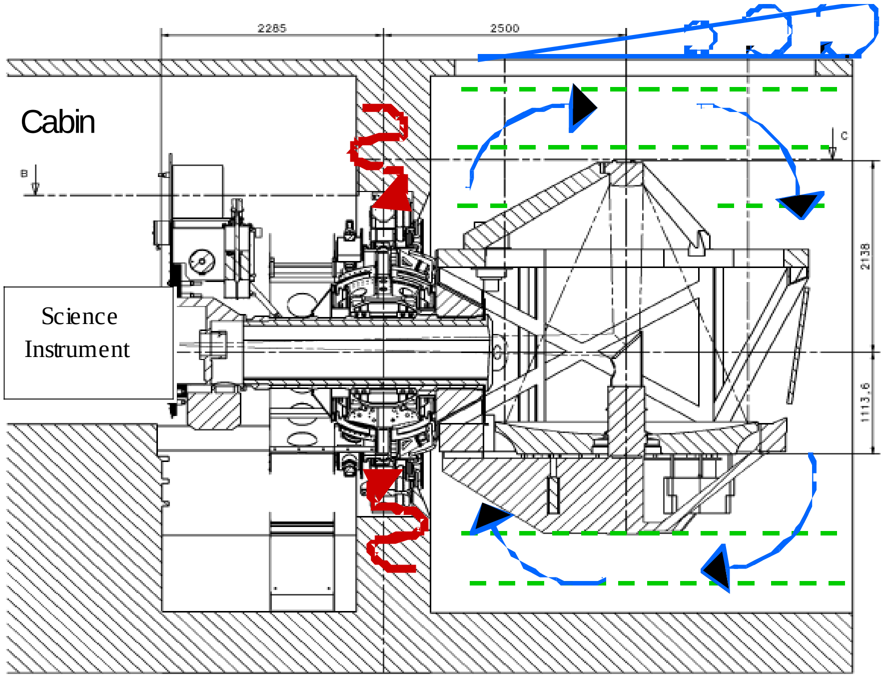


Figure 5.5-2. A schematic showing some of the various disturbances that try to move the telescope and need to be compensated to achieve the desired pointing stability.

To help explain the design features of SOFIA, relative to the pointing stability requirement, I have broken it down into five stages. This section discusses these five stages of pointing stability and the respective predicted pointing stability performance for each stage.

5.5.1 Stage 1: Platform − Aircraft

The nominal angular stability of a 747SP during cruise conditions is on the order of fractions of a degree (0.1° to 0.25°), or in terms of arcseconds, approximately 400−1000 arcseconds. This is more than three orders of magnitude greater than the requirement. Clearly, improving the angular stability of an aircraft such as a 747, that is already very stable, by three orders of magnitude is not possible. Therefore, the SOFIA telescope installation design needs to isolate the telescope from the aircraft rotational motions.

5.5.2 Stage 2: Rotation Isolation System (RIS)

During the early SOFIA feasibility studies, it was decided to use a portion of the same basic design approach as the highly successful KAO. The heart of this approach is a spherical ball that isolates all three rotational degrees of freedom of the telescope from the aircraft called the RIS, which is described in the previous section. As shown in Figure 5.5-3, the sphere is located in the center of the new aircraft bulkhead with a Nasmyth tube connecting to the optical metering structure in the cavity, through the sphere to the SI-mounting flange in the cabin. Structurally this concept is similar to holding a dumbbell in the middle with the telescope metering tube assembly in the cavity as the weight on one end and the SI in the cabin as the weight on the other end. This approach requires that the center of mass be actively controlled to be in the center of the sphere, which is accomplished by the use of moveable and removable counterweights on the SI end of the telescope. The RIS consists of a large sphere that is “floated” on a film of hydraulic fluid. The hydrostatic bearing supports the entire weight of the metering structure, Nasmyth tube, SI, counterweight flange assembly, etc., and of course the sphere itself, a total of approximately 18,000 pounds. It is designed to have minimal friction so that the aircraft rotational excursions are isolated from the pointing portion of the TA and the telescope remains fixed in inertial space while the aircraft moves around the telescope. As shown in Figure 5.5-4, it works extremely well as we were all able to push around and move 18,000 pounds of the floating telescope with our pinky fingers.

As illustrated in Figure 5.5-5, disturbances that cause pointing excursions or rigid body rotations of the floated portion of the telescope include:

- friction in the bearing or RIS seal system,
- forces from the cables attached between the floating telescope and the portion of the TA that moves with the aircraft,
- the steady and unsteady aerodynamic forces on the telescope structure in the cavity caused by airflow over and in the cavity,
- CG offsets coupled with aircraft translation accelerations, and
- pointing system hardware resolution or accuracy limitations.

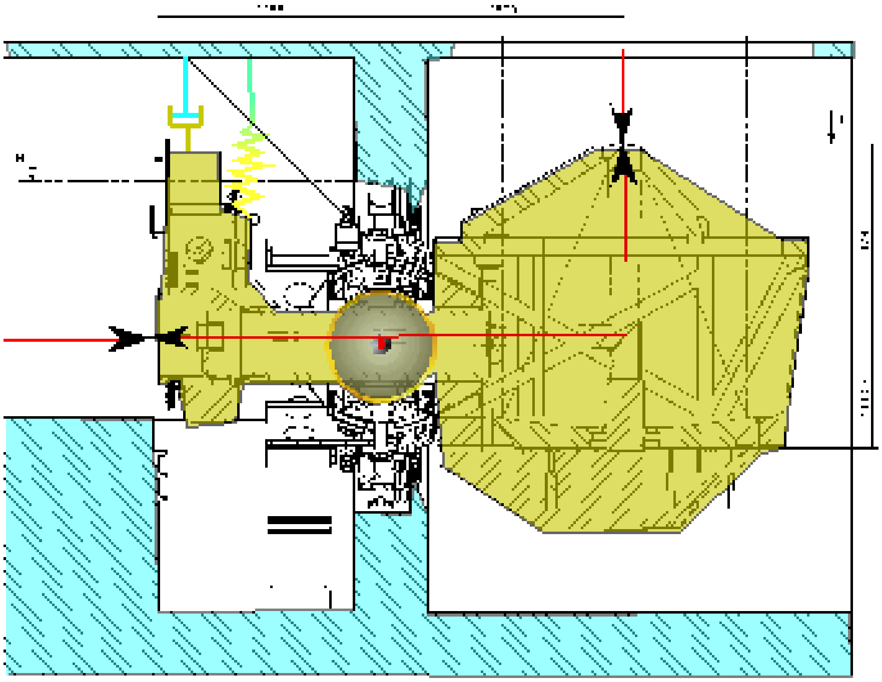


Figure 5.5-3. CAD drawing highlighted to show the RIS (the gray sphere) in the center, with the red dot showing where the center of mass for the floated part of telescope (highlighted in yellow) needs to be actively maintained.

Figure 5.5-4. A clip from the video showing Kaiser Adeni being able to move about 18,000 lbs of the floating telescope with his pinky finger because the RIS works so well.

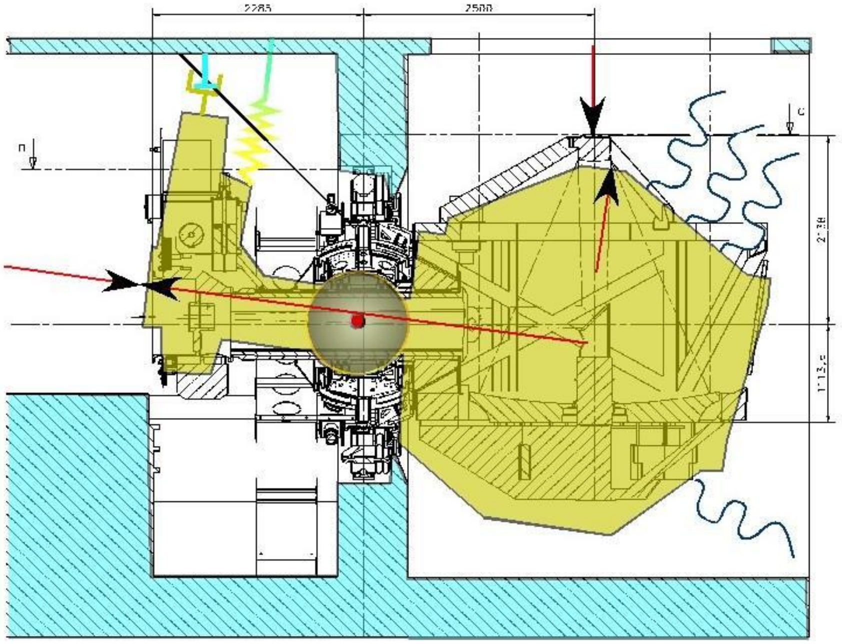


Figure 5.5-5. Shows the telescope with a rigid body disturbance.

The predicted cavity acoustic environment as measured in the SOFIA wind tunnel tests and scaled to full-scale flight conditions is shown in Figure 5.5-7. However, the acoustic environment alone does not provide enough information to determine the net forces on the telescope that cause rotations and pointing errors. To estimate the net disturbance torque applied to the telescope, a 7-percent scale model of the telescope was mounted into the cavity of the 7-percent aircraft wind tunnel model. The telescope was instrumented with 56 dynamic pressure transducers so that data could be collected about the telescope disturbance forces simultaneously to the data being collected for the other objectives of the wind tunnel test.

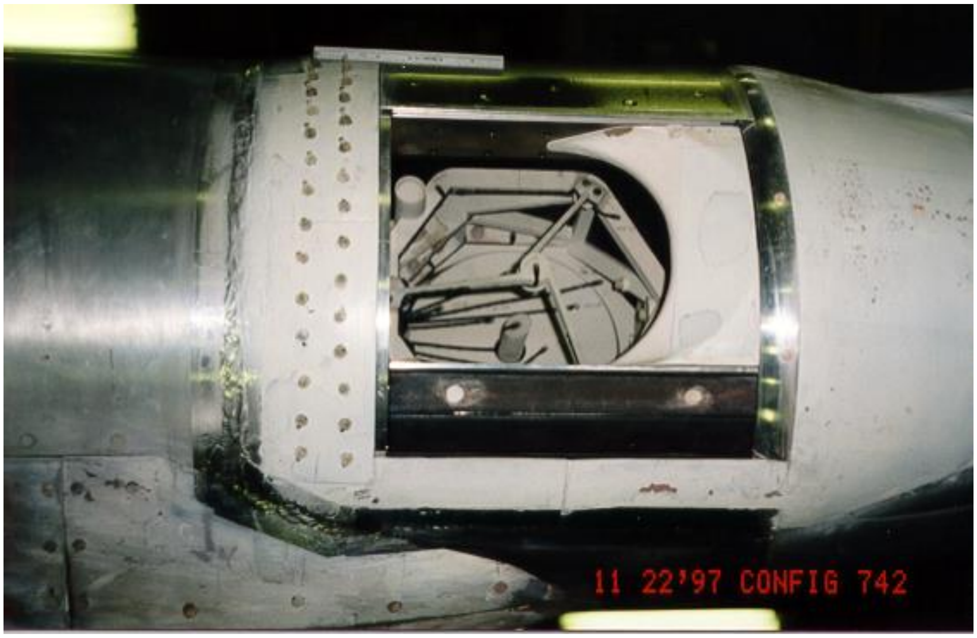


Figure 5.5-6. Photo showing cavity area of the 7-percent wind tunnel model with the instrumented telescope in the cavity.

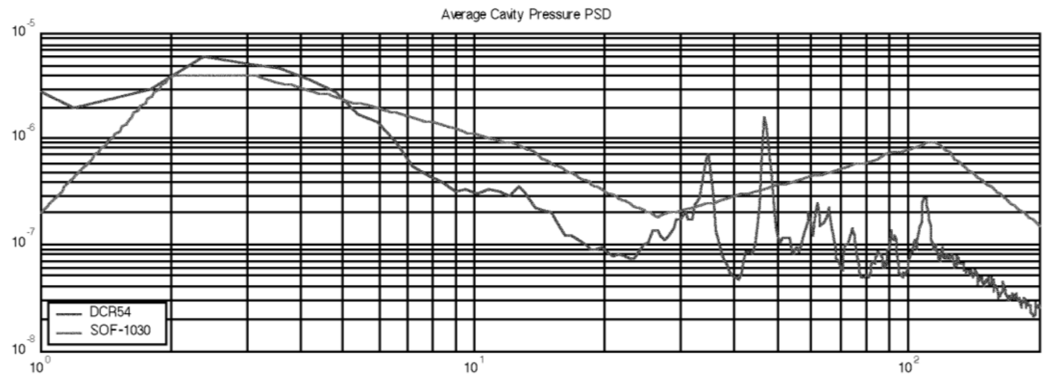


Figure 5.5-7. Cavity acoustic environment Power Spectral Density (PSD) in psi squared per Hz. The smoother line shows the predicted environment per the specification, and the second more jagged line is as measured during the last wind tunnel test series.

To derive the net disturbance torque, each pressure sensor was allocated an area for which the measured pressure was assumed to apply. Then the total torque was calculated by summing each pressure sensor times its tributary area and the moment arm from the center of the RIS sphere to that pressure sensor. This was done for each axis of rotation. The resulting moment plot for one axis is shown in Figure 5.5-8. The resulting predicted rigid body motion of the telescope, which is primarily caused by these aerodynamic disturbance forces, is shown in Figure 5.5-9. One can see the resulting image motion at the focal plane is on the order of 100 arcseconds, which is an order of magnitude better than stage 1, but still more than two orders of magnitude away from the requirement.

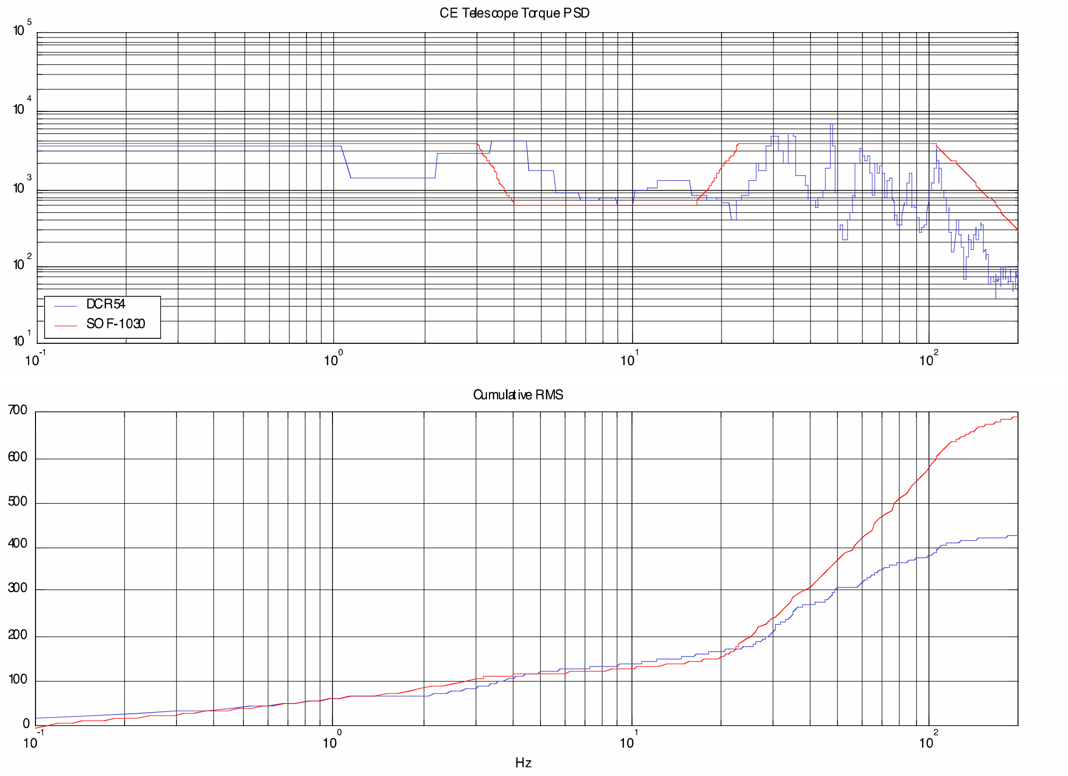


Figure 5.5-8. The upper curve shows the PSD of the disturbance toque in (N-m)^2 per Hz versus frequency, the lower curve shows the cumulative RMS torque in Newton-meters. Both plots show the predicted (smoother line) and the measured values.

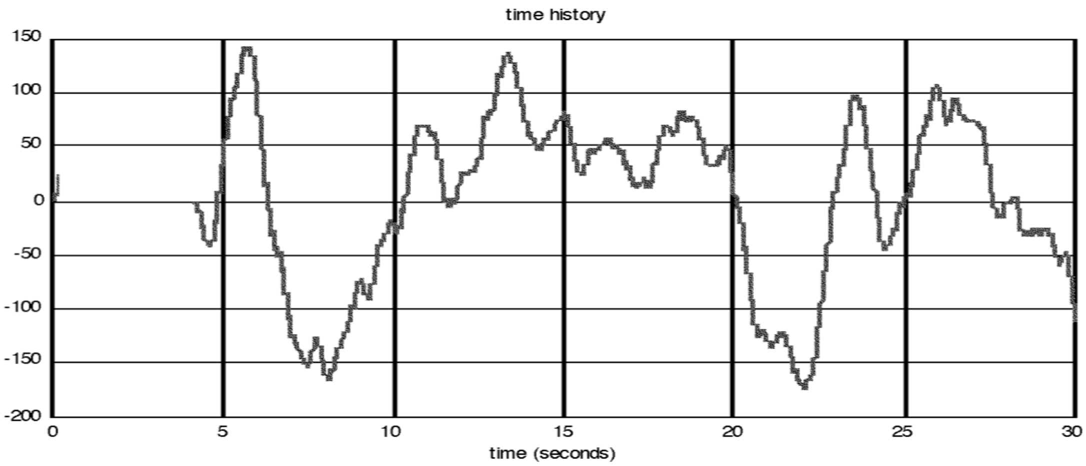


Figure 5.5-9. Plot showing the predicted resulting image motion at the focal plane in arcseconds as a result of the rigid body motion of the telescope without a control system.

5.5.3 Stage 3: Control "Rigid" Body Rotation

This stage is the primary servo loop to control the telescope attitude. It consists of a set of gyros as the primary sensors, one of which is shown in Figure 5.5-10, and a spherical torque motor as the actuator. The spherical torque motor is capable of applying torque to the floated telescope about all three axes. The primary control loop is closed around the gyros with input from a tracker camera, typically the FPI, to compensate for gyro drift.

Since the objects being observed from the geometrical perspective are essentially at infinity, if the telescope was rigid, this could be the last stage of a very precise pointing system. Unfortunately, the telescope is not a rigid body. The first or lowest structural mode, which has been dubbed the dumbbell bending mode, is around 21 Hz (this mode is illustrated in Figure 5.5-11). As a result, control system stability constraints limit the bandwidth of this servo control loop to approximately 8−12 Hz. Furthermore, because the gyros are located on the cabin side of the RIS near the center of the Nasmyth tube, they do not sense the actual angular error of the line of sight (LOS) of the telescope (where the primary mirror is pointed) nor are they able to compensate for the image motion caused by the bending of the Nasmyth tube. So even if the control system that is closed around the gyros were not bandwidth limited and worked perfectly, there would still be significant image motion at the focal plane caused by Nasmyth tube bending. As shown in Figure 5.5-13, the approximate image motion at the focal plane from a translational acceleration is about 100 arcseconds per G. A nominal time history of aircraft motion in the vertical direction is shown in Figure 5.5-14, and you can see by multiplying the top plot in this figure, by the 100 arcseconds per G factor, the resulting image motion after stage 3 compensation is still over 3 arcseconds RMS, which is still more than a factor of 10 above the 0.2-arcsecond requirement.

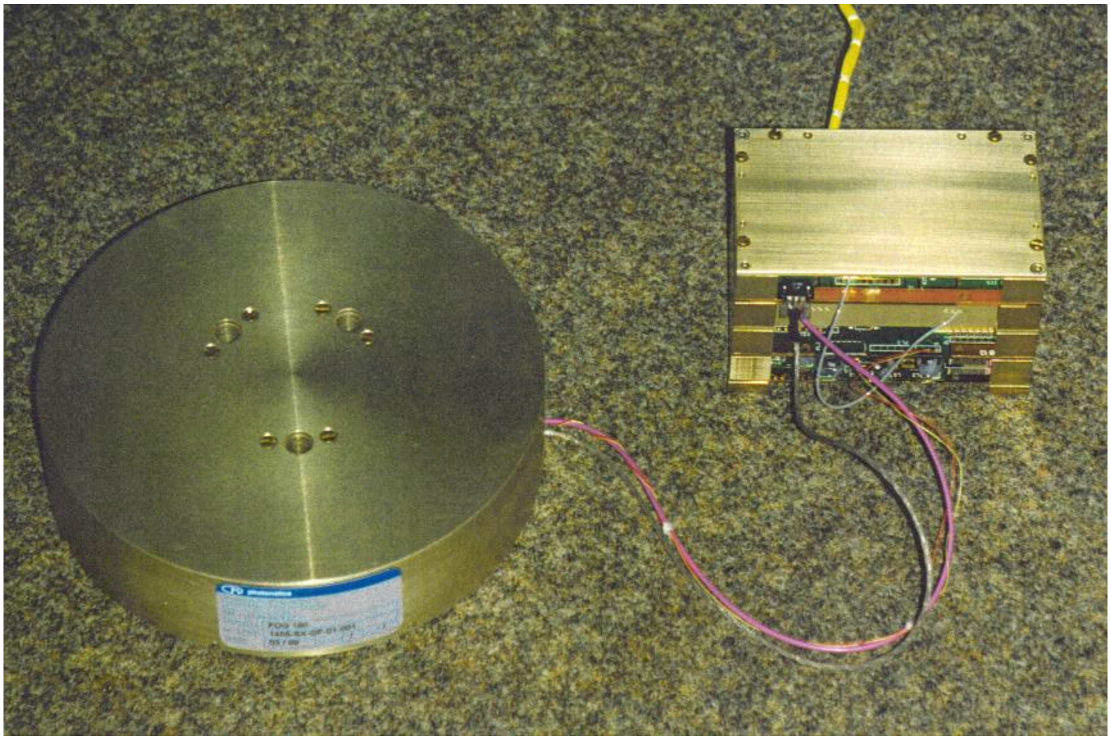


Figure 5.5-10. One of three orthogonally mounted glass-fiber laser-optic gyros which measure angular displacements of the floating telescope.
Each has a 3-km-long fiber with a resulting angular increment/accuracy of 0.0008 arcseconds.

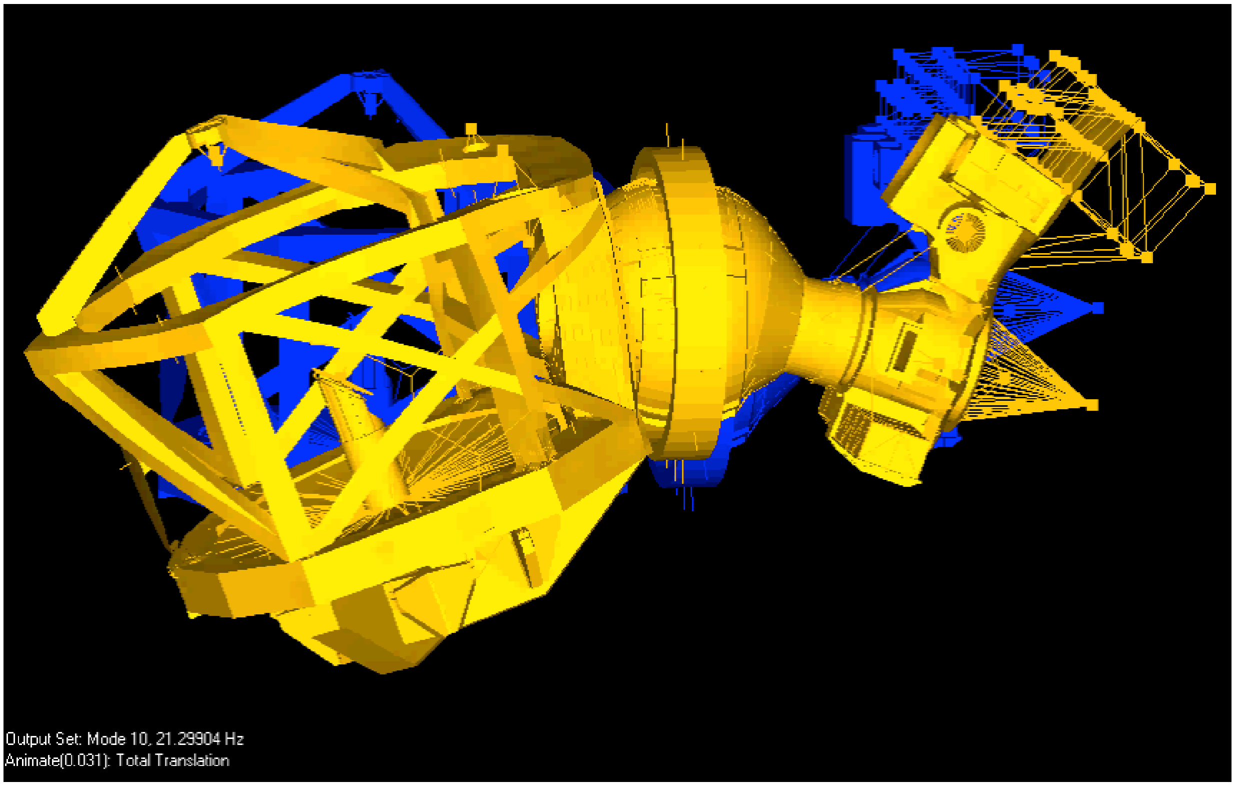


Figure 5.5-11. The exaggerated deformation from an FEM showing the shape of the 21-Hz first mode.

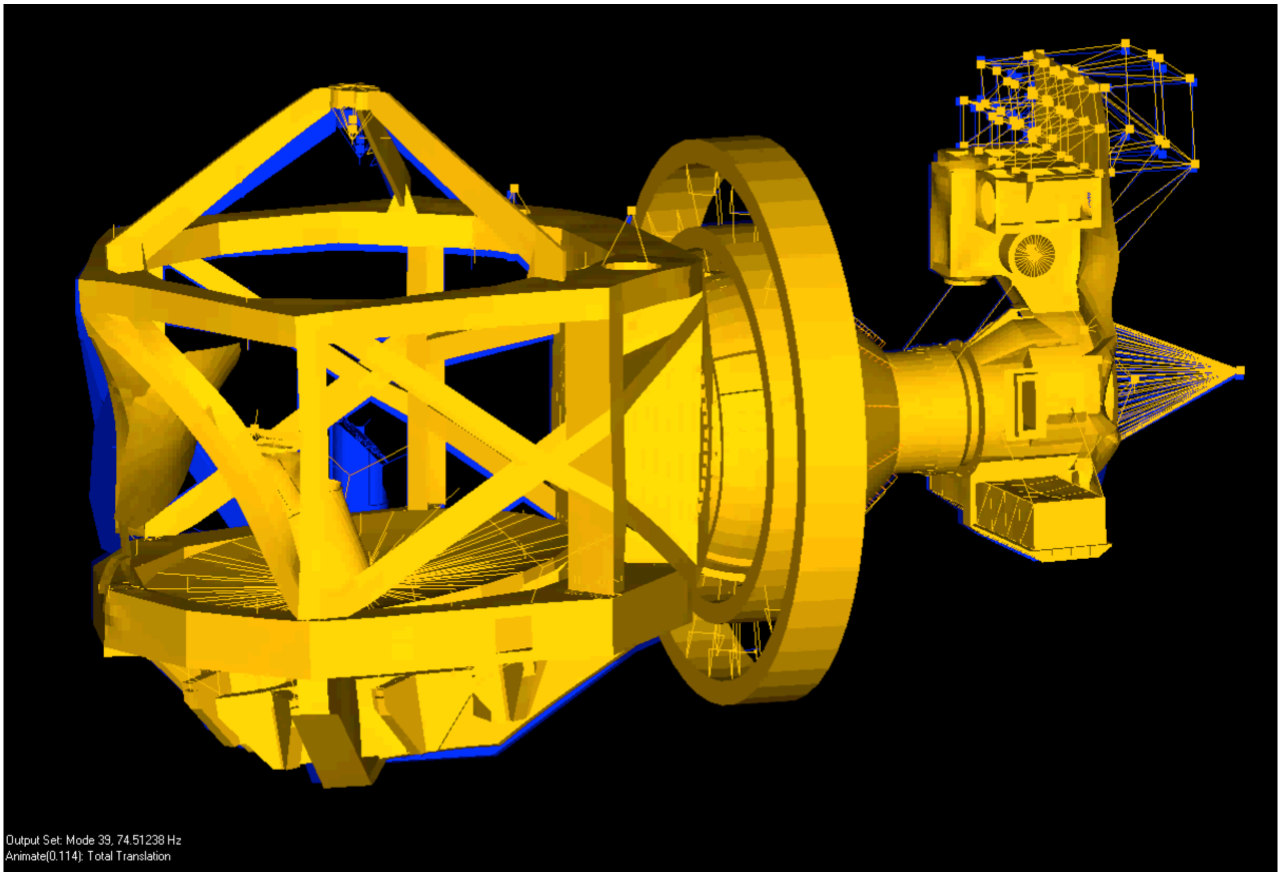


Figure 5.5-12. Image showing exaggerated mode we called the Primary Mirror rocking mode (about 74 Hz).

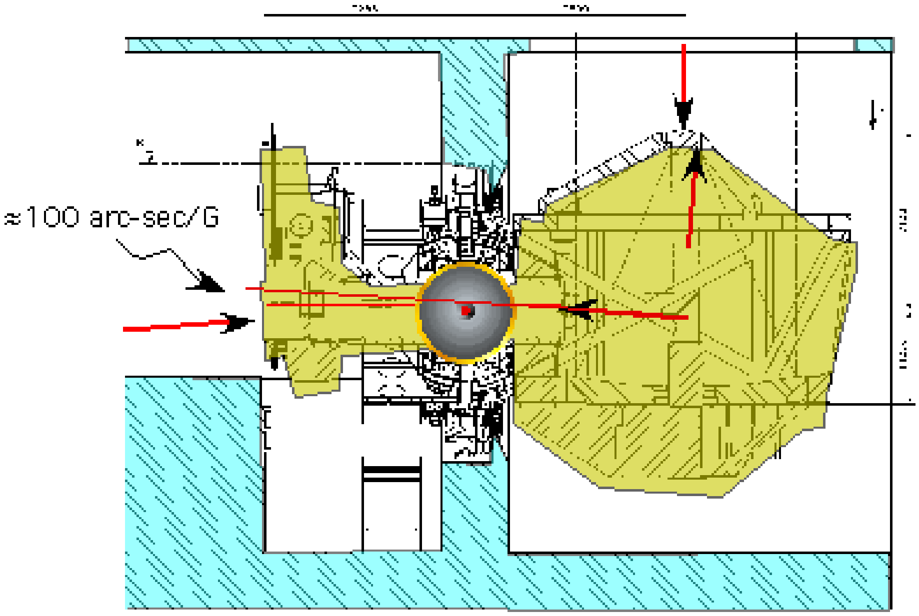


Figure 5.5-13. Illustration showing the resulting image motion due to the flexing of the Nasmyth tube when the telescope is subject to G loads.

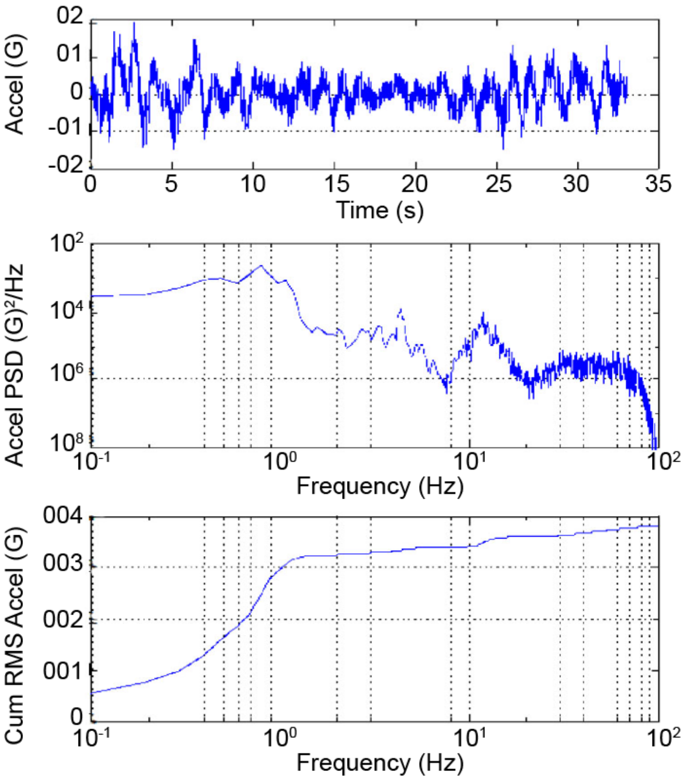


Figure 5.5-14. Example of plots in just one of three axes showing the aircraft vibration/motion that the telescope needs to be able to handle.

5.5.4 Stage 4: "Open Loop" Control System

This stage attempts to compensate for the telescope structure flexibility described above. First, sensors are needed to determine the flexural state of the telescope. Next this information is processed with knowledge of the structural characteristics of the telescope to provide additional input that is used to either move the telescope or to steer the image via the secondary mirror mechanism. Even though one of the actuators for this stage is the secondary mirror, which is used to steer the image, this is not considered image motion compensation (IMC) since actual image motion is not sensed. The estimated image motion error is derived from other measurements on the telescope structure and corrective actions are sent open loop to either the fine drive controller (the stage three servo loop) or to the secondary mirror mechanism depending on frequency of the error. The low-frequency component (about 5 Hz and below) can be considered quasi-static errors and are within the bandwidth of the stage 3 controller such that the entire floated portion of the telescope can be moved to compensate for the errors caused by the Nasmyth tube bending. The higher-frequency errors are compensated by steering the secondary mirror, which already has relatively fast tilt and chop capability for scientific operational requirements. Currently, accelerometers co-located with the gyro package are the primary sensors, and the flexible body compensation (FBC) control loop bandwidth is limited to be less than 35 Hz. Also, the only structural deformation for which FBC is currently attempted is the Nasmyth tube bending mode.

To come up with the best estimate for what the telescope pointing performance would be, a complete end-to-end simulation/analysis was done including all the factors mentioned above. This simulation included a special version of the telescope FEM, all the disturbances, realistic versions of all the sensors and actuators, the control system algorithms, and the optical ray trace that included all the mirrors. As shown in Figure 5.5-15, the prediction for the total RMS pointing stability (up to about 100 Hz) was about 1 arcsecond.

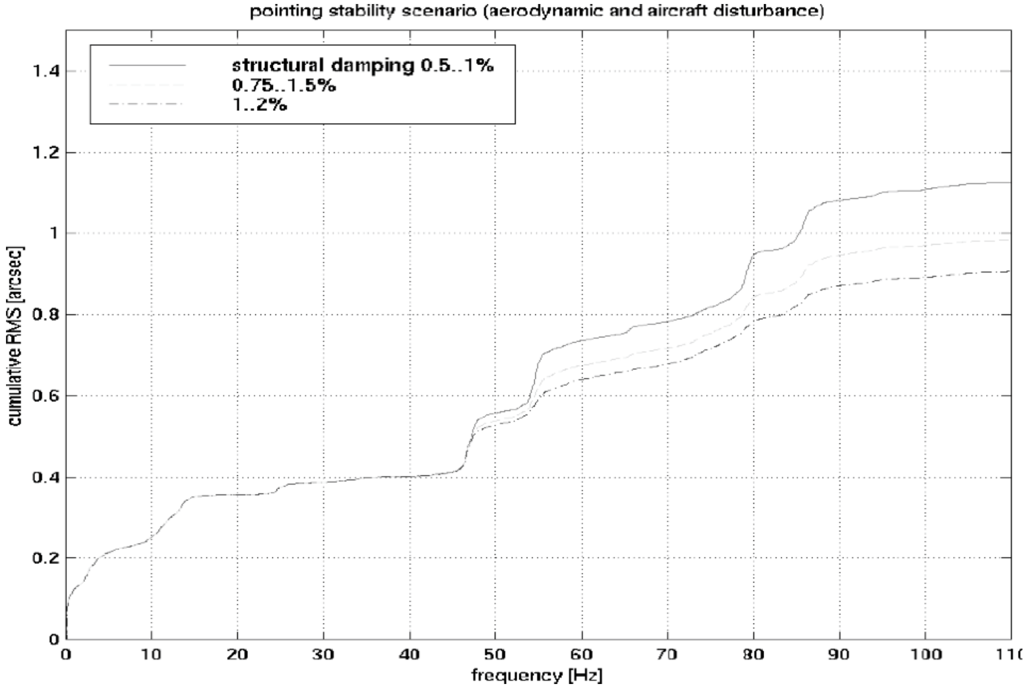


Figure 5.5-15. The predicted cumulative RMS image motion for SOFIA based on the simulations plotted as the cumulative RMS stability error versus frequency for three different levels of assumed damping.

5.5.5 Stage 5: Image Motion Compensation (IMC)

IMC requires both a sensor that can sense the location of the desired image and an actuator that is capable of steering the image back to the desired location so it would be a fully closed loop control system. In the best case, the sensor would sense the actual object of interest or another nearby celestial object. Alternatively, an artificial source such as produced by a laser (as done at ground-based observatories) can be used as the image source in some closed loop IMC schemes. For SOFIA, the actuator that would be considered is the secondary mirror mechanism because it already has capability for image steering. This is because science requirements for square wave chopping have resulted in a secondary mirror mechanism whose dynamic response can be characterized as a 4th order Bessel function with a bandwidth of 120 Hz. Unfortunately, the original FPI could not operate fast enough to provide an adequate error signal for IMC. IMC was not part of the baseline plan for SOFIA implementation but should be considered as part of the future pointing improvement activities, especially since the original FPI has already been replaced with a much faster one.

5.5.6 Pointing Stability Improvement Ideas

As of the writing of this book, this pointing stability requirement of 0.2 arcseconds RMS has not been met. This was the only requirement at the Critical Design Review (CDR) of the telescope (May 2000) that did not have a clear path to be met. As a result, at that time, we created the SOFIA Pointing Improvement Team (SPIT), which was co-chaired by Dr. Hans Kaercher (lead engineer at MAN) and me. Since this requirement still hasn't been met, I'm including the list of ideas that SPIT came up with that we were planning to pursue during the commissioning phase.

This list is lifted from the paper that I wrote for the 2000 SPIE conference (ref. 30); an updated version (ref. 31) gives a recent assessment of the achieved pointing history. The SPIT identified approximately 13 ideas that could be implemented that have the potential to improve the pointing stability. The plan was to evaluate these concepts and incorporate the best ones. Clearly many of these improvement concepts needed to be combined because some, such as the additional sensors, only provided more data to the servo controller, so the servo system still needed more capable actuators to correct for the errors.

Pointing improvement concepts can be characterized into one of the following categories:

Plant − The objective of the plant, or in this case, the telescope structure, is to make the plant behave as much like a rigid body as possible. The telescope structure for SOFIA utilizes carbon fiber composite material and the design has been thoroughly analyzed and optimized to maximize stiffness. There is likely little more that can be done with the current configuration to increase the stiffness. However, another characteristic of the plant that affects the pointing performance is the structural damping. A very stiff composite structure inherently has very little damping, but damping can be added. In this area there may be opportunities for improvement.

Sensors − Sensors are required to detect the deviation or error from the desired image position and provide this information to the control system. Ideally, it is best to sense the desired output of the system, which for SOFIA would be to sense the image at the focal plane. However, this is not always possible in the bandwidth necessary and alternate sensors are required. As mentioned above, the primary sensors for SOFIA are gyros located near the center of the Nasmyth tube. Accelerometers are the sensors for the FBC to provide the control system the necessary information to estimate the image motion caused by the Nasmyth tube bending and derive the necessary actuator commands to correct this error.

Actuators − Actuators are the mechanism by which the control system attempts to steer the image back to the desired location in the focal plane. With the current actuators this is done by either moving the entire floated part of the telescope or by tilting the secondary mirror to steer the image.

Control System − The job of the control system is to take the data from the sensors and decide what commands to send to the actuators. Several control theories are available and can be optimized to provide the best performance, but the ultimate performance is limited by the characteristics of the plant, the sensors, and the actuators.

Disturbances reduction − The primary disturbances for SOFIA are the aero-acoustics in the open port cavity and the aircraft motions that are transmitted to the telescope through the telescope VIS.

The following describes the 13 pointing improvement concepts:

1. Pressure Feed Forward − *Sensor*. Description: Dynamic Pressure sensors mounted on the telescope to measure aero-disturbance torque directly. This gives the control system a head-start (feed forward) opportunity to correct for these disturbances before the telescope has been disturbed from its desired position. This could be used in conjunction with the baseline capability (Fine Drive torque motors) or with optional improved mass actuators.
2. Active Acoustic Suppression − *Disturbance reduction*. Description: Using a to-be-determined (TBD) separate system of sensors, control system and actuators (like dynamic pressure sensors and speakers) to actively reduce the acoustic sound level in the cavity. This

improvement concept is unlikely to be implemented because it is likely not feasible due to the high complexity and amount of power likely to be required.

3. Passive Acoustic Suppression Internal − *Disturbance reduction*. Description: Using internal cavity treatments, such as acoustic foam or shaped surfaces, to reduce the acoustic sound level in the cavity.
4. Passive Acoustic Suppression External − *Disturbance reduction*. Description: Using additional upstream boundary layer treatments, such as a porous fence (like the KAO) or other treatments to reduce the aero-acoustics in the cavity and the resultant loading on the telescope. These concepts have been tested and proven during the SOFIA wind tunnel tests but have not been currently adapted as part of the baseline because they also have adverse effects on the observatory. Specifically, these additional treatments increase the drag of the aircraft which reduces the loiter time, and they also further degrade the optical properties of the air flowing over the cavity opening.
5. Identification of "real" acoustic disturbance − *Control system/servo improvement*. Description: During flight tests with a telescope simulator, dynamic pressure measurements will be made at the same 56 locations as the wind tunnel test measurements. Depending on the results, data will be used to fine tune servo system, incorporate passive acoustic control, and/or modify the plant (telescope structure characteristics).
6. Identification of Telescope Structure "real" Elastic Behavior − *Control system/servo improvement*. Description: Determine the actual telescope structural characteristics (modes, etc.) with ground tests with the telescope completely assembled into the aircraft. The "real" plant data can then be used to update the servo system parameters.
7. Constrained layer damping − *Plant improvement*. Description: Add constrained layer damping to various locations on the telescope structure with the objective to increase structural damping. The positive effects of increased damping on the telescope pointing stability performance have already been demonstrated by several analyses.
8. Tuned Mass Dampers (TMDs) (passive) − *Plant improvement.* Description: Add TMDs to specific locations on the telescope structure to move and/or damp out specific structural modes that are causing problems.
9. Mass Actuators − *Actuators*. Description: Add mass actuators to locations TBD on the telescope. Mass actuators can provide dynamic corrective forces to the telescope structure at desired locations. They work by reacting against their own inertia and do not require a bridge across the rotation isolation system to develop the desired actuator forces. They could be used to augment the fine drive torque motors and provide higher bandwidth corrective telescope rigid body torque. Additionally, the mass actuators could be used separately with the optional pressure feed forward set of sensors to reduce or eliminate the net disturbance torque that would cause rigid body motions of the telescope.
10. Faster FPI − *Sensor*. Description: Develop a faster more sensitive FPI that can provide higher bandwidth "true" error signals to the servo system. The Deutsche SOFIA Institute (DSI) team supporting the telescope has implemented a new FPI that may enable this capability.
11. Faster Chopper or M3 actuator system − *Actuator*. Description: The secondary mirror already has a mechanism to move (tilt) the mirror as required for science observing functions. However, the mechanism has been optimized for those functions, such as tilting the mirror

through predetermined motions such as square waves where phase lag is not important. The existing mechanism could be modified or replaced to provide the improved characteristics and higher bandwidth required to become the image steering actuator for several of the pointing improvement schemes described here. Alternatively, actuators such as piezoelectric actuators or another type of very fast actuator could be added to the tertiary mirror that is currently not articulated.

12. Internal Laser − *Sensor*. Description: A laser source could be used that will hit targets on all three optical elements and sense changes in alignment and then use various actuators on the telescope to correct for the sensed alignment errors. This improvement idea includes the concept of adding an inertially stabilized laser source that could act as an artificial star source that goes through all of the telescope optics to a "special" (the laser detector) FPI.
13. Additional Gyro on the Primary Mirror − *Sensor*. Description: Attaching an additional gyro onto the primary mirror or primary mirror cell may provide data showing where the primary mirror is pointing. It could also be used in combination with the principal gyro package mounted on the Nasmyth tube to determine the bending of the Nasmyth tube as an alternate or perhaps more accurate FBC sensor. A single axis gyro (for the cross-elevation angular changes) may be all that is necessary for significant improvement.

    One idea that has been partially implemented and tested is the Active Mass Damping system that is attached to the primary mirror cell. The purpose is to minimize the motion of the primary mirror. So far, the testing has shown positive results, but for some reason, it has not been fully implemented yet.

5.6 Science Instruments/Cryo Safety

5.6.1 Science Instruments (SI)

By Dr. Ed Erickson

The author, Nans Kunz, as SOFIA's Chief Engineer, was involved with safety considerations for Science Instruments, but thought a more complete discussion of them is appropriate here.

As depicted in Figure 2.1-1, SOFIA includes the SIs that receive and record light from the telescope. SIs are a *sine qua non* essential components of an observatory, without which no science can be done. Modern SIs are typically unique and highly sophisticated, employing state-of-the-art technologies.

Provision of the components of SOFIA were planned to be developed as follows:

> Telescope: by German contractors, funded and managed by the German Aerospace Center DLR (or previous related German government organizations)
>
> Aircraft and mission systems: by American contractors, funded by NASA, managed by USRA with oversight by the SOFIA Project Office at NASA Ames
>
> SIs: U.S. SIs would be funded by NASA, with USRA to be responsible for selection and development. German SIs would be provided by sponsoring German science organizations (not DLR).

SOFIA is designed to permit observations over wavelengths from 0.3 microns to 1.6 millimeters, arguably the greatest range of any observatory. Obviously, a wide variety of specialized SIs is needed to exploit this capability. One of the major selling points and expectations of the science community for SOFIA was its ability to support the development of new SIs and SI technologies. (ref. 32). It is noteworthy that at the end of 1995, there were 16 state-of-the-art SIs available, that had flown and were qualified for flight on the KAO.

In Germany, development of two SIs was begun soon after SOFIA was approved. Two teams, one at a university and one at a government laboratory, arranged for development funding independent of the DLR’s support for SOFIA.

In the U.S., SI developments were managed by USRA, with no involvement by the NASA Project Office, other than providing the funding. USRA received 19 proposals to develop SOFIA SIs in response to a solicitation. Of these, eight were approved to begin development in 1997, at a total estimated cost of ~$17 M, to be developed via grants (not contracts) over a 5-year period. The resulting roughly $3.4 M per year of SI funding was to be fenced from the aircraft budget. Development of the approved U.S. SIs began in late 1996.

When severe cost overruns for the aircraft development were revealed in 2000, budgets for the U.S. SI teams were cut dramatically, and the highest priority SI was cancelled. The relatively small SI development teams attempted to cope with their reduced budgets, which of course resulted in increased development costs and delays. Subsequently, two more SIs were cancelled.

In 2008, NASA HQ took charge of selecting new U.S. SOFIA SIs. In response to a 2011 solicitation, 11 proposals were received. Of these, one of the original SOFIA SIs was approved for significant upgrades, but no new SIs were selected for development.

In July 2015, NASA solicited proposals for development of one more SI, with “notional” schedule requiring delivery in 2018. Such a schedule is excessively aggressive by comparison with the development durations of new high-tech SIs for ground-based telescopes. In response to this solicitation, three proposals were received in October 2015. Two of the proposals were accepted for Phase A studies. Of these, one was selected for development in September 2016. This rate of new SI developments for SOFIA is far below that originally advertised by NASA and expected by the science community (ref. 32).

By October 2015, four of the five surviving U.S. SIs and both German SIs had completed commissioning and had made science observations from SOFIA. The original U.S. SI that was approved for an upgrade in 2011 is expected to be completed and commissioned in 2016.

5.6.2 Cryogen Safety

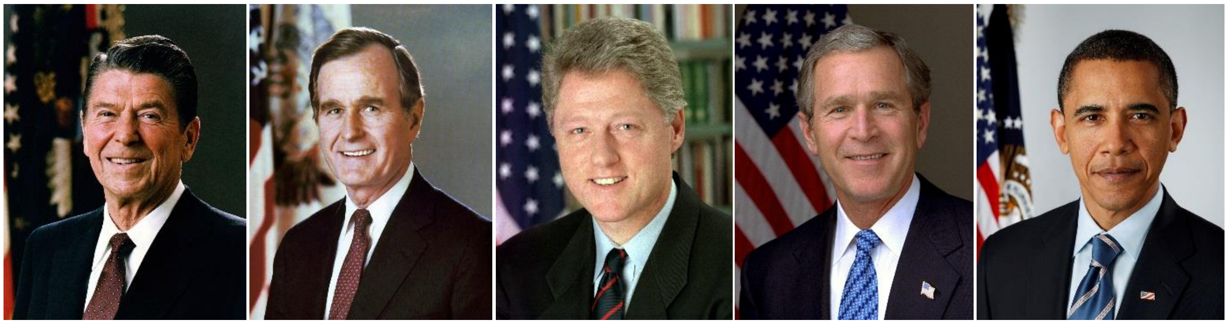
Many IR SIs use cryogens to cool down their detectors and optics: liquid nitrogen (LN_2), liquid helium (LHe), or both. Since a loss of vacuum in a dewar can lead to an unexpected rapid boil off of cryogen, testing was done to evaluate any safety issues. Just in case you were not aware, LHe volume expands by a factor of 745 with very little heat required to vaporize the liquid. Analysis and testing was done to determine relief-valve sizing required to avoid having a bomb within the pressurized fuselage cabin, next to the observing team. This was also another hurdle for the FAA certification. It is noteworthy that some 50 cryogen-cooled SIs without relief valves were flown without incident on the KAO during its 21-year operational lifetime.

6.0 HISTORY PART 1: PRE-DEVELOPMENT

6.1 History Prequel

At the start, you don’t know or realize how long you will end up working on a given project, and how much of your career or life you will devote to making a particular project successful.

But in hindsight, it can be surprising, the span that your involvement covers, and what other changes in the world around you have occurred. To provide some appreciation for this history timeline of SOFIA, I have included some photos and graphics of some of the major events which took place during the life (so far) of the project.



Ronald Reagan George HW Bush Bill Clinton George W Bush Barack Obama

Figure 6.1-1. The U.S. Presidents that span the SOFIA development.

Beggs Fletcher Truly Goldin O’Keefe Griffin Boldin

Figure 6.1-2. The NASA Administrators that span the SOFIA development.

Ballhaus Compton Munechika McDonald Hubbard Worden

Figure 6.1-3. Ames Research Center -Center Directors that span the SOFIA development.

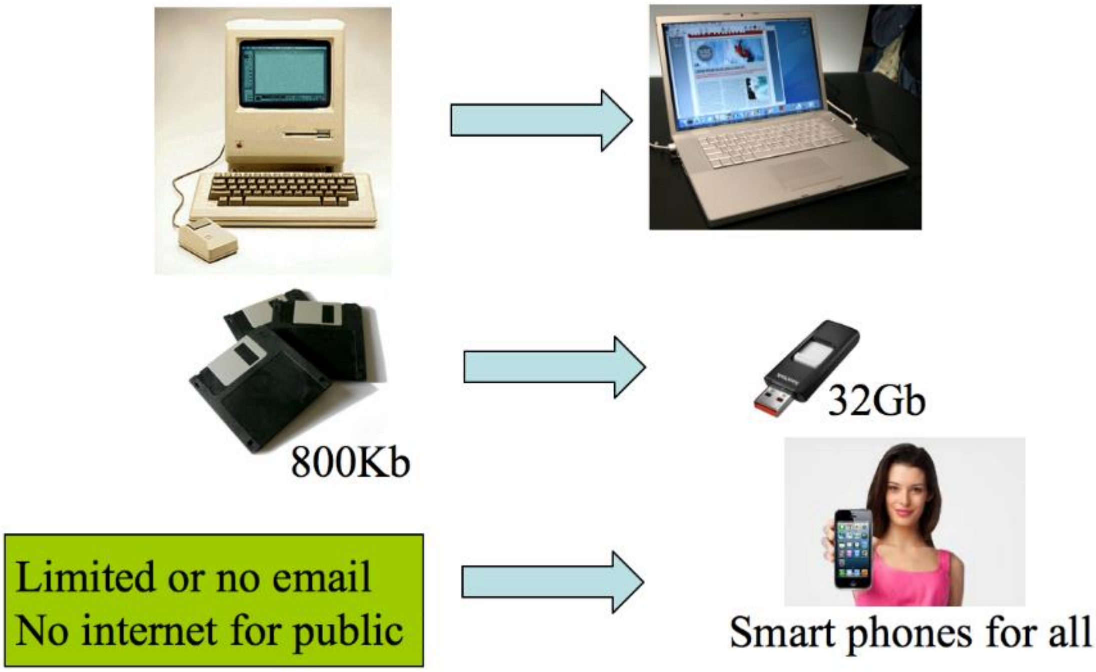


Figure 6.1-4. A crude diagram of how technology advanced during the span of SOFIA's development.

Technological advancement exploded during the development of SOFIA. For example, Moore's law: *computer technology capability doubles every 2 years* was in effect. Limited CAD, FEM on main-frame computers was available when we started the project studies in 1985.

6.2 Pre-1985

For me, I worked in a branch within the Engineering Directorate, called the Research Equipment Engineering branch, where we provided engineering support to multiple organizations at Ames. For the first several years of my career at Ames Research Center, those of us in this branch were available to any researcher or scientist, at no cost, to help them develop what they needed to conduct their research, or to actually lead major projects to deliver major infrastructure, such as the Vertical Motion Simulator, or VMS, for one example. Whether the researcher was an aerodynamicist, biologist, or an astrophysicist, our jobs were to help design and build experimental hardware or substantial infrastructure to help them conduct their research. I worked on everything from spaceflight hardware that flew on USSR satellites (Cosmos 79) or our own NASA Space Lab, to airplane modifications/experiments, to wind tunnel models, and wind tunnel modifications/improvements, and in one project for me a complete small in-draft wind tunnel. Many of these projects involved pushing the state of the art to accomplish something that hadn't been done before, and one of the projects I led (a flow-through wind tunnel model balance) was awarded a patent. The various projects that we worked on in this branch had tremendous breadth, and, typically, most people in the branch were working multiple projects at the same time.

6.3 SOFIA Pre-1985 Milestones (1965−1984)

- 1965−1969 First use of NASA aircraft for IR astronomy (CV-990 and Lear Jet)
- 1969 Planning started for installation of 36-inch telescope in a C-141
- 1969 First astronomy community interest in Boeing 747

- 1971 National Academy of Sciences (NAS) Decade Survey (Greenstein) Report recommended study of Large Airborne Telescope (LAT)
- 1974 First research flight of KAO; Initial studies on larger system
- 1977 Boeing delivered to NASA Ames a study for a 2.5-*meter* telescope behind the wing of a Boeing 747
- 1983−1984 Success of IRAS shows need for follow-up/observations
- 1984 Airborne Astronomy Symposium celebrates KAO 10th Anniversary at Ames
- 1985 "Stratospheric Observatory For Infrared Astronomy (SOFIA) Preliminary Feasibility Study" report issued
  [the name SOFIA was not coined until 1985]

6.3.1 1985 SOFIA study funding provided – partnership with Germany started

6.3.1.1 Ames Research Center Environment

Figure 6.3-1. NASA Ames Research Center – Ames aircraft on ramp (Aerial view). Ames operated aircraft for both scientific and aeronautical research.

As background for the following history of SOFIA year-by-year sections, it's important to understand the Ames Research Center environment regarding aircraft operations at the start of SOFIA development. Without going through the entire history of Ames, during the 1980s and early 1990s there were significant aircraft operations at Ames Research Center. In addition to SOFIA's direct predecessor, the KAO (as discussed in earlier sections) there were two primary categories of aircraft: platform aircraft, where the primary research objective is to bring various SIs or payloads to a desired location/orientation in the atmosphere with minimal modifications to the actual aerodynamics of the aircraft; and research aircraft, where the aeronautics of the aircraft themselves are the objectives of the research. As you can see in Figure 6.3-1, even in 1993, Ames operated an extensive fleet of aircraft. In addition to these aircraft and the three associated hangars, Ames had the infrastructure and expertise and processes for complete turnkey operations. These included the engineering, manufacturing, integration, air-worthiness verification, and flight-testing of unique aircraft modifications for experimental aircraft research.

6.3.1.2 Ames' Airborne Science Program

Beginning in the mid-1960s, NASA Ames hosted and sponsored a broad-based "Airborne Science Program," led by Dr. Michel Bader, Chief of the Space Science Division. Observations related to Earth sciences, atmospheric phenomena, and astronomical research were enabled on NASA aircraft by the technical and administrative infrastructure at Ames. Teams from industry, government, and university laboratories brought state-of-the-art SIs, which they used to make measurements not possible from the ground.

Prominent among these disciplines was airborne infrared astronomy. Remarkable scientific findings obtained from NASA's Convair 990, Learjet, and C-141 KAO led the science community and Ames management to promote development of a new LAT. This was renamed SOFIA—The Stratospheric Observatory for Infrared Astronomy—as suggested in 1985 by Carl Gillespie, a senior KAO staff member. By the early 1980s, the idea was gaining significant traction within and outside of NASA, supported vigorously by the users of the KAO.

6.3.1.3 Airborne Astronomy Symposium

An Airborne Astronomy Symposium was held at Ames in July of 1984, celebrating a decade of operation of the KAO. There were nearly 100 participants and 50 presentations describing the scientific results obtained from the KAO and the cutting-edge SIs that had been developed for it. German scientists, who had already expressed strong interest in participating in the development of a LAT attended. There were encouraging discussions with them on the possibilities of collaboration to build such a powerful successor to the KAO.

6.4 1985

Figure 6.4-1. The inauguration of President Ronald Reagan of his second term − January 21, 1985.

6.4.1 The Naming of SOFIA

Early in 1985, the LAT concept was under discussion at NASA HQ. On a flight returning from meetings in Washington, senior KAO staff member Carl Gillespie was pondering alternatives for the generic and prosaic name *LAT*. He hit upon *SOFIA*, the *Stratospheric Observatory for Infrared Astronomy*. His brilliant revelation was immediately adopted by all concerned. NASA usually renames its astronomy missions after they are operational for well-known astronomers (e.g. the *KAO*). However, the moniker *SOFIA* seems likely to be retained because it is so apt.

6.4.2 My Experience before SOFIA

In the summer of 1985, I was nearing the completion of my involvement with the 40×80×120 Wind Tunnel, now known as the NFAC (National Full-scale Aerodynamic Complex). My role was work-package manager and field engineer for vane sets 1 and 2. This was a major project with many work packages and associated work-package managers, to modify the 40×80 wind tunnel (originally built in the early 1940s), to add significant new and updated capabilities, including a completely new arm with an 80-ft×120-ft test section. As with most engineers in this directorate, we usually ended up starting involvement on new projects prior to completion of previous projects, and in many cases we ended up working several different projects at the same time.

6.4.3 My meeting with Larry Caroff

My first exposure to the concept of SOFIA was in a meeting in 1985 with Dr. Larry Caroff, Chief of the Astrophysics Branch, in his office at Ames. He described the scientific potential and challenging engineering effort SOFIA would entail. By that time, the Boeing 747 series of aircraft had been identified as the logical aircraft because of its large fuselage and high-altitude and flight duration capabilities. He said contacts had already been established with BMAC in Wichita, and that a likely collaboration was under discussion between officials at NASA HQ and the German Bundesministerium fű̋r Forschung und Technologie (BMFT). Tentative guidelines were that the U.S. would provide the aircraft and mission systems and Germany would supply the telescope and 20 percent of operations costs in return for a comparable fraction of the observing time for German astronomers. A SOFIA Science Working Group, including German scientists had been formed, comprised mostly of the KAO users. I was fascinated by the concept, and took the tempting bait. Little did I realize that I would spend 22 years—the bulk of my professional career—guiding the technical development of this world-class observatory.

6.4.4 Ames Research Center establishes SOFIA Study Office (SSO)

In 1985, $100 K of funding was taken from the KAO budget to support initial SOFIA studies at Ames. The SSO was established, under the direction of experienced project manager, Gary Thorley. He was accustomed to managing projects approved for development, so he seemed a bit out of his element with a program in pre-preliminary-study status. Based on earlier work on engineering considerations for SOFIA, I was named Principal Study Engineer, and assigned on loan to the Study Office from my home organization, the Engineering Directorate at Ames. Dr. Ed Erickson, Facility Scientist for the KAO, was the lead Study Scientist. Early in FY86, NASA HQ funding for the SSO began ramping up.

6.5 1986

6.5.1 January Challenger Accident

On January 28, 1986, the NASA Space Shuttle *Challenger* exploded soon after launch, killing all seven crew members. Consequently, all NASA programs involving flight were affected because of increased concerns about mission safety. For SOFIA this meant increased scrutiny of the design and plans for operation throughout its development.

6.5.2 May SOFIA Technology Workshop at Ames

By early 1986, numerous potentially interested contractors, both in the U.S. and Germany, had been identified and contacted. In addition, studies of different technical issues had been carried out by cognizant scientists and engineers. Over the objections of SSO chief Gary Thorley, Dr. Erickson organized a workshop to collect and disseminate the best available ideas for the development of SOFIA. Twenty papers were presented over a 2-day period, including two from German contractors. Topics included concepts for telescope configurations, optical design, lightweight mirrors, aircraft (only 747) modification, and performance, air flow control and effects, telescope stabilization, imaging ("seeing") limitations and computing needs. Thirty non-Ames participants, 7 Germans, and 24 people from Ames attended. Informative and fruitful discussions of all technical aspects of the development occurred. In addition, numerous contacts among interested organizations and individuals were established, some of which would endure for decades.

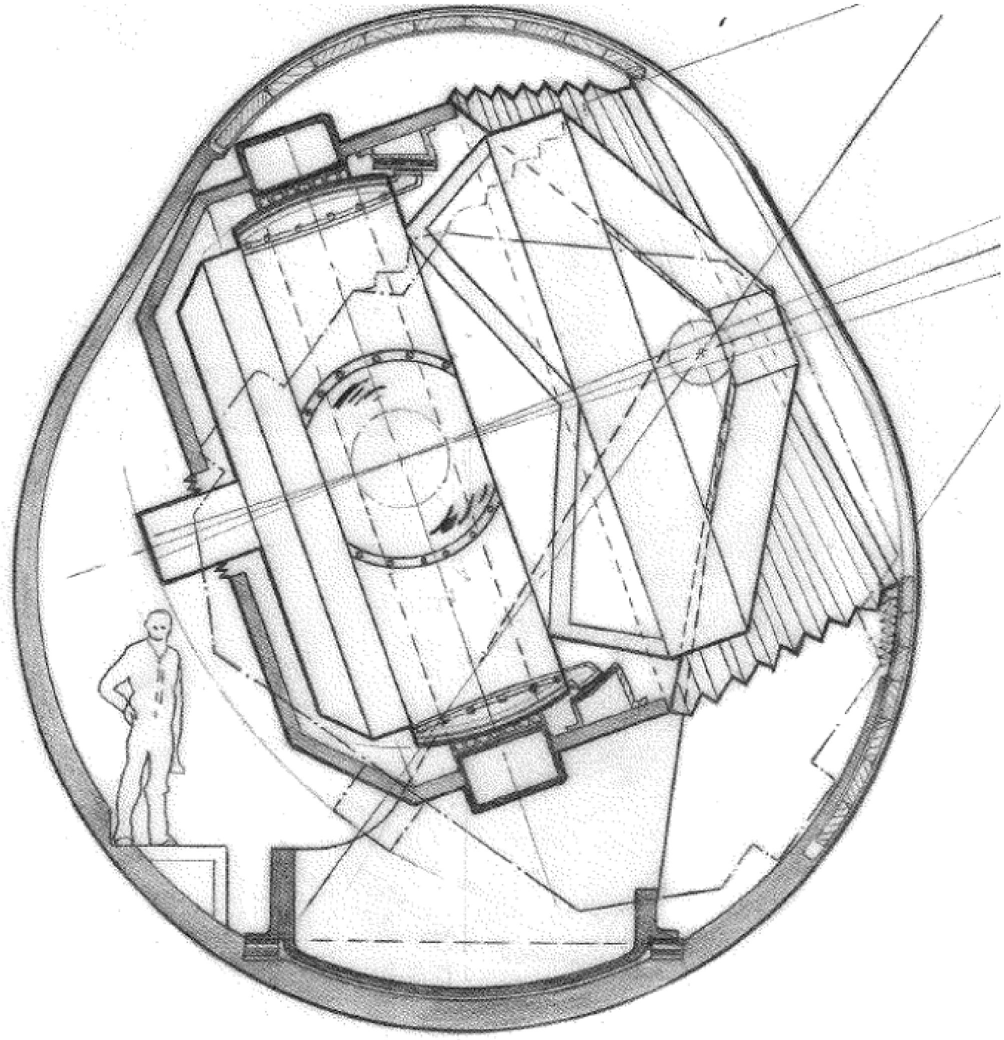


Figure 6.5-1. This early concept from a paper in the 1986 SOFIA Technology Workshop shows what a 3.5-meter telescope might look like in the front of a B747.

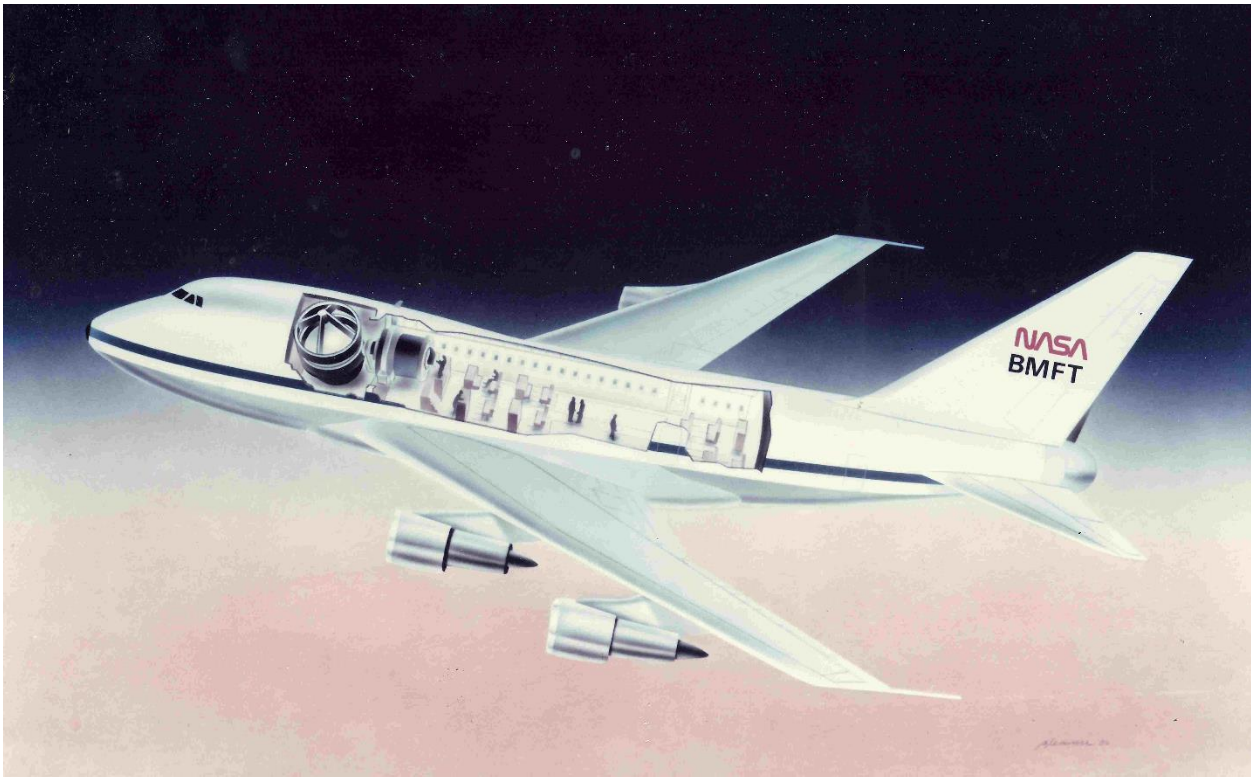


Figure 6.5-2. An early artist's concept of SOFIA with a 3.5-meter telescope.

6.5.3 In-house Concept Studies

Following the SOFIA Technology Workshop, preliminary design (Phase A) studies began at Ames and in Germany. Among these of course were examination of previous conclusions and more detailed consideration of primary technical issues and concepts.

6.5.3.1 Aircraft Selection

As described in Section 5.1, the 747SP model was convincingly confirmed to be the aircraft of choice by comparing its characteristics with those of other current wide-body aircraft—both commercial and military.

6.5.3.2 BMAC in Wichita

A contract was arranged by the SSO with BMAC in Wichita, Kansas to examine the feasibility of an effort to modify a 747 airframe to accommodate a SOFIA telescope. BMAC was interested in the SOFIA project in large part because of how its large open port optical system might relate to the Star Wars concept of intercontinental ballistic missile interception by an airborne optical weapon (AOA) as discussed in Section 5. BMAC was in the process of installing cargo doors in commercial airlines' 747s, for use by the military in case of a crisis needing transport of equipment and troops. Also, the two Air Force One 747-200s were being outfitted there for use by the President. At the first meeting in Wichita, the estimate for the aircraft modification increased from \$25 M to \$250 M. All considerations at the time were for an installation of the telescope ahead of the wing, as depicted in Figures 6.5-1 and 6.5-2.

Figure 6.5-3. Part of BMAC's interest in SOFIA likely was its relevance to an open port optical weapon system for the Star Wars Program, championed by President Reagan.

6.5.3.3 Size of the Telescope

The thinking at that time was to put the biggest telescope possible in the biggest airplane that could fly for extended periods at 41,000 feet or higher; and that the bulged area in the front of the airplane allowed a bigger telescope, as can be seen from Figure 6.5-1. In fact, this was not really practical, even for the 747 fuselage.

The 2.5-meter effective diameter was a mandate that occurred during phase A. That's when we first learned that the BMAC modification cost estimate to implement a 3.1–3.2-sized primary mirror diameter telescope that we were working at that time, was significantly more (about a factor of 10) expensive than expected. We were looking for a compromise to keep this study effort alive and feasible, so NASA HQ put out a call to the science community asking what was the minimum size telescope they thought would be worthwhile for this project. They came up with the 2.5-meter size. (I think that there was some concern or idea that we might get mandated to use the spare Hubble mirror which is 2.4 meters). At that time, we went full speed ahead thinking that we could get back to the bigger mirror size on later studies. The initial BMAC study confirmed the feasibility of installing a 2.5-meter telescope in a 747SP (ahead of the wing).

6.5.4 Phase A Studies in Germany

A collaborative agreement between NASA and the DFVLR was reached. In the partnership, the U.S. would supply and modify the aircraft, provide onboard mission systems and ground support infrastructure, and support 80 percent of operations cost. Germany would supply the telescope, support for its integration and testing in the aircraft, and 20 percent of operations costs in return for 20 percent of the science observing hours for German astronomers. On this basis, the DFVLR funded contracts to study telescope designs with two competing industrial teams: MAN and Zeiss on one team, Dornier and Zeiss on the other. Requirements were supplied by the SSO, whose members explained and discussed details at meetings with the contractors at their facilities in Germany.

6.6 1987

From 1987 onward, technical meetings and studies, scientific promotional presentations, and management deliberations began occurring rapidly. Listed here is a summary of these, with pertinent details elaborated.

6.6.1 February

Telescope System Phase A Study midterm review at Ames Research Center.

6.6.1.1 February−September

Boeing-MAC Phase II Study.

6.6.1.2 May

German Phase A studies completed.

6.6.1.3 July

SOFIA concept review held at Ames Research Center.

6.6.1.4 September

Ames Conceptual System study finished; SOFIA “Phase A System Concept Description” (The Red Book) published.

SOFIA

Stratospheric Observatory For Infrared Astronomy

PHASE A SYSTEM CONCEPT DESCRIPTION

DOCUMENT NO. PD-2001 SEPTEMBER 1987

NASA

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035

Figure 6.6-1. The cover of the 437-page SOFIA Phase A System Concept Description, PD-2001, otherwise known as the Red Book − September 1987.

6.7 1988

6.7.1 June

NASA's Space and Earth Sciences Advisory Committee (SESAC) recommends that SOFIA proceed into definition phase, based on documents and presentations by Ames personnel.

6.7.2 June

Planning for wind tunnel tests begins.

6.7.3 October

Phase B (Definition Study) kickoff for Aircraft System (AS) at Ames.

6.7.4 October

Phase B (Definition Study) kickoff for TA at Zeiss.

6.8 1989

6.8.1 January

Telescope fixed at 2.5 meters by NASA HQ/DFVLR agreement.

6.8.2 February

Wind tunnel model design complete and fabrication begins

6.8.3 May

Project Definition Review completed at Ames Research Center; found SOFIA well planned and defined and approved the project to proceed into the development phase contingent on a successful completion of wind tunnel test.

6.8.4 June

Draft Memorandum of Understanding (MOU) for development and operations phases reviewed by Ames and DLR.

6.8.5 July

Non-Advocate Cost Review successfully completed, affirmation of project readiness for 1991 start; Federal Republic of Germany listed as responsible for TA.

6.8.6 July

Definition studies completed by NASA.

6.8.7 September

Telescope and AS Phase B final reviews are completed and reports published.

6.8.8 October

Boeing re-organizes; No longer interested in "one-off" mods like SOFIA probably because their experience in modifying the two Air Force One 747s was not profitable.

1989 Continued

BERLIN WALL TUMBLES

'Beginning of the End' for Communism

NOVEMBER Berlin wall falls; Reunification of East and West Germany considered

November 3, 2011
Nans Kunz

Figure 6.8-1. The falling of the Berlin Wall was clearly a big event, which affected the SOFIA development timeline − November 9, 1989.

6.9 1990

6.9.1 March

SOFIA I wind tunnel model tests start.

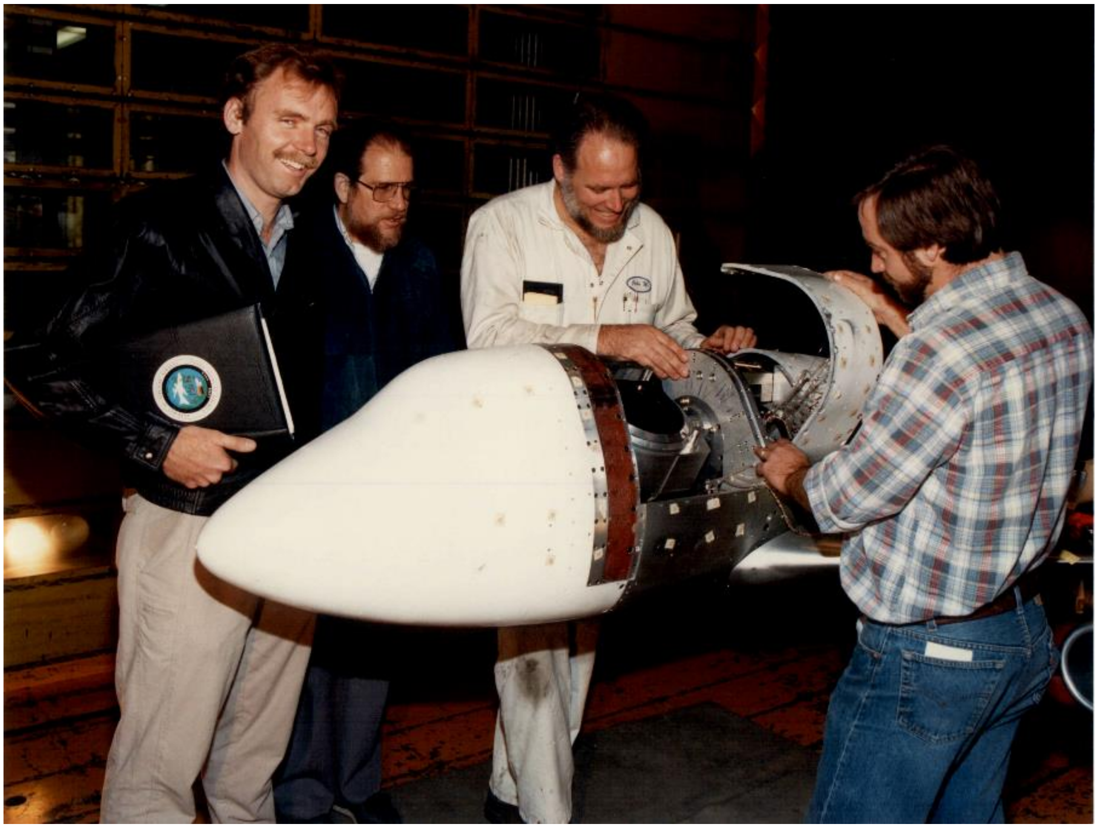


Figure 6.9-1. The SOFIA 7-percent model with the forward cavity in the 14-ft Transonic Wind Tunnel. I'm at the left and Senior Technician John Wallace is in the white coveralls.

6.9.2 April

SLC device is developed for wind tunnel model.

6.9.3 May

Rumors about German Space Agency (DARA) budget cuts begin.

6.9.4 June

Non-Advocate Review is held for SOFIA in accordance with the agency's new start-gate policy; SOFIA deemed ready to proceed to development again and recommended for 1992 start.

6.9.5 June

Preliminary engineering study of SOFIA Ground Support Facility.

6.9.6 June

AS modification procurement activities underway, Source Evaluation Board (SEB) established.

6.9.7 July

Wind tunnel tests successfully completed; A low-drag passive SLC device derived that exceeds performance expectations.

Redesigning of cavity door begins to incorporate installation of a curved SLC device.

6.9.8 July

In-house studies of Telescope Sub-Systems begin.

6.9.9 October

Consoles and electronic systems (CES) mock-ups evaluated.

6.9.10 October − Reunification of Germany

Requires reduction of German government agencies' budgets; interested German officials express intent to continue partnership when funding becomes available.

6.10 1991

6.10.1 NAS Decade Survey (Bahcall) Report

Recommends SOFIA as the top priority moderate new missions for NASA.

6.10.2 May

DARA budget cuts due to reunification of East and West Germany meant the loss, at least temporarily, of our German partner. This prompts NASA to plan for an all U.S. program in FY92 with an option for help from DARA in FY94.

6.10.3 May – Search for Aircraft Modification Contractors

Road trip to identify companies w/interest/capability to perform the SOFIA aircraft modification taken by Sylvia Cox, Gary Thorley and me

6.10.4 July−September − In-house Descope Studies to Reduce Total Cost

I led effort for Descope Case 5 that considers an aft-cavity location to reduce aircraft modification costs.

6.10.4.1 Descope Case 5 − The Adoption of the Aft-Cavity Configuration

The precipitating event was the falling of the Berlin wall in November 1989, which resulted in DARA not being given enough money to keep their 20-percent partnership commitment with NASA on SOFIA. On the NASA side, we were instructed that we could keep SOFIA project prospects alive if we came up with a version where the total cost of SOFIA development on the NASA side did not exceed the cost of our previous 80-percent share. So internal to NASA, in the summer of 1990 we came up with various de-scope options. I initiated and led descope Case 5 that looked at the cost savings of just moving the full size (2.5-meter) telescope to aft of the wings (instead of in the front), as shown in the 1977 Boeing study, and mentioned as a possibly simpler configuration by a BMAC engineer. As you can imagine, it was a pretty low time in the SOFIA development. The other four descope options involved reducing the telescope size/functions. Anyway, primarily Ames engineer Rick Brewster and I worked descope Case 5, where I (alone) came up with the bulkhead location and the placement of the telescope within the bulkhead and the general design that we finally ended up with. Rick did multiple FEM analyses of the aft fuselage, developing structural reinforcement strategies and showing that it was possible to maintain both stiffness and strength, for lateral and vertical bending, and torsion, with a reasonable reinforcement scheme. Since we had a very credible independent cost estimate of our primary forward cavity design, essentially weight based, it was easy to use this model to come up with credible cost estimate for the aft-cavity design, that showed cost savings of more than 50 percent of the estimated aircraft modification.

That was the fall of 1990. With this descope study, the aft configuration looked like the way to go, but we needed to verify feasibility for the all-U.S. approach, and shortly after this we released five contracted studies: three of these were to look at U.S. companies that might be able to build a suitable telescope and two to look at the aircraft modifications required to put the telescope cavity aft of the wings. The two aircraft companies were E-Systems in Greenville, Texas and a Lockheed group down in Ontario, California. The studies completed by these two aircraft modification companies validated both the design feasibility and cost savings of the aft-cavity configuration. This, in parallel with a test flight we made with one of the Space Shuttle carrier 747s to make sure the engine exhaust plumes would not adversely affect the science, let us proceed with the aft configuration. I apologize for this lengthy description, but this decision wasn’t just made in a day; it was originally the solution to a project funding shortage, and then was verified as a valid approach with many advantages over the previous forward cavity location. So the date depends somewhat on your point of view whether the decision point was the completion of descope Case 5 report, which showed the aft-cavity location yielded significant benefits and cost savings and was the only viable solution at that time due to imposed funding restrictions, or whether it wasn’t until the external independent studies which also endorsed this configuration were completed later in 1991.

6.10.5 September

Planned January 1992 wind tunnel test was indefinitely postponed because of anticipated switch to aft configuration for the telescope installation.

6.10.6 September

NASA Research Announcement (NRA) planned for two aircraft studies to confirm the feasibility and in-house estimate of savings for aft installation.

6.10.7 October

Aft-cavity location adopted as new baseline for the AS.

Figure 6.10-1. Shows the changes in the artist concepts and SOFIA sticker when the cavity was moved from the front to the back.

6.10.8 October

CFD studies on aft cavity are run after much effort “gridding” the geometry.

6.10.9 October

NRA released for Telescope System studies.

6.10.10 October

Aft installation follow-up studies determine background IR noise caused by engine exhaust plumes. This required calculating the IR emission from the exhaust, which would be scattered from telescope optics and cavity into the focal plane of the telescope.

6.10.11 December

NRA released AS study.

6.11 1992

6.11.1 March

IR measurements made of the Shuttle Carrier Aircraft (SCA) engine exhaust plumes using IR cameras mounted in Lear jet.

6.11.2 March

Kickoff meetings for telescope NRA studies.

6.11.3 April

Kickoff meetings by E-Systems and Lockheed Aircraft Services Ontario for NRA studies of the aircraft modifications.

6.11.4 August

Second flight test on IR noise is made with cameras mounted inside SCA.

6.11.5 September

Further options investigated to reduce total project costs including in-house approach.

6.11.6 December

Final reports of telescope cavity aft of the wing is submitted by aircraft contractors, Results concur with Ames in-house study regarding feasibility and cost savings for aft cavity.

Feasibility of modifying existing SOFIA wind tunnel model for an aft-cavity investigated.

6.12 1993

6.12.1 April

Efforts under way to prepare for aft configuration wind tunnel test.

6.12.2 April

In-house approach approved by OSS at HQ and by Ames Research Center New Business Filter Committee.

6.12.3 June

Ames Research Center Code R agrees to de-mothball 14-ft wind tunnel for SOFIA test; test entry planned for 1994.

6.12.4 June

CFD model on full 747SP finalized for first test run.

6.12.5 June

Began locating surplus section 46 of 747SP to mock up the aft-cavity configuration at full scale.

6.12.6 June

14-ft wind tunnel begins refurbishment.

6.12.7 June

Pro-engineer selected as project and Ames CAD package.

6.12.8 August

HQ OSS proposes SOFIA as an FY95 new start to Administration/Comptroller.

6.12.9 Germany Is Back

Thanks to continued lobbying by German scientists and support from DARA officials, funding was made available to continue the U.S.-German partnership to build SOFIA.

6.12.10 Ames' Plan for Development

The SPO continued plans for “in-house” approach, whereby Ames would act as the prime contractor for the development of NASA program elements. The plan consisted of four main elements: buy a used airplane; get it modified on a fixed-price contract with an aircraft company; develop the Mission Control and Communications System (MCCS) in-house; and design the cavity door in house. Preparations were made to buy a used 747SP that was available for $4.5 M. Specifications and procurement details were prepared for the aircraft modification contract. A work breakdown structure (WBS) was prepared for the in-house management of the development. Requirements documents were prepared: SOF 1009 was the specific science requirements, SOF 1010 was the aircraft modification spec, SOF 1011 was the telescope specification, and I think that SOF 1014 was the CES, now called the MCCS, specification.

6.13 1994

6.13.1 July: Second Airborne Astronomy Symposium

Celebrating the second decade of KAO operations, this 4-day conference was held at Ames. Some 250 individuals, mostly astronomers, participated, and 128 papers were presented. There were numerous allusions to the increasingly likely approval of SOFIA and remaining efforts to achieve it. These included a panel discussion *The Future of IR Astronomy* led by Dr. Larry Caroff, and a concluding paper *SOFIA, The Future of Airborne Astronomy*, by Drs. Ed Erickson and Jackie Davidson (ref. 33). The KAO results presented and the enthusiasm generated in this meeting was undoubtedly a significant factor in promoting awareness of the need for SOFIA in both the U.S. and German science communities.

6.13.2 Wind Tunnel Tests

Wind tunnel tests at Ames iterated models of the shear-layer control configuration to obtain an optimized aft-ramp geometry for the aft-mounted telescope cavity opening.

6.13.3 Detailed Engineering Design Efforts

Intensive, detailed design work continued on both sides of the Atlantic, with numerous meetings and communications treating all manner of issues in collaborative efforts which resolved most remaining design concerns. The project ‘Concept Definition Study’ (Blue Book) was finalized.

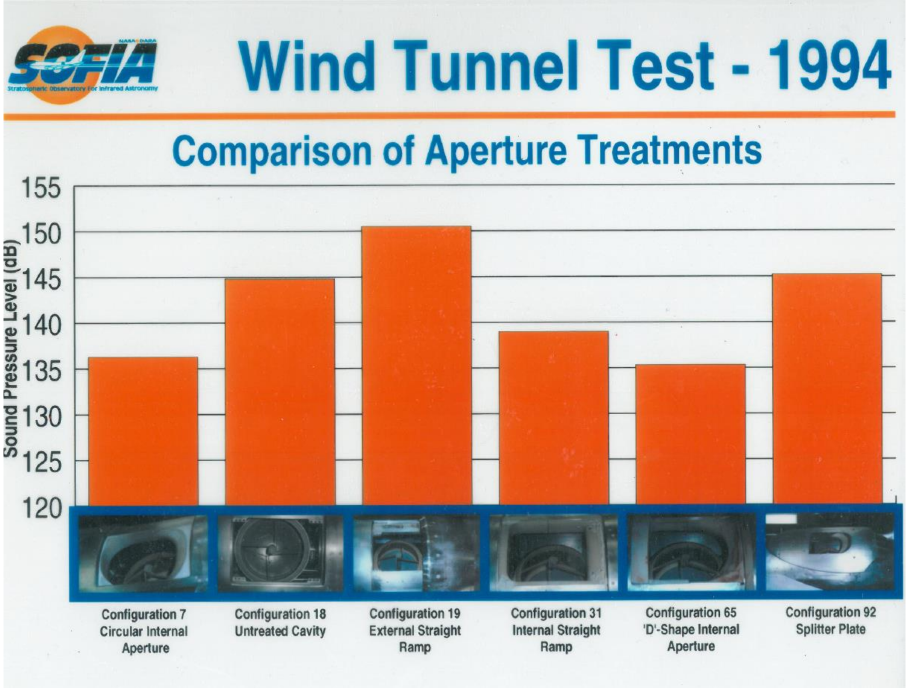
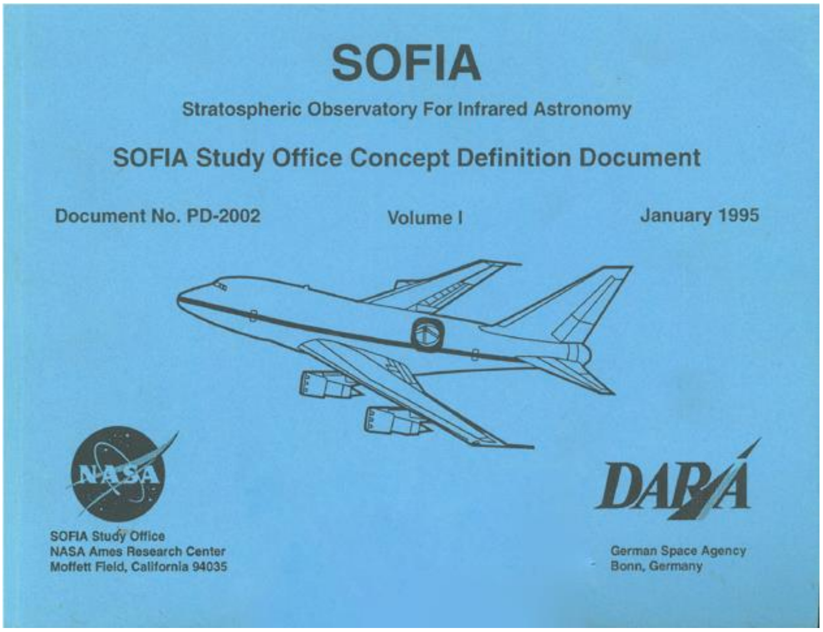


Figure 6.13-1. 1994 Results of various Wind Tunnel Tests showing the comparisons of aperture treatments.

6.14 1995

6.14.1 Phase B Definition Study Published

The SSO published the comprehensive Phase B Definition Study with extensive contributions from the German contractors supported by DARA. These two volumes were further evidence that SOFIA was prepared to enter the development phase.



SOFIA

Stratospheric Observatory For Infrared Astronomy

SOFIA Study Office Concept Definition Document

Document No. PD-2002 Volume I January 1995

SOFIA Study Office
NASA Ames Research Center
Moffett Field, California 94035

German Space Agency
Bonn, Germany

Figure 6.14-1. The cover of the 360-page Volume I, of the SOFIA Concept Definition Document, PD-2002 − January 1995.

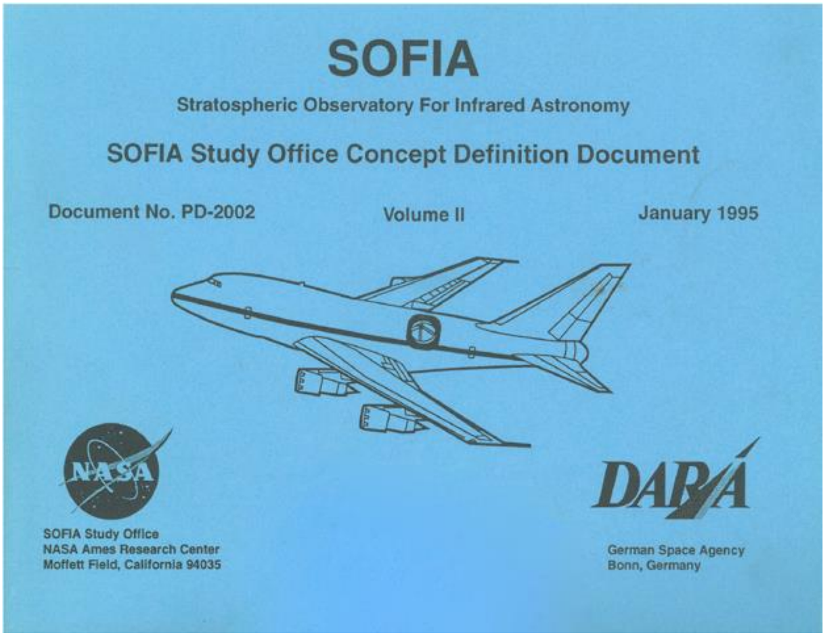


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Figure 6.14-2. The cover of the 448-page Volume II, of the SOFIA Concept Definition Document, PD-2002 − January 1995.

Figure 6.14-3. A photo of a group of us with our German colleagues in Munich, Germany, where we discussed strategies and plans of how to proceed with SOFIA − 1995.

6.14.2 Trips to Germany in 1995

Among the numerous meetings in Germany to iron out engineering details, some also inevitably involved planning for procedures to efficiently coordinate the installation and testing of the telescope.

6.14.3 SOFIA New Start Approved!!

Congress approved the budget for a new start of SOFIA in FY96 in the summer of 1995. This occurred about a month following a SOFIA Evening for Congressional Staffers at the German Embassy in Washington D.C. arranged by Dr. Hans Peter Roeser, a KAO user and major German proponent of SOFIA. Members of the SOFIA Science Working Group and NASA officials attended. Thus, the U.S./German partnership extended beyond technical collaboration.

6.14.4 Kuiper Observatory Operations Terminated

As previously agreed, the KAO ended operations at the end of FY95 (September), in order to use its $13 M annual budget to help offset the cost of SOFIA development. This step was recognized as a sacrifice for obtaining SOFIA by the KAO users. They had been led to believe that SOFIA would be flying in about 5 years. Nevertheless, most KAO investigators harbored bittersweet memories of their experiences on the unique facility and were sad to see its life end prematurely.

6.14.5 SSO becomes the SOFIA Project Office (SPO)

The Ames SSO morphed into the SPO, led by Chris Wiltsee with Ramsey Melugin as deputy. I was named Chief Engineer, and Dr. Ed Erickson became the Project Scientist, with Dr. Ted Dunham as Facility Scientist.

Figure 6.14-4. September 29, 1995: KAO operations end. Group photo at the farewell celebration attended by many members of science teams that had flown on the KAO.

6.14.6 HQ Mandates Implementation of Privatization Concept

Despite the extensive planning by the SSO to act as prime contractor in the SOFIA development, NASA HQ insisted that a science organization should take this role. Part of the announced rationale was encapsulated in phrases like "Government-owned, contractor-operated," "Better, Faster, Cheaper (a concept of then NASA Administrator Goldin); "NASA wants to buy science not infrastructure." This "privatized" approach, imposed somewhat earlier, required a complete revision of the detailed development plans that had been refined with extensive effort by the SSO, incorporating the extensive and unique experience of personnel at Ames.

6.15 Decision to Privatize SOFIA

It turns out that NASA HQ had proposed a privatized development of SOFIA as a strategy to win the approval for the new development start of SOFIA development. Let's look at rationale for this privatized approach to development. Ultimately, the goal of SOFIA was to deliver world-class astronomical science data, at the lowest cost to NASA (taxpayers). Generally, in addition to being politically popular, hiring private commercial companies or contractors can sometimes be more efficient than the sponsoring organization would be. Private entities may have more direct experience, infrastructure, tools, etc., to get the job done. Another reason may be that the government prefers to allocate its manpower to other tasks. For example, when a government facility needs a new building, it makes sense to hire an architectural firm to work with the future users of the facility and design the building to meet all the user requirements as well as all the building codes and standards. Then these detailed plans are back in the control of the government, who can then release them via a procurement process, such as Invitation For Bids (IFB), that puts these plans/specifications out for multiple contractors who can submit bids to do this work for a given price. The government organization can then select the lowest price credible bid and hopefully end up with the desired facility at the lowest cost to taxpayers.

Let's look at this rationale with respect to SOFIA. The dictated privatization approach for SOFIA was to award the overall contract (development and operations) to a science organization that would be responsible for science operations, with the general philosophy that NASA is not buying any new infrastructure, just science data and let the science organization figure how best to deliver the desired science data. From the top level, this doesn't sound too bad, but read on.

So, per this approach, this science organization would hire sub-contractors who would be responsible for the significant aircraft modifications and integration of a large one-of-a-kind telescope into an open port cavity of the modified aircraft. After the modifications were completed, the science organization would hire sub-contractors to be responsible for flight operations and routine maintenance of the aircraft. So, even before we review the experiences, you can see that this approach involves forcing contractors with at least three significantly different capabilities to work together to write a proposal to win this contract from NASA. This by itself appears to reduce the probability of getting the optimum contractor for each of these three or more phases/capabilities needed to deliver the SOFIA science.

Lesson 2:

Don’t write the Call for Proposals for a major project in such a way as to *force* all the phases of development to be bid in a single proposal. This forces different types of organizations to team together to make a proposal, and you may therefore end up with the prime contractor managing major elements of the program for which that prime has no prior experience. Example: USRA, a science and science mission operations organization, was selected as the prime, managing a major systems development contract—modification and integration of the aircraft system—as well as aircraft operations.

Now look even deeper into the fundamental rationale normally associated with privatization (finding the most qualified and experienced organization): in 1995, what science organization had the most experience with airborne observatory development and operations? Hint, it was talked about in earlier sections. Yes, it was NASA Ames Research Center, which had been responsible for over 20 years of the highly successful KAO operations, and the KAO development before that. So not only was there no outside organization with more experience with the needed skills than the internal NASA organization, there were essentially no outside organizations in the world with *any* airborne observatory operations experience. In addition, because of budget issues, KAO operations were going to be shut down in order to provide additional funding for SOFIA development; therefore, any of the appropriate KAO staff could be readily available to support SOFIA. Additionally, the SOFIA project team at Ames had already been working with the KAO team for 10 years, learning what worked well and what could use improvement with regard to airborne astronomy operations, infrastructure, etc., thus incorporating many lessons learned into the various SOFIA requirement documents, and design concepts.

What about the aircraft modification? Since the inception of Ames Research Center in 1938, the Center had been involved with aeronautics and aircraft research, including designing and implementing major modifications and even building unique one-of-a-kind aircraft. NASA Ames Research Center had end-to-end capabilities to make aircraft modifications, including the theoretical aerodynamics, the engineering, airworthiness, fabrication, installation, and flight-testing operations. Although Ames did not have the full capabilities to carry out a modification of the scope required for the SOFIA development internally, we were much more capable of managing and monitoring a contract with an aircraft modification company than any other outside astronomical science organization. Then although the actual observing flight operations, which were, even with the development schedule at that time, about 5 years away, it should have been obvious that NASA Ames Research Center internally had the most experience to optimize these operations deciding which tasks to keep internally and which tasks to contract out to maximize efficiency.

But despite the 10 years of pre-development activities, including: documenting the science goals/requirements, what worked from KAO operations, what could be improved from KAO users’ perspectives, proving feasibility of many technical challenges including large open port cavity issues, and putting all this into various requirements documents, the privatization approach for SOFIA was supposed to provide this documentation only as non-binding information to the winning bid contractor.

Note: The above analysis convincingly shows an obvious error in an upper-management decision process. Although hindsight also validates the erroneous nature of this decision, all the data/information noted above was well-known current information at that time, showing this as an illogical decision. It should also be pointed out that very few science organizations had experience managing a large systems contract, experience that would be crucial to successful development. Using hindsight, again, only two of the four proposals that were submitted in response to the Request for Proposal (RFP), involved large systems houses with the necessary management experience.

Lesson 3:

Privatization is not always the best choice, and each case should be evaluated logically looking at available data. Many NASA Projects are very unique, and NASA internal organizations and employees may actually be more experienced and skilled, and therefore better choices for related development activities to provide the desired end product more efficiently than external private contractors. Moreover, the structure of any privatization approach should be carefully evaluated with respect to the kind of experience required.

Corollary to the above: Putting a science-based organization in charge of major systems development makes no sense unless that organization has previously and successfully demonstrated the ability to manage such a development.

Many of us who had already put in many years into SOFIA pre-development activities were thrilled that the SOFIA Program was finally approved to go into development, but we were simultaneously concerned/disappointed/unhappy/etc. with this privatization approach that seemed obviously flawed from the simple engineering logic perspective.

6.16 1996

6.16.1 Selection of Contractors

Given the Congressional approval of the project and the requirement to privatize according to NASA HQ's dictum, the SPO promptly began preparing an RFP to advertise the opportunity to manage the development and operations. Four candidate organizations formed teams and responded with proposals. Of course, none of these teams had done even a Phase A study, so they were given the requirements documents and counseled by the SPO to the extent of each team's requests.

6.16.2 December 1996: GO!

Contracts were signed in both the U.S. and Germany with scheduled delivery date 2001. The SEB had selected the winning team, headed by USRA, and their contract with NASA was signed. DARA had selected a team comprised of MAN-G, MAN-T, and Kayser-Threde to build the telescope in Germany; their contract was signed this same month. The scheduled delivery date was 2001.

6.16.3 Government Work Packages

As part of the agreements with the bidding U.S. contractor teams, the SPO offered as options, Work Packages that could be carried out by Ames employees, under the management of the contractor, at his request. The idea was to let the contractor take advantage of the special skills and experience of the people who had been involved with planning the project for years. USRA accepted two engineering Work Packages, one for design of the cavity door, and one for the cavity cooling system.

6.16.4 Level 1 Requirements at Approval

Wavelength Range 0.3−1600 microns

Unvignetted elevation range 20° to 60° above the horizon

Configuration: SI Access in Cabin during flight

Telescope effective Aperture Diameter 2.5 meters

Time at ≥41,000 feet ≥6 hours

Observing hours per year ≥960

Lifetime ≥20 years

PI Teams per year capability ≥40

Education Goals: NASA OSS Guidelines

Airworthiness: FAR FAA Certification

IR functional capabilities: chopping, nodding, & scanning

Image quality 80 percent encircled energy within 1.5 arcseconds at visible wavelength

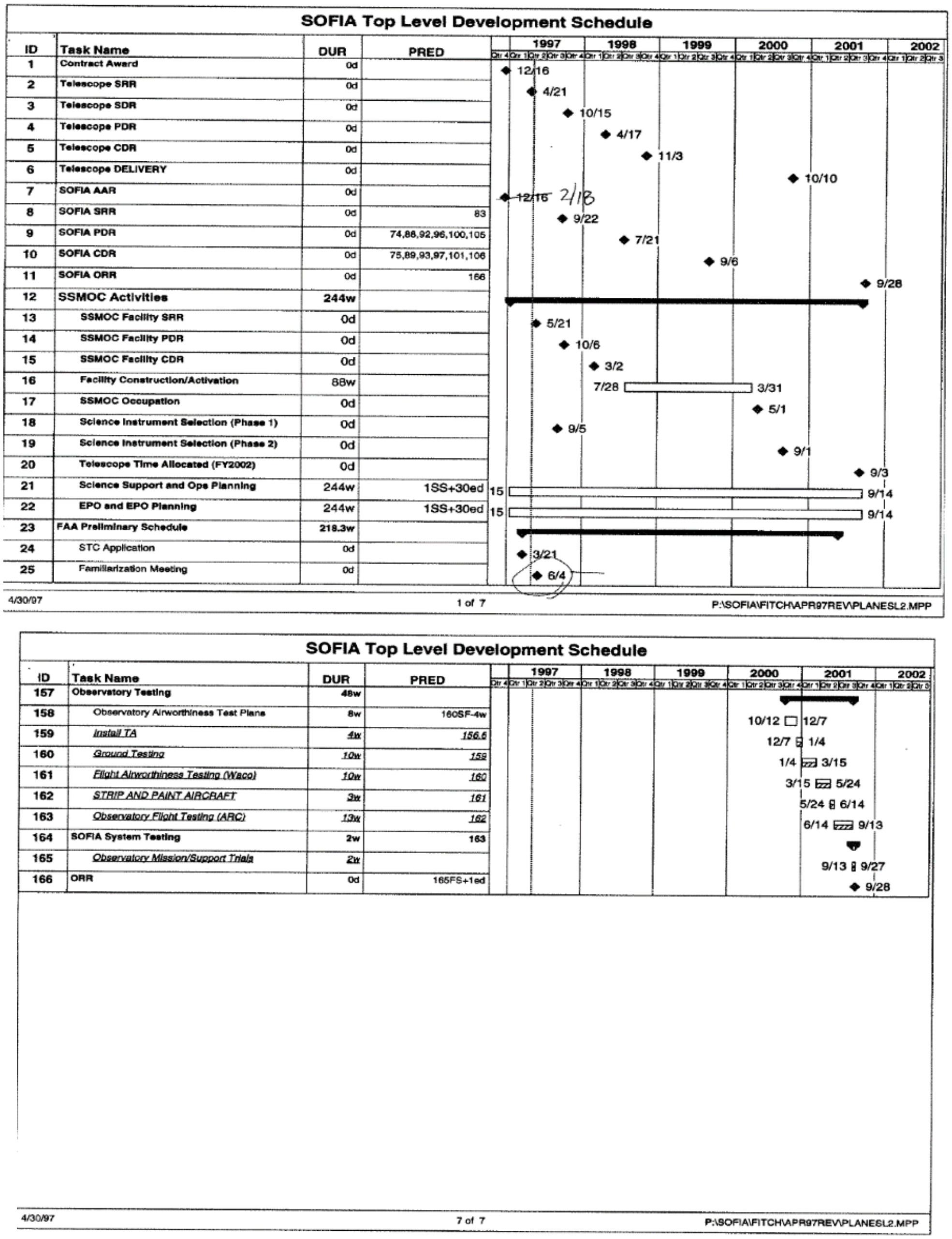
Image stability at focal plane 0.2 arcseconds RMS

6.16.5 Optimism that the Winning Group would actually Work Well

USRA, United Airlines, and Chrysler Technology (which later became E-Systems in Waco)—the winning group.

6.16.6 ORR in 2001

The image below shows a couple of pages out of the official privatized contract top-level schedule. You can see the original key milestone dates including ORR (operational readiness review) where SOFIA was essentially supposed become operational in September 2001.



SOFIA Top Level Development Schedule

ID	Task Name	DUR	PRED
1	Contract Award	0d	
2	Telescope SRR	0d	
3	Telescope SDR	0d	
4	Telescope PDR	0d	
5	Telescope CDR	0d	
6	Telescope DELIVERY	0d	
7	SOFIA AAR	0d	
8	SOFIA SRR	0d	83
9	SOFIA PDR	0d	74,88,92,96,100,105
10	SOFIA CDR	0d	75,89,93,97,101,106
11	SOFIA ORR	0d	166
12	SSMOC Activities	244w	
13	SSMOC Facility SRR	0d	
14	SSMOC Facility PDR	0d	
15	SSMOC Facility CDR	0d	
16	Facility Construction/Activation	88w	
17	SSMOC Occupation	0d	
18	Science Instrument Selection (Phase 1)	0d	
19	Science Instrument Selection (Phase 2)	0d	
20	Telescope Time Allocated (FY2002)	0d	
21	Science Support and Ops Planning	244w	1SS+30ed
22	EPO and EPO Planning	244w	1SS+30ed
23	FAA Preliminary Schedule	218.3w	
24	STC Application	0d	
25	Familiarization Meeting	0d	

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SOFIA Top Level Development Schedule

ID	Task Name	DUR	PRED
157	Observatory Testing	48w	
158	Observatory Airworthiness Test Plans	8w	160SF-4w
159	*Install TA*	*4w*	*156.6*
160	*Ground Testing*	*10w*	*159*
161	*Flight Airworthiness Testing (Waco)*	*10w*	*160*
162	*STRIP AND PAINT AIRCRAFT*	*3w*	*161*
163	*Observatory Flight Testing (ARC)*	*13w*	*162*
164	SOFIA System Testing	2w	163
165	*Observatory Mission/Support Trials*	*2w*	
166	ORR	0d	165FS+1ed

4/30/97 7 of 7 P:\SOFIA\FITCH\APR97REV\PLANESL2.MPP

Figure 6.16-1. Graphic of Schedule showing ORR in 2001.

6.16.6.1 NASA Contract Award

NASA contract awarded to USRA-United Airlines-Chrysler Tech Team.

6.16.6.2 December

In Germany, DLR awards contract to team of MAN-G, MAN-T, and Kayser-Threde.

In the organization chart, Figure 6.16-2, for the majority of the development phase, note that the L3 icon is the last and current company name for essentially the same group of people based at Waco, Texas. That organization actually changed company affiliation three times during SOFIA primary development. It started during the bidding process as Chrysler Technologies, and then become part of E-Systems during the proposal evaluation process. Shortly after award, they become Raytheon, and finally L3.

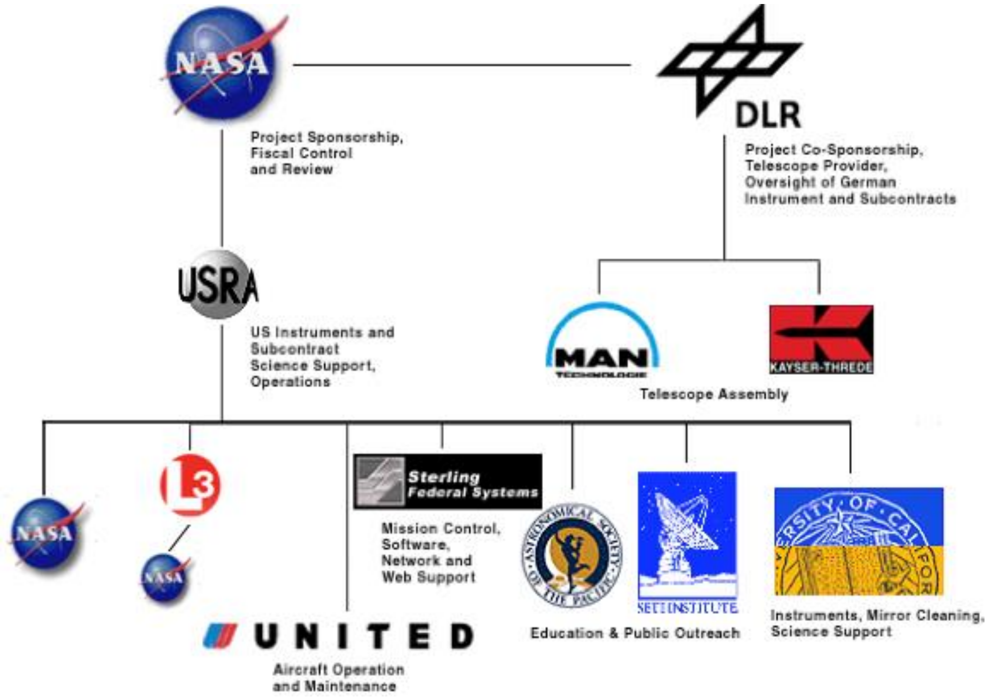


Figure 6.16-2. The organization chart.

Lesson 4:

An unprecedented procurement approach that initially sounds like a bad idea probably is. At the least, NASA HQ should have insisted that the procurement approach be reviewed by experienced project manager(s), instead of just lawyers and procurement officials. It's not enough to be legal; the procurement approach must also *make sense* from a systems management perspective.

Even in a privatized approach, an effective way of incorporating the results of in-depth NASA studies should be incorporated into the procurement process. For example: 10 years of developing SOFIA subsystems was not effectively captured by the contractor. One way to achieve this end is to contractually require adoption of at least selected specifications and design concepts developed by NASA.

Lesson 5:

Don't put a contractor in charge of approving government-provided products, especially on a cost-plus contract. This rewards the contractor for schedule delays that they can blame on the Government-Furnished Equipment (GFE). Examples: contractually, the German Telescope was GFE to the U.S. contractor – a source of considerable friction and inefficiency; work products from NASA work packages were evaluated by the contractor.

7.0 HISTORY PART 2: OFFICIAL DEVELOPMENT START TO FIRST FLIGHT – 1997 to 2007

This section describes major events that occurred during development of SOFIA from the official approval as a project until the first test flight. Much of the hardware development is depicted chronologically in pictures, which largely reflect the engineering highlights and planning described in Sections 5 and 6. In addition are pictures of personnel involved in the development, both in formal and informal situations. I include commentary on issues that seemed particularly important to me, mostly relating to program delays: the AS CDR, TA integration into the plane, the hangar facility at Ames, the aircraft D-check, first light and ORR planning meeting, and the decision to transfer the program to DFRC and its implementation.

7.1 Contracts signed December 1996 both sides of the ocean

7.2 1997

7.2.1 First trip to Germany – Way Too Many People

Perhaps partly as a celebration, more U.S. contractors and NASA participants travelled to Germany for a kick-off meeting than were necessary to begin serious planning for development.

7.2.2 747SP is Purchased from United Airlines ($13 M)

United Airlines, a subcontractor for USRA, provided a used aircraft that had been out-of-service for some time. The plane, originally operated by Pan American World Airways, was originally christened the “Clipper Lindbergh” after American aviator Charles Lindbergh. Note that the price was ~$8 M higher than the 747SP that the SSO had identified when NASA was planning to serve as prime contractor for the development.

7.2.3 System Requirement Reviews Completed (2)

Requirements for both the AS and TA provided by NASA were accepted by the contractors.

7.2.4 Software Development Philosophy – not to be trusted

USRA insisted that development of all the high-level TA control software would be their responsibility, rather than the German contractors who had planned to provide it. USRA assigned this sophisticated task to a team with no experience in astronomical software at the facility of their aircraft modifier subcontractor (Chrysler Tech) in Waco, Texas. Scientists and programmers with extensive KAO experience were at least allowed to contribute ideas. This situation changed for the worse later – see Section 7.11.8.1.

Figure 7.2-1. The SOFIA primary mirror blank − 1997.

Because of the long time predicted to manufacture the SOFIA primary, manufacturing began almost immediately after award of the contracts. This blank made from Zerodur was estimated to weigh 4.5 metric tons, and the final version of the light-weighted mirror weighed only 880 kilograms, see Figure 5.4-9.

7.2.4.1 U.S. SIs Selected for Development

See Section 5.6 for a discussion of SIs.

7.2.4.2 Baseline Flight Test Completed

The 747SP purchased from United Airlines was flown to their maintenance facility at San Francisco, where it was serviced, painted and certified for minimal use. It was then flown to Waco, Texas to the Facility of Chrysler Technologies, the USRA subcontractor that would modify it for installation of the telescope and operation as an observatory. Performance data from this flight established the flight characteristics of the unmodified aircraft.

Figure 7.2-2. The 747SP "Clipper Lindbergh" purchased from United Airlines on its flight from San Francisco, California to Waco Texas where it would be modified to become SOFIA.

7.2.4.3 SOFIA V Wind Tunnel Test Completed

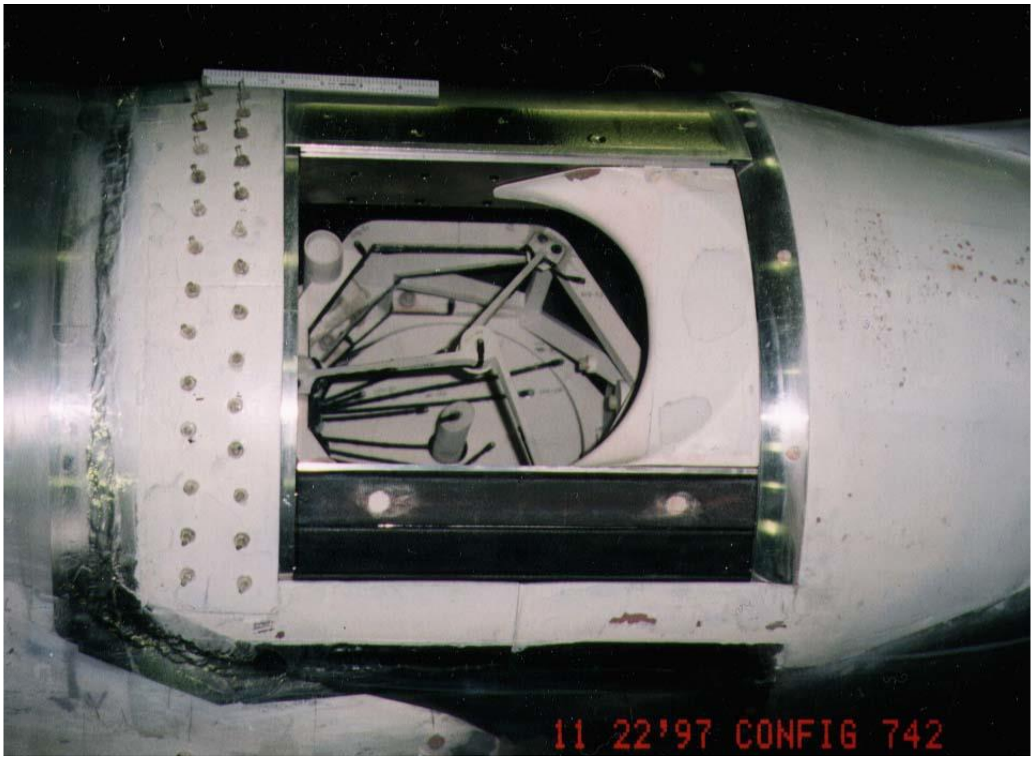


Figure 7.2-3. The SOFIA 7-percent wind tunnel model in the Ames 14-ft wind tunnel with the PED configuration − November 1997.

7.2.4.4 Early Indication of Inexperienced Project Management (2-week delay predicted)

When a 2-week delay in the 5-year development duration was predicted, the project management mandated a significant effort to overcome this small potential problem.

7.2.4.5 First ECRs Removal of Floor Beam and Ceiling Structure

The aircraft modifier, Chrysler Technologies, claimed a floor beam and an overhead "liferaft" beam in the vicinity of the planned TA SI flange were load bearing and so could not be removed. My straightforward analysis showed this to be untrue. After another 747SP with these beams removed was identified, the contractor agreed to remove them for additional cost. Despite the fact that the contractor's original proposal showed no such obstructions and did not itemize them as significant cost items, an Engineering Change Request (ECR) was granted and funded by the SPO.

7.2.4.6 Early Progress, Three External Review Groups (Independent Annual Review (IAR), External Independent Readiness Review (EIRR), and Project Managers)

NASA reviews vetted the SPO's project plans and schedule.

7.2.4.7 Project Structure

The NASA SPO at Ames was required to communicate primarily with the prime contractor, USRA, despite the fact that its subcontractor for the AS modification (Chrysler Technologies, which had been taken over by E-Systems) had by far the largest part of the direct responsibility and funding for the observatory development. Although the NASA engineering team could interact with the AS modifier engineers, decisions could only be processed through USRA, which proved to be a major impediment to progress.

I established a Data Review Board (DRB), coordinated and managed by Dr. Ann Dinger. In weekly meetings, my engineering team would rank the issues we saw in the data deliverables with a high, medium, or low classification. This ranking would determine how much additional attention and/or rework was needed from the AS contractor, if approved by USRA.

7.3 1998

The Raytheon Company bought the Waco Division of E-Systems Inc., where the AS modification was to be done. Obviously, there was a concern for the company's health.

Figure 7.3-1. Already the second change of ownership for our key SOFIA aircraft modification company at Waco − 1998.

7.3.1 TA Preliminary Design Review (PDR) Completed

The TA PDR confirmed the design established prior to starting development, but included the details and improvements established in the meantime.

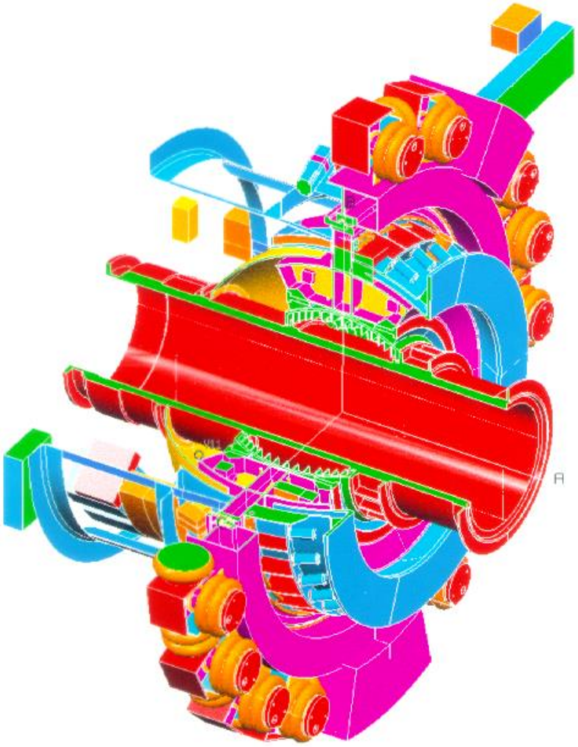


Figure 7.3-2. Cut-away 3-D CAD drawing of the TA SUA − October 1998.

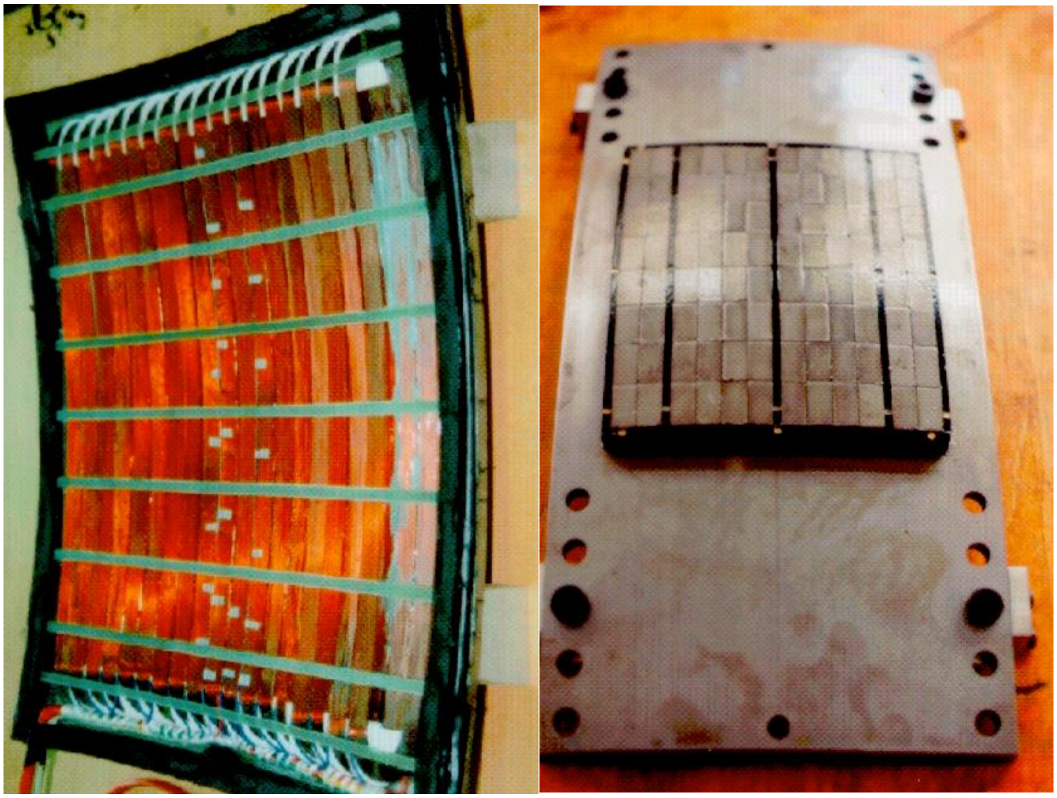


Figure 7.3-3. One segment of TA fine drive armature winding (left) and part of the TA spherical rotor with permanent magnets attached (right).

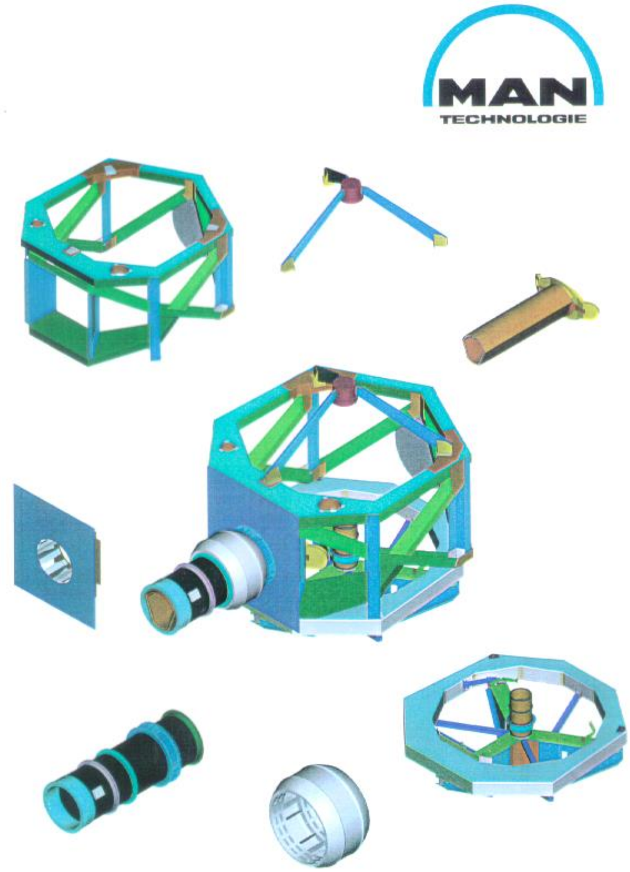


Figure 7.3-4. CAD drawings of the planned metering structure − October 1998.

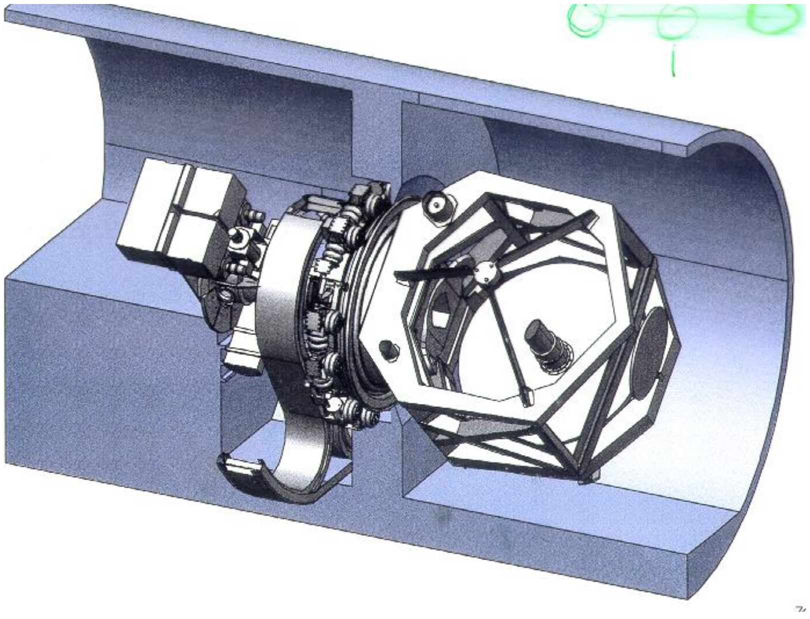


Figure 7.3-5. 3-D cut-away CAD model of the complete TA installation into the fuselage − October 1998.

7.3.2 AS PDR Completed

Figure 7.3-6. A lot of us spent a lot of time in this Hotel, Alte Post, in Gustavsburg, Germany a short walk from the train station and a short walk from MAN-G.

We had a lot of dinners in this small restaurant in Gustavsburg, around the corner from the Alte Post during this phase of SOFIA development.

Figure 7.3-7. November, 1998 − Left to Right: Dr. Ed Erickson, Dr. Jackie Davidson, me (Nans Kunz), Dr. Sean Casey, and Maureen Savage.

With the primary SOFIA partners/developers spread across six locations in two different countries, a lot of us spent a lot of time traveling.

Figure 7.3-8. Larry Caroff SOFIA Program Manager and Chris Wiltsee, SOFIA Project Manager waiting in an airport.

7.3.3 Development Continues

By 1998, a significant number of hardware components for both the AS and TA had been or were being manufactured, according to previously agreed upon specifications.

7.3.4 Interface Control Documents (ICDs)

ICDs were the mechanism for establishing mutually satisfactory requirements for planning TA/AS and SI/TA systems compatibility. These ICDs were numerous, detailed, and iterated many times by relevant parties until unanimous agreement on them was obtained. The SPO followed the development of and contributed to many of the ICDs.

7.3.5 DCR 12

As information was accumulated, it sometimes became necessary to revise and reconfirm agreement on the content of ICDs and the SPO requirements documents. This was done by means of DCRs. An example is DCR 12, which included new information about the predicted aircraft loads and telescope cavity environment determined from wind-tunnel tests at Ames. Of course, this came from engineering considerations on the U.S. side. To understand the implications required detailed technical analyses and discussions with the German telescope contractor and the DLR, involving for example the adequacy of the TA VIS, and the attainable pointing stability of the telescope. In the end, all parties agreed on appropriately altered specifications. The exercise demonstrates the typical continuity of effort we made to assure the success of SOFIA.

7.4 1999

Figure 7.4-1. The prototype bulkhead segments with simulated VIS brackets about to be installed into the scrap section 46 (upper left of photo) to practice/evaluate installation procedures − Waco, July 1999.

7.4.1 Development Continues − Schedule Slips

Although progress was evident in the development of both AS and TA elements, it was clear that some milestones were being missed. Because there was no Integrated Master Schedule (IMS), however, the overall effect of these delays was not apparent.

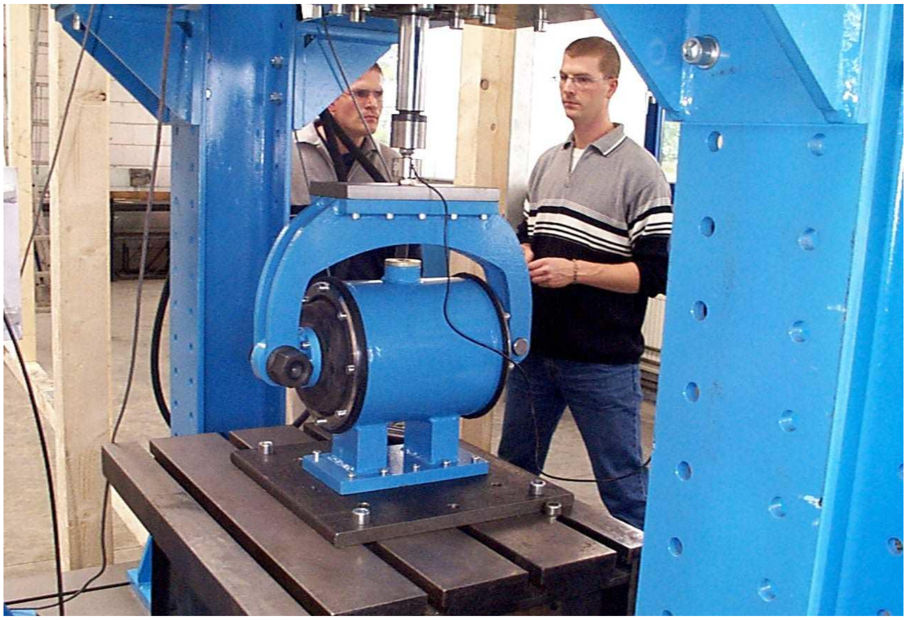


Figure 7.4-2. The damper concept for the TA VIS being tested − August 1999.

Figure 7.4-3. The air bladder components of the TA VIS being tested.

Grinding of the primary mirror blank to minimize its weight was in progress at REOSC in France – see Figure 5.4-9.

Three-percent Stability and Control wind tunnel tests were completed, showing the aft-ramp SLC design to have negligible effect on the aircraft operation.

7.5 2000

7.5.1 First Structural Cut of Aircraft Fuselage – 21 March 2000

It had taken over 3 years since the contract award for the first structural modifications of the aircraft to begin.

The year 2000 was busy. In the spring, various meetings, including the Telescope CDR and the SPIE conference lined up such that several of us had to spend 3 weeks in Germany, so a few of us got together with our German colleagues and managed to get in some skiing at Stubaier Gletscher in Austria over one of the weekends.

Figure 7.5-1. Skiing at Stubaier Gletscher in Austria − April 2000.

7.5.2 TA CDR in Gustavsburg, Germany

Figure 7.5-2. TA CDR in progress, within the MAN facilities at Gustavsburg, Germany − May 2000.

Figure 7.5-3. The official telescope CDR photo at MAN in Gustavsburg, Germany − May 2000.

Figure 7.5-4. Dr. Ed Erickson, Dr. Jackie Davidson, and I in front of the MAN display truck − May 2000.

After the official TA CDR photo, Dr. Ed Erickson, Dr. Jackie Davidson, and I posed in front of the MAN display truck. Yes, the MAN company that designed and built the SOFIA telescope is the same company that manufactures these trucks.

Highly successful, the TA CDR confirmed the design and plan to meet all specifications, and in turn level 1 requirements, except for the 0.2-arcsecond pointing stability.

Shortly after CDR is when Hans Kaercher and I co-created/chaired SPIT specifically to address this very ambitious and difficult requirement, recognizing that it involved several second-order effects that could only be estimated at that time, and that we would most likely required actual full-scale flight data to quantify the disturbances being applied to the telescope.

At some point during the CDR process, the image quality and image stability specifications were combined to be 80 percent encircled energy within 5.3 arcseconds diameter image size at First Science Flight improving to 1.6 arcseconds within 3 additional years.

Figure 7.5-5. The large piece of steel that the TA inner cradle will be made from − May 31, 2000.

Figure 7.5-6. Sami Gazi (Telescope Project Manager) and Jackie Davidson (USRA Project Scientist) − June 2000.

7.5.3 August 2000: AS CDR in Waco, Texas

Figure 7.5-7. USRA Project Manager, Tom Bonner, at the AS CDR in the Hilton Hotel, in Waco, Texas − August 2000.

Figure 7.5-8. Dr. Alfred Krabbe and Chris Wiltsee during a tour of the aircraft at CDR.

Figure 7.5-9. Dr. Hans Peter Roeser, Dr. Larry Caroff, and Phil Hazelrig during the CDR aircraft tour.

August: AS CDR completed (at least officially) According to the CDR schedule, the Flight Tested aircraft was to be delivered to Germany for TA integration December 2001. The schedule showed aircraft flight testing to be completed using a dummy TA in 1 year, ~August 2001. In fact, first flight did not occur until 2007 – 6 years later!

7.5.4 Two HQ External Review Teams (EIRR and IAR) Concur AS CDR Completed

7.5.5 CDR Status and Schedule

My development team provided to the NASA project management an Independent, 88-page report of our evaluation of the AS CDR status and schedule, showing it to be seriously unrealistically optimistic. Briefly, the report asked “where’s the beef,” referring to the lack of evidence to support the CDR conclusions.

7.5.6 “Black Thursday” (about 2 months after CDR)

The AS contractor informs SPO they need significantly more money and time. They cannot meet current schedule.

Lesson 6:

For oversight: external review teams can be misled. They should have the means and the authority to dig as deeply as necessary to truly understand the project status.

For Project Managers: hiding reality or not dealing with the issues at hand usually does not work in the long run. The NASA project manager must develop an open and honest working relationship with the prime contractor project manager. Without this level of trust, there will almost certainly be nasty ‘surprises’ to deal with.

7.5.7 TA and AS Hardware Developments

Long lead-time items were being prototyped, tested, or manufactured.

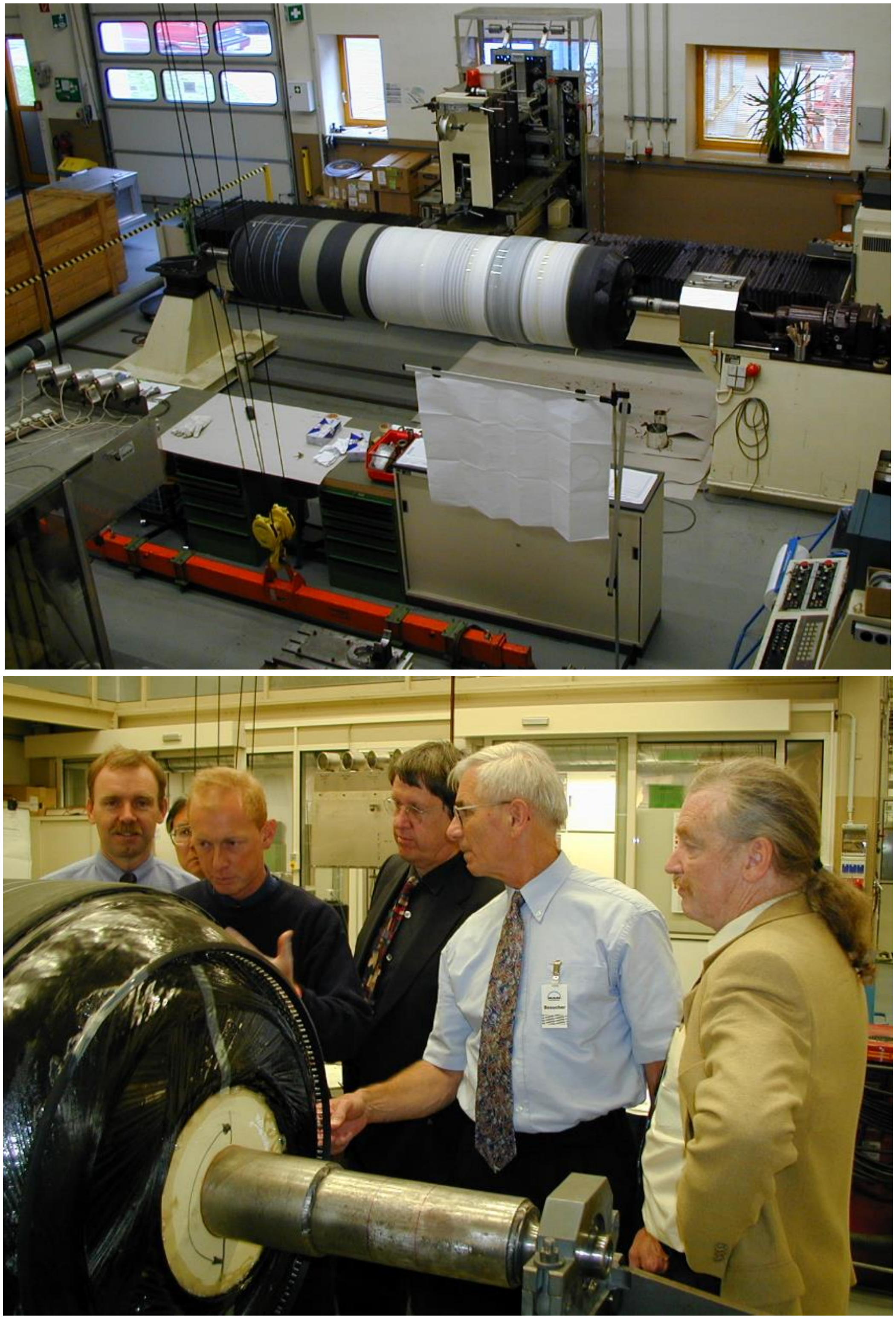


Figure 7.5-10. The SOFIA Nasmyth tube being made via a filament winding process at MAN − September 19, 2000.

Figure 7.5-11. Inner cradle component being manufactured at VOEST in Vonn, Austria. Ramsey Melugin, Benny Chin, and Dr. Ed Erickson − September 2000.

Figure 7.5-12. Another inner cradle component being manufactured at VOEST in Vonn, Austria with me − September 2000.

Figure 7.5-13. The SPO at the Ames Chili cook-off in October 2000.

Figure 7.5-14. Aft bulkhead being installed into aircraft, Waco − October 2000.

At Raytheon/L3 in Waco, the new SOFIA pressure bulkhead was nearing completion, Figure 7.5-15. Note that hole is bigger than it looks in this photo; this is where the telescope will be installed.

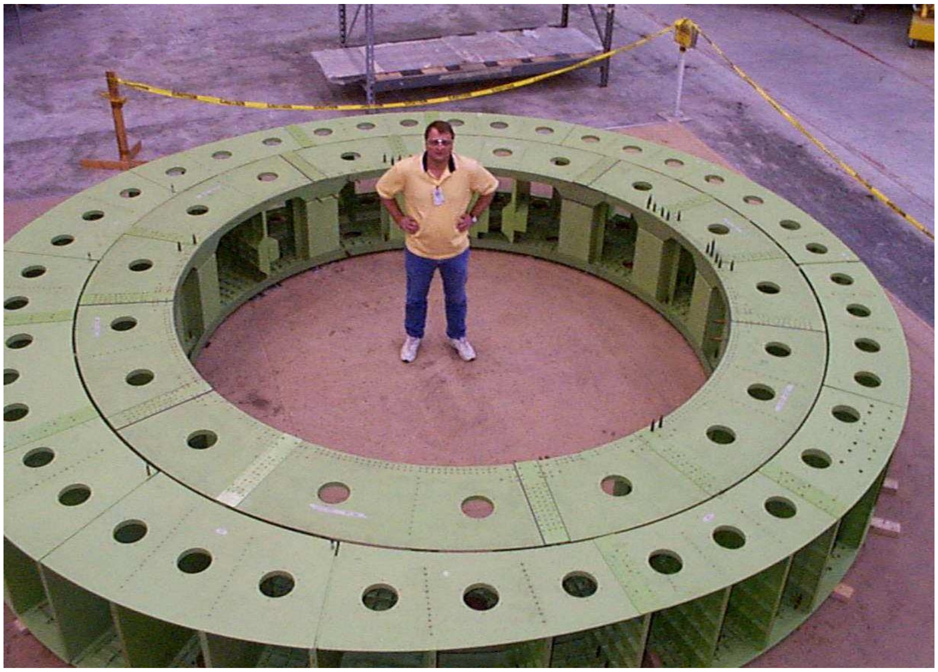


Figure 7.5-15. The new SOFIA pressure bulkhead, with Tommy Kaluza standing in the middle.

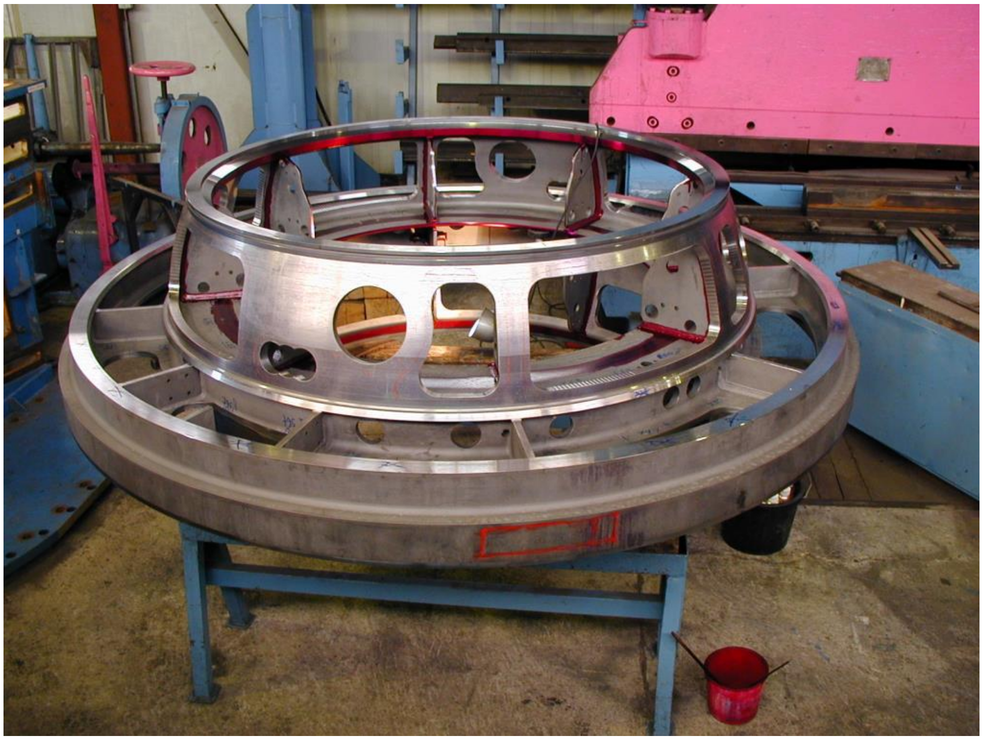


Figure 7.5-16. Status of the inner cradle/SUA − October 2000.

7.6 2001

7.6.1 Program Manager for SOFIA Fired and Replaced

NASA HQ, upset with the delay announced by USRA and the AS contractor so soon after the CDR, replaced the NASA Program Manager; The NASA SPO and contractor personnel remained unchanged.

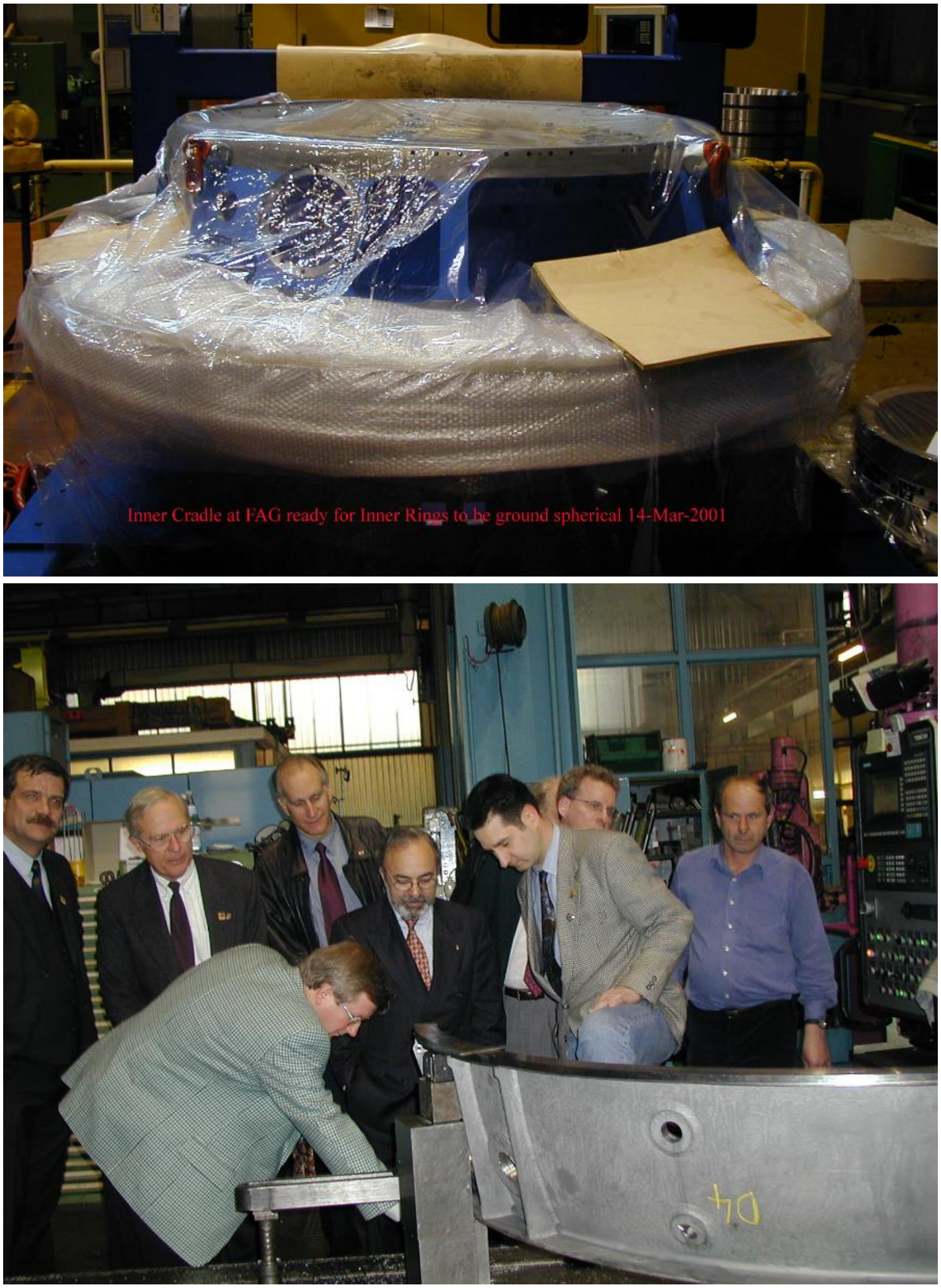
Lesson 7:

The Center with primary responsibility for the project should carefully monitor the progress of the project, and not just pay ‘lip service’ through some generic review. When necessary (and it is incumbent on Center management to be on top of this), the center should provide help, guidance, and mentoring, especially when the project and/or program manager lacks the appropriate level of experience. That assistance should come directly from a project manager who has managed a large, complex systems contract. If the Center lacks such an experienced senior manager, then they should use all means to hire one *before* the project gets deeply in trouble. A good model for this is how JPL oversees projects there.

7.6.1.1 New NASA Program Manager Cliff Imprescia

Figure 7.6-1. The assembly hall at MAN in Augsburg, Germany where the many telescope components will be assembled, integrated, and tested for the first time − March 2001.

Figure 7.6-2. Guenther Stoeffler, the MAN SOFIA engineering manager at Augsburg, Alois Himmes, the DLR SOFIA Program manager, and Dr. Eric Becklin, the chief scientist for USRA/SOFIA checking out TA hardware in the assembly hall at MAN in Augsburg − March 2001.



Inner Cradle at FAG ready for Inner Rings to be ground spherical 14-Mar-2001

Figure 7.6-3. Checking out the status of the telescope stator at Voest Alpine − March 16, 2001.

7.6.2 Program re-baselined – ORR rescheduled for March 2005.

Figure 7.6-4. The mirror coating vacuum vessel being delivered to Ames − April 2001.

Figure 7.6-5. The mirror coating facility vacuum vessel inside the Hangar N211 at NASA Ames Research Center − April 2001.

Figure 7.6-6. The inner cradle almost ready to ship to MAN − May 2001.

Figure 7.6-7. Chris Wiltsee and Larry Caroff at Larry's retirement luncheon − May 2001.

Figure 7.6-8. Dr. Larry Caroff former SOFIA Program Manager with his replacement, Ames engineering manager Cliff Imprescia.

Figure 7.6-9. Inside the aircraft on the main deck looking aft − May 2001.

7.6.3 TA − Integration and Testing begins in Germany

Figure 7.6-10. A social gathering including several of us from Ames, our contractor partners from Waco and our partners from Germany. This is in Mainz − June 2001.

Figure 7.6-11. The carbon fiber Nasmyth tube almost ready to begin integration. At MAN in Augsburg, Germany − June 2001.

Figure 7.6-12. A large group of us checking out the Nasmyth tube − June 2001.

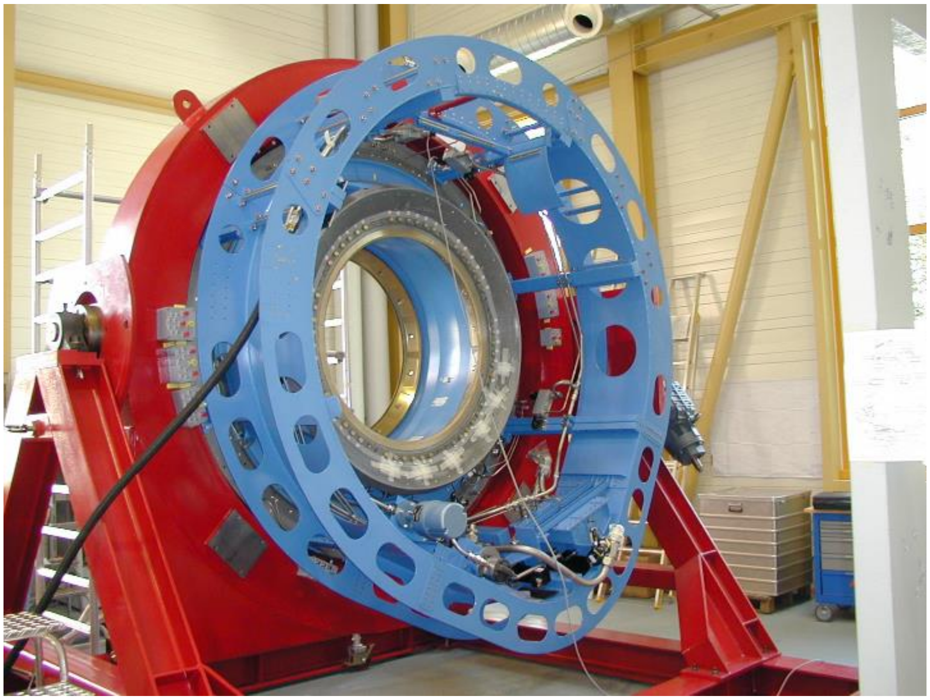


Figure 7.6-13. The inner SUA with the 1.2-meter-diameter spherical socket ready to for 1.2-meter-diameter RIS (photo shown in telescope engineering highlights section).

Figure 7.6-14. Composite metering structure.

Figure 7.6-15. My children, Erin and Alex, standing in front of the SUA during our visit to the Augsburg Facility in Germany − July 2001.

Figure 7.6-16. The old skin being removed from the belly of the aircraft, Waco, Texas − July 2001.

Modifications were completed on N-211 Hangar at Ames, in close cooperation between USRA and NASA Ames facility personnel. At an expense of ~$10 M, the modifications included overdue upgrades to the hangar as well as all features necessary to accommodate SOFIA operations and personnel.

Figure 7.6-17 shows the inside of the N211 Hangar at Ames, June 2001, that was modified for optimized SOFIA operations, including the mirror coating facility, a ramp for direct access from the second floor directly to the aircraft door for personnel and SIs, multiple SI labs, a modification to the hangar door to accommodate the very tall tail of the SOFIA 747SP, as well as enough offices for <u>everyone</u> supporting SOFIA operations. The value of co-located operations was a primary lesson from the KAO (ref. 3).

Figure 7.6-17. Inside of the N211 Hangar at Ames − June 2001.

Figure 7.6-18. The inside of N211 during the verification test of the newly updated fire suppression system − June 2001.

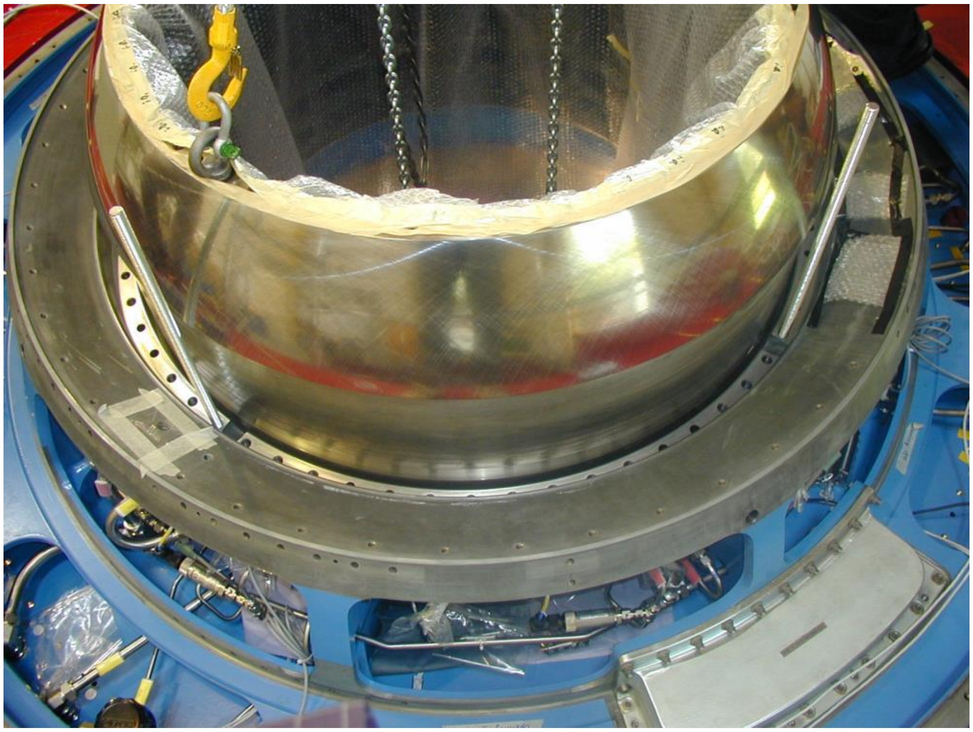


Figure 7.6-19. The RIS sphere being installed into the socket − August 2001.

Whereas development of the TA remained nearly on schedule, the AS modification was slipping again, relative to the schedule USRA, L3, and the SPO had agreed upon after the delay abruptly announced in November 2000.

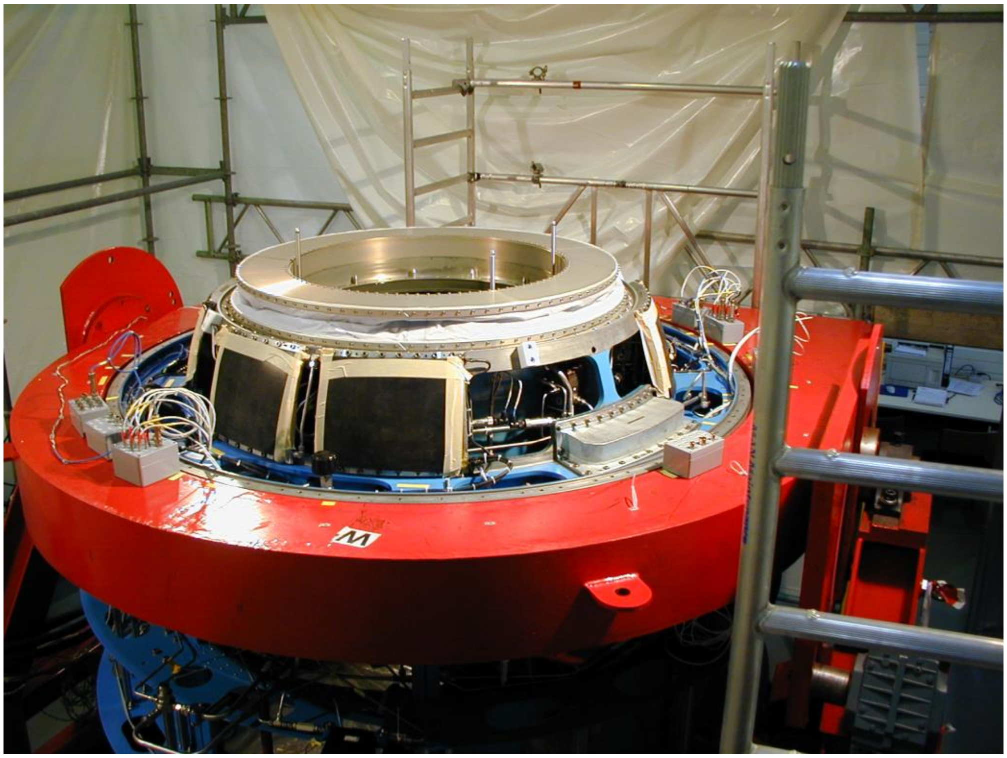


Figure 7.6-20. The inner SUA or SUA I ready to receive the Nasmyth tube − late September 2001.

Figure 7.6-21. The Nasmyth tube ready to be inserted into the RIS inner SUA − late September 2001.

Figure 7.6-22. Installation of the Nasmyth tube into the RIS/Inner SUA − September 26, 2001.

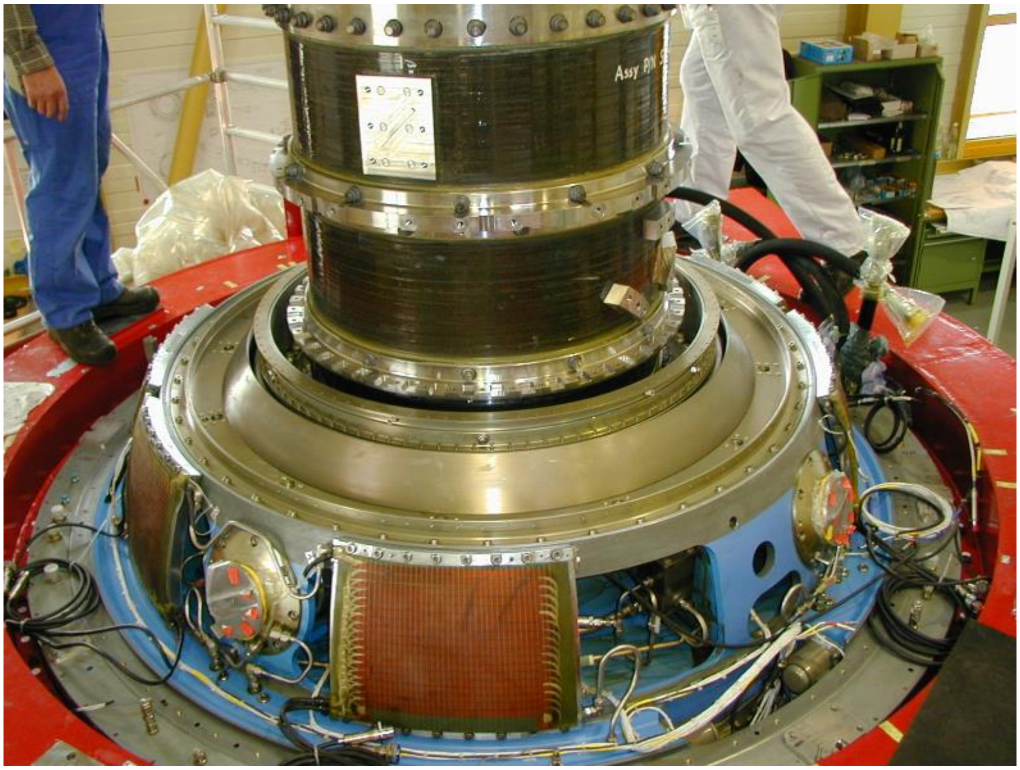


Figure 7.6-23. Telescope inner cradle w/Nasmyth tube installed.

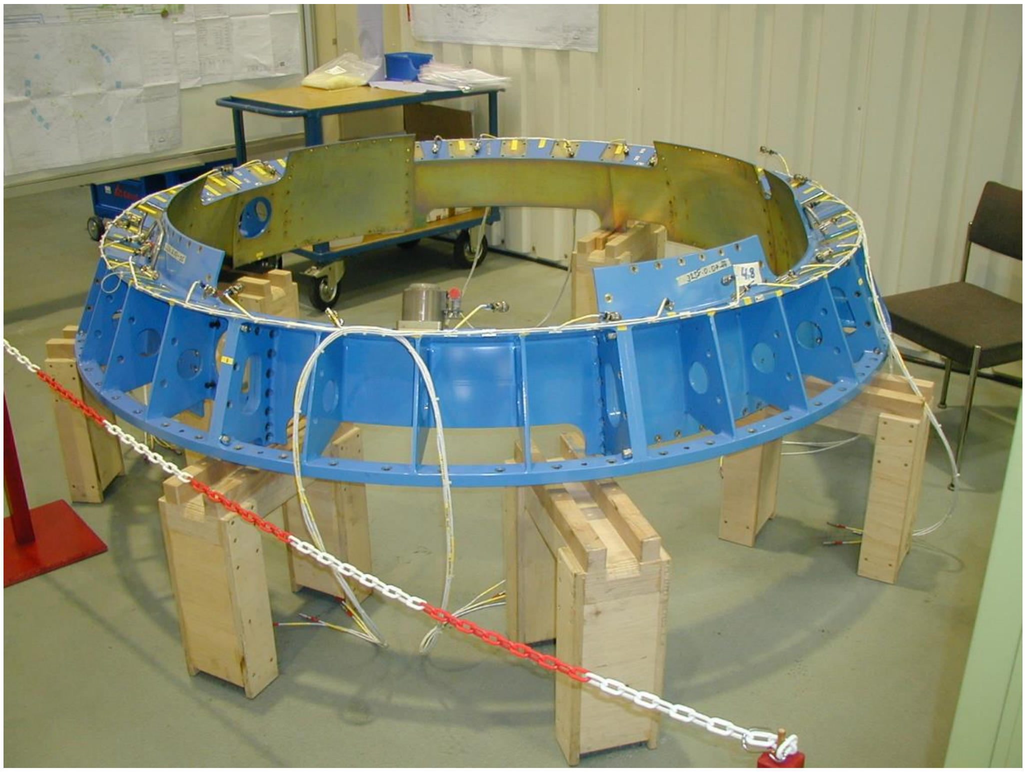


Figure 7.6-24. The fine drive bumper system with one of the many bumpers/snubbers attached − October 2001.

Figure 7.6-25. The high bay area at MAN in Augsburg where the telescope was assembled.

Figure 7.6-26. L3's John Fitch and I checking out the dummy bulkhead in Augsburg that was used to assemble and integrate the SOFIA telescope for the first time.

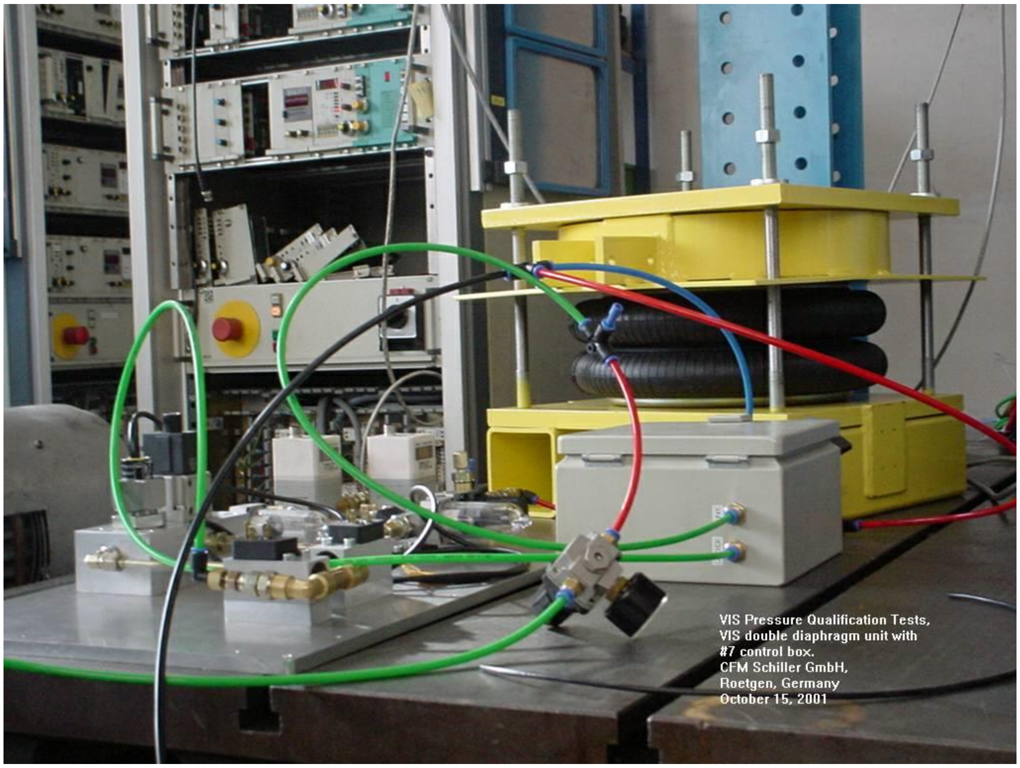


Figure 7.6-27. The VIS pressure qualification tests at CFM Schiller GmbH, Roetgen, Germany − October 15, 2001.

Figure 7.6-28. One of the dual diaphragm VIS components.

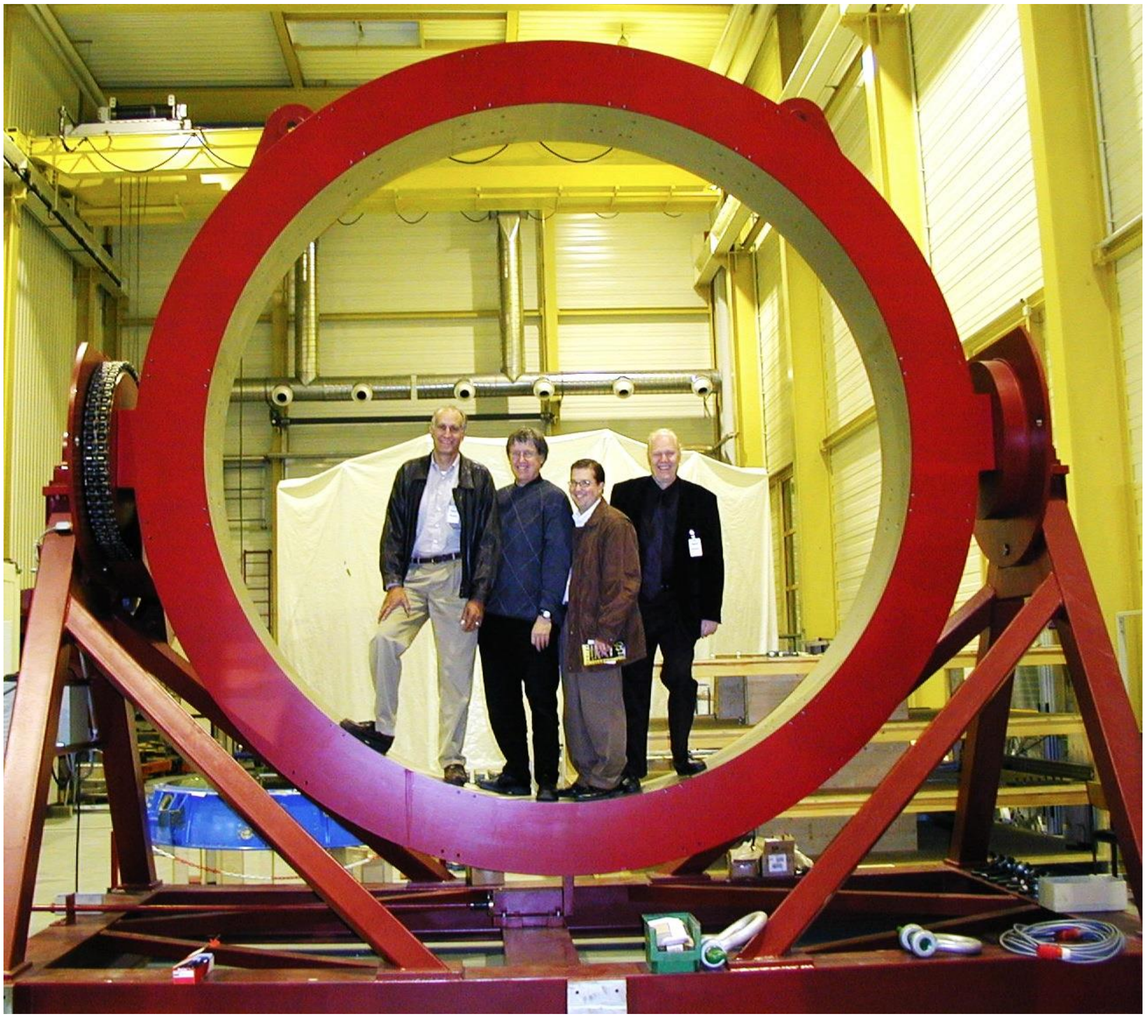


Figure 7.6-29. Another view of the same dummy bulkhead with Cliff Imprescia, Dr. Hans Kaercher, John Fitch, and Dr. Eric Becklin.

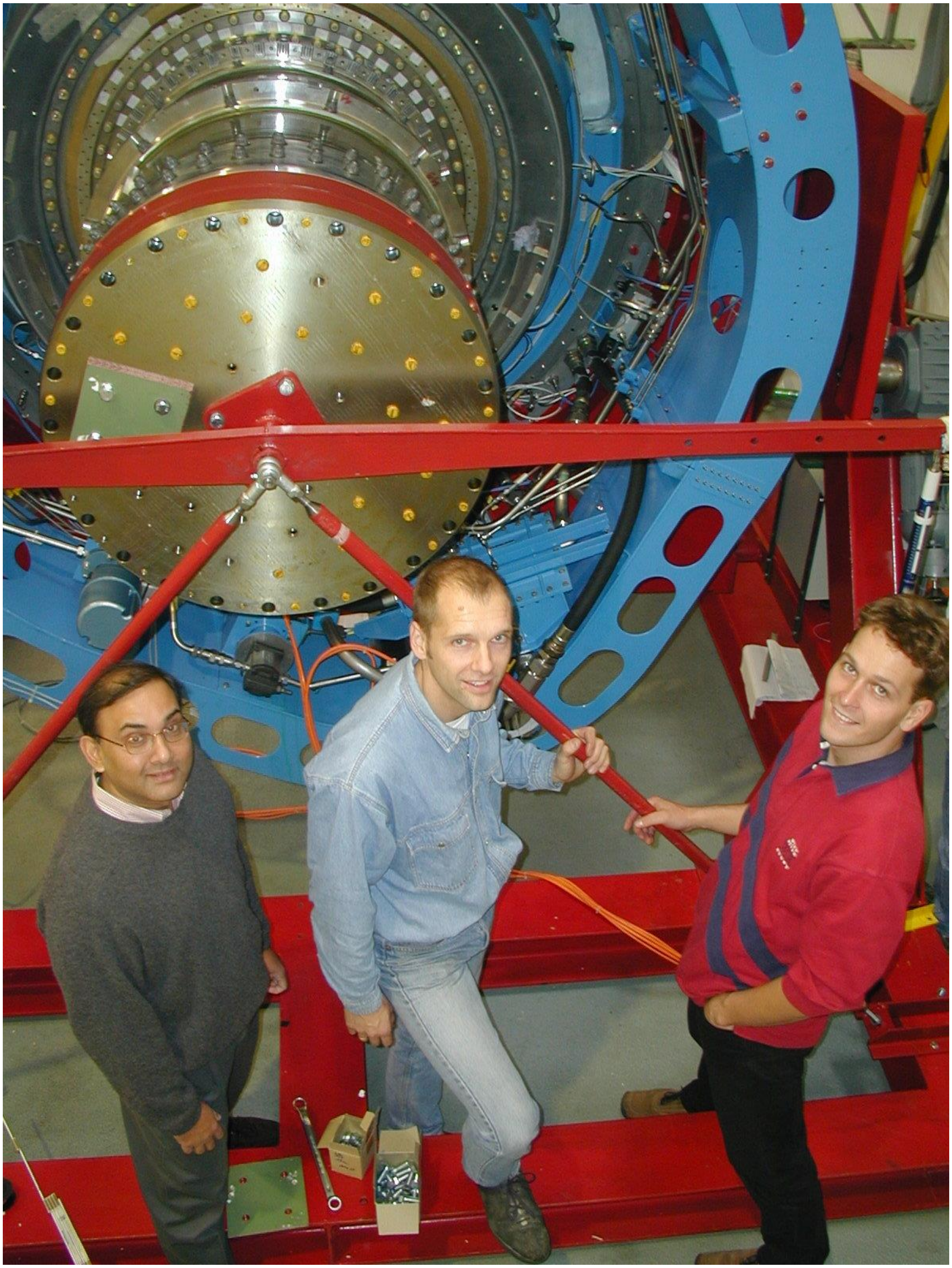


Figure 7.6-30. Kaiser Adeni, Ulrich Weiss, and Martin Seuss with the SUA I as it is coming together.

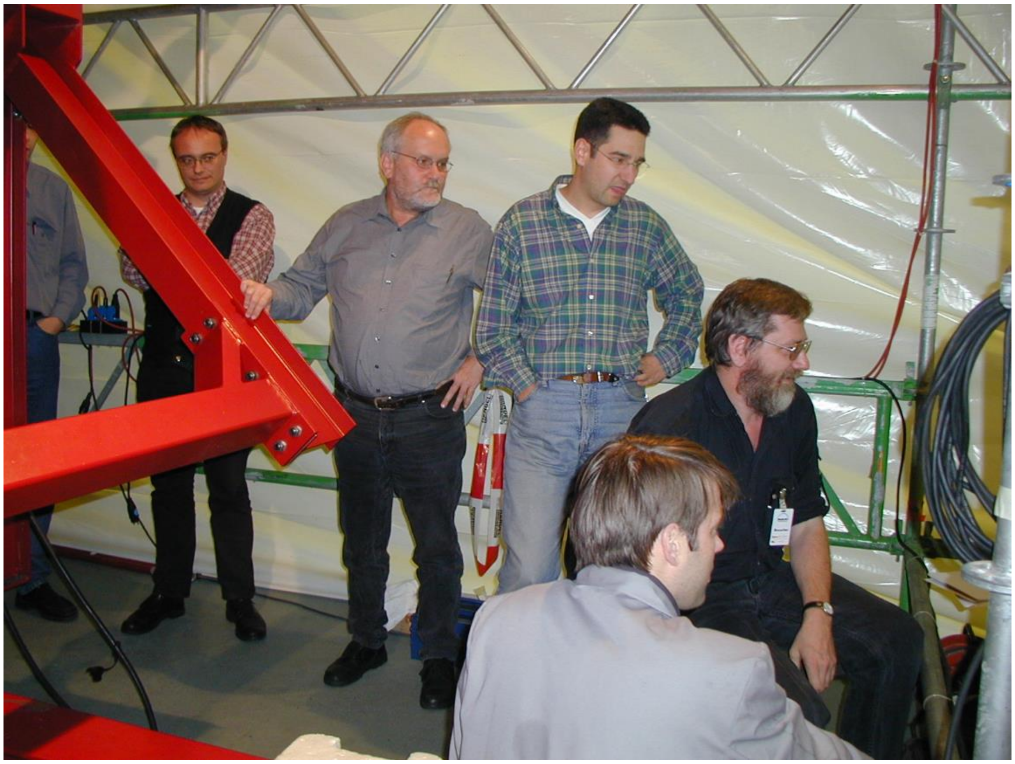


Figure 7.6-31. An anxious moment during one of the many tests done during the assembly of the SOFIA telescope − October 2001.

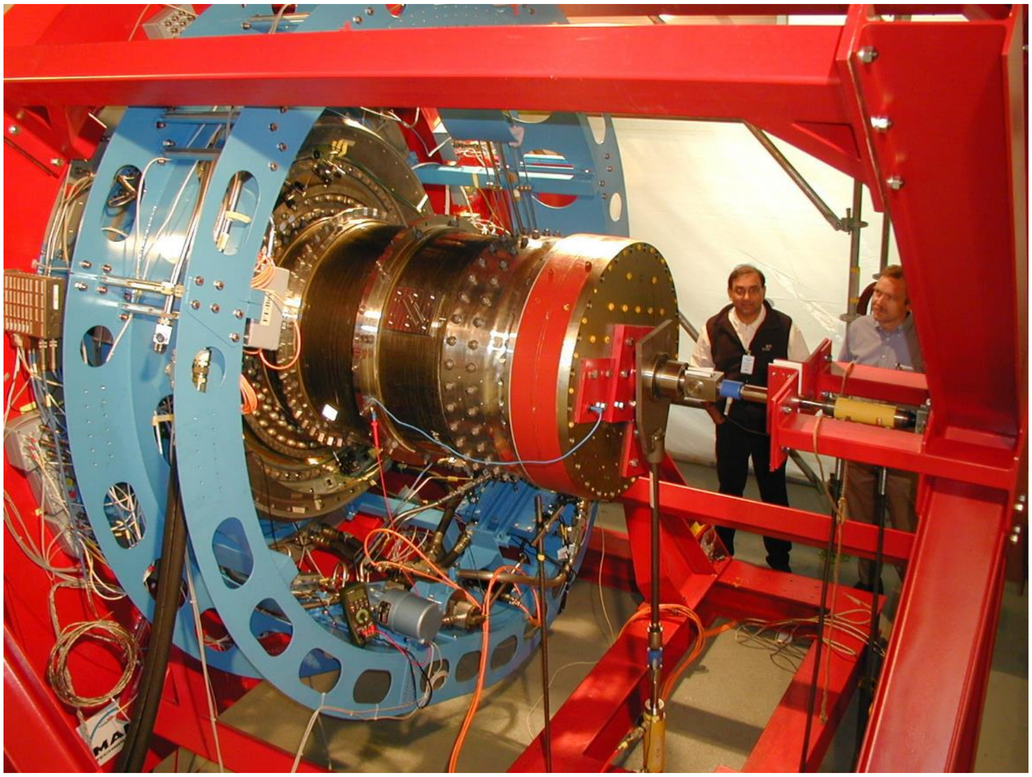


Figure 7.6-32. The SUA I during one of the many test setups verifying the many unique and complex systems.

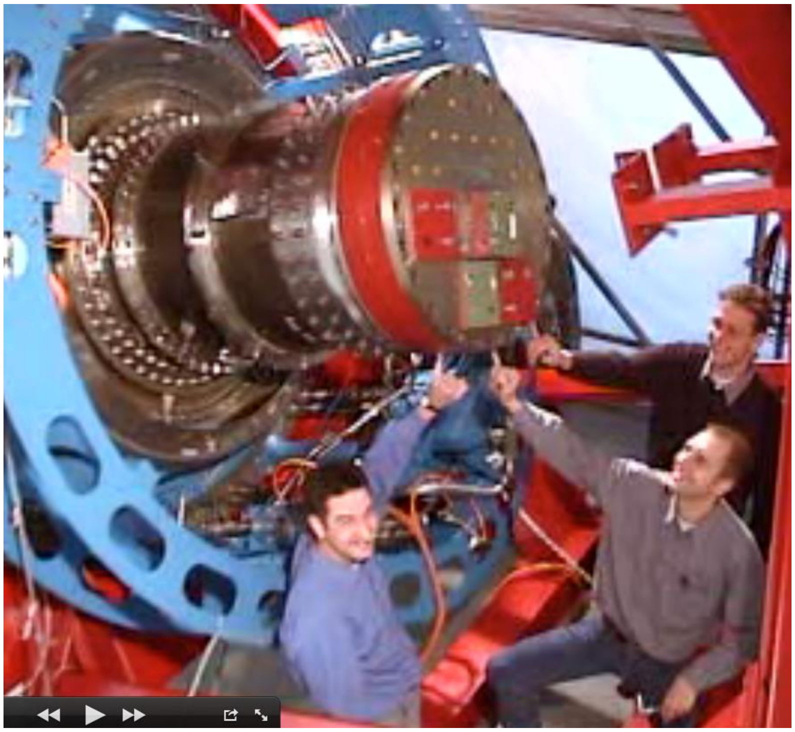


Figure 7.6-33. A clip from a movie showing us moving around about 10,000 lbs with the tips of our fingers, during the first major test of the SUA I. The RIS works great!

Figure 7.6-34. The celebration of a very successful test of SUA I involving the RIS, a major milestone.

Figure 7.6-35. Several of us celebrating a successful milestone of SUA 1, in Kaiser Adeni's Augsburg apartment, Germany − October 29, 2001. Kaiser was the on-site representative for the SPO.

Figure 7.6-36. Another view of several of us celebrating a successful milestone of SUA 1, in Kaiser Adeni's Augsburg apartment, Germany − October 29, 2001.

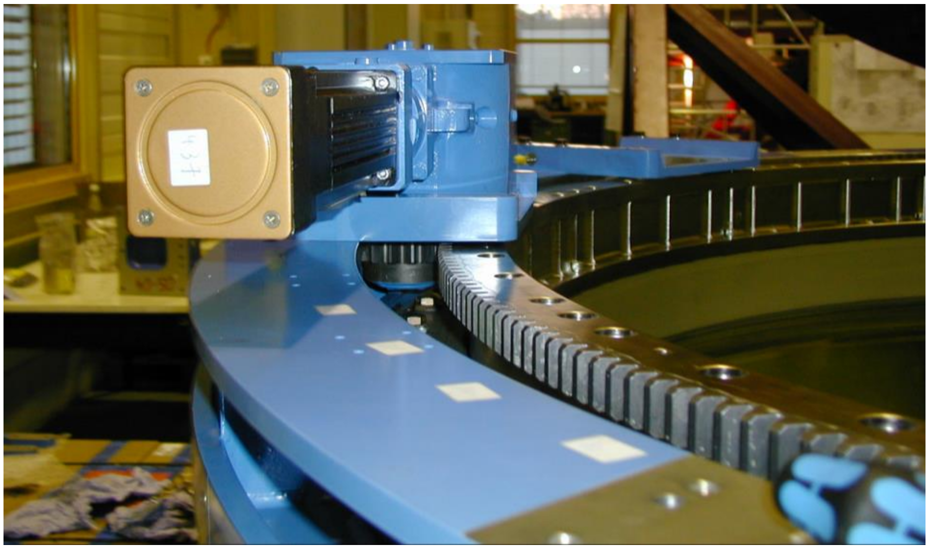


Figure 7.6-37. Part of the outer SUA (SUA III) showing the coarse drive gear setup.

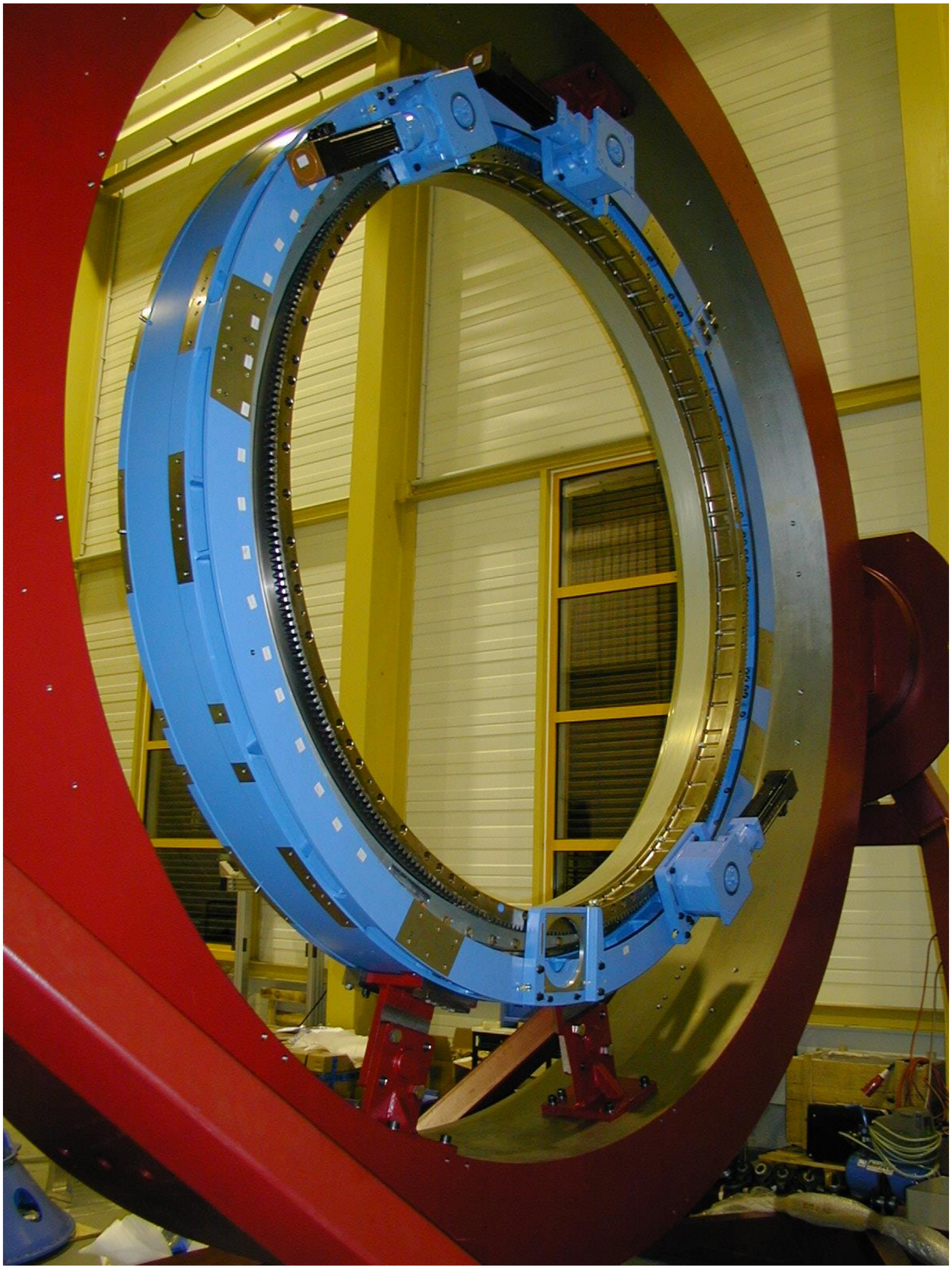


Figure 7.6-38. The SUA III installation starting into the dummy bulkhead to begin integrating and testing of the VIS and coarse drive systems − November 22, 2001.

Figure 7.6-39. The VIS brackets that attach the telescope to the aircraft or dummy bulkhead.

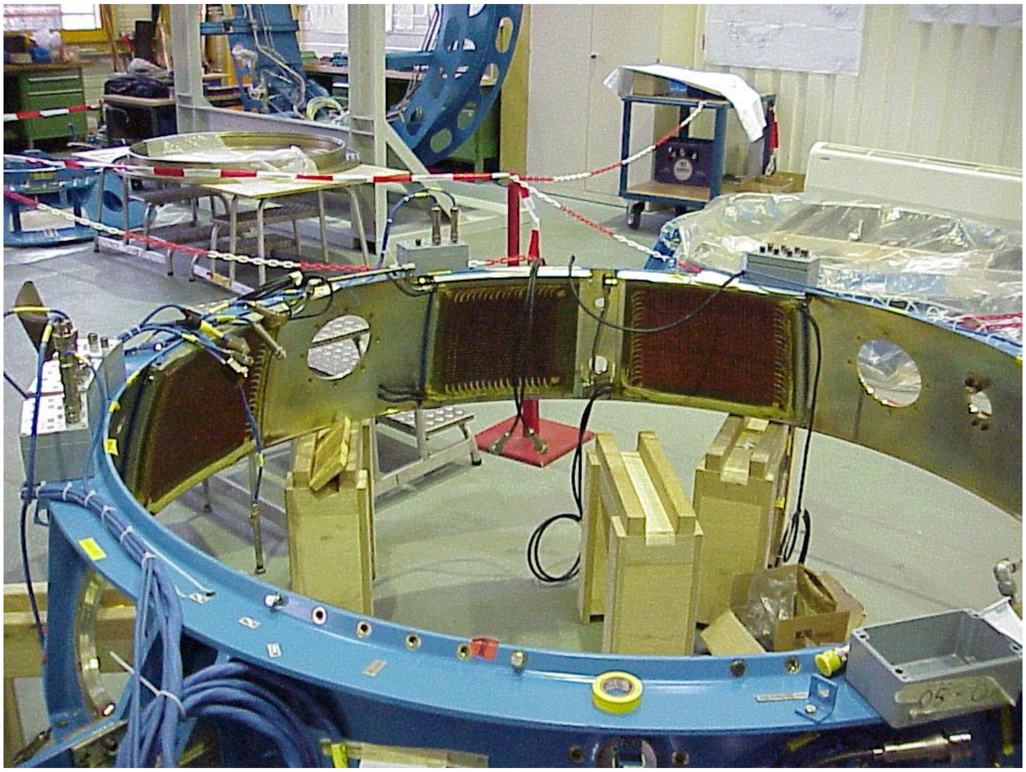


Figure 7.6-40. Back in the assembly room, many more components of the SUA being prepared for assembly − November 2001.

Figure 7.6-41. The SOFIA management team from NASA, USRA, L3, and MAN posing with the incomplete telescope in Augsburg, Germany − December 2001.

Figure 7.6-42. Another layer of the SUA being installed on the cabin side − December 6, 2001.

Figure 7.6-43. Dr. Guenther Stöffler, project manager, and Rainer Kaindl, design engineer, posing with telescope metering structure after it successfully passed the FAA conformity and Maintenance Inspection Point (MIP).

Figure 7.6-44. The old SOFIA 7-percent wind tunnel model cleaned up and painted and put on display at the NASA Ames Research Center visitor center.

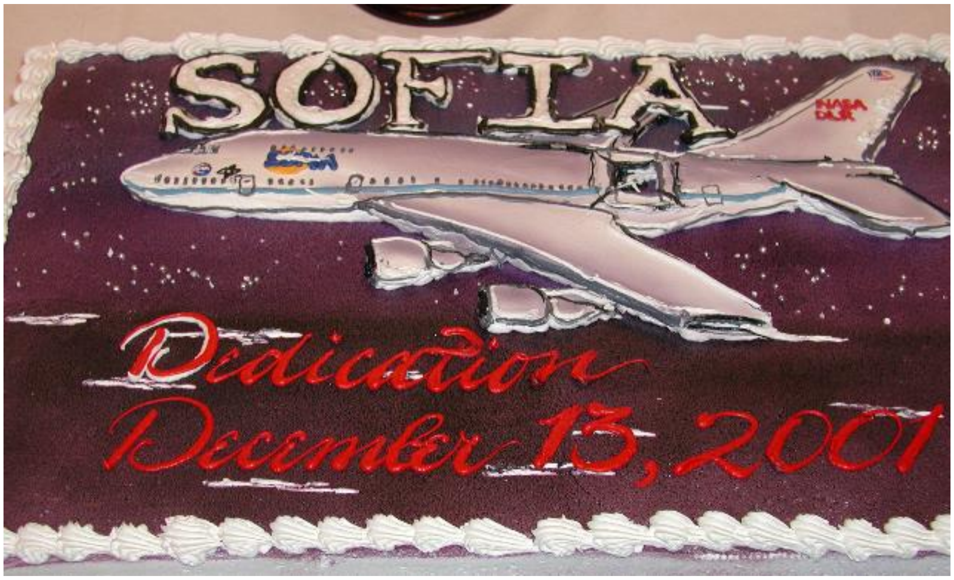


Figure 7.6-45. The cake from the dedication ceremony.

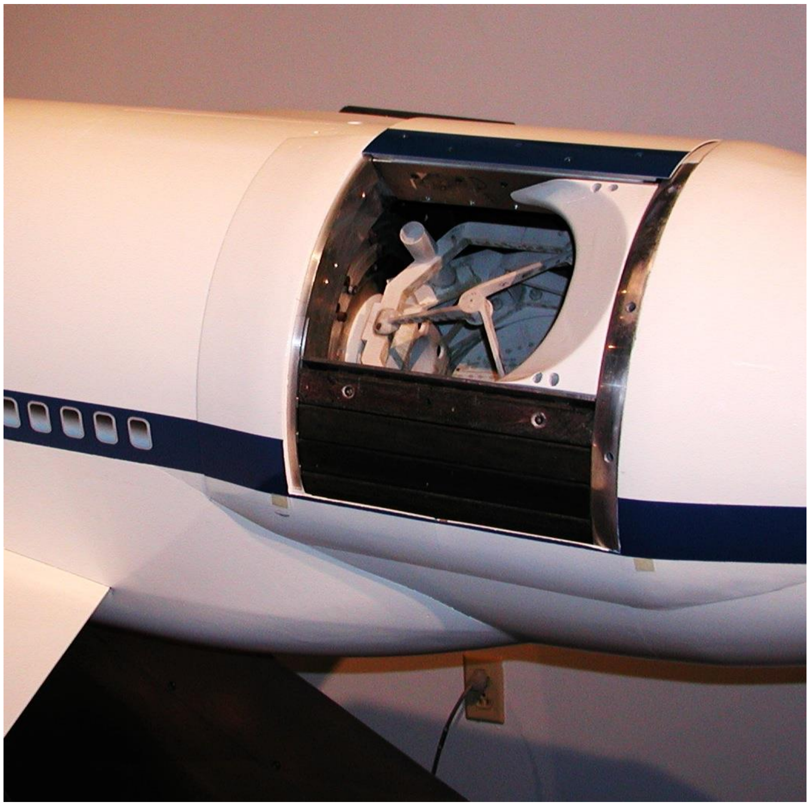


Figure 7.6-46. The cavity area of the model with the final configuration.

Figure 7.6-47. The SPO Deputy Project Manager, Ramsey Melugin, with this new Visitor Center display.

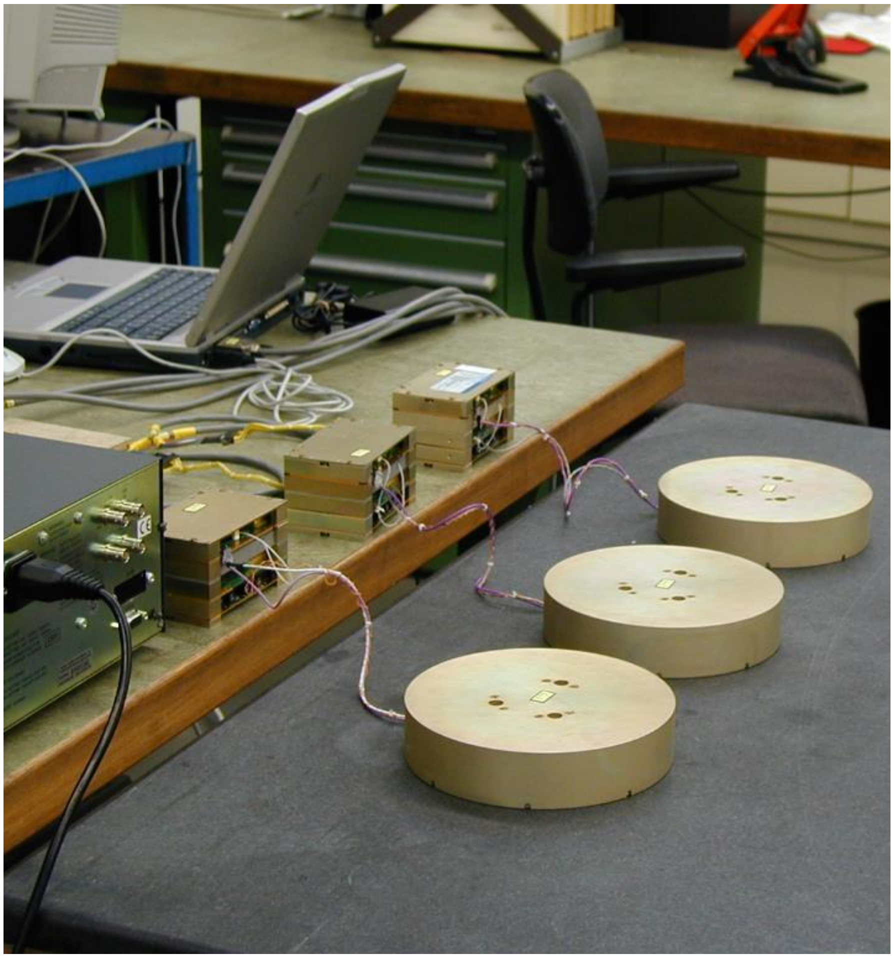


Figure 7.6-48. The telescope fiber optic gyros being bench tested − December 2001.

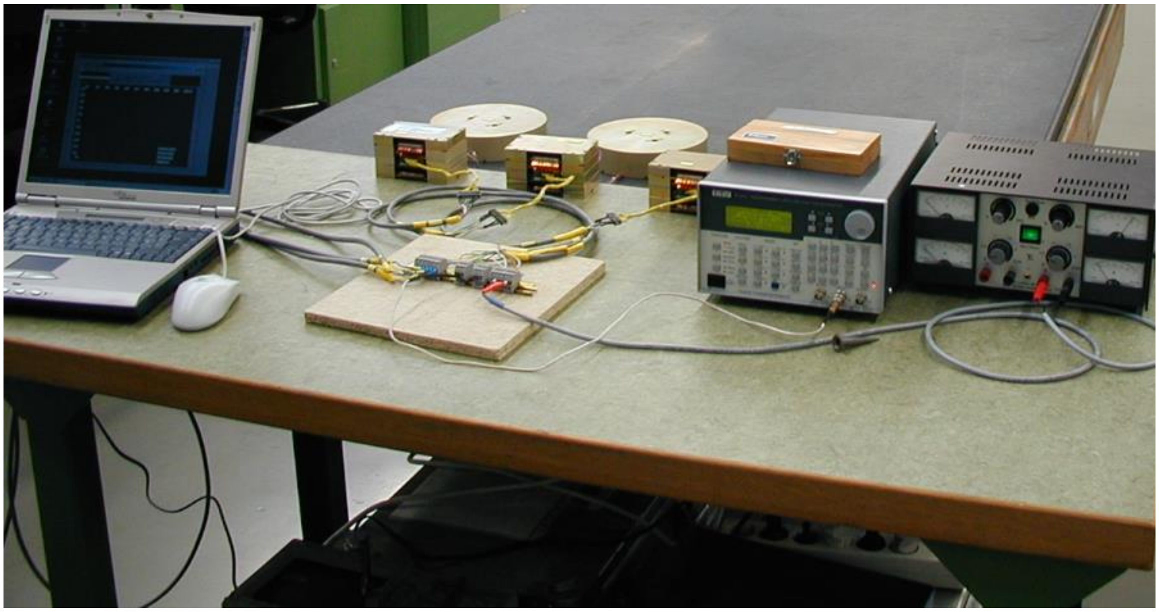


Figure 7.6-49. Another view of the telescope fiber optic gyros being bench tested − December 2001.

7.7 2002

Status of the telescope January 2002: As depicted in the following photos, all the elements of the TA had been or were nearing completion. USRA and the AS contractor urged that the TA be shipped to WACO as early as possible to begin integration into the aircraft, before its modifications were completed. The German contractors were reluctant to ship the TA before it had been thoroughly tested in the MAN facility in Augsburg Germany, but that is what happened.

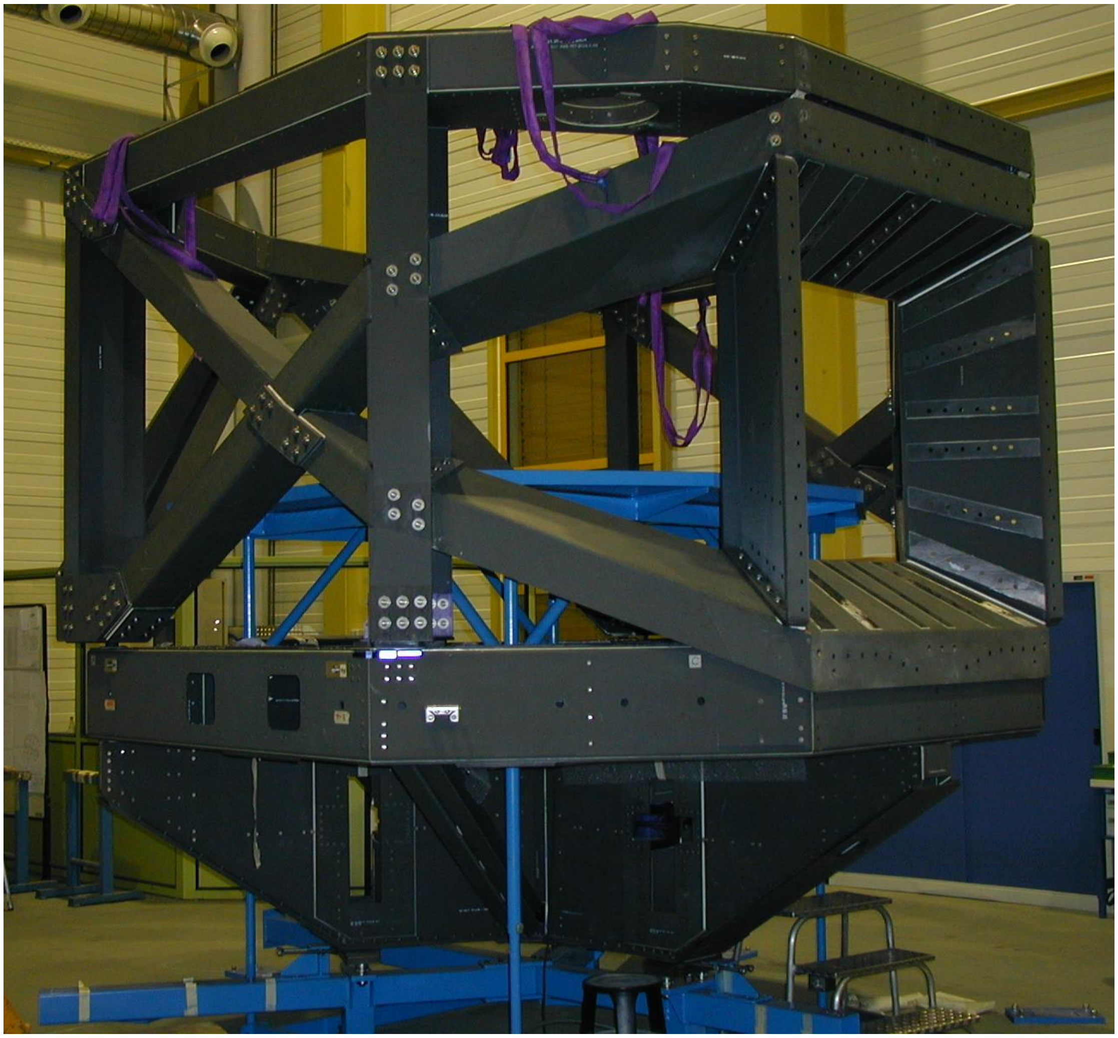


Figure 7.7-1. The composite metering structure including the primary mirror cell.

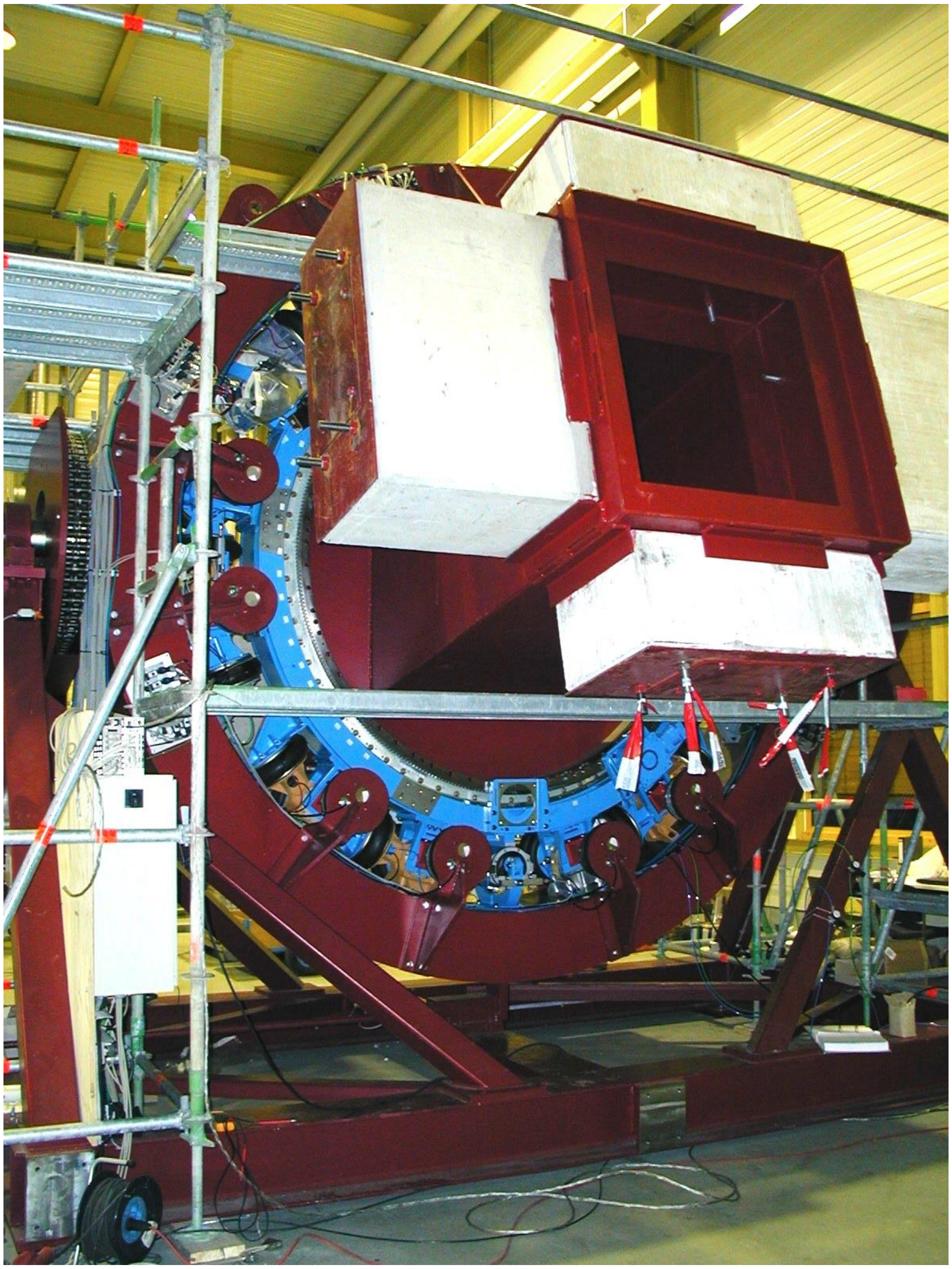


Figure 7.7-2. The outer SUA with the mass simulator to represent the mass and inertia of the inner SUA plus associated telescope systems.

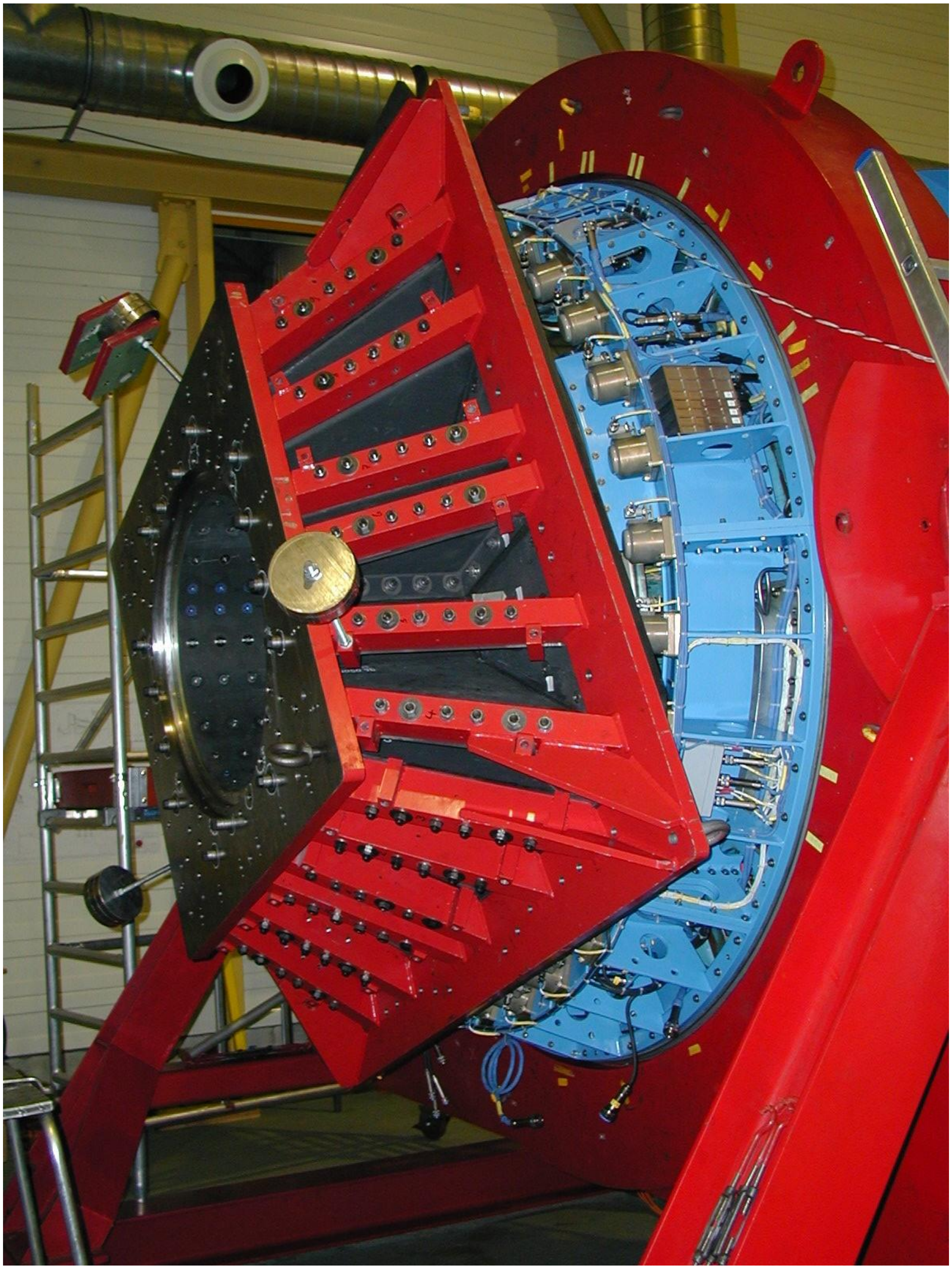


Figure 7.7-3. The inner SUA cavity side.

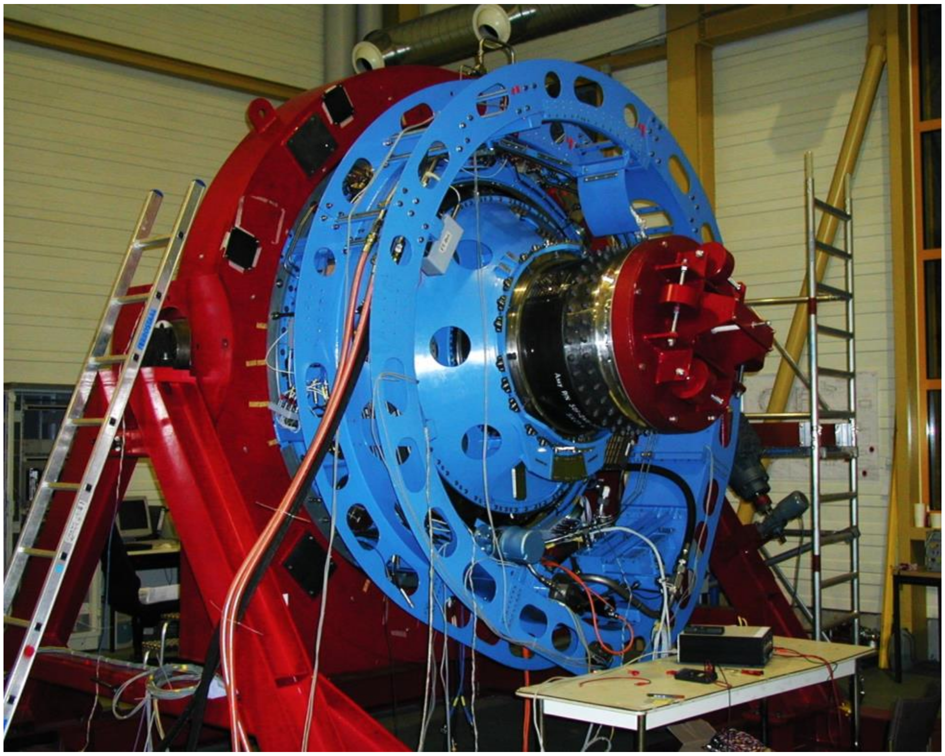


Figure 7.7-4. The inner SUA cabin side.

Figure 7.7-5 shows the carbon fiber composite Primary Mirror support cell, fabricated by MAN, being prepped to be shipped to REOSC (SAGEM) in France, the subcontractor to Kayser-Threde that figured and polished the Primary Mirror, so that the mirror can be installed into it.

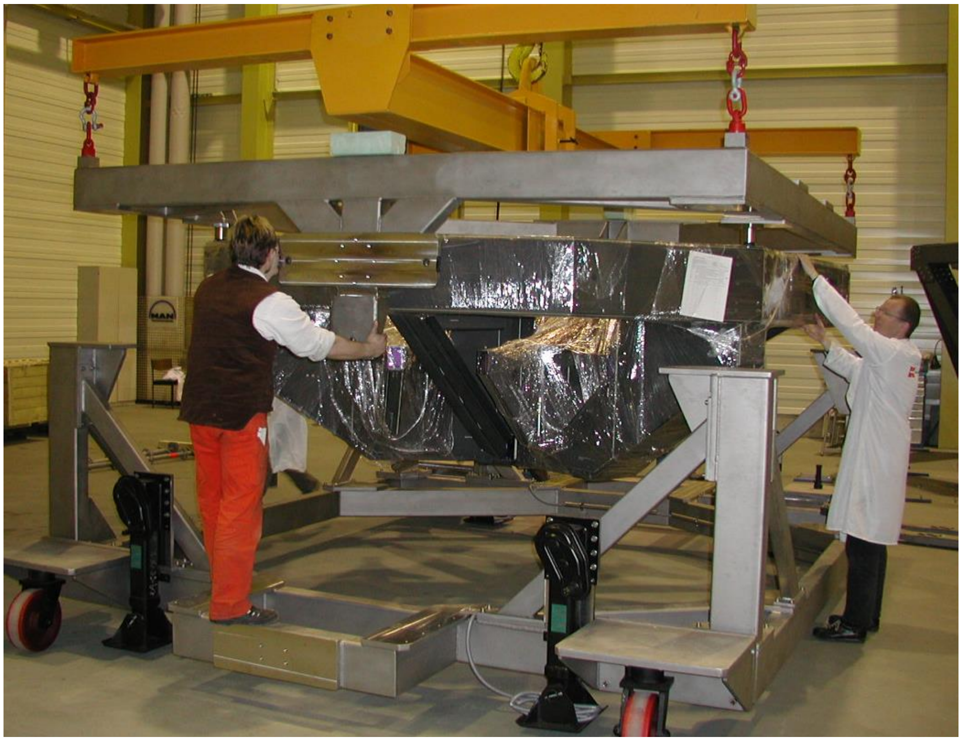


Figure 7.7-5. The carbon fiber composite Primary Mirror support cell − January 2002.

Figure 7.7-6. Cliff Imprescia, Alois Himmes, Dr. Eric Becklin, and Phil Hazelrig at a dinner function in Mountain View − January 29, 2002.

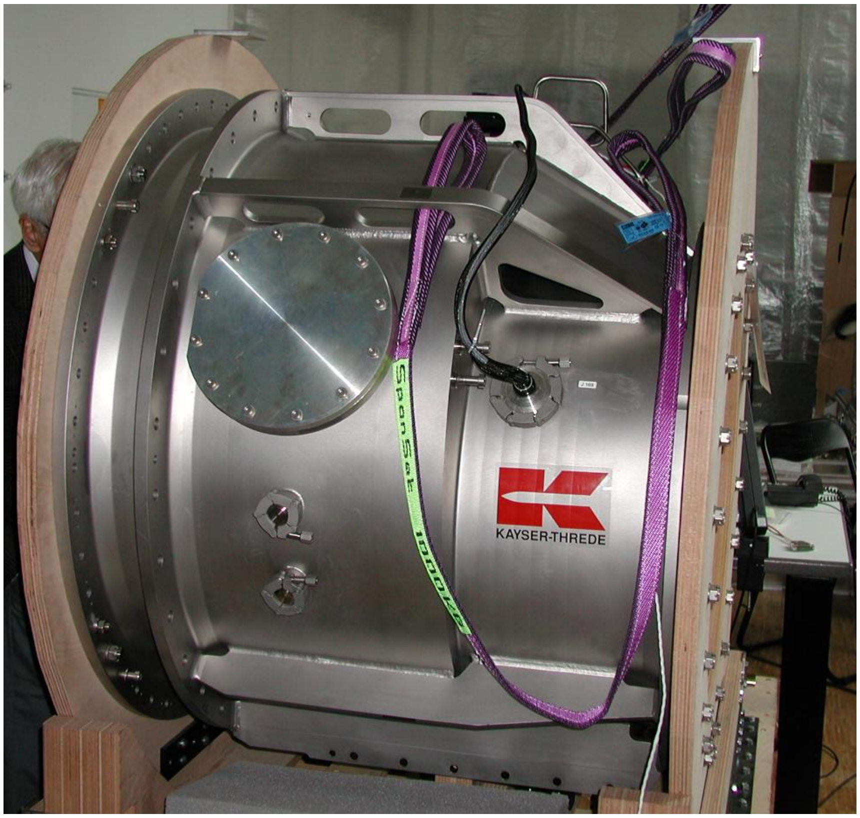


Figure 7.7-7. The SI flange assembly nearing completion at Kayser-Threde −February 2002.

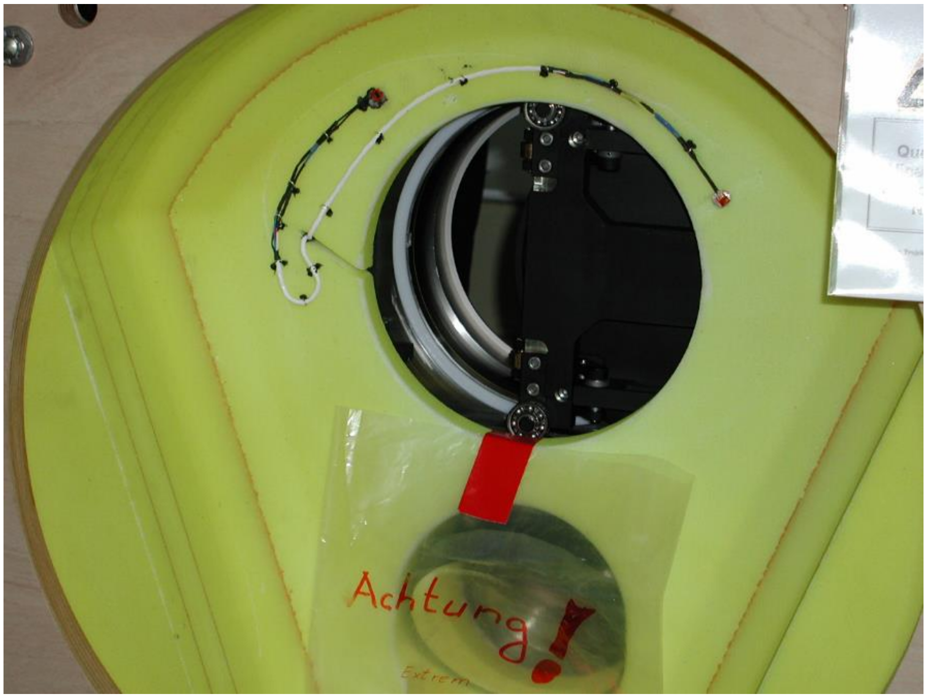


Figure 7.7-8. The inside of the SI flange assembly, showing the gate valve and the path to the FPI.

7.7.1 TA Ground Testing Completed

Figure 7.7-9. Kaiser Adeni and I posing in the composite TA metering structure.

Figure 7.7-10 shows one of the many pieces of the multiple layers of the SUA. On this you can see a couple of the spherical “motor” segments, and seven of the snubbers whose purpose is to safely limit telescope fine drive motion in the LOS and Cross Elevation rotational directions in case of software failure.

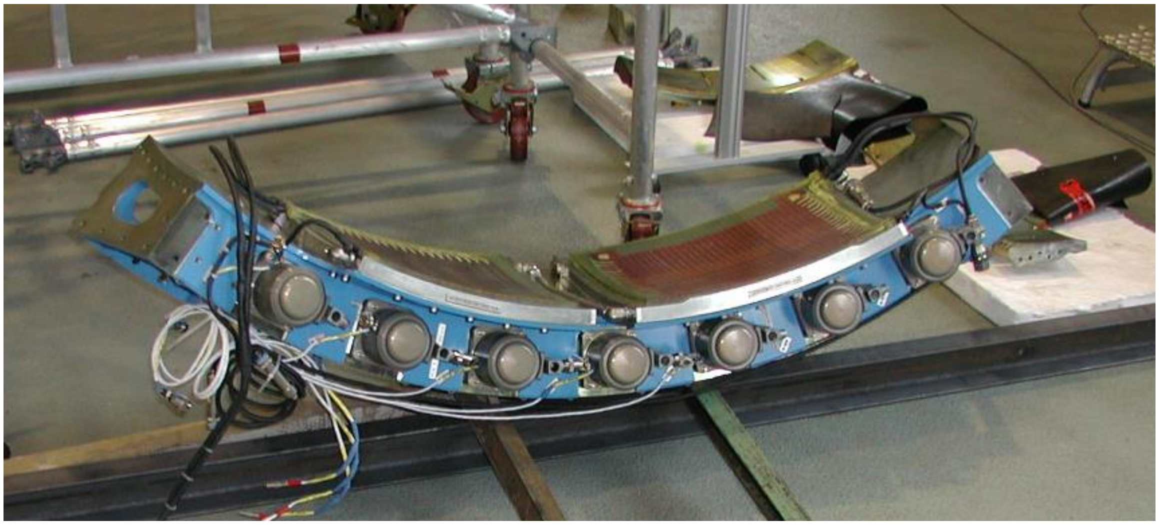


Figure 7.7-10. One of the many pieces of the multiple layers of the SUA − February 22, 2002.

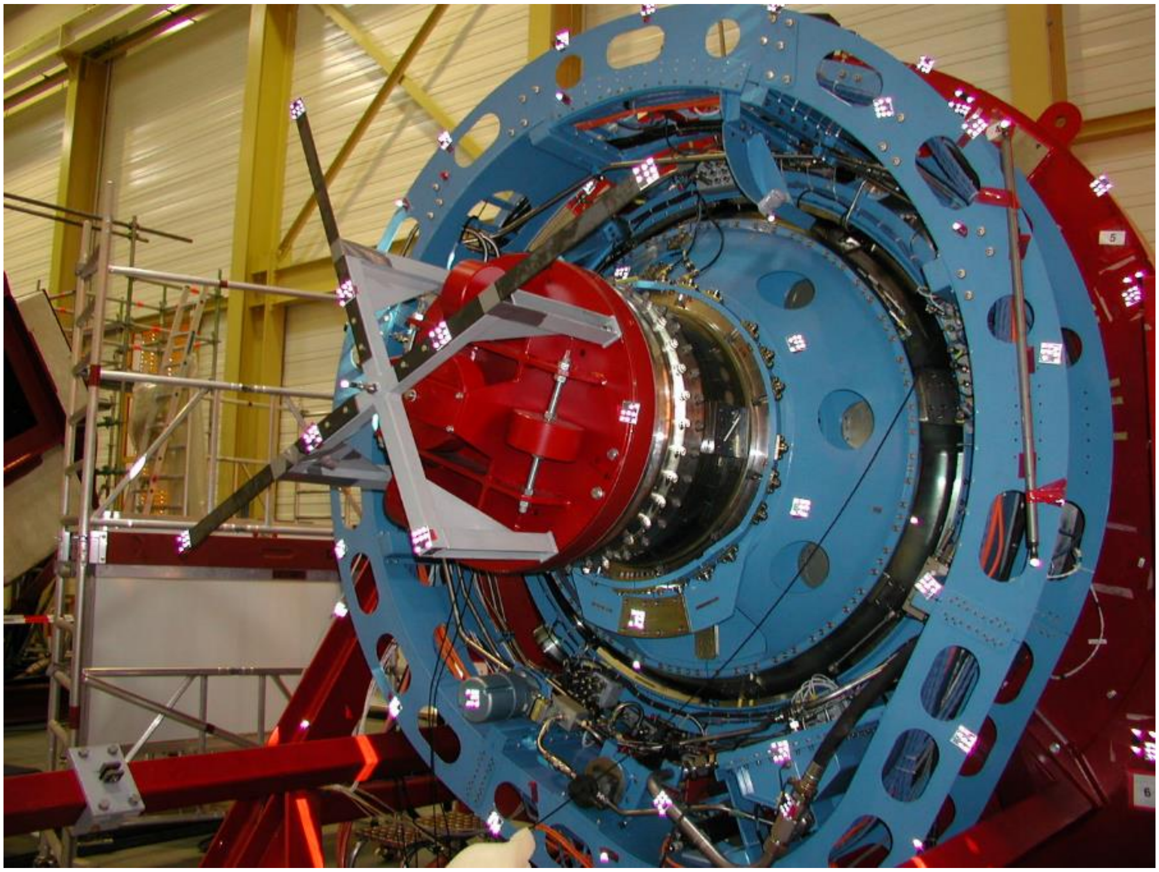


Figure 7.7-11. The inner SUA or what we called the SUA II, with reflective optical targets to help measure and calibrate one of the many control systems − March 5, 2002.

Figure 7.7-12. The outer SUA or SUA III, with a mass/inertia simulator to measure, adjust and optimize performance of the VIS and damping system − March 5, 2002.

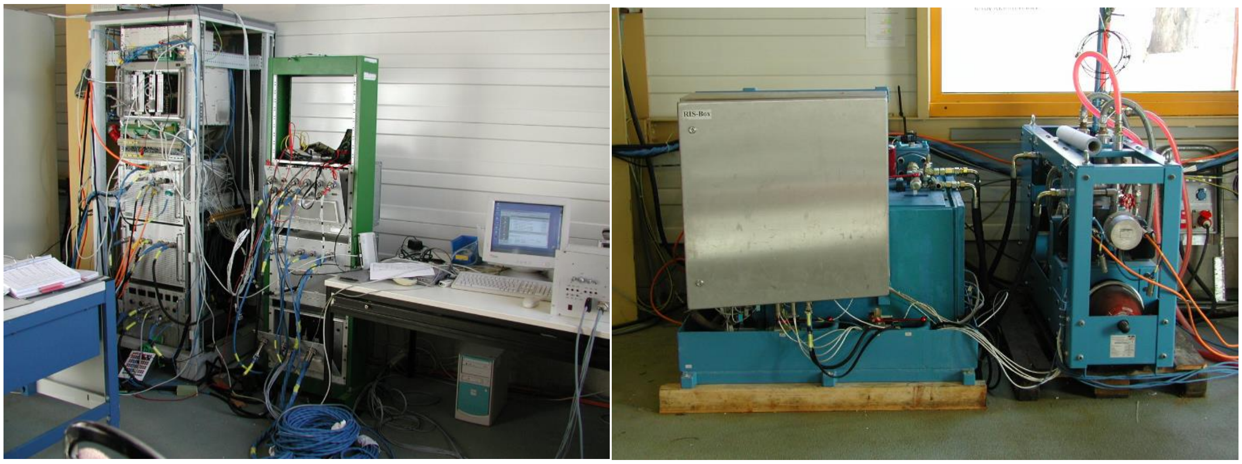


Figure 7.7-13. A few of the many support systems required to operate the many SUA systems.

Figure 7.7-14. I’m with the SUA − March 27, 2002.

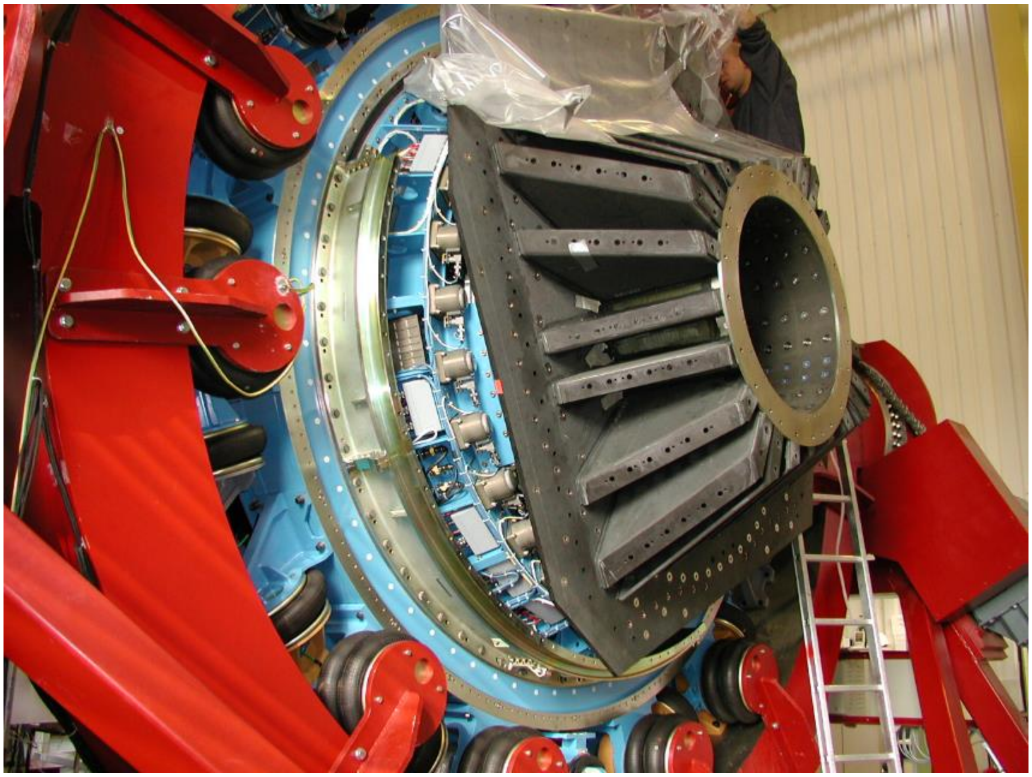


Figure 7.7-15. The cavity side of the TA showing a good view of a few of the many sub-systems.

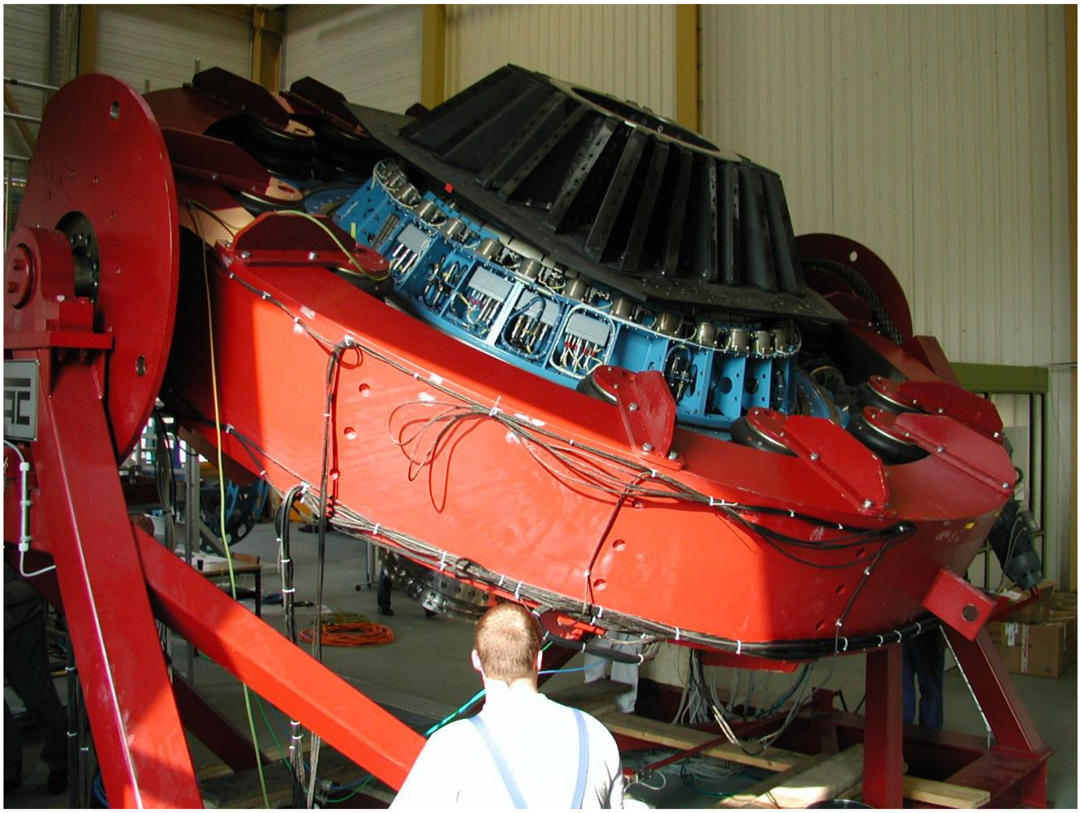


Figure 7.7-16. The cavity side being rotated up.

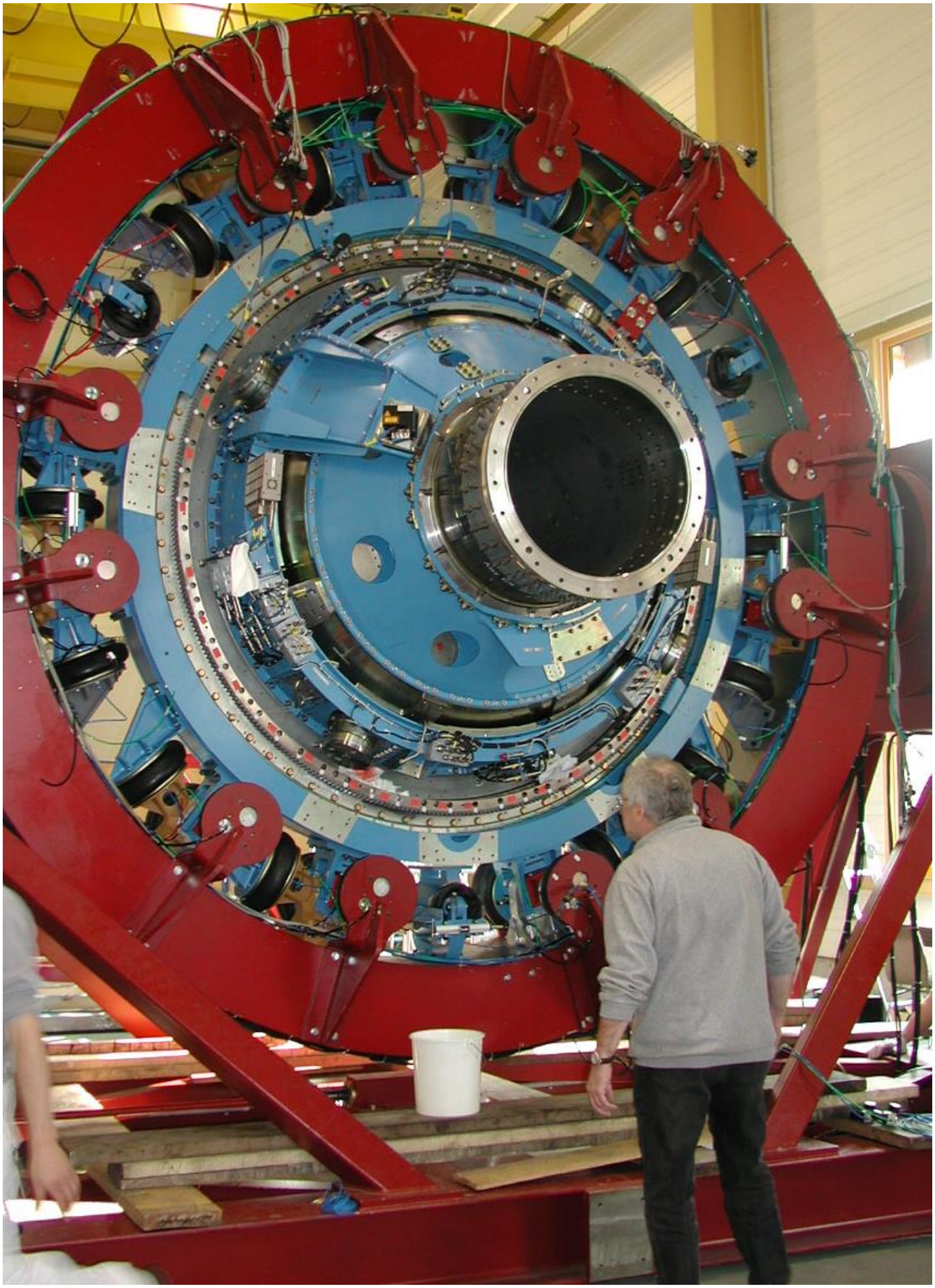


Figure 7.7-17. Cabin side of the integrated SUA, with Walter Schubach − April 10, 2002.

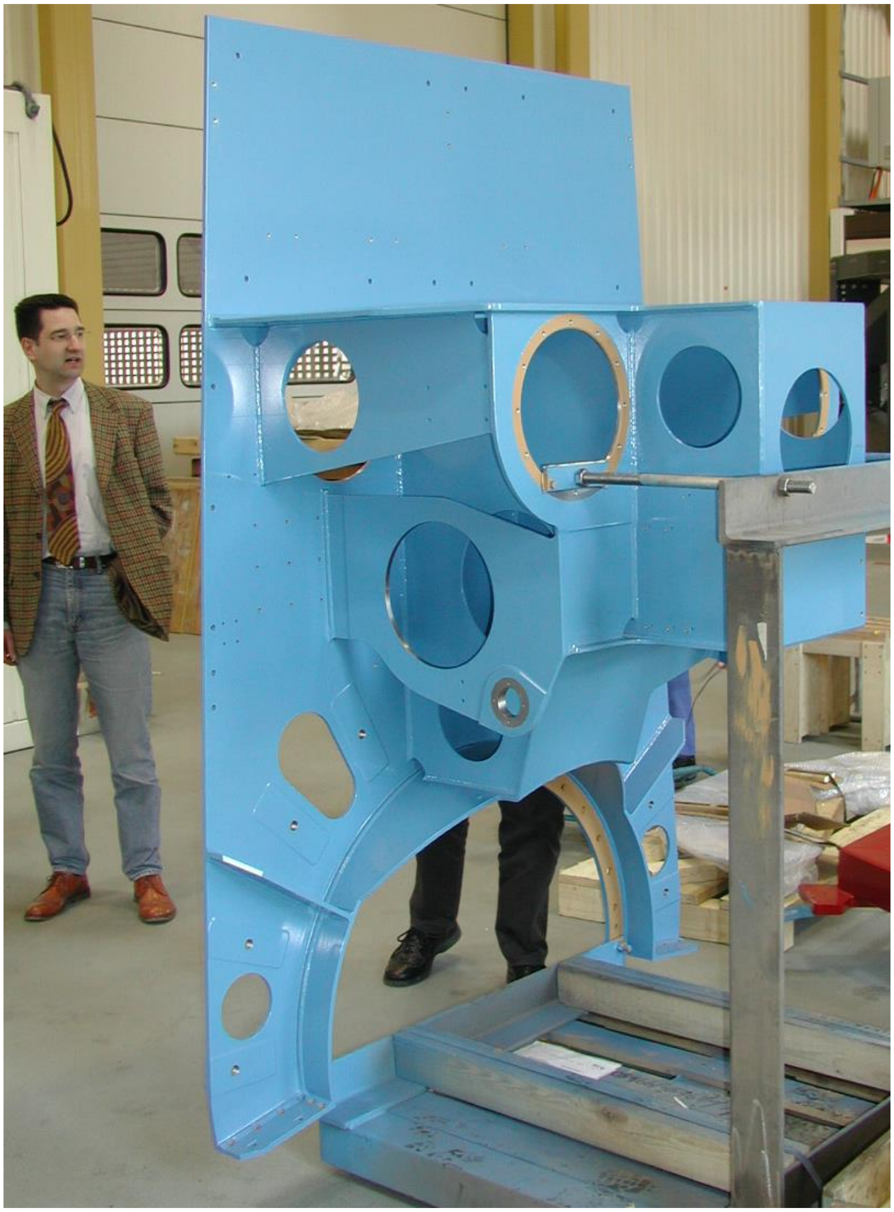


Figure 7.7-18. The counter-weight weldment ready to be installed onto the cabin side of the SUA with Eckhard Bremers − April 2002.

In Figure 7.7-19, you can see NASA Ames technician, John Wallace, in the assembly warehouse in Augsburg, Germany helping attach the instrument flange assembly (made by Kayser-Threde) to the end of the CFRP Nasmyth tube made by MAN.

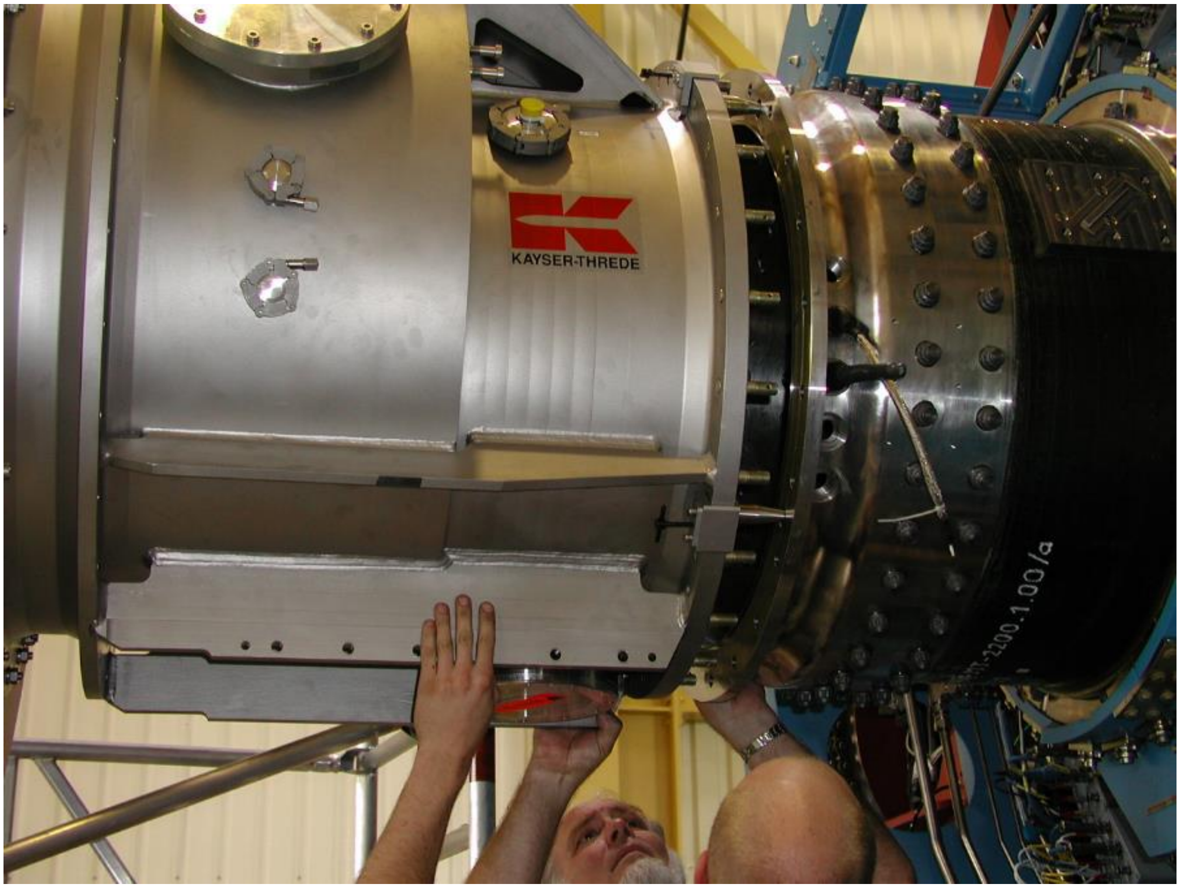


Figure 7.7-19. NASA Ames technician John Wallace helping attach the instrument flange assembly − Mid-April 2002.

Figure 7.7-20. More of the cabin side of the TA coming together, the counter weight frame being attached − April 2002.

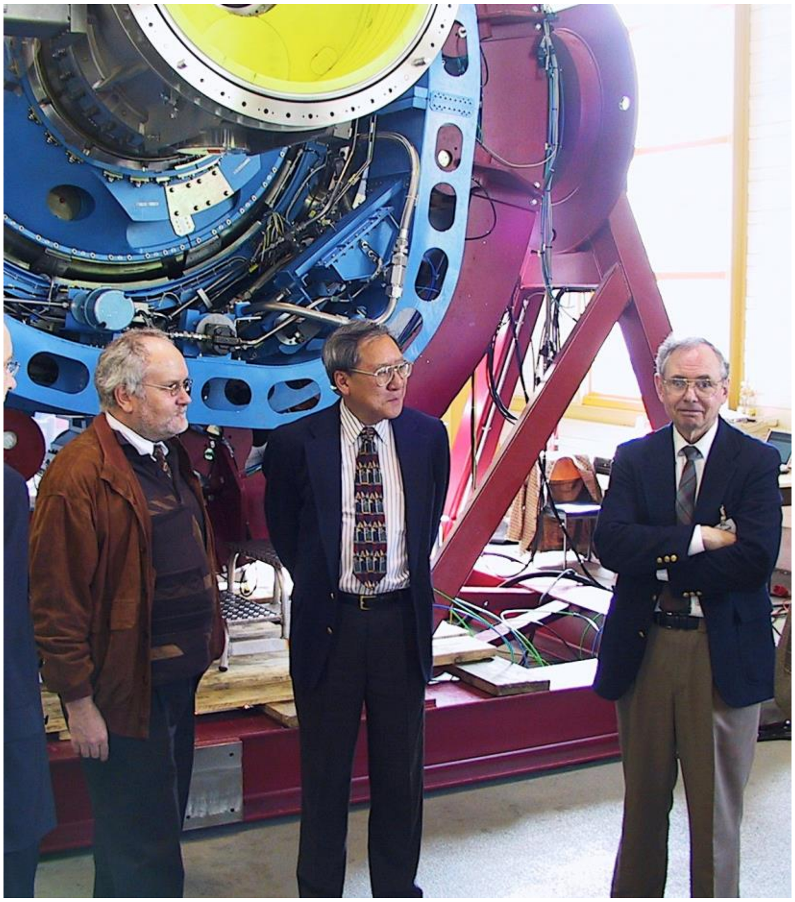


Figure 7.7-21. Walter Schubach and Ben Chin giving VIP tour to Ames' Center Director, Harold McDonald, at the TA assembly warehouse in Augsburg, Germany − May 2, 2002.

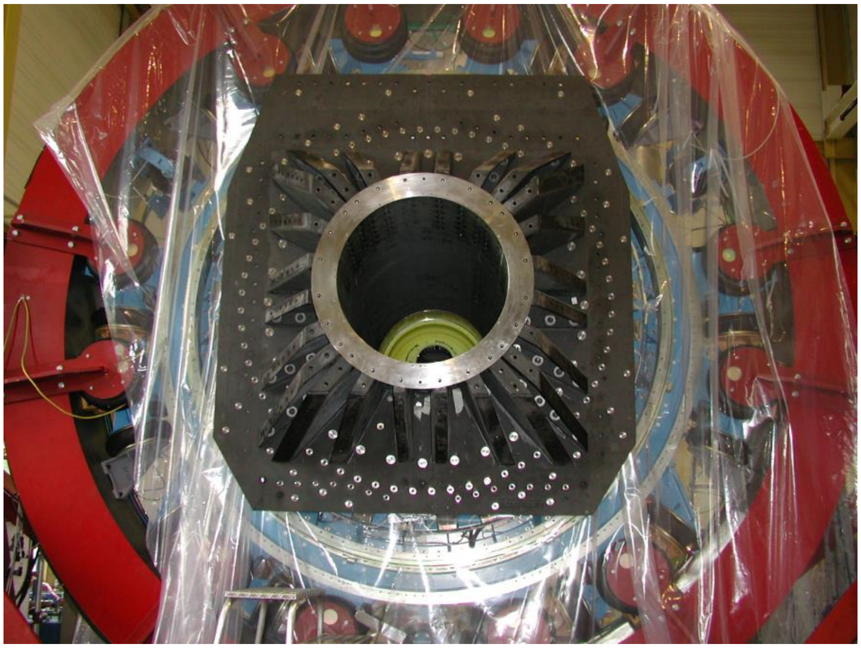


Figure 7.7-22. The completed SUA with the star frame ready for the composite metering structure to be mounted − May 30, 2002.

Of course, all these multiple complex systems that are part of the TA require the associated control systems. Figure 7.7-23 shows a small sample of the many electronics boxes at Kayser-Threde in Munich.

Figure 7.7-23. A small sample of the many electronics boxes at Kayser-Threde in Munich − May 2002.

Figure 7.7-24. Pieces of the lower flex door coming together at Ames − May 30, 2002.

Figure 7.7-25. The assembled secondary mirror mechanism, designed and built by CSEM in Neuchatel, Switzerland was put through final environmental testing at a facility in Austria − June 2002.

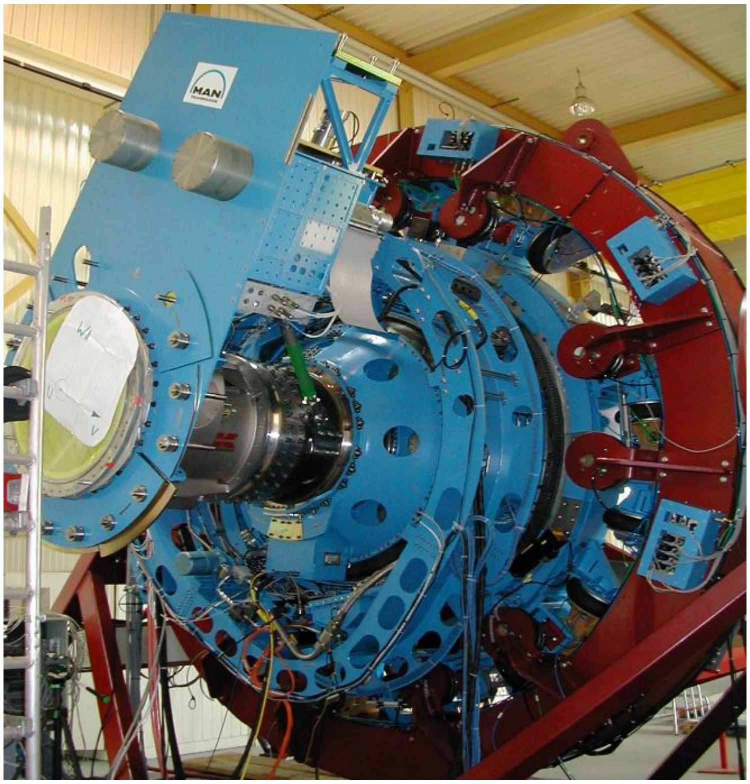


Figure 7.7-26. The cabin side of the TA, near completion of pre-ship integration within the dummy bulkhead (the red structure) at MAN in Augsburg, Germany − July 12, 2002.

Figure 7.7-27 shows a complete side view of the TA, near completion of pre-ship integration mounted within the dummy bulkhead, with a mass/inertia simulator to represent the primary mirror attached to the carbon fiber composite metering structure (the left side) at MAN in Augsburg, Germany, July 12, 2002.

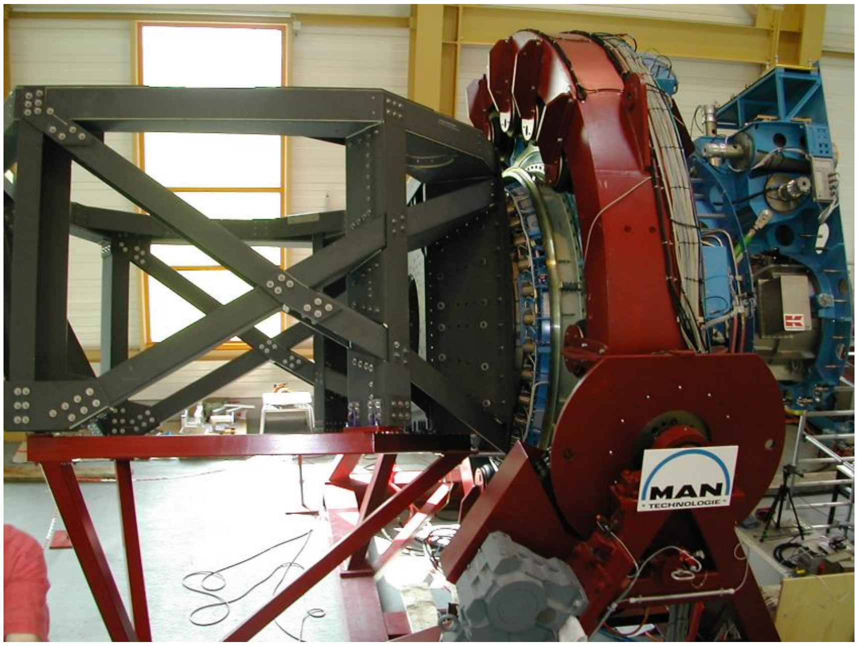


Figure 7.7-27. A complete side view of the TA.

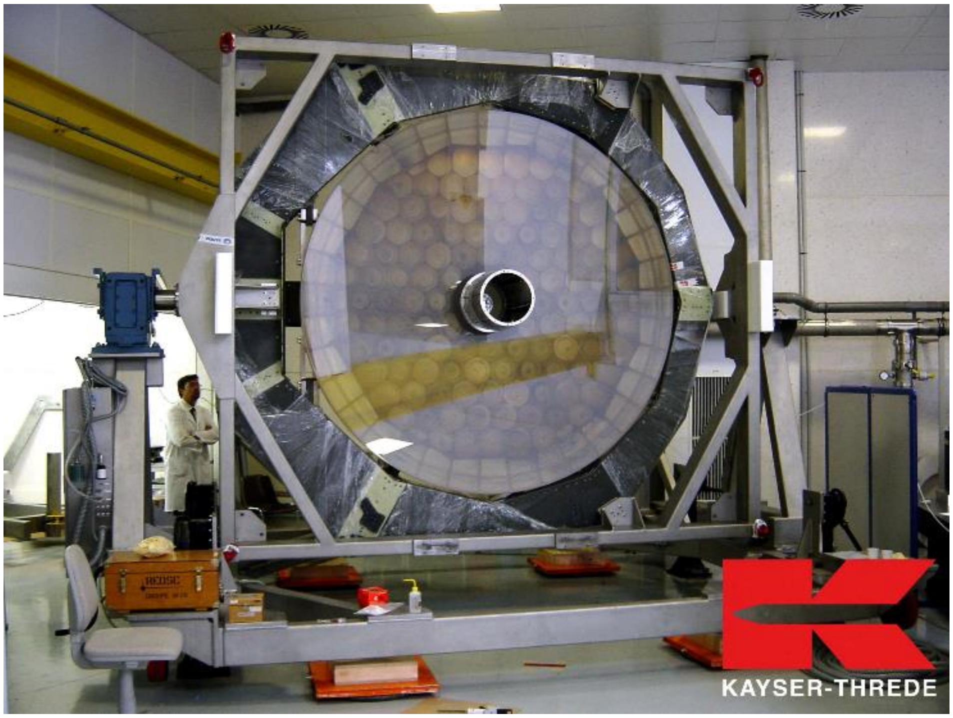


Figure 7.7-28. The uncoated primary mirror mounted within the CFRP mirror cell, attached to a fixture in preparation to be shipped.

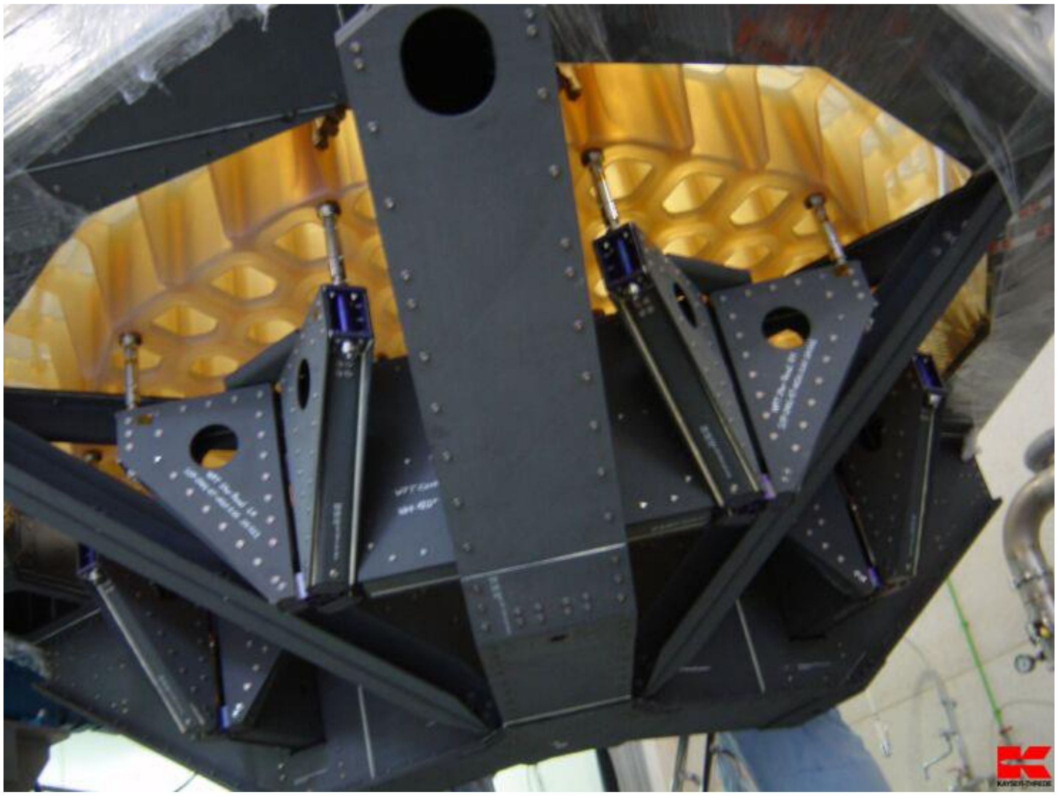


Figure 7.7-29. The backside of the primary mirror assembly showing the whiffle tree support system.

Figure 7.7-30 shows the cavity side/carbon fiber composite metering structure of the TA that is mounted in the dummy bulkhead at MAN in Augsburg, Germany, July 12, 2002.

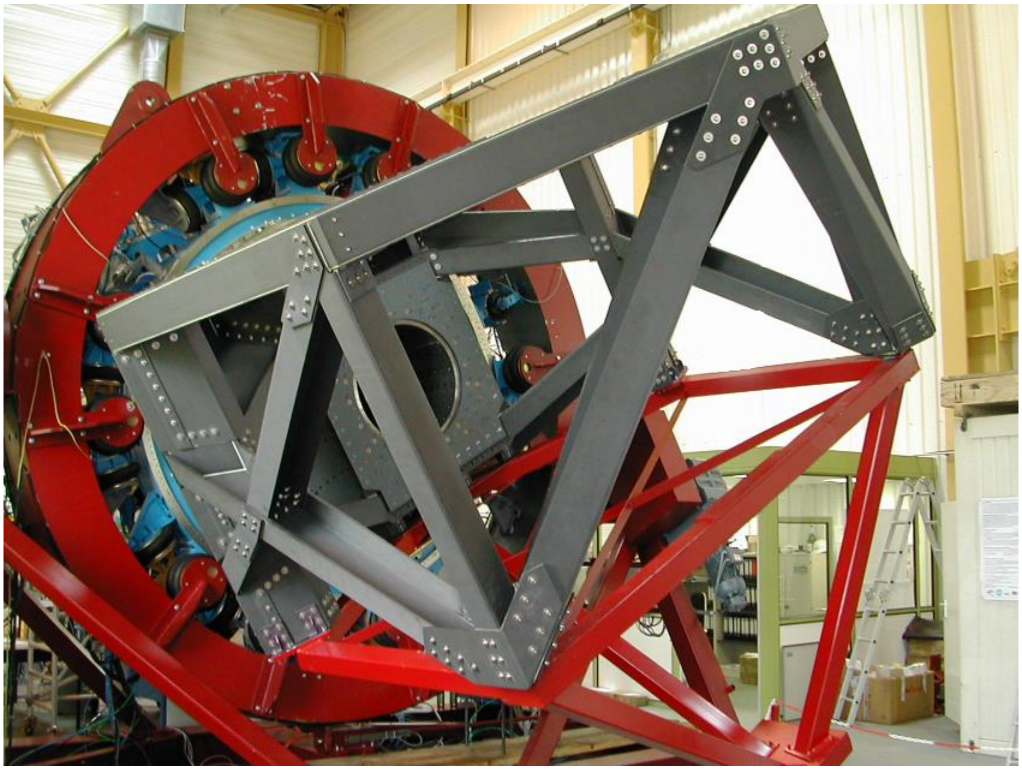


Figure 7.7-30. The cavity side/carbon fiber composite metering structure.

Figure 7.7-31. Dr. Ed Erickson giving a speech at a Pre-ship Review dinner event, with Dr. Hans Kaercher sitting in front of him.

Figure 7.7-32. The telescope Pre-ship review board members − summer 2002.

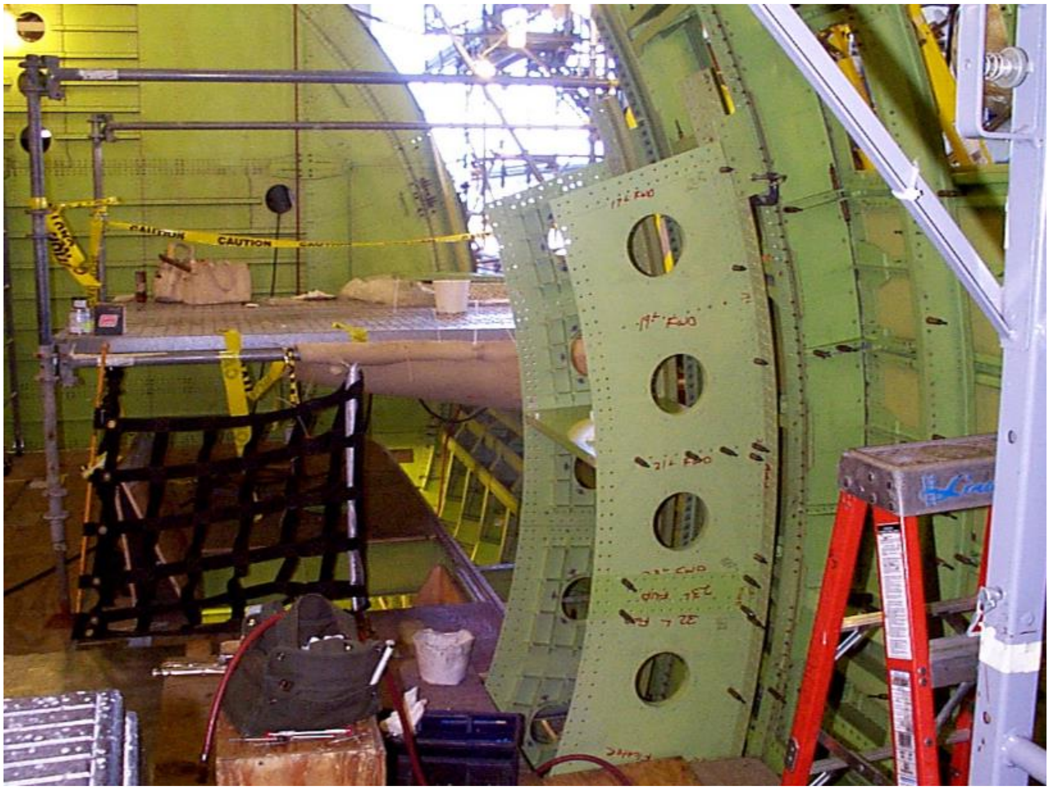


Figure 7.7-33. In Waco, the bulkhead installation begins. The view from the cabin looking aft into the cavity area − July 2002.

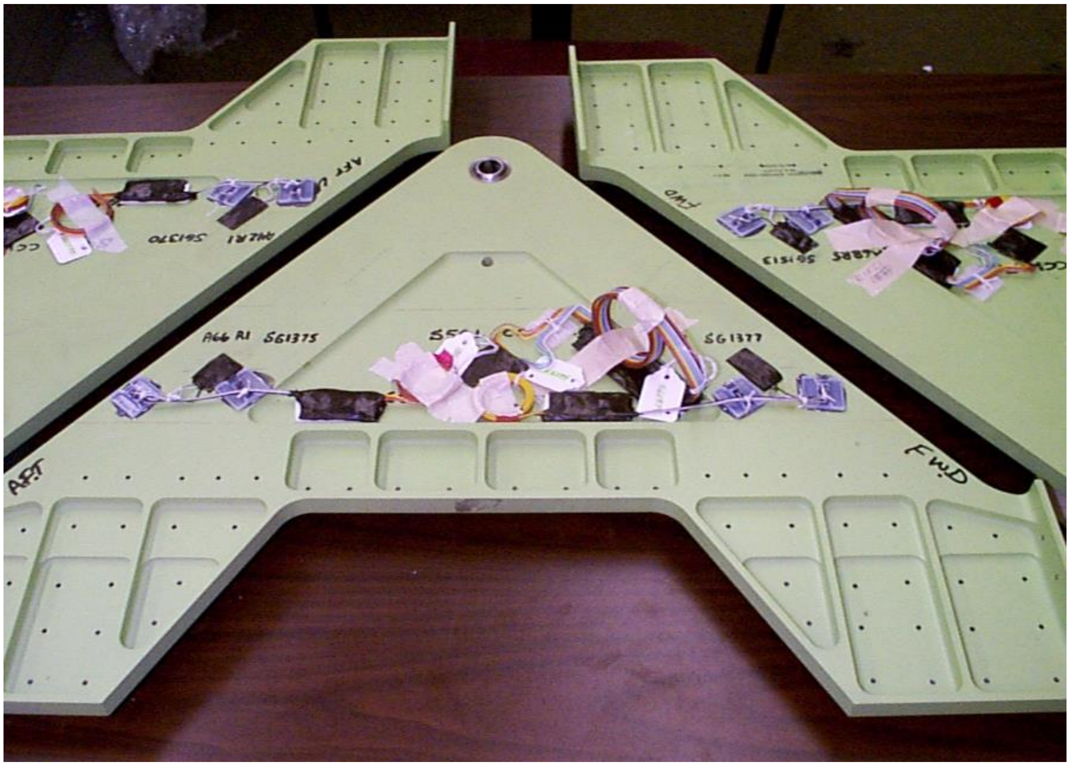


Figure 7.7-34. The bulkhead to fuselage attachment structures. A pinned joint.

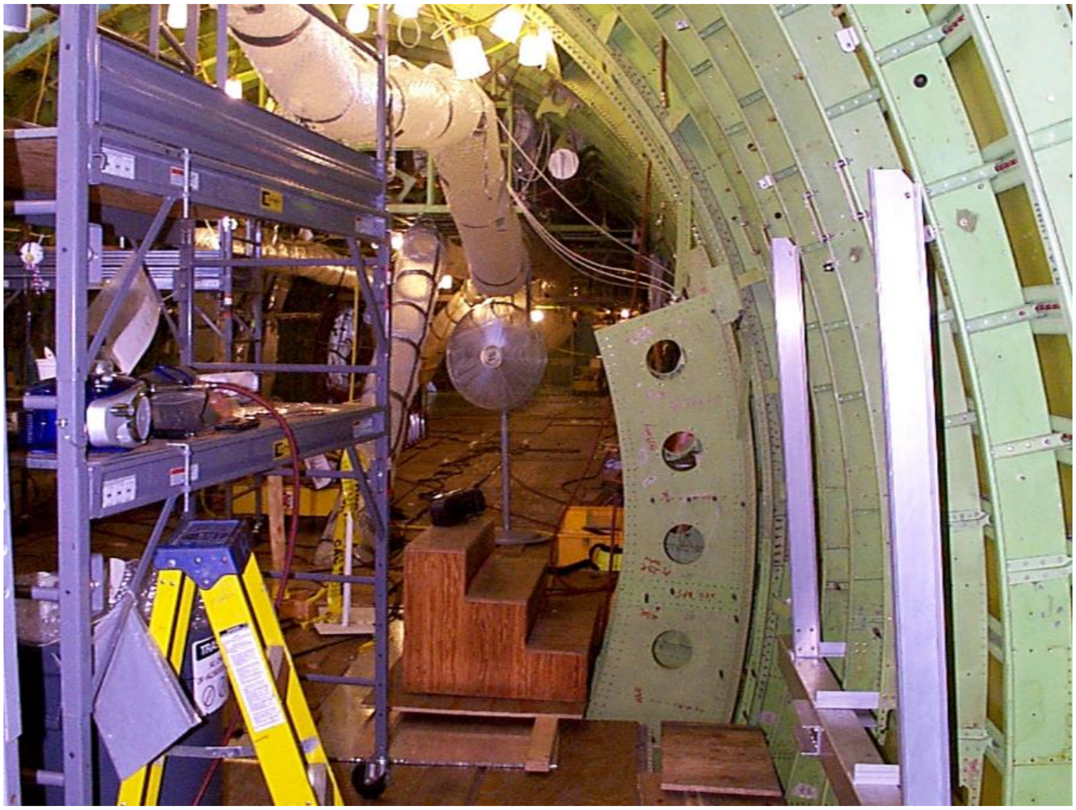


Figure 7.7-35. From the cavity, the view looking forward with the start of the bulkhead installation in place − July 2002.

Figure 7.7-36. Status of the aircraft modification, re-skinning-re-enforcement − August 15, 2002.

Figure 7.7-37. Ready to ship! The large TA pieces being loaded into a Beluga in Germany, September 1, 2002, to be delivered to Waco Texas.

7.7.2 Telescope Contract Milestone -Project Final Review Completed

7.7.3 TA Shipped to Waco, Texas September 2002

Figure 7.7-38. The Beluga carrying the SOFIA telescope taxiing to the hangar after landing at the airfield in Waco, Texas − September 4, 2002.

Figure 7.7-39. Three of our German colleagues, Walter Schubach, Eckhard Bremers, and Heinz Hammes celebrating the arrival of the telescope at Waco.

Figure 7.7-40. As a milestone event, there was an official celebration with associated speeches. Dr. Tom Greene is at the podium.

Figure 7.7-41. Unloading the large SOFIA telescope components from the Beluga into the hangar where the SOFIA aircraft was located.

Figure 7.7-42. A small group of us, inside the Beluga/Super Transporter aircraft with some of the telescope shipment − September 4, 2002.

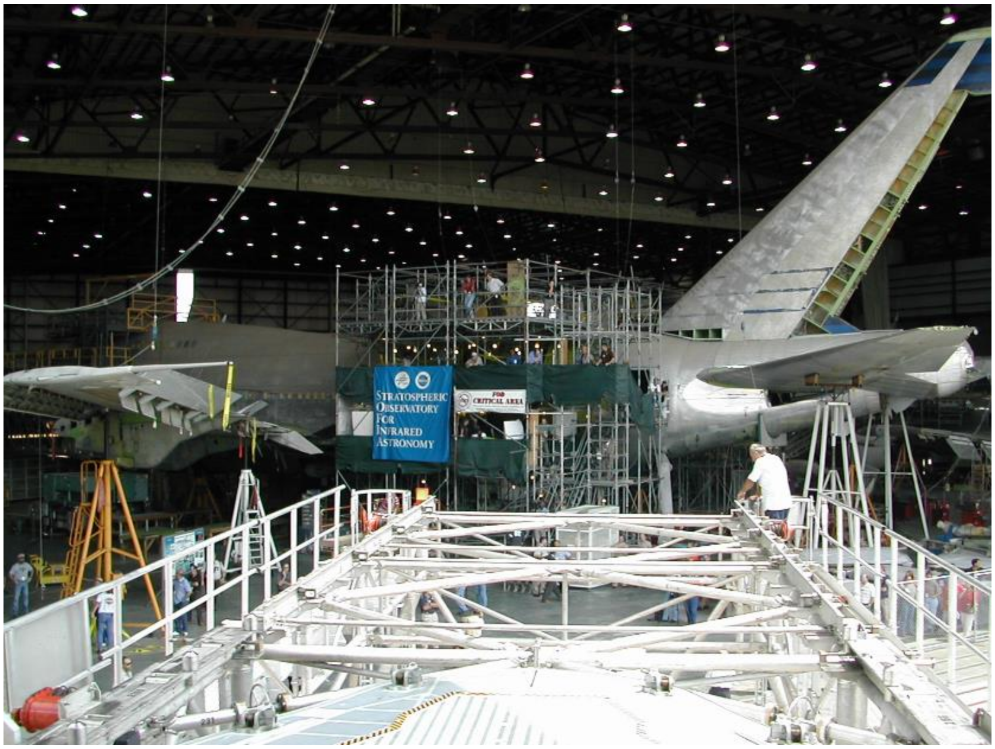


Figure 7.7-43. The view/status of the SOFIA aircraft as seen from the deck of the Beluga at the time of the SOFIA telescope delivery.

Figure 7.7-44. Not all telescope components were shipped in the Beluga; many were delivered via more normal shipping methods and arrived by trucks the following days.

Figure 7.7-45. Of course, this amount of unique hardware also comes with significant documentation (this is only a portion).

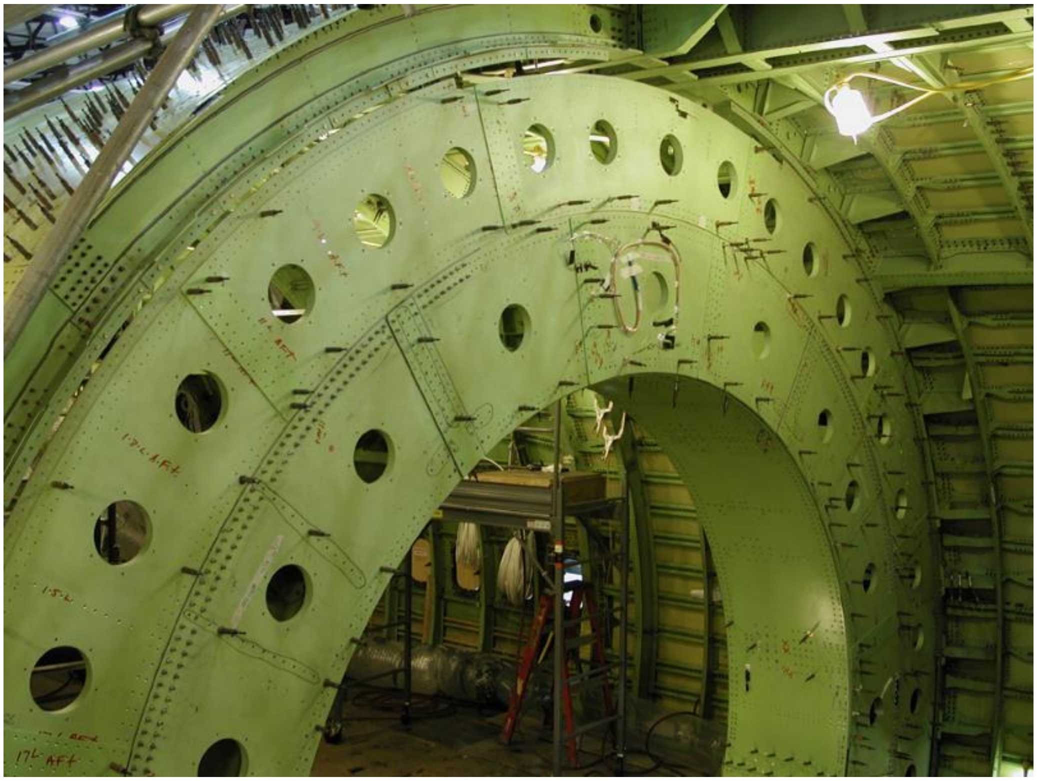


Figure 7.7-46. Status of the pressure bulkhead installation where the telescope will be mounted, looking forward from the cavity area into forward fuselage − October 2002.

Figure 7.7-47. NASA Ames Research Center technicians, John Wallace and Ron Strong, working down in Waco, Texas, preparing telescope support systems for installation into aircraft − October 2002.

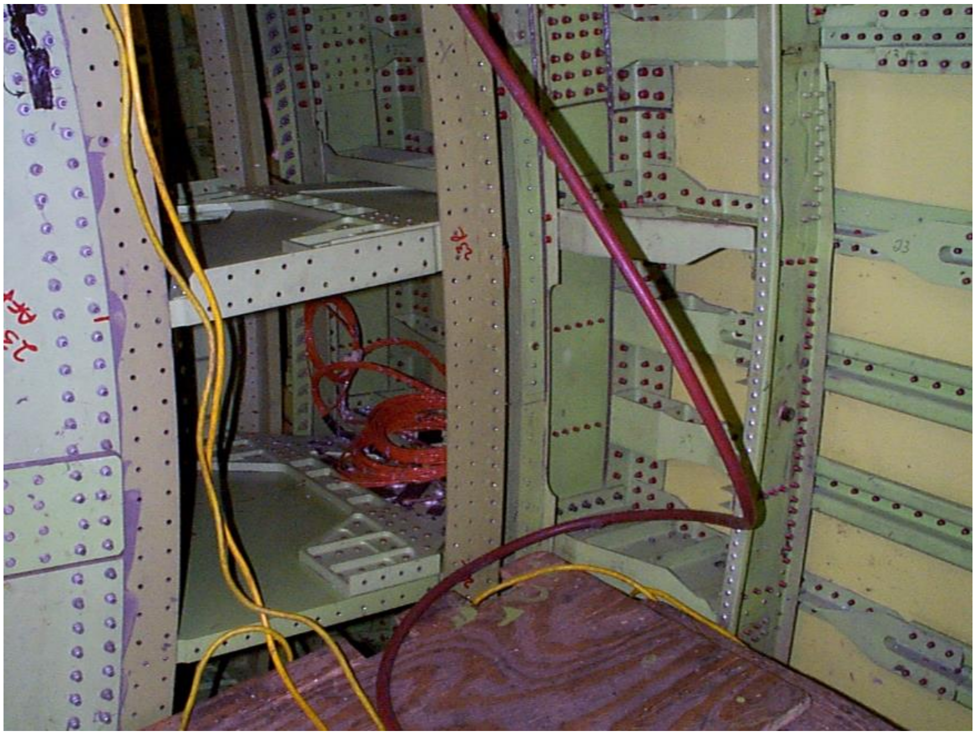


Figure 7.7-48. The pin joint pressure bulkhead being installed into the aircraft − November 2002.

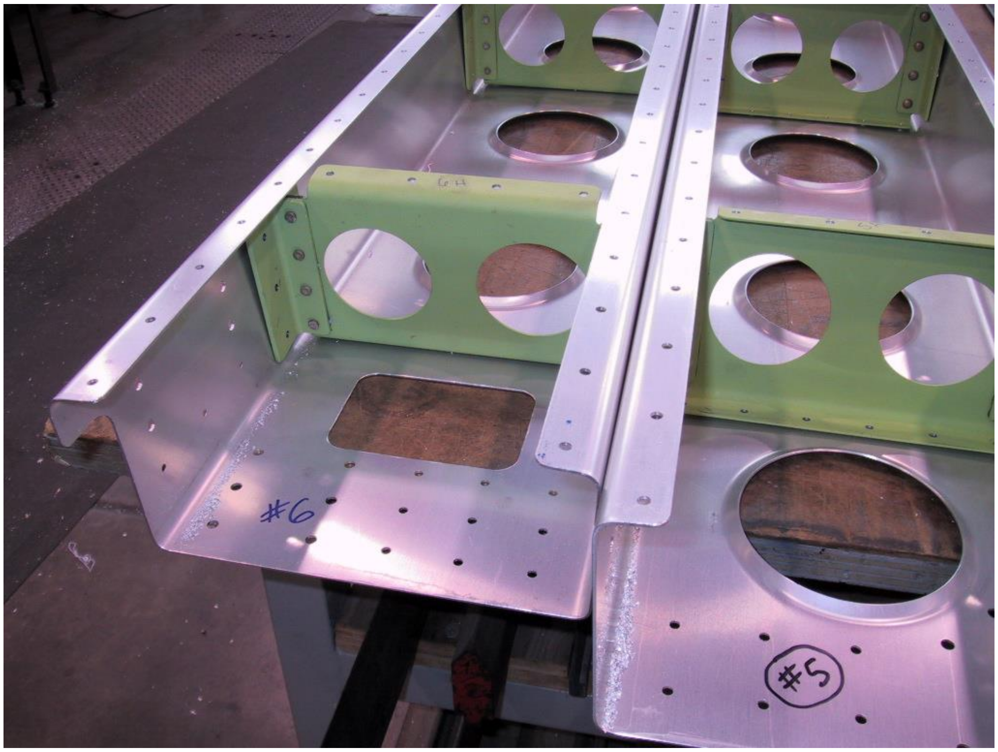


Figure 7.7-49. The segments of the LFD being assembled back at NASA Ames Research Center − December 2002.

Figure 7.7-50. The Secondary Mirror Mechanism being tested in the thermal chamber − December 2002.

7.8 2003

7.8.1 Telescope Integration into Aircraft Begins

Finally, the integration of the telescope into the aircraft began; at last, the airplane was ready to start installation of the telescope. After some problems with the lifting fixture, the first major piece of the telescope, the SUA, was installed in January as seen in Figures 7.8-4 to 7.8-8. This was another milestone event. At the same time, a lot of other SOFIA activities were in progress at several locations, as you can see in all the figures in this section, including the cavity door fabrication and verification going on up at Ames as seen in Figures 7.8-12 to 7.8-14.

Figure 7.8-1. SOFIA Science Steering Committee (SSSC) near SOFIA telescope bulkhead − January 2003.

Figure 7.8-2. SSSC members near SOFIA Landing Gear − January 2003.

7.8.2 Shuttle Columbia Accident – February 1

A tragedy that hopefully that everyone who reads this already knows about was the Shuttle *Columbia* accident that killed all seven astronauts during reentry of the space shuttle on February 1. I'm not going to include the lessons learned from that accident in this book, but I highly recommend everyone read the *Columbia* accident report as there are a lot of valuable lessons that are documented. However, having been around NASA long enough, I knew that a NASA-wide tragedy such as this would impact all NASA projects, when what I call the safety pendulum swings back to the safety side. I immediately took advantage of this to address several technical concerns that I hadn't been allowed to pursue due to cost and schedule issues. Fortunately, Chris Wiltsee (the SOFIA Project Manager) immediately gave me the go-ahead to pursue these concerns. Later that year, one part of the NASA-wide changes as a result of the *Columbia* accident was to create a position called independent Technical Authority (iTA with a small "i") and since I was the Chief Engineer for SOFIA, I became the iTA warrant holder for SOFIA. That allowed me to bypass both project management and center management and go directly to Rex Geveden, the Agency's Chief Engineer, with any technical concerns that I felt were not being addressed. This turned out to be extremely valuable; although I never had to use it, just knowing that I had this authority was enough to get done what I thought needed to get done. As you'll read later I did end up using it once, but it was not to bypass management at Ames.

Another result of the *Columbia* accident was the creation of the NASA Engineering & Safety Center (NESC), which also ended up having a positive impact on SOFIA—ironically, so since the *Columbia* accident was clearly a tragedy.

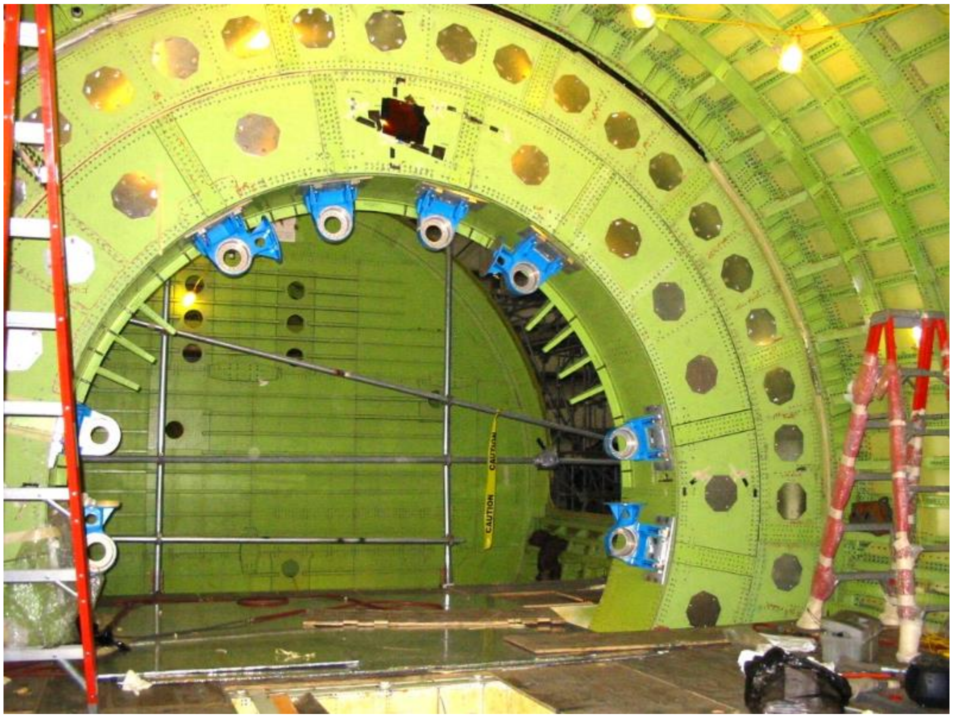


Figure 7.8-3. Inside the aircraft looking aft through the bulkhead where the telescope will be mounted and looking out a small portion of the cavity opening.
The telescope VIS bases (the blue hardware) are being fitted and aligned prior to beginning telescope system installation − January 2003.

Figure 7.8-4. The aircraft modification almost ready to begin installing the TA − January 2003.

Figure 7.8-5. Inside aircraft just before SUA installation.

Figure 7.8-6. Lowering SUA into cavity − January 2003.

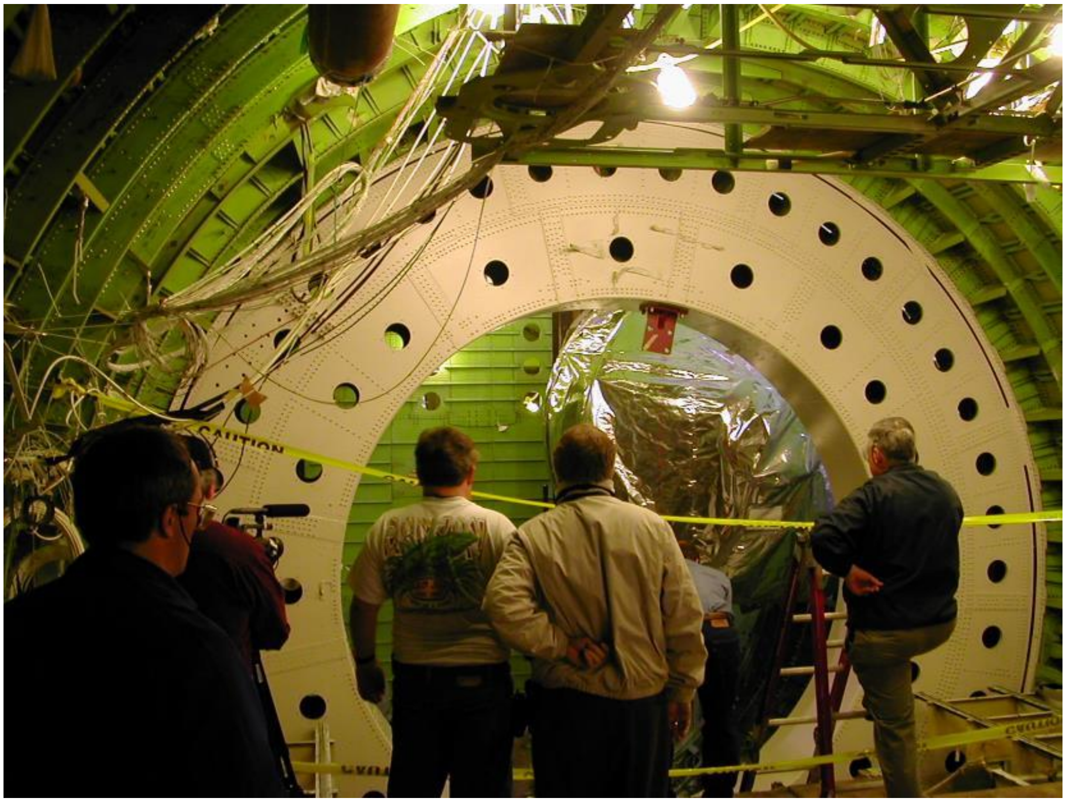


Figure 7.8-7. The view of the SUA being lowered into place from the inside of the cabin area looking aft − January 2003.

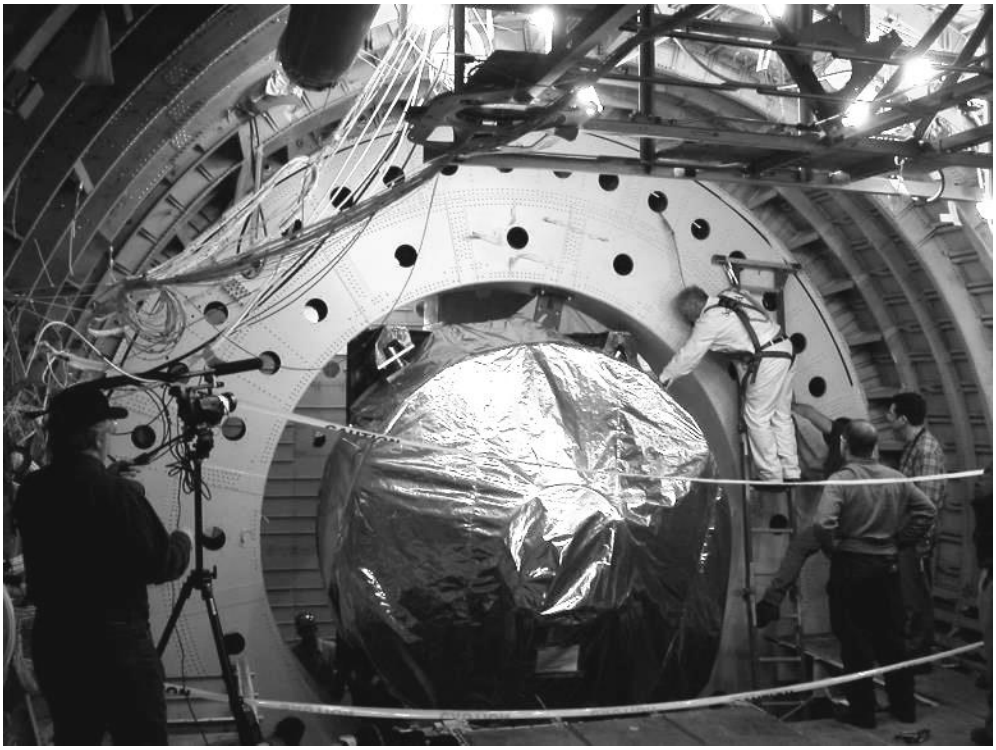


Figure 7.8-8. SUA almost in place.

Figure 7.8-9. The SUA installation continuing with NASA Ames Technicians John Wallace and Ron Strong helping out our German colleagues installing the VIS and related hardware that attaches the telescope to the aircraft − February 2003.

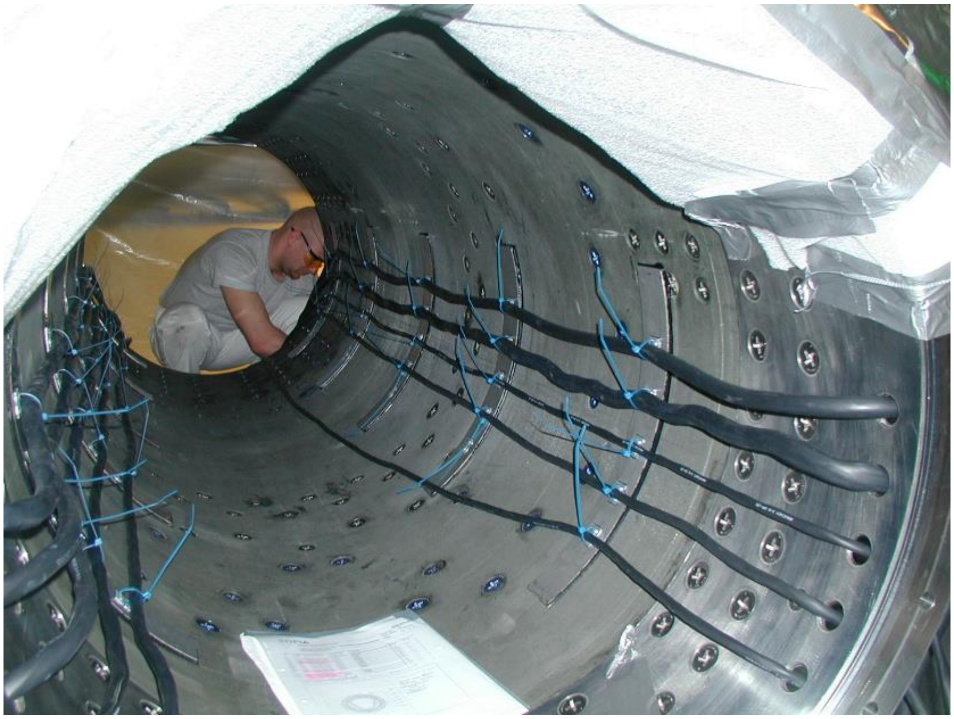


Figure 7.8-10. Inside the Nasmyth tube running the wiring from the cabin side to the cavity side of the telescope − March 2003.

Figure 7.8-11. Meanwhile in Austria environmental test facilities, the secondary mirror mechanism was being tested again to make sure it would work properly at the extreme temperature environment that it would experience during operations − March 2003.

Figure 7.8-12. Also in March, back at Ames, the Lower Flex Door (LFD) was being tested with sandbag weights to verify the structural integrity under predicted worse case loading − March 2003.

Figure 7.8-13. The LFD test setup with the first layer of 70-lb sandbags − March 2003.

Figure 7.8-14. The LFD with three layers of the 70-lb sandbags loading the structure with both the engineers and technicians handling load − March 2003.

Figure 7.8-15. Lifting the telescope carbon fiber metering structure to install into the aircraft cavity onto the SUA − May 2, 2003.

Figure 7.8-16. Lowering telescope metering structure into the cavity − May 2, 2003.

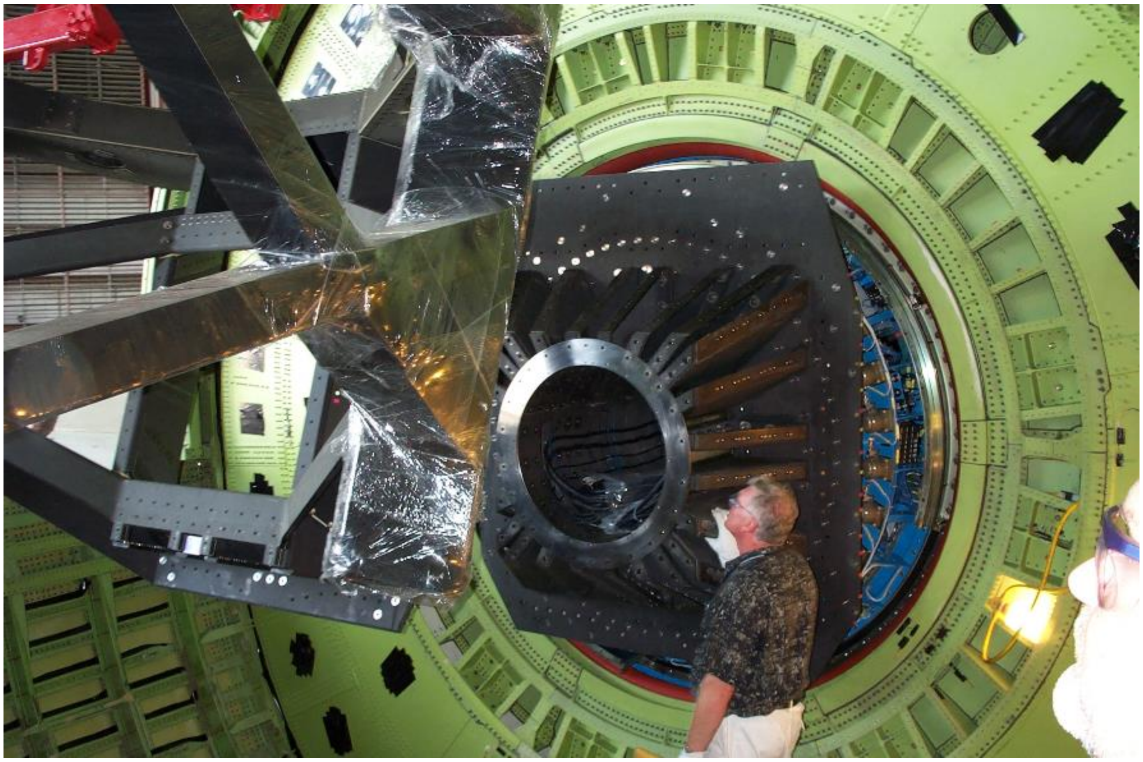


Figure 7.8-17. The telescope metering structure getting close to the SUA attachment interface in the aircraft cavity − May 2, 2003.

7.8.3 UAL Departs SOFIA Program under Bankruptcy Protection

Another event in 2003 was that, due to an airline industry downturn as a result of the 9/11 tragedy at the World Trade Center in 2001, coupled with economic difficulties and increased oil prices, United Airlines went into bankruptcy. As part of their new plan, United Airlines had to give up their role as a partner in the SOFIA development and operations. Despite this, several people who were long-time United Airlines employees chose to retire or quit United Airlines and continue to be part of the SOFIA team. At the time, this was very beneficial and looked like it would work out very well. This included United Airlines Chief Pilot, Tom Speers, as well as several key people involved with aircraft maintenance, several of whom moved into the offices in hangar N211.

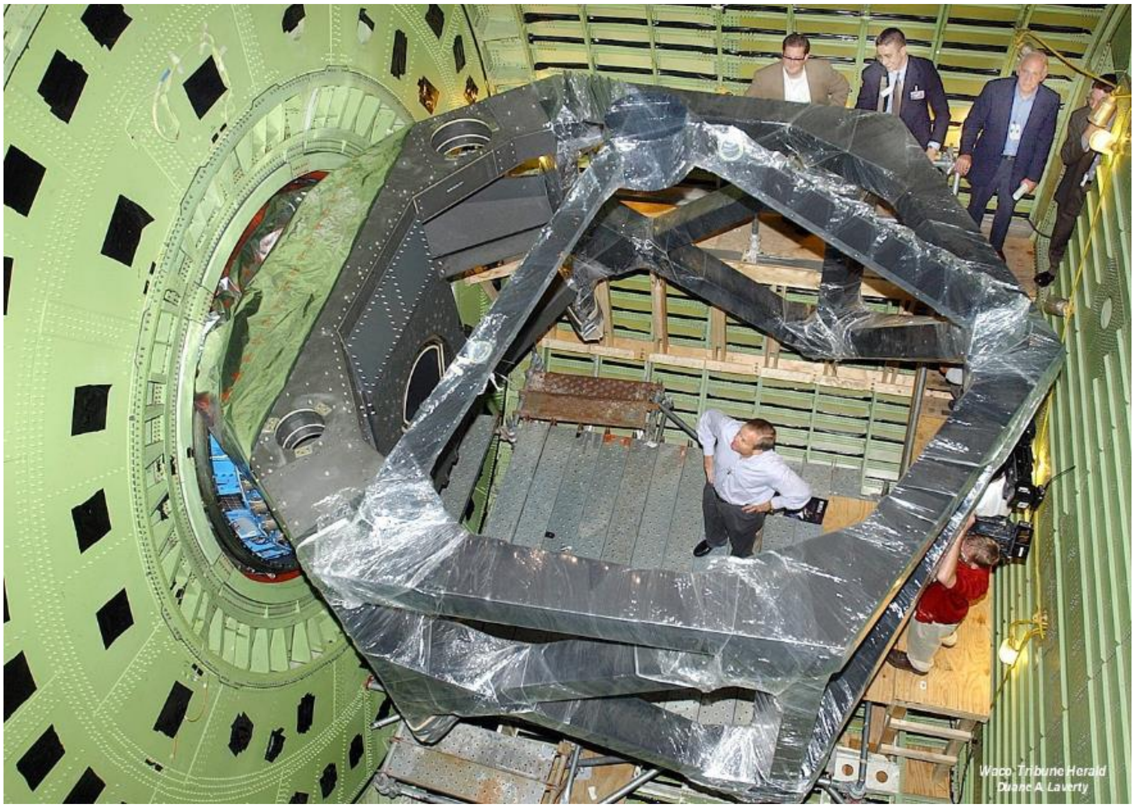


Figure 7.8-18. The telescope metering structure in the cavity almost ready for the installation of the primary mirror cell − May 2003.

7.8.4 Hangar at Ames is Ready

As you can see from Figures 7.8-19 and 7.8-20, the modifications and updates to optimize the hangar N211 to support SOFIA operations and include the mirror coating facility were completed and ready for the delivery of the aircraft and move-in of the operations team. Because of the height of the tail of the 747SP, the building had to be modified to include a notch above the hangar entry-door to accommodate the tail. N-211 seemed like the perfect fit to support SOFIA operations since the 747SP fit in, but not with a whole lot of room to spare. So, it was planned to be the only aircraft in the hangar with custom modifications such as the blue ramp as shown in Figure 7.8-20 that allowed direct easy access from the SOFIA offices and SI labs via a new elevator [the SI labs were on the ground floor] to the inside of the aircraft.

Figure 7.8-19. The outside of Hangar N211 at Ames showing the large notch modification installed above the door to accommodate the tall tail of the 747SP.

Figure 7.8-20. The inside of Hangar N211 at Ames with modifications for SOFIA complete including the mirror coating facility and a custom on-ramp to help deliver the SIs from the SI labs to the door of the SOFIA aircraft − June 2003.

Figure 7.8-21. John Wallace, Andy Roberts, Ron Strong, and Walter Miller − June 19, 2003.

Figure 7.8-22. The cavity aperture and some of the cavity door parts at Ames − June 2003.

Figure 7.8-23. That's me posing in front of the primary mirror assembly just before the beginning of the installation − July 15, 2003.

Figure 7.8-24. Primary Mirror installation − July 15, 2003.

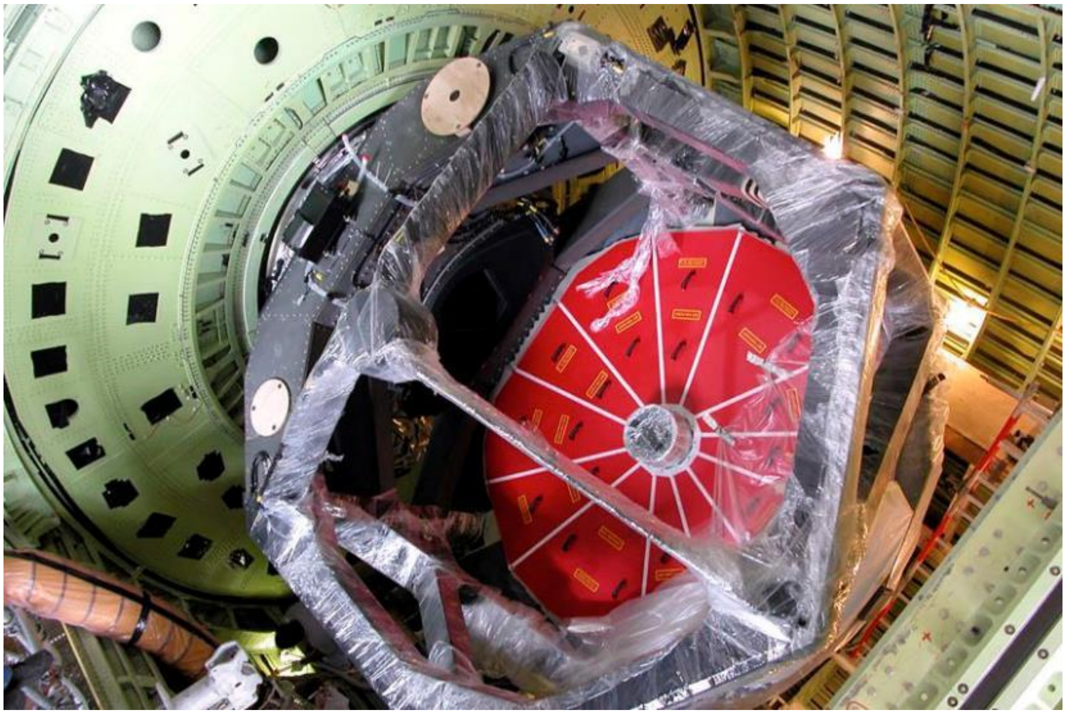


Figure 7.8-25. Looking down into the SOFIA open cavity with the most of the telescope major assemblies installed.

Figure 7.8-26. John Fitch, Carol Carroll, and Cliff Imprescia in the SOFIA cavity with the telescope − July 23, 2003.

Figure 7.8-27. Tom Bonner presenting award to Walter Schubach at his farewell celebration July 23, 2003, with Chris Wiltsee in the background.

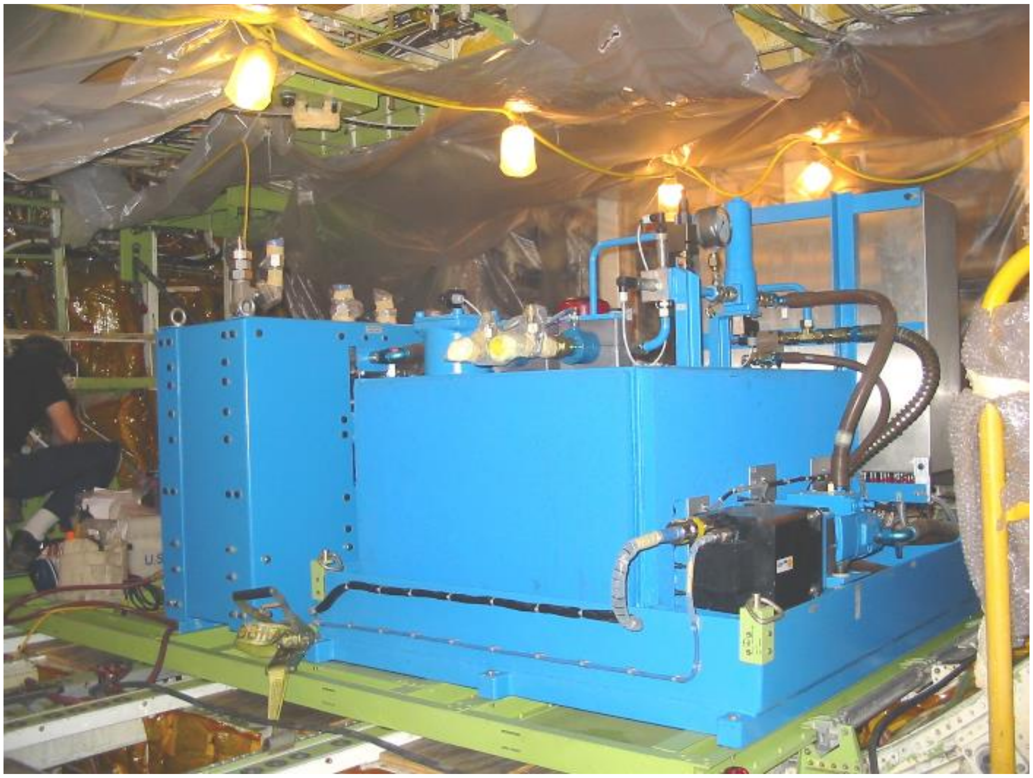


Figure 7.8-28. Another TA support system (the hydraulic system for the RIS) on a pallet installed in the forward part of the forward lower cargo bay (under the main floor) − July 31, 2003.

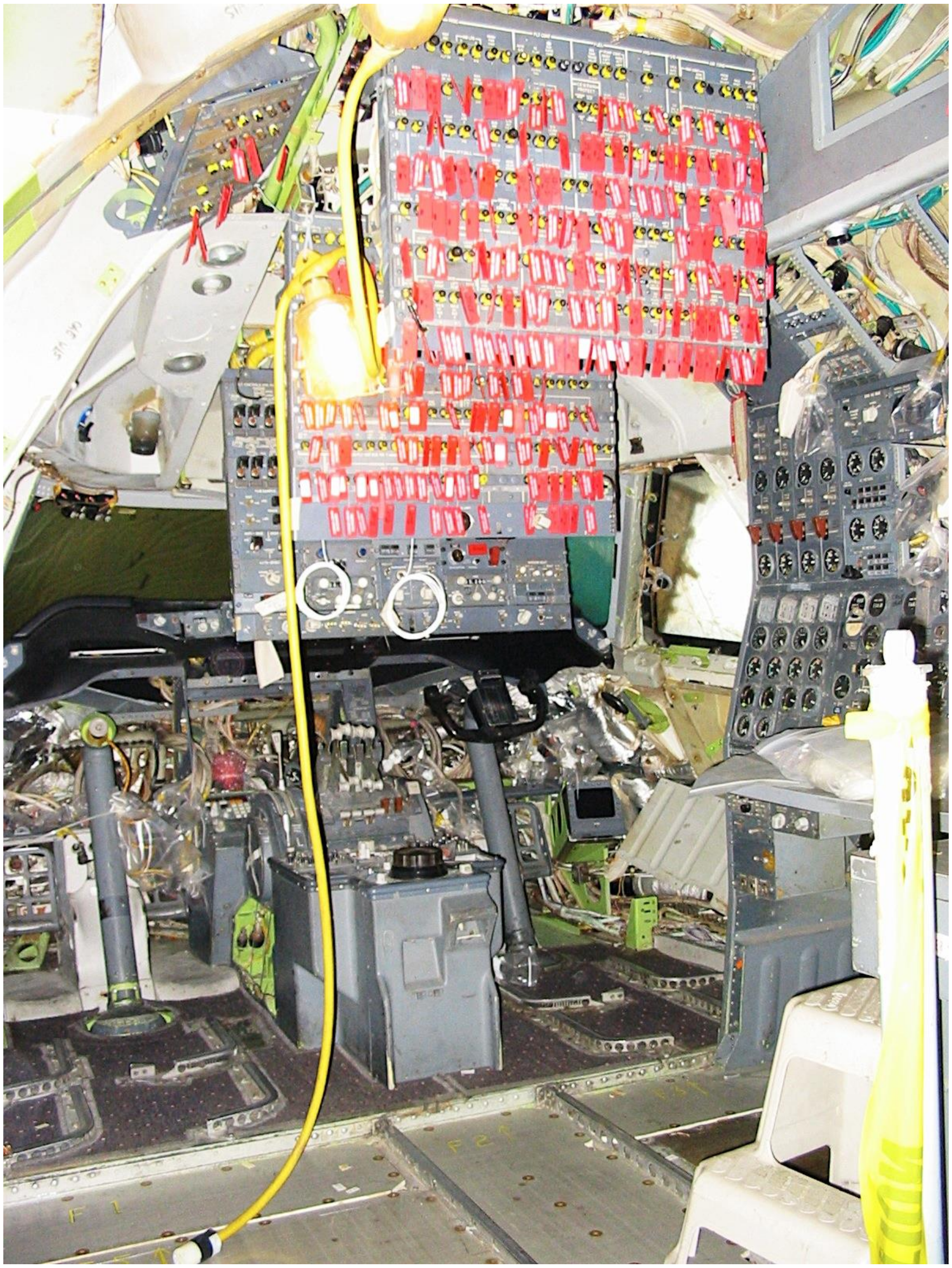


Figure 7.8-29. Status of the SOFIA cockpit − August 8, 2003.

Figure 7.8-30. The aft racks that are part of the telescope being installed and hooked up − August 2003.

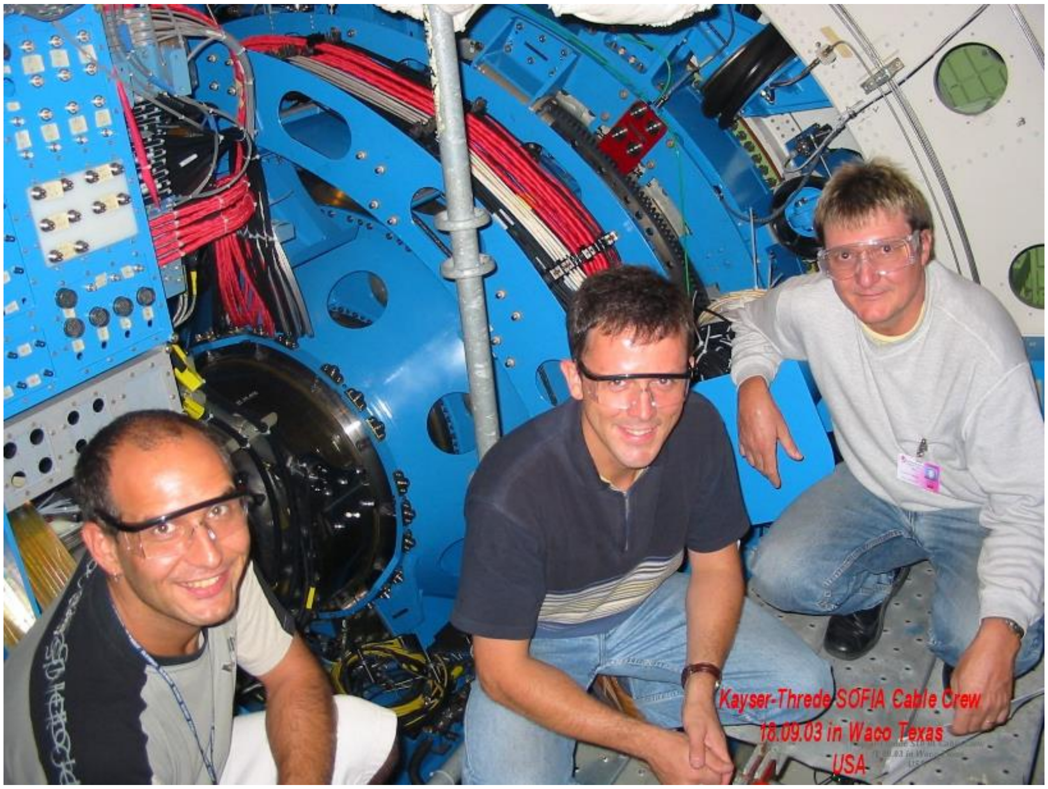


Figure 7.8-31. Part of the German team from Kayser-Threde that installed the cables from the many telescope consoles to the many locations on the telescope − September 18, 2003.

Figure 7.8-32. Looking aft in the upper deck of SOFIA, showing the Water Vapor Monitor installed onto one of the former window locations − September 19, 2003.

7.8.5 Telescope Installation into Aircraft

A lot of progress was made installing the telescope and supporting systems into the aircraft in 2003. Since the airplane modification itself was not complete, the installation was proceeding in parallel with aircraft maintenance and modification work. As a result, people from NASA and several companies and organizations from all around the world were working side-by-side making progress on SOFIA. As you can see from Figure 7.8-33, the physical installation of the telescope into the aircraft was essentially complete in the fall of 2003. Of course, a lot of systems still needed to be hooked up and verified prior to having a completely operational telescope.

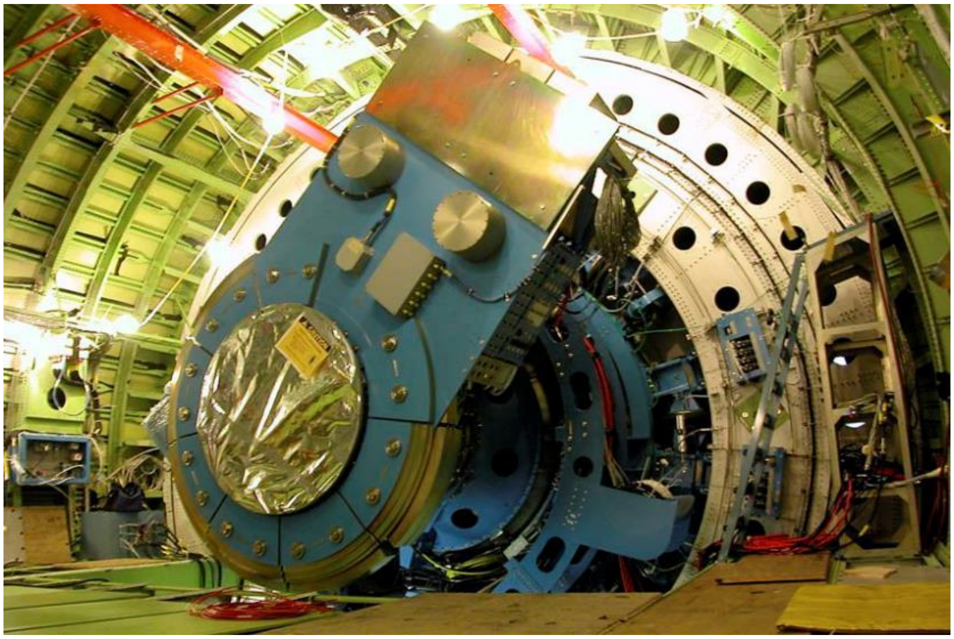


Figure 7.8-33. Inside the aircraft looking aft − Fall 2003.

7.9 2004

As 2004 started, we were a little over 1 year away from our scheduled ORR. The general status was the telescope was mostly installed and the aircraft structural modifications were also mostly complete. It seemed like many unexpected delays were caused by the normal routine maintenance associated with an almost 30-year-old airplane. When the 747SP that we had purchased to make SOFIA was taken out of service by United Airlines, its economic life was used up. So the aircraft for SOFIA was due for all kinds of maintenance, of course including the D check, which is about 80,000 hours of labor plus the time it takes to fix and repair any problems found. Another 747SP one serial number away from the one we actually used was also operated and maintained by United Airlines and ended up in a boneyard and had been cut up to provide the aft fuselage—so-called Section 46—for the test fit and installation of the dummy bulkhead.

Although L3 has aircraft engineers and technicians, it does not normally do D-check maintenance. In addition to lacking the number of experienced technicians, L3 also lacks some of the infrastructure to do a D check for the 747. Similar to work that is done, for example, on your car by a dealer, where they have an official book that tells him how long it should take for a given task, the D check is the same. However, the actual hours that were being spent doing the various maintenance tasks were over a factor of 2 more than the book rate. For example, in a normal D-check facility, there is scaffolding that allows technicians to get into any point of the airplane fairly easily such as the tail, which for the 747SP, is over 60 feet off the ground. In order for a technician at L3 to reach the tail required a Cherry Picker, which of course requires an operator, and for safety, another person on the ground. So instead of one person, this task now required three people and a piece of heavy equipment. And of course, with a cost-plus contract, L3 received pay for all their time regardless. Looking back, it appears that despite the large amount of the airplane that was modified, it probably would have been better to have done the D check at a normal maintenance facility prior to the start of the modifications. At the time, the D check would have cost around $8 million. So even though it seems wasteful to start removing and modifying structure that was freshly maintained, it probably would have been much more cost effective and less impactful on the schedule if the D-check work had been done at the beginning in parallel of the design phase. This was pointed out to me by Tom Speers, the former Chief Pilot of United Airlines and the Chief Pilot of SOFIA at that time.

Lesson 8:

If your project involves making a modification of a used airplane, consider getting the routine maintenance up-to-date prior to the start of the modification even if the modification involves altering the parts of the airplane affected by the maintenance.

Figure 7.9-1. SPO management getting another tour/status update from John Fitch (the L3 SOFIA manager) − January 2004.

Figure 7.9-2. Another piece of unique SOFIA hardware, the dessicant dryer system whose purpose is to keep the telescope dry during descent after the telescope has been cold soaked to 40,000 plus feet atmospheric conditions while observing out of an open port cavity. This hardware was developed and made by CTT, in Nykoeping, Sweden. Delivered to Waco − January 2004.

Figure 7.9-3. Aircraft control surface components being refurbished and prepped to be painted − April 2004.

One of the key milestones of the modifications is the proof pressure test in which the airplane is pressurized to 1.33 times the maximum expected operating pressure plus a margin for the relief valves, so the test was at 12.5 psi. As you might expect, a 747 fuselage is a very big balloon and 12.5 psi is a very high pressure so this test which is a verification of the structural integrity that involves a very high amount of potential energy. Just so you have some appreciation of the forces involved, the total force on just the bulkhead is about 650,000 lbs. Since the telescope is mounted into the bulkhead and so is also part of the pressure barrier, it also receives a fair amount of this force that gets transmitted to the bulkhead via the VIS and the flexible seal. As you can see from Figures 7.9-7 to 7.9-9, it was a very suspenseful event, but we succeeded.

Figure 7.9-4. Photos show an example that in addition to all the unique engineering aspects of creating the modifications and additions required for SOFIA, that we also have an old used airplane that needs maintenance as well − April 24, 2004.

Figure 7.9-4 shows one of the main floor beams in front of the telescope installation where the floor is actually part of the fuselage pressure boundary over the wheel well had a major crack that needed to be repaired. One example of a great many maintenance tasks done in parallel with the SOFIA modifications. The figure on the right shows where the cracked area was removed. Figure 7.9-5 (left) shows the crew working on this repair including Albert Ruggles, Raytheon's/L-3's lead structural engineer. The photo on the right is the finished repair.

Figure 7.9-5. Photo on the left is the crew working on this repair; on the right is the finished repair (April 24, 2004) just a few hours before the proof pressure test.

Figure 7.9-6. The aircraft shortly before starting the proof pressure test with a net to provide some safety/containment in case of structural failure.

Figure 7.9-7. The back room of the hangar during the proof pressure test with all of us watching the numbers as the pressure increases.

Figure 7.9-8. A very suspenseful event as the pressure inside the fuselage increases.

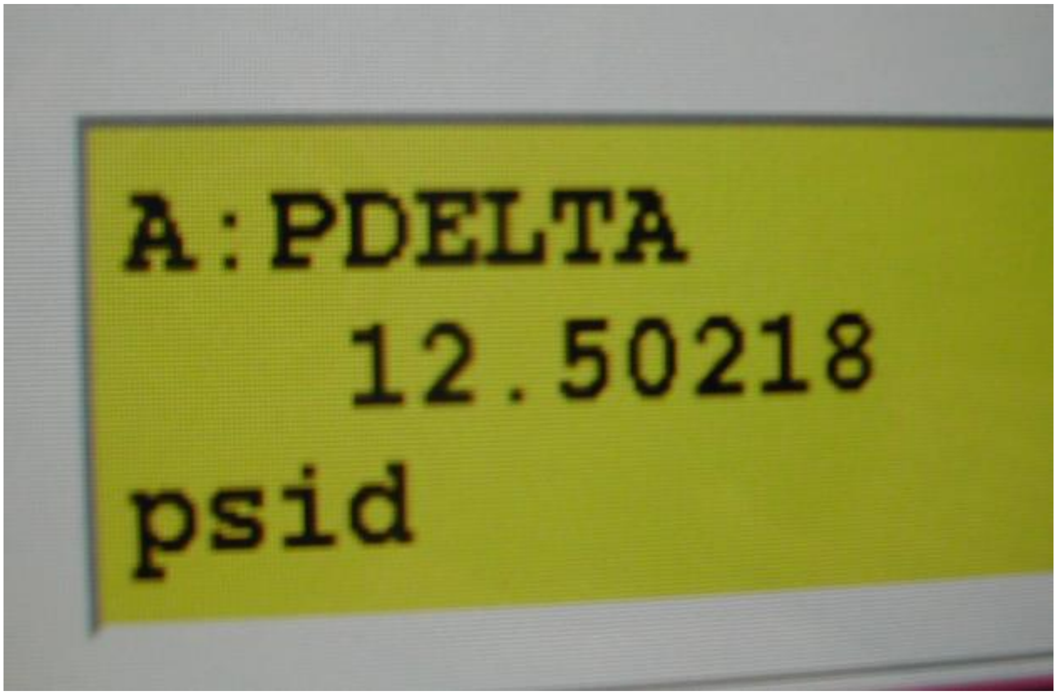


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Figure 7.9-9. Requirement/goal successfully achieved − April 24, 2004.

7.9.1 First Light Tests of the Telescope; ORR Re-planned

Shortly after this proof pressure test, the telescope integration was complete. In August, ground-based tests of the telescope were made from the ramp by observing stars with the High-speed Imaging Photometer for Occultations (HIPO) SI mounted at the focal plane. After some minor problems with the telescope controllers’ software was fixed, the telescope was shown to be fully operational, see Figures 7.9-10 to 7.9-12. The point spread function in the focal plane (Figure 7.9-11) was somewhat distorted because the backup aluminum secondary mirror was used instead of the high optical-quality silicon carbide secondary mirror. So in August 2004, we had a working telescope and verification of the structural modification of the fuselage as well as the connection between the telescope and the fuselage. According to the program’s schedule, we were due to reach ORR March of 2005. At first, it did not seem impossible to reach this milestone in the 7−8 months remaining.

However, at the monthly review in September in Waco, the L3 engineers described all the work on the aircraft and mission systems that was left to do and the staff on hand to do it. It was a very memorable event: several of the top managers were arguing that it was possible, but a logical review of the numbers associated with the remaining work plus the schedule performance of the past few years just didn’t support their contention that it could be done. This review was also attended by several scientists, who, as much as they wanted this to be true so they could start observing, argued that the managers’ proposed schedule was grossly overoptimistic. There were very passionate arguments at this particular review, but the NASA and USRA managers adamantly maintained their position. It turned out the ORR date they announced was badly missed, as I predicted, again with serious negative repercussions from NASA HQ.

Also in September, the new NESC started an independent review of the open port cavity and whether it would be safe to begin the flight-testing. Although they were not invited by anyone on the SOFIA project, I welcomed their independent review. They were brought in because of a concern by Warren Hall, the chief pilot at Ames. Since we were pushing the limits so far beyond other open port cavity experiences, I was happy to have this in-depth technical review.

Later in 2004, the cavity door installation started. As I mentioned earlier, the cavity door engineering team was based at Ames. Their effort was part of one of the work packages offered to the contractors. So this Ames team started making a lot of trips to L3 at Waco.

Meanwhile, back in Germany, DLR created the DSI, based at the University of Stutgart, to support SOFIA science operations.

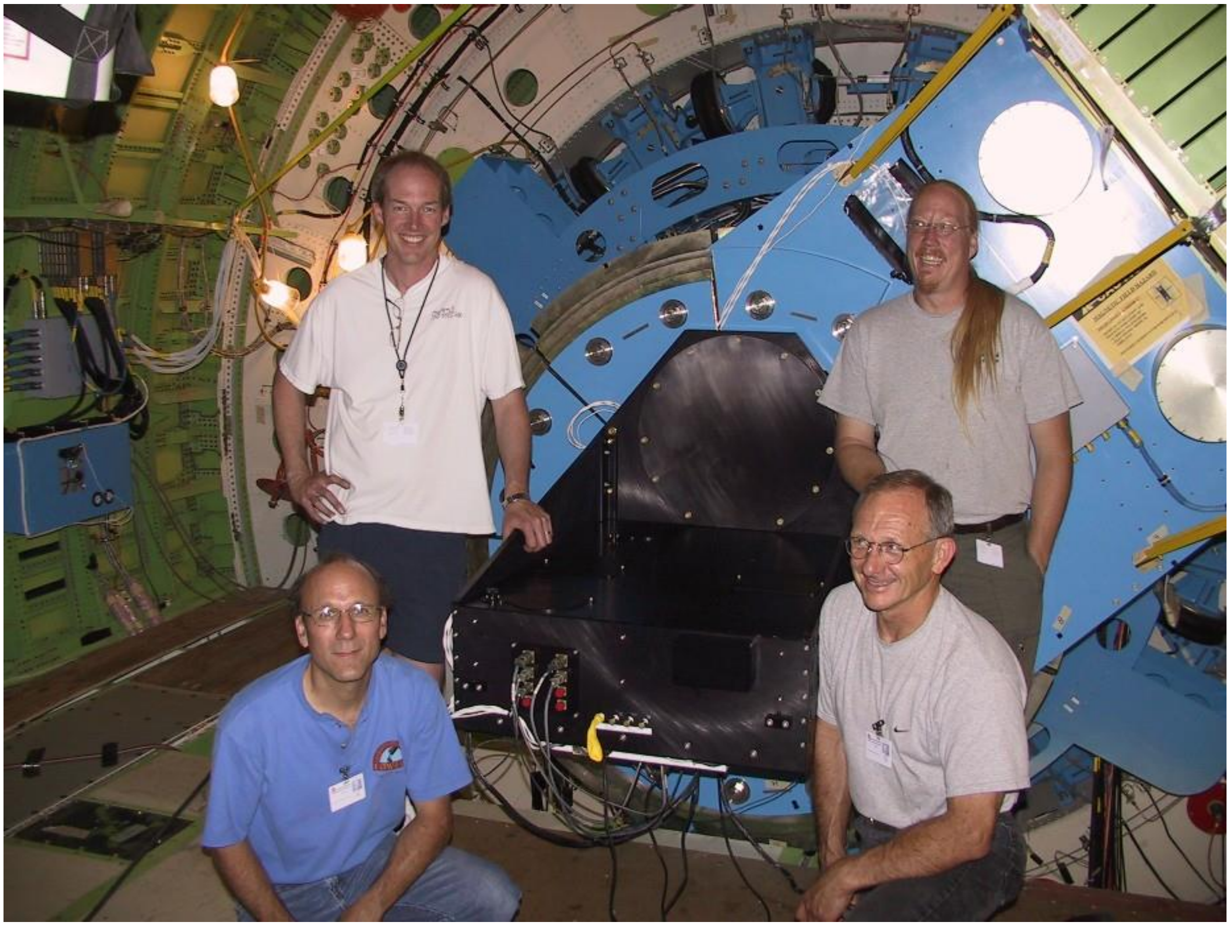

Figure 7.9-10. Dr. Ted Dunham and his team with his HIPO SI installed on the telescope—the first instrument to be installed on SOFIA − August 16, 2004.

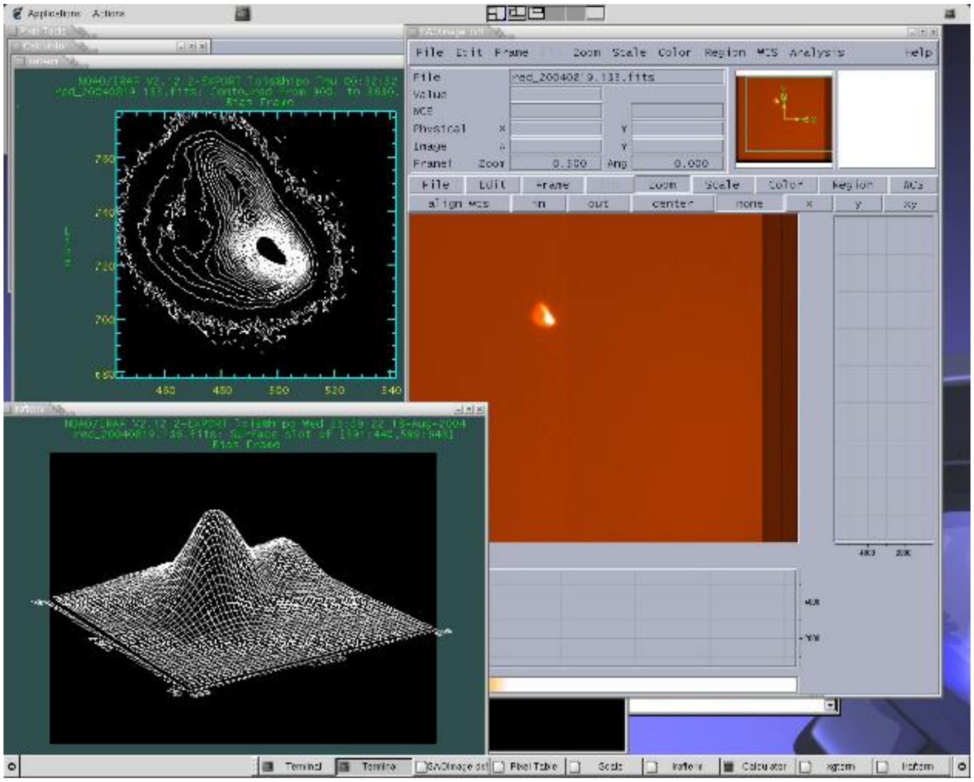

Figure 7.9-11. A screen shot from the SI output, from successful line operations − August 19, 2004.

7.9.2 Ground-based − Line Operations Demonstrated

Figure 7.9-12. Open port cavity with working telescope − September 2004.

7.9.3 “First Light” August 2004

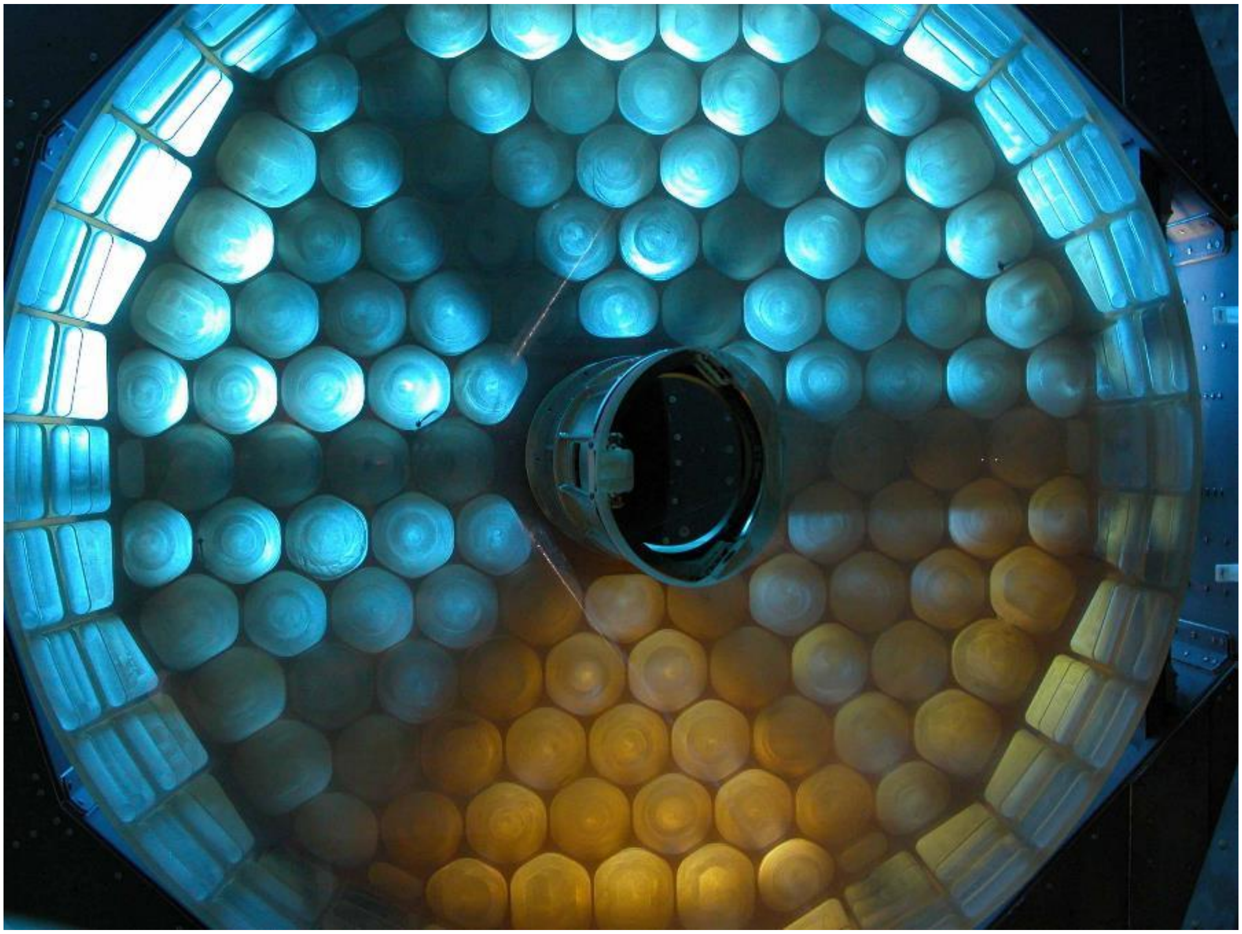

Figure 7.9-13. The astronomy Picture of the Day October 22, 2004 of the SOFIA primary mirror mounted in the SOFIA cavity prior to the reflective aluminum coating being applied and being lit from behind showing all the light weighting machined honeycomb structure. Photo by Ron Strong.

Figure 7.9-14. NASA Ames engineers Glenn Sasaki and Fred Martwick helping install the partial external door − December 2004.

7.10 2005

The cavity door installation was underway. As mentioned earlier, the cavity door was a government work package, so the engineering team for the door was based at Ames and as it turned out, the final fabrication of the door components was also done at Ames. Also, as mentioned earlier, one of the challenges for the door was to have well-controlled motion while being mounted to the flexible fuselage structure. This did require the precise installation of some key components. As you can see from Figures 7.9-14 to 7.10-7, the Ames cavity door team spent a lot of time in 2005 down in Waco, Texas. And by the end of the year, they had made great progress, as shown in Figures 7.10-9 and 7.10-10.

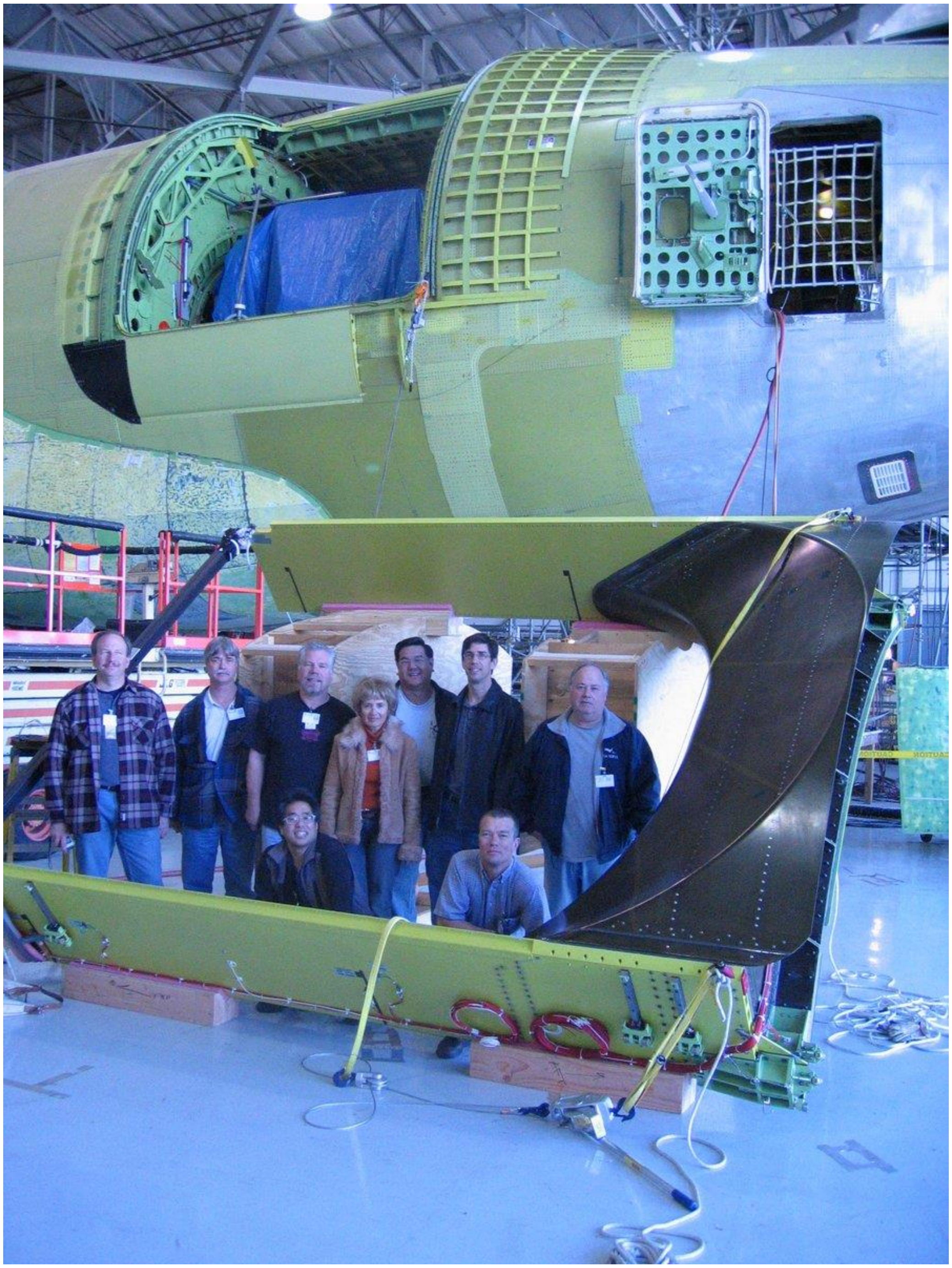

Figure 7.10-1. The Cavity door team posing with the aperture that is being prepared to be installed − January 2005.

Figure 7.10-2. NASA Ames engineer John Perry working on cavity door system installation.

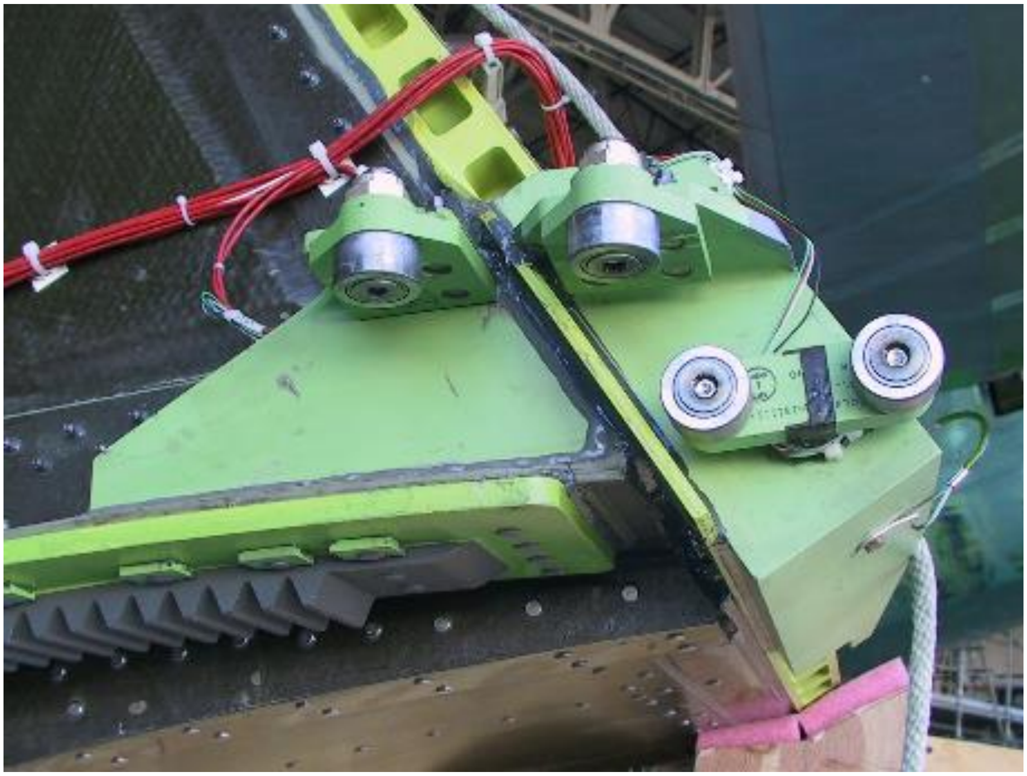

Figure 7.10-3. Just a small sample of multiple sets of mechanisms that enable precise cavity door motion while accommodating the flexibility of the 747 fuselage structure.

2005 was supposed to be the year we reached ORR per the second master schedule, but as it turned out, we didn't make it. The primary delays were not caused by SOFIA-unique modifications, but more by routine maintenance and installation of fairly standard support equipment. Also, by this time, L3/USRA had blown their cost and schedule incentives. So they were strictly on a cost-plus contract from a business perspective. In addition, L3 had another major customer who happened to have a fixed-price contract with penalties for schedule slips, so you could imagine where their first-string technicians were working.

Lesson 9:

When your cost-plus work is being done within the same facility as someone else's fixed-price work (with schedule-slip penalties) don't expect to get the first-string team to be working on your job.

Corollary: Carefully consider the formulas for cost and schedule incentives. If not properly specified and managed, then at some point, they may hit a floor and then all incentives for the contractor to deliver quicker at a lower cost are gone.

Figure 7.10-4. Cavity Door aperture being installed − February 2005.

Figure 7.10-5. Cavity Door Aperture in place showing the aft ramp that we developed for SOFIA to catch the airstream-shear layer and provide a quiet cavity environment for the telescope during open-door flight.

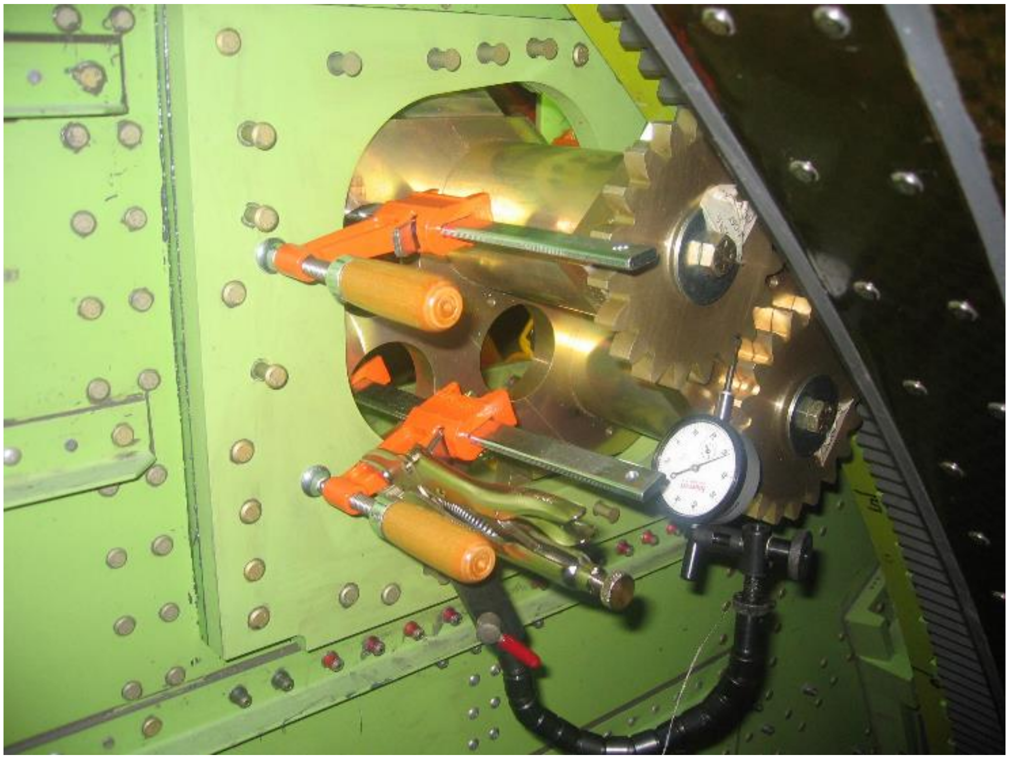

Figure 7.10-6. One of the cavity door drive systems being measured for a proper tolerance fit during the installation process − April 27, 2005.

Figure 7.10-7. The NASA Cavity Door System Engineering Integration Team posing in front of the cavity opening after the successful installation of the lower flex door − May 2005.

Figure 7.10-8. September 2005 Tour of SOFIA during the executive management review.

L3 was still trying to get the maintenance done and they were hiring extra manpower, and some of them had questionable expertise. As a result, there were about three mishaps that were close-calls which caused a work stoppage. Regarding the maintenance, a mod audit was conducted to verify that what was already done had met all the required standards.

As a result, the ORR milestone was missed. Also, perhaps related, Cliff Impresca, the Program Manager for SOFIA and the Director of the Engineering Directorate at Ames, retired. Per International Conference on Smart Material Research (ICSMR) recommendations, a new approach began under new program management. It took awhile, but later that spring, Joel Kearns was assigned as the new program/project manager. Joel was primarily hired (from industry) as the engineering director for Ames from outside of NASA, but again, our Ames engineering director also ended up being the program manager for SOFIA. At this time, we also had a deputy program manager, Carol Carroll. As Joel came aboard the SOFIA Program, he did not impose any drastic, immediate changes in approach. He first spent a lot of time with a lot of us that were already working on SOFIA to come up to speed; it was a very smooth transition. It was also clear that the privatization approach wasn't working under USRA's direction, so program control was being transferred back to the SPO at Ames. One of the first priorities was to come up with a credible master schedule. Joel did this by involving all of the key players and although it took a little longer than planned, by August, we had completed and established an IMS under control of our SPO. It had way over 5000 lines linking all program elements and listing very specific deliverables.

In the monthly reviews that followed, it was clear that this new approach was working. The schedule clearly identified what was to be completed by each monthly review. It also identified the critical path, which allowed the resources to be moved, adjusted, and optimized so that the critical path milestones could be met. And now since the schedule had credibility, people made sure that they either completed what they were supposed to complete or had a good explanation of why not, plus a plan for recovery. With this credible schedule, it looked like we were finally going to get to first flight by the end of 2006.

Lesson 10:

For a project of this size, it is essential to have a detailed Integrated Master Schedule (IMS) to clearly identify the critical path and to have enough detail such that the time estimates are credible. This IMS can then be used to help manage the resources and priorities to meet scheduled milestones.

More good news: in October, the independent review, being conducted by the NESC, about the cavity acoustics was completed. Their conclusion was that we had done all our homework, meaning analysis, wind tunnel testing, CFD, etc. and the results showed we were good to go to begin flight testing.

Figure 7.10-9. Cavity door system mostly installed − October 20, 2005.

Figure 7.10-10. Showing status of SOFIA. Late 2005 at L3 down in Waco, Texas.

7.11 2006

2006 turned out to be a very rough and wild year for SOFIA. It started with the SOFIA proposed budget for fiscal year 2007 being zeroed out. Per the current budget law, it states that the President must submit the following fiscal year budget to Congress between the first Monday in January and the first Monday in February. So in 2006, this happened the last week of January while I was skiing with the NASA-wide ski trip at Vail, Colorado. This was before smartphones, so while on vacation, I had not heard anything about this, probably a good thing. When I returned to work, I learned about this and was shocked. But, I also learned that the NASA administrator, Mike Griffin, had already been grilled by Congress as to why SOFIA was being cancelled. Actually several people pointed me in the direction of the online video where he was being grilled by Congress and I saw that his answers based on the premises of technical issues were not correct. So, I had a dilemma. Although no one in either the SOFIA project management or the center line management asked me specifically to do anything, it seemed like they were looking for me to do something. It took me a few days to think about it, but per the independent warrant holder that I was, thanks to the *Columbia* accident in 2003, I had an official communication path to the NASA-wide Agency Chief Engineer, which at that time was Chris Scolese. So I decided to write an email to him describing the technical status of SOFIA. I did not mention Mike Griffin's testimony nor directly say anything about what he said being wrong. But I did give a technical status on SOFIA in several areas including the same area that he had been questioned about. I wrote the email very carefully, primarily as a brief technical status to inform the agency Chief Engineer. Of course, when I sent it, I cc'd SOFIA Program Management and Ames center management.

Then I went on my annual ski trip to Mammoth Mountain with my friends and colleagues, a trip we had been doing for more than 20 years in the last week of February. When I came back to the office, again, another huge surprise. A lot of people looked at me kind of funny like, "it was nice knowing you." Finally, some people directed me to watch the video of more Congressional grilling of NASA top management. In this case, it was Congressman Ralph Hall grilling Dr. Mary Cleave, the Associate Administrator of Science Mission Directorate (SMD), about SOFIA. He directly asked her if she knew Nans Kunz and if she respected his engineering skills. She answered yes. Then, he stated things from my email that the technical status of SOFIA was fine. As you can see from Figure 7.11-4, my email also showed up on NASA Watch under the title, *SOFIA's Engineer Contradicts Claims by Griffin and Cleave*. Because of this, a lot of people gave me credit for saving the SOFIA Program, but they also thought that my time might be limited. Fortunately, my email did not mention or criticize anybody. If you like, as of the writing, my email is still on NASA Watch and is available for you to read in its entirety. The key points raised in my email were that we had done our due diligence. Plus, we had been reviewed by the best independent review organization, the NESC, and they concurred that we were ready to proceed. This, in addition to our German partners raising issues regarding the joint agreement involved with our development and our operations of SOFIA, prevented SOFIA from being cancelled outright. Instead, a SOFIA Options Review Team (SORT) was commissioned to consider options for the future of SOFIA.

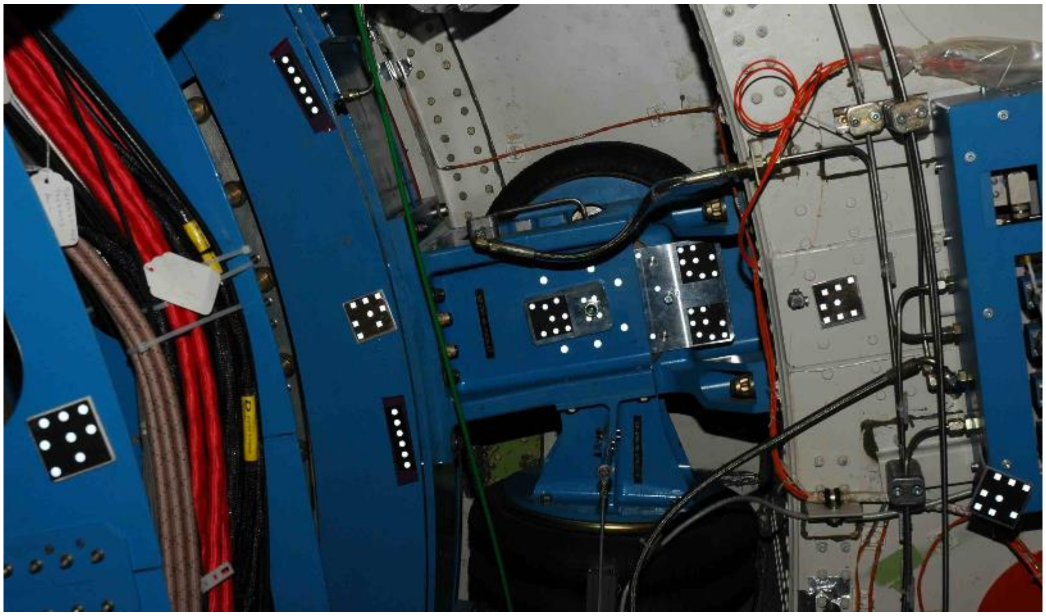

Figure 7.11-1. Special targets used with a photographic technique and post-processing to measure distances and orientation of various systems of the telescope.

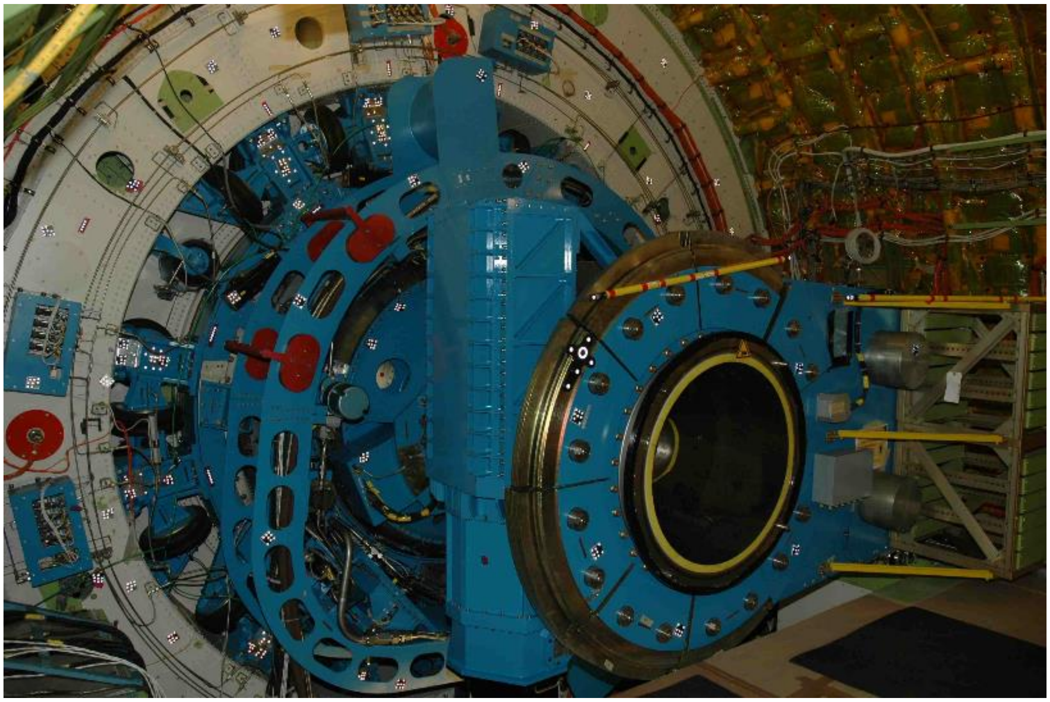

Figure 7.11-2. The telescope with special reflective targets to calibrate/measure the various coordinate systems.

Figure 7.11-3. Control cables for the empennage: this view is from the fuselage area aft of the telescope cavity looking forward where you can see the control cables that are re-routed from near the top center of the fuselage to lower down on the right side − January 2006.

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SOFIA's Engineer Contradicts Claims by Griffin and Cleave

By Keith Cowing on March 4, 2006 6:56 PM

Memo From SOFIA Chief Engineer to NASA Chief Engineer Chris Scolese regarding SOFIA Technical Issues

"I am the Chief Engineer of the SOFIA Program and under the current implementation of the iTA I am also the Systems-Technical Warrant Holder (STWH). This email is in regard to the SOFIA technical issues that were raised during the House Committee Hearing for NASA's 2007 Budget Proposal last week (February 16th)."

➡ **Editor's note:** Rep. Ralph Hall made specific mention of this memo in a question to NASA Science Mission Directorate Associate Administrator Dr. Mary Cleave during a House Science Committee hearing on NASA's FY 2007 science budget on 2 March 2006.

Figure 7.11-4. Screenshot of NASA Watch regarding my email about SOFIA's technical issues.

7.11.1 March SORT Review Held- Passed w/Flying Colors

The chairman of SORT was Kenneth Szalai, former center director of NASA DFRC. The team was put together and the review process was started. The key event was a multi-day presentation down at L3 in Waco, Texas. This occurred on March 20–22, 2006. There were many presentations and reviews plus tours of the SOFIA hardware for the SORT team. I personally was on the agenda for about a 1-hour presentation for the first afternoon. Since it was early in the process, I was asked a lot of questions. Fortunately, I was very involved in all of the technical issues of SOFIA and I was able to answer all the questions, including background, rationale, trade studies, testing verification, etc. As a result, my presentation lasted over 3 hours, but when it was over, several people came up and told me that I saved the program. The SORT team did their due diligence, reviewed everything, and was due to report their recommendations to Dr. Mary Cleave.

The debrief of the review was held in Washington D.C. on April 25, 2006, and although I was not part of the SORT team, I was invited to attend. Also in attendance was Dr. Pete Worden, the soon-to-be center director for NASA Ames Research Center. Despite that, it was my understanding that the charter of this review was not to include the continuation of the SOFIA Program, Kenneth Szalai, the chair of the SORT review did just that. In addition, he went out of his way to praise me, and indicate how important to the program I was; I was very flattered.

Figure 7.11-5. Status of SOFIA – May 25, 2006.

Figure 7.11-6. Inside looking aft towards the installed telescope.

Figure 7.11-7. Status of the cockpit.

7.11.2 June 2006 – Ground Vibration Test Conducted on Aircraft on Time per IMS Established August 2005

Meanwhile, back at L3, a major milestone was achieved on schedule. The ground vibration test, a major milestone with configuration audit and oversight by the FAA was completed on time per the IMS that was established the previous summer—the first major milestone that was on time for years. The shifting of program control back to NASA Ames was working; we finally had a credible schedule that was working, with the first flight scheduled before the end of the year.

7.11.3 HQ Meeting at KSC: Decision to Move Program Control to DFRC

But then we had an Agency Program Management Council (PMC) meeting at Kennedy Space Center (KSC). It was on June 15, 2006, and it involved Mike Griffin and Senior Engineering Management from all NASA centers. SOFIA was just one thing on the agenda. It was another debrief by Kenneth Szalai about the SORT review of SOFIA. And again, I was invited to this meeting that I had never attended before. A strange thing happened on my way to the meeting. As I got into the elevator to go upstairs to the meeting, I ended up with Mike Griffin and it was just the two of us in the elevator. I was debating with myself whether I should introduce myself considering my email that showed up on NASA Watch contradicting him, a few months prior. I ended up keeping my mouth shut, but to this day, thinking I should have introduced myself. During the meeting, the SOFIA debrief seemed to go well, I had considered speaking up, but again, I did not. The SOFIA recommendation was being discussed right before lunchtime and it appeared it was going to proceed as currently managed by NASA Ames. However, after lunch, somehow the recommendation was made to move control of the SOFIA Program to DFRC. At first, this appeared to be just related to the flight-test phase. That evening, in the lobby of the hotel, Robert Meyer, the engineering director at DFRC, asked me if I would stay on as the chief engineer of SOFIA. I said yes.

7.11.4 The Biggest Setback: My Evaluation of the Move to DFRC

In summary, after passing a very thorough review (SORT) with flying colors, SOFIA development was finally going great. We had actually met major milestones on time, based on the detailed schedule that was established a year earlier by the SPO at Ames. By that time, we were working under new and experienced Program management, and were in the process of moving away from the previously HQ-mandated privatization approach. We had a complete and credible schedule, which had us well on the way to the first flight in less than a year—with operations planned to start soon after. The N211 hangar modifications were completed and optimized for SOFIA operations based on lessons learned from over 20 years of KAO operations. The hangar included the unique mirror-coating facility as well as multiple SI labs, and everything needed for SOFIA operations to be within one building.

Also, despite United Airlines leaving the SOFIA Program, several very experienced aircraft maintenance personnel and managers took an early retirement from United Airlines to join the SOFIA Operations Team, and had set up their operations offices within N211. In fact, they had established enough infrastructure and documented enough of the operations maintenance procedures, that they had achieved certification of N-211 as an official FAA certified maintenance station.

Despite all these positive outcomes, and what finally looked to be a well-run program, apparently someone within NASA HQ thought it was time to make a major change to the SOFIA Program. The decision was made to move the SOFIA Program Management to DFRC (now AFRC) with the stipulation that DFRC would maintain control of the SOFIA Program until they determined SOFIA was fully operational. This NASA HQ decision led to the biggest setback and subsequent delay in the start of SOFIA operations.

So why was this decision such a setback? First, look at the incentive built into this decision from NASA HQ. DFRC got to keep control of this program and control of about $70 M per year, until they determined SOFIA was fully operational. This gave them a very big financial incentive to delay this milestone as long as possible. There are multiple ways this can be done. First would be to set back the current status, despite the program having just passed perhaps its most thorough review with flying colors. In fact, the transfer of the program to DFRC was based on the premise that the program was messed up. Yes, the program was way over cost and schedule, but as described in the previous sections, this was primarily caused by the HQ-mandated privatization. And for the past year we (the Ames SPO) were finally transitioning away from this mandated privatization approach with demonstrated good success. So DFRC was essentially incentivized and given the authority to find faults, however remote, that could be blamed on Ames for mismanagement—a win-win for DFRC with regard to competing with Ames. This gave them the opportunity to implement a new method or approach for several of the systems that were nearing completion; the engineers and managers at DFRC could choose to develop those systems their way, instead of incorporating work which was based on lessons learned from over 20 years of KAO operations, plus an additional 10 years during SOFIA development of working closely with the science community. A third fundamental way to put off achieving any given milestones was to set milestone requirements as high as possible.

As will be described in the upcoming sections, DFRC—oblivious to or ignoring the need for SOFIA to start obtaining science results as soon as possible—implemented all these actions. Again, this is not meant to criticize DFRC personnel, since for the most part they were just doing their jobs. For example, center management's job was to do everything they could to maximize the amount of NASA funding going to their center. That would include arguing that it was prudent, even if costly, to do an exhaustive review to satisfy themselves that the design and fabrication of everything already completed was safe and operational. Thus the engineering staff was encouraged to go back to make sure what was already completed or near completion would meet DFRC standards for test flights and operations, despite the fact that these systems and operations plans had been reviewed and approved by multiple independent organizations. As you will see, the net result was at least a 6-year delay to the start of operations, with the associated cost to the NASA SMD budget of several hundred million dollars. The milestone event requirements of Full Operations Capability (FOC) were finally declared in 2014 by AFRC. So it was 8 years since DFRC (now AFRC) was given control of SOFIA Program Management that the goal of FOC was reached. At that point, the SOFIA Program Management was finally transferred back to the science organization, NASA Ames.

Lesson 11:

Incentives are critical. A negative incentive to achieve a milestone can result in an effort to maximize the time required to achieve that milestone. In this case, DFRC (now AFRC) took 8 years to reach the milestone goal of declaring SOFIA fully operational. Ames, a Science Research Center, wanted to begin science operations as soon as possible.

An obvious question then is why, when the SOFIA Program was finally doing well and the optimized operations facility was complete and ready for operations (including being an FAA certified maintenance station) would a decision be made to base operations at another location that had neither the facilities nor a staff experienced with airborne astronomy. What were the potential motives for this decision? I've heard many things about why this decision was made, but as you can imagine and as I should stress, I can't confirm any of them, but I can share some of what I have heard.

First, it's pretty clear that the Associate Administrator (AA) for the SMD initially wanted to just cancel the SOFIA Program, which was clearly running over cost and schedule, and had been approved prior to her having the role as the AA for SMD. That would have enabled her to spend the SOFIA budget on other promising science program areas. However, neither the outright cancellation nor the SORT review process worked to cancel the SOFIA Program. So she was stuck with the SOFIA Program budget, and may or may not have had a role in any of the following speculations.

One potential reason that I have heard and which, again, I have no information to verify, is that the Southern California federal congressional representatives were able to convince/influence NASA HQ to make this move, of course with the primary motive to benefit their constituency.

A second reason, which I think makes more sense than the above, is that due to a decreasing Aeronautics Mission Directorate budget, DFRC was running out of work and needed programs and projects to provide funding support for their staff. The argument goes that this decision, approved by the NASA Administrator was made for the basic purpose of solving the problem of a work shortage/workforce surplus at DFRC. Science dollars could be used to support staff at a Flight Research Center.

A third possible reason, is from a top-level management perspective, without looking into the details, it may appear to make sense to move a program that is about to enter the flight-test phase of development to a center that specializes in flight testing. Although, just to be clear, I had already contacted DFRC to get them involved helping out with SOFIA flight testing in order to utilize their resources and expertise.

A fourth possible reason involving center directors, and perhaps combinations of some of the above, could be that Ames had just been assigned a new Center Director who came from outside of NASA. He may not have had the political clout at NASA HQ required to counter some of these ideas or perhaps views that were promoted by the then current DFRC center director and by the former DFRC center director who was also the chair of the SORT review.

As probably noticed, most all of this book is based strictly on facts, so why include the above speculations about how this decision was made? The related fact is that even though I was one of the key participants with a major role in the SOFIA Program, neither I nor anyone that I know of that was significantly involved with SOFIA were involved with this decision, nor informed about the rationale or purpose of this major decision. And, as could be easily seen both with the information available at that time and in hindsight, this decision led to the biggest set-back for SOFIA, delaying science operations for at least 6 years and costing NASA the associated several hundred million dollars. So there is another lesson here. Note that the decision makers in this case were at or near the top of NASA management, so even related to just the SMD, the SOFIA annual budget was barely over 1 percent of the SMD budget, and of course well less than half of 1 percent of NASA's total budget; we might therefore speculate that these same percentages, or less, of the Administrator's and Associate Administrators' time was spent getting familiar with the SOFIA Program and related issues. Their plates are very full; they are called on to deal with dozens of major programs, budget issues, politics, which new programs to start, which programs to end, and I'm sure of multiple other issues. This just supports this lesson:

Lesson 12:

Involve the right people when making a major decision. There are multiple ways this can or could have been done. By including significantly involved participants, either by delegating the decision or in information-gathering discussions, not only can more informed decisions be made, the significantly involved participants are more likely to understand—and possibly accept - the decision purpose or rationale.

7.11.5 September: Program Office Transferred to DFRC

So at first work continued on SOFIA as it did prior to the PMC meeting. The official program transfer date was sometime in the future. We continued working per the very detailed IMS and making progress accordingly, including having the aircraft painted in NASA colors for the first time in early September. The civil registration serial "tail" number is N747NA, signifying a U.S. plane owned by NASA-and identified with NASA Ames Research Center (the first 7 of 747). I believe that most of us thought that DFRC was primarily going to be involved in the flight testing. It was not until the memo from Rex Geveden, mandating that the actual science operation was to be carried out from the DFRC, came out that we realized the full negative impact of this decision. It turned out the actual first day of the program being controlled by the DFRC was exactly on my birthday, September 18, 2006. Not a good birthday present.

Figure 7.11-8. A small group of us posing in front of SOFIA being painted − Early September 2006.

7.11.6 Details of Mandated Transfer of Program Office to DFRC

The memo from Rex Geveden specified that DFRC would manage completion of the SOFIA development, that flight operations would occur from and be managed by DFRC for the lifetime of the program, and that all necessary physical infrastructure (including the mirror coating facility, equipment for the SI laboratories, SI support hardware) would be transferred from Ames to DFRC. Further, DFRC would retain Program Management authority until SOFIA achieved FOC, at which time the Program Management would be transferred to Ames. Ames would manage Science Operations.

7.11.7 Implementation of the Transfer

When the program was transferred in September 2006, the telescope had been fully installed and tested with ground/ramp operations and the aircraft was only a few months away from beginning flight tests. Bob Meyer became the SOFIA Program Manager at DRFC. Rather than examining the existing plan and discussing it with those involved, he quickly started making changes to our approach for completing development. Despite the program finally being on a good successful track, Bob held a planning meeting to change it. I remember the meeting was like it was the very beginning of a new project, not a major project that was approaching the finish line on a detailed IMS. At the first monthly review, under DFRC program control, instead of reviewing the over-5000-line IMS that we had used very successfully for over a year to keep track and stay on schedule, a simple top-level less-than-10-line schedule was presented This abrupt transition spelled big trouble ahead.

The general approach was that management of all the various systems was being transferred to DFRC personnel who were just coming up to speed on SOFIA, as well as being given control of the various areas. This was despite the fact that most people who were already involved with major roles were willing to stay on SOFIA and report to DFRC. Since the science operations were still going to remain at Ames, the SOFIA Program was divided into two projects: the Platform Project, which consisted of the aircraft, the mission systems, and the telescope, to be controlled and managed by DFRC; and the Science Project to be managed by Ames. For me personally, I was asked to stay on as both the Program Chief Engineer and the Platform Chief Engineer.

Note: the following sections may appear to be criticizing DFRC personnel, but this is not the intent. DFRC is likely like most NASA centers and they have a lot of talented, knowledgeable, and hardworking people. But, also like all organizations, there are a few people that aren't good. For the most part, the people assigned to work on SOFIA were knowledgeable and hardworking people and they were doing what they were instructed to do by their management. The major setback that was caused by the transfer of the SOFIA Program to DFRC was not the fault of the DFRC engineering and technical staff. Instead, it was the fault of the combination of (1) upper management doing their job to maximize the flow of money to their center and (2) the general philosophy of a flight research center. Of course, there were a few mistakes made, but most people were trying to do a good job.

As mentioned before, the detailed IMS was abandoned. With it gone, L3 lost most of their incentive to meet the schedule and budget. So, L3 took advantage of this transfer of program control to new management: the planned first-flight date ended up slipping a few more months. DFRC management wanted to do things their way.

The primary things that were holding up the first-flight date were the cavity door installation and the normal routine maintenance associated with a used 747, the D Check, and mostly not the unique SOFIA-related modifications. This was exacerbated by United Airlines having dropped out of the SOFIA Program. There was a lot of documentation that was in disarray with regards to maintenance records. For example, as part of the transition away from the privatization approach, HQ was allowing the DFRC SOFIA Program management to control the requirement for FAA certification. However, despite me advocating against the FAA certification for the previous 9 years, at this time, I wanted to keep the FAA process through the first flight because 1: we had invested a lot of time, effort, and associated money through the past 9 years, and 2: it seemed like a great independent organization to do a complete configuration audit that is associated with their process and first flight. In December, despite me being the designated Chief Engineer advocating to keep the FAA involved through the first flight series, a DFRC employee with theoretically a lower position was allowed to drop FAA involvement because of the inconvenience of one of the standard 747 parts that lacked the proper paperwork.

Figure 7.11-9. Roll out from the paint hangar − September 25, 2006

7.11.8 The MCCS Fiasco

This is about the MCCS setback. The background is that the MCCS development started with what the KAO had been using, upgrading, and optimizing for over 20 years.

The MCCS manages and monitors the observatory mission systems, interfaces to the aircraft systems essential for carrying out astronomy, and enables communication among all participants on board. Some examples: it enables the cavity door opening to track the elevation angle of the telescope, keeps the flight crew apprised of the door status, interfaces the observatory data systems with the SI computers, monitors operations of the telescope, displays status and trends of all systems for monitoring by personnel, tracks the agreement between the aircraft location and the flight plan, etc.

With the start of SOFIA, the MCCS began with a systematic and in-depth review of what the KAO had been using for what parts worked well, which ones needed improvement and careful reviewing, and extracting all of the lessons learned. The SOFIA MCCS team had participation from KAO software experts, the KAO scientists, and the scientists that were building the new generation of instruments for SOFIA. By 2006, the MCCS team had been planning it for 10 years, taking advantage of new technology and working closely with the science community. Over 90 percent of the detailed design was completed, essentially waiting on hold for a reliable start of operations date. The idea was to purchase new IT (information technology) infrastructure to start SOFIA science operations with computer infrastructure that was not already several years old. So at the time of the transfer of the SOFIA Program to DFRC, highly evolved MCCS plans existed; these were based on a total of more than 30 years of history and optimization involving both experienced operations staff and the science end-users.

Although previously I mentioned that DFRC had a lot of talented and hard-working engineers and staff, there were also exceptions—the biggest exception being the person that was assigned to lead MCCS to completion. This person seemed to fit the stereotype that the less smart people are sometimes the most arrogant. He had no appreciation for the work that was already in the MCCS and he had a different idea of how it should be done. He started promoting his idea and either making up lies or showing that he did not understand the existing MCCS approach because he was stating things that were just not true.

For example, he did not understand the concept of a Heading Turner (which interfaces with the aircraft autopilot to keep the telescope centered in the cavity-door opening) and how the aircraft Flight Management System (FMS) could be firewalled to protect against incorrect inputs from the MCCS workstations. (The KAO employed a very effective automated Heading Turner.) Instead of going the route of a firewalled FMS, which was going to be FAA certified, he opted to go the route of fortifying the MCCS with a VxWorks Single Board redundant computer system, thereby unnecessarily complicating the MCCS architecture in multiple ways. As the lead of the MCCS Tiger Team, he ignored the consensus of the Tiger Team and threw away the entire concept of using commercial off-the-shelf LAN (local area network) architecture and workstations and Linux operating system (OS) in favor of his paranoid scheme of fortified MCCS computers. Then, to give the appearance of a systematic approach, he started a trade study, but it was soon clear that it was just for appearance.

This sham and his aggressively adamant attitude caused the former MCCS team, which included three scientists with over 40 years of accumulated software experience on the KAO, to quit the effort. It was clear that he already had his mind made up and was not really interested in anybody else's opinion. Again, despite me as the Chief Engineer pointing out several flaws in both his approach and his rationale, the program manager allowed him to proceed. The resulting MCCS was unnecessarily expensive, inflexible and complex. It is still suffering to this day, crashing on an average of about once per observing flight. By the way, SOFIA still does not have an automated Heading Turner.

In addition to complicating the architecture of the mission systems, this profound revision of the MCCS also led to a fundamental change in the operational concept for the observatory. As mentioned before, the goal of SOFIA was to provide scientists and their state-of-the-art instrumentation access to photons from the universe in a research environment. This implies the ability to readily adapt and modify the observatory support systems as needed to maximize science productivity, a flexibility which was a hallmark of the KAO operation. This flexibility was an integral part of the Ames design of the MCCS. Furthermore, up to this point, the telescope and all the observatory equipment were designed such that software could do the worst thing at the worst time without affecting safety. Aircraft safety was isolated and protected from observatory operations. This was accomplished by several techniques, for example both manual and automated override of observatory systems via analog hardware for detecting malfunctions and preventing damage. The new approach assumed these software-independent safety barriers did not exist and, as a result, put a huge burden on the MCCS software.

Lesson 13:

The obvious lesson is for management to retain and value experienced personnel and their contributions. The DFRC-imposed MCCS development excluded the extensive KAO heritage and know-how of the Ames team, as well as that of experienced scientists in the user community.

7.12 2007

First flight was not accomplished in 2006. This was due to the disruption caused by the transfer of the program, the splitting of the project management and the associated changes to the approach, as well as probably to the normal setbacks in reaching a first-flight status for an airplane that had not flown for as long as the SOFIA airplane at that time. It was clear that our primary objective at that time was to get the airplane fly-able and onto NASA property as soon as possible.

7.12.1 First Flight – April 27

We finally reached flight-test status in April; of course, it was the biggest milestone up to that time. First flight was a huge event and it occurred on a beautiful day down in Waco, Texas. Flight-testing was DFRC's area of expertise. DFRC had brought a lot of their resources, including a trailer that was the control room for the first test-flight series and a chase plane. The actual date was April 27; as you can see from Figures 7.12-1 to 7.12-6, it was attended by a lot of people. For me personally, having put in almost 22 years of my career and life, I actually teared up when SOFIA lifted off the runway, of course, while I was taking pictures.

Figure 7.12-1. Me in front of SOFIA in the morning of the day of the first flight − April 27, 2007.

Although it was a huge celebratory day, there were things that showed indications of how SOFIA’s future would be handled. The following is not meant to disrespect DFRC (now AFRC) in anyway. As a flight research center, they are geared to develop new state-of-the-art aerosciences technology. They have outstanding pilots and infrastructure to collect and analyze flight-test data to share with others. Their efforts may lead to new technologies that get incorporated into new aircraft that will get manufactured in mass production and piloted by any pilot. Those cases obviously need very thorough data collection and understanding of how an aircraft behaves throughout its flight envelope.

However, in the case of SOFIA, it is a one-off platform aircraft that will always be flown by NASA pilots. In addition, we had completed 9 different wind tunnel tests at 2 different scales in 3 different wind tunnel facilities. Thousands of data points all indicated that the cavity door design we developed would have negligible effect on the 747SP handling characteristics. Of course, this modification was only on the fuselage and did not directly involve any of the wings, control surfaces, or engines. This negligible effect was verified by multiple CFD analyses. In addition to verifying the feasibility of this large cavity opening, a lot of this work was done in parallel with the development effort with the goal to minimize the flight testing that would be required to help get to science operations as soon as possible. As mentioned earlier, this work was verified by the NESC. The original flight test schedule was planned to last a few weeks—less than 2 months—which was still significantly more than what was used very successfully to flight test the KAO initially in 1973, and again after the aft ramp was installed on it in 1992.

Prior to the transfer of the program to DFRC, Tom Speers, the former Chief Pilot of United Airlines was working on SOFIA for USRA. He had stayed with SOFIA when United Airlines left the SOFIA Program, as mentioned earlier. Despite being very experienced himself, with lots of time flying both regular 747s and 747SPs, he had arranged for another pilot to be the primary test pilot—a pilot who was actually the test pilot for Boeing when the 747SP was brought into service. However, DFRC's approach was different. The primary test pilot selected was the most senior DFRC pilot, despite his having no flight experience in a 747SP. Again, I'm not criticizing because I'm sure, as a former astronaut, he was an outstanding individual in multiple areas. This selection was just another indication that the objective of the SOFIA flight test was not understood. The objective, of course, was to experience the difference between SOFIA's flight characteristics and the flight characteristics of an unmodified 747SP. These had been established for our aircraft in 1997—see Section 7.2.4.2.

One quick background note on a 747SP is that it has the same wing and engines as a regular 747, despite being 48 feet shorter. So, on more than one occasion, I've heard pilots compare the 747SP to a sports car. Back to SOFIA's first flight: at lift-off, probably because of the lack of direct experience on a 747SP, the vertical G-force was quite high to the point that it caused a redline in a lot of the instrumentation that was monitoring the loads and stresses in the aircraft structure and telescope. This caused the abort of many of the planned flight maneuvers. Furthermore, during the flight, a cockpit warning indicator light came on and the flight crew in the cabin wasn't sure what to do about it so they had to communicate with Tom Speers, who was beside me in the control room, to figure out what to do. I couldn't help but think that Tom Speers should have been in the cockpit with them. Fortunately, it was not a serious issue and it was resolved quickly. Then, on the landing, my understanding was that it was so hard that if the aircraft had been in service with normal commercial airlines, the event would have precipitated a mandatory inspection. Fortunately, no damage was done.

Figure 7.12-2. Another photo from my camera of the takeoff of SOFIA on its first flight − April 27, 2007.

Figure 7.12-3. Photo of SOFIA taken from a chase plane during its first flight above Texas landscape − April 27, 2007.

Figure 7.12-4. Adele Belous, Paul Fusco, Rick Brewster, Dave Ackard, and Fred Martwick, all having significant roles with SOFIA development at Ames, in front of SOFIA after the successful first flight.

Figure 7.12-5. Another small group of us in front of SOFIA after the successful first flight.

Figure 7.12-6. The official group photo, after the successful first flight − April 27, 2007.

7.12.2 SOFIA Ferried from Waco to DFRC – May 31

After a few more successful test flights, it was finally time to get SOFIA out of L3 and onto NASA property. As you can see from Figures 7.12-7 and 7.12-8, DFRC brought out 3 F-18s (perhaps excessive?) to accompany SOFIA on its flight from Waco to Edwards Air Force Base (DFRC's location) in Southern California.

Figure 7.12-7. SOFIA with a small group of F/A 18 aircraft to be used as chase planes for ferry flight to DFRC − May 2007.

Figure 7.12-8. SOFIA with a chase plane on its way to DFRC − May 31, 2007.

7.12.3 Status – Summer 2007

The status of SOFIA at this time was it was fly-able, although flown only with the cavity door closed at this point. The cavity door drive system was experiencing difficulties associated with the FAA certification requirements that were imposed earlier. Although by this time, the SOFIA Program Management at DFRC had dropped the FAA certification requirements, we were too far along in this approach to change the door controller requirements to which the supplier had agreed. The company in Chicago that was developing the cavity door drive system was having multiple problems from hardware testing to the electronic control systems and associated software verification. Just as a small sample, there were over 200 sensors involved with the door mechanism.

At Ames, we had hangar N211, which had been modified and customized for optimum SOFIA operations at a cost of nearly $10 M. These modifications included the mirror coating facility, a notch above the main hangar door to accommodate the tall tail of the 747SP, a ramp that went from the second floor to the door of the aircraft to facilitate installing SIs, and laboratories outfitted for the SIs. Within the offices in N211, we had the SPO personnel as well as the USRA personnel, including those who retired from United Airlines to stay with the SOFIA Program when United left. Of course, the ex-United employees were involved with the aircraft operations including maintenance. Adjacent to N211 is building N213, which is where the cavity door engineering team is located. Also, within N211 is the actual sheet metal/machine shop where the cavity door components were assembled, tested, and finalized. At DFRC, of course they had the flight-test infrastructure and air space, but unfortunately, they didn’t even have a hangar to park SOFIA indoors.

The next phase of flight-testing required operating the cavity door, so it appeared that the best thing to do was to get the door completed and working as soon as possible. To me, it seemed real obvious how to best make progress on SOFIA. I actually put together a logical plan on a PowerPoint® presentation that I presented to DFRC management, but my plan involved locating the aircraft in N211 so that the cavity door team would have maximum access and the primary mirror could be coated as well. This seemed to make sense regardless of where operations ended up. But, I was just probably being too optimistic and naïve because my objective was to get SOFIA operational. It became really clear that DFRC management’s primary objective was to anchor SOFIA operations and funding with them. They were probably afraid that if the SOFIA aircraft was seen inside N211 at Ames by too many people, it would be obvious that that’s where it belonged.

Shortly after, SOFIA arrived at DFRC; there was a big rollout celebration on June 27. This was a very happy and sad occasion at the same time for many of us because it was great to see SOFIA getting close to operational readiness, but also disheartening to see so many DFRC management personnel giving speeches to the media as if they were responsible for what was accomplished. As shown in Figure 7.12-9, I posed outside of SOFIA with four longtime SOFIA scientist friends who had worked on SOFIA.

As mentioned earlier, I was designated as the Chief Engineer for both the Platform Project and the Program. But at some point, I don’t remember exactly when, the engineering director decided that I shouldn’t be the Platform Chief Engineer. This probably made sense since nobody working on the platform reported to me nor did I report to the engineering director. I’ve always been very open with my opinions, plans, and what I think is the right thing to do, so I would have been happy to meet and report to him as often as he wanted. For the most part, I spent a lot of time bringing a lot of people up to speed on the various aspects and technical issues involved with SOFIA, but it was becoming pretty clear that I had no real authority when it came to making important decisions. There were several examples of this including the MCCS, as I mentioned earlier. There was clearly an attitude where the opinion or suggestion of anybody from Ames was considered so biased that it was given no credibility, both for small issues and bigger issues. Of course, this wasn't true of everyone at DFRC, as there were a lot of key people assigned to SOFIA that were smart and trying to do what was right, but this attitude did exist, kind of like a cloud. Several times, I felt that a janitor at DFRC would have more authority than I would.

7.12.3.1 Aircraft control cable issue

Just one more example of many other technical issues that I will not include to avoid being too negative and long. This example involved the aircraft control cables that were re-routed as seen in Figure 7.11-3. Since the control cables ended up being longer than the original length, L3 did extra work to try to maintain the original overall stiffness. Just a quick background for this issue, the cables are made of steel and the fuselage is made of aluminum, and as you might know, the CTEs of steel and aluminum are different. So, since the control cables run from the cockpit to the tail, as the temperature of the aircraft changes, so does the tension of the cables. As such, there is a specific maintenance procedure to adjust the tension in the control cables. It involves the aircraft being at a uniform temperature and adjusting the cable tension within a certain range depending on what the temperature is. So, since the CTE of aluminum is greater than steel, the desired tension goes down at lower temperatures. As we in the SOFIA project at Ames were reviewing the data documentation, we noticed that the actual slope of this tension curve appeared to be steeper than what was in the maintenance manual. So it appeared that the control cables were stiffer than perhaps they should have been. And the concern was that extrapolating the actual data we had on the SOFIA control cables indicated that they might go slack when the aircraft would be exposed to the cold temperatures at altitude. We double-checked the design and analysis done by L3 and it looked fine, so the issue was what should we do given the risk of the cables going slack in flight. One solution that we came up with which we thought would be easy to accept was to repeat the standard maintenance approach at a colder ambient temperature so that even with the steeper slope, the control cables would not go slack during the exposure to the cold temperatures at high altitude.

So we brought up this issue and solution during one of the regular planning meetings at DFRC, but for some reason, the person leading the area that would be in charge of this effort didn't want to do it. At first, he tried to discredit the analysis and data, as the data were limited, but it was all we had. That is why we promoted the standard maintenance approach at a colder temperature, which appeared to be a win-win since it would prevent the cables from going slack if the data were correct and it would still be an acceptable standard maintenance if the data were off. At that point, he argued that he was concerned the cables would get too tight when the aircraft would be exposed to the high temperatures on the DFRC area ramps. At this point, as you might imagine, there was a lot more in the discussion, including making more standard cable tension measurements at various temperatures to try to verify the tension slope, but the approach that they chose was to develop special control cable tension measuring devices that would be attached to the cables during flight. This turned out to be a significant effort since it did involve the development of new hardware and flight safety and it also caused a problem during the next flight because one of the key L3 structures people was supposed to be on board, but because this hardware attached to the control cables, L3 management didn't allow him to be on board because they thought it was unsafe to fly with that kind of hardware attached to the control cables. It finally flew and the data from the one flight were discussed during the flight debrief very briefly. The only data that were shared was that the cables did not go slack. There were neither any specific numbers nor any mention if any temperature data were taken. I remember the discussion well as I was participating via tele-conference instead of being there personally and as I asked questions to try to get a good understanding of the data collected, I was essentially shut down. It was clear that DFRC didn't want to deal with this issue any longer and despite not really resolving it, they closed it out.

Figure 7.12-9. Dr. Ted Dunham, Dr. Larry Caroff, Dr. Michael Haas, me, and Dr. Ed Erickson at the SOFIA roll out celebration at DFRC − June 27, 2007.

7.12.4 November – I Resigned from SOFIA

As mentioned above, I disagreed with DFRC's decisions on many technical issues. Despite DFRC's primary justification for doing all they were doing, or redoing, being safety, as stated above, they also ignored some safety issues in my opinion. But the primary disheartening activities were that it was real clear that DFRC management's primary goal was not to get to operations but to anchor SOFIA under their control at DFRC. It was really heartbreaking for me to see all the progress being set back. Although I didn't always agree with SOFIA management, I was always able to keep fully busy attempting to make progress on what I thought should be done. But at this time, with over 22 years of my life and career invested, it was just too difficult and heartbreaking to not be able to push SOFIA progress in the right direction. So in November, I resigned from the SOFIA Program.

8.0 HISTORY PART 3: POST FIRST FLIGHT – 2007−2015

Post 2007-2015

After leaving SOFIA in November 2007, I was quickly recruited to become the capture manager for a SMall EXplorer (SMEX) satellite study proposal. Looking back, I feel I was lucky to end up in this position because the activity was very intense and involved working with scientists during a very early stage of a new project. I ended up with a great team, and because the proposal submission had a very specific deadline, we ended up putting in a lot of extra hours to meet the objectives by this deadline. I think that this was good for me 2 months directly after I left SOFIA so that I didn't sit around and mourn. And, as it turned out, our Transiting Exoplanet Survey Satellite (TESS) proposal actually won in a highly competed selection. TESS is now in development, planned for launch in December 2017.

After leaving SOFIA, I also made it really clear that I would help anyone who needed help on SOFIA. People were welcome to come and discuss their ideas or ask questions and I always tried to help and guide them as much as possible. As a side note, the telescope development was done under a fixed-price contract to DLR such that the contractors' (MAN and Kayser-Threde) obligations ended a year after the installation was complete. So, SOFIA operations on the German side would be done under a new contract. As mentioned earlier, this contract was awarded in 2004 to a newly created organization called the DSI. Since the DSI was not directly involved in the development of the SOFIA telescope, except for Hans Kaercher, who remains as the consultant for SOFIA to this day, the majority of people who were most familiar with the engineering aspects of the SOFIA telescope and who were still involved were at Ames. So, I ended up being consulted many times about various aspects of SOFIA, including rationale or background for various telescope design features.

Figure 8.1-1. The first visit of SOFIA to Ames − January 15, 2008.

On January 15, 2008, SOFIA was finally flown up to Ames to allow a visit for all those who had supported SOFIA development for up to 20 years and anyone else who wanted to check it out. It was actually kind of strange in that the day before the visit, the weather was a beautiful blue-sky day, as well as the day after. But, for some reason, the weather on the day of the visit was a very unusual foggy day all day long. That just seemed kind of strange. Later in 2008, in July, the SOFIA primary mirror finally got coated for the first time in the mirror coating facility in N211 at Ames, as seen in Figures 8.1-3 to 8.1-5.

Figure 8.1-2. SOFIA visit to Ames, shown here with the KAO − January 15, 2008

Figure 8.1-3. The SOFIA primary mirror gets coated for the first time, in the mirror coating facility at NASA Ames Research Center − July 2008.

Figure 8.1-4. The mirror coating team checking out the results.

Figure 8.1-5. An interesting selfie using the freshly coated primary mirror.

As someone who was no longer directly involved in the SOFIA Program, I cannot provide a whole lot of detail on what was done for these 9 years other than listing a few milestone events such as finally getting to door-open flight testing in 2009. I did remain involved with the

Education and Public Outreach (EPO) staff, who were still based in N211 at Ames. Both through them and from other invitations, I ended up giving presentations about SOFIA fairly often.

Figure 8.1-6. Door open test flight − 2009.

Figure 8.1-7. A close-up of the cavity area, during open door flight testing. Note the cover over the mirror − 2009.

One of the questions that I would get asked on a fairly regular basis was had I ever flown on SOFIA and my answer, of course, was no. Fortunately, in my job as the NESC Chief Engineer for Ames, which I started in late 2009, I was finally able to participate on an observing flight in June 2014, as you can see in Figures 8.1-8 to 8.1-13. Since my contributions were recognized by SOFIA management, I was treated as a guest of honor and got to ride in the cockpit during taxi, takeoff, and the first part of the flight, where I had a great discussion with the pilots. We talked about several things and I asked them specifically about what they felt when they opened the cavity door. And their response was, “How the hell did you do that?” Because the only way that they could tell that the cavity door was open was the indicator light on the control panel; they felt no difference in the flight characteristics between when the door was open or closed. Of course, I explained to them all the work we had done in multiple wind tunnel tests over a period of time. They were pretty impressed that a door that big could be opened in flight while they were cruising at altitude with no changes in the way the aircraft flies. I enjoyed speaking to the pilots and was glad that I finally got to fly on a SOFIA observation flight.

Figure 8.1-8. The day I finally got to join a SOFIA observation flight − June 12, 2014.

2014 also had a couple of other milestones, one being that SOFIA finally met the requirements to be considered fully operational; and as it turned out, it was the 10-year anniversary of the creation of DSI to support SOFIA operations. On the not-so-good news side, once again, there was discussion about zeroing out the SOFIA budget for 2015. Fortunately, that did not happen, and our German partner was able to complete the heavy D-check maintenance that was due. This time, it was done by Lufthansa Airlines at one of their facilities in Germany in fall 2014.

In June 2014, the milestone of being fully operational, as defined by DFRC management back in 2006 with their previously mentioned negative incentive, was finally achieved by AFRC, allowing moving program control back to Ames. So, it took almost 8 years for DFRC/AFRC to complete the SOFIA observatory after being given an aircraft that was a few months away from flight testing with a working telescope installed as shown in Figures 7.9-10 to 7.9-12 (2004) and

7.11-9 (2006). Much of this delay was due to the tedious—and in my opinion overly detailed—aircraft flight-test program called "envelope expansion," which expended many flights evaluating the performance of the plane under different flight conditions.

Figure 8.1-9. The view from where I was sitting during taxi, takeoff, and the first part on the flight − June 12, 2014.

In addition to excessive flight-testing, DFRC spent NASA money on several other areas instead of science operations gathering new science knowledge for mankind. To avoid being too negative and too long, I'll only include three more examples. First, of course, DFRC didn't even have a hangar to park SOFIA, unlike Ames, as mentioned earlier, which had a hangar facility that was optimized for SOFIA operations. So DFRC had to find hangar space to lease. And of course, the hangar was just an empty hangar, so a lot of money had to be spent to build offices, science labs, and operations infrastructure. So, from a NASA-wide perspective, NASA dollars were being spent to lease and build duplicate infrastructure that still turned out inferior to the existing infrastructure we already had. Another example was despite a trade-study clearly showing that it didn't make sense to spend money to move the mirror coating facility from Ames to DFRC, from NASA-owned to NASA-leased property, DFRC management chose to spend SOFIA money disassembling, moving it down and rebuilding it in Palmdale. The trade-study was very conservative and assumed that the mirror coating would have to be done very regularly and the flights to Ames would have no other purpose. The last example I experienced on my SOFIA flight when, shortly before takeoff, two personnel gave a short briefing regarding flight safety. One was a maintenance technician the other an avionics technician. They were on the flight to deal with possible contingencies, but were unoccupied because none arose. On the KAO, the the Mission Director and the Mission Pilot described safety issues as part of the preflight briefing; extraneous personnel flew only when there had been recent problems with one of the on-board systems.

Figure 8.1-10. The takeoff was towards the east during sunset and the rising of a super moon − June 12, 2014.

Figure 8.1-11. The view inside the cockpit showing the mix of old and new instrumentation and controls − June 12, 2014 (compare to Figure 7.8-29).

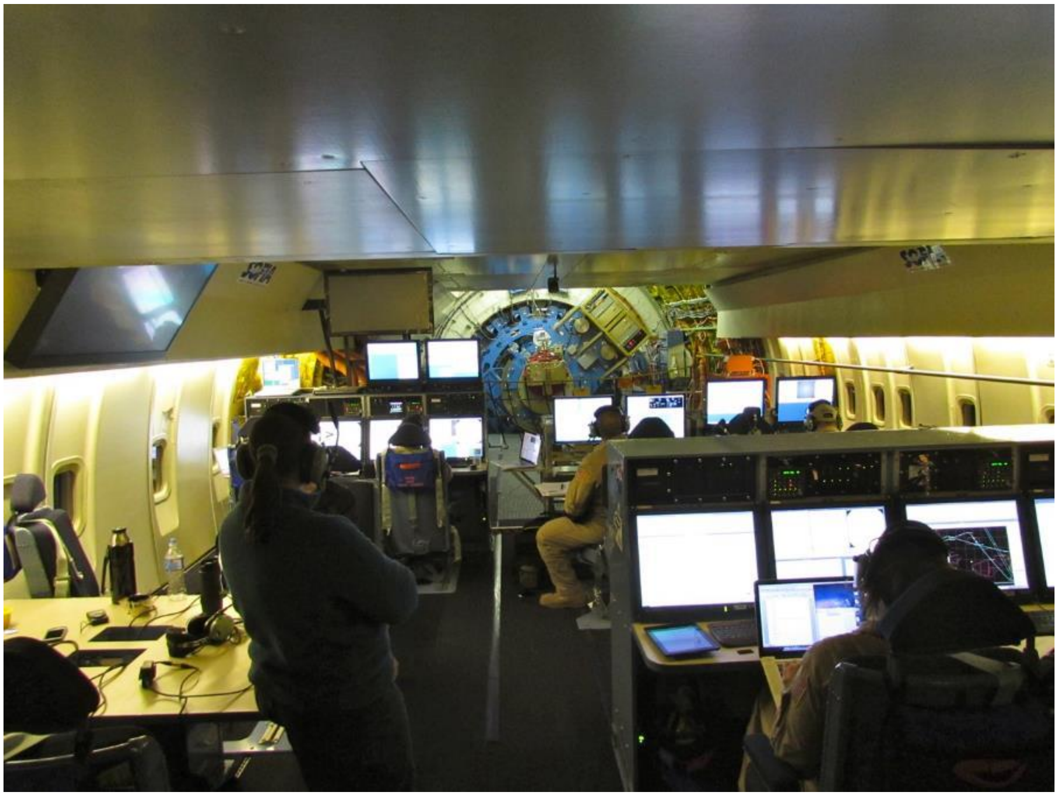
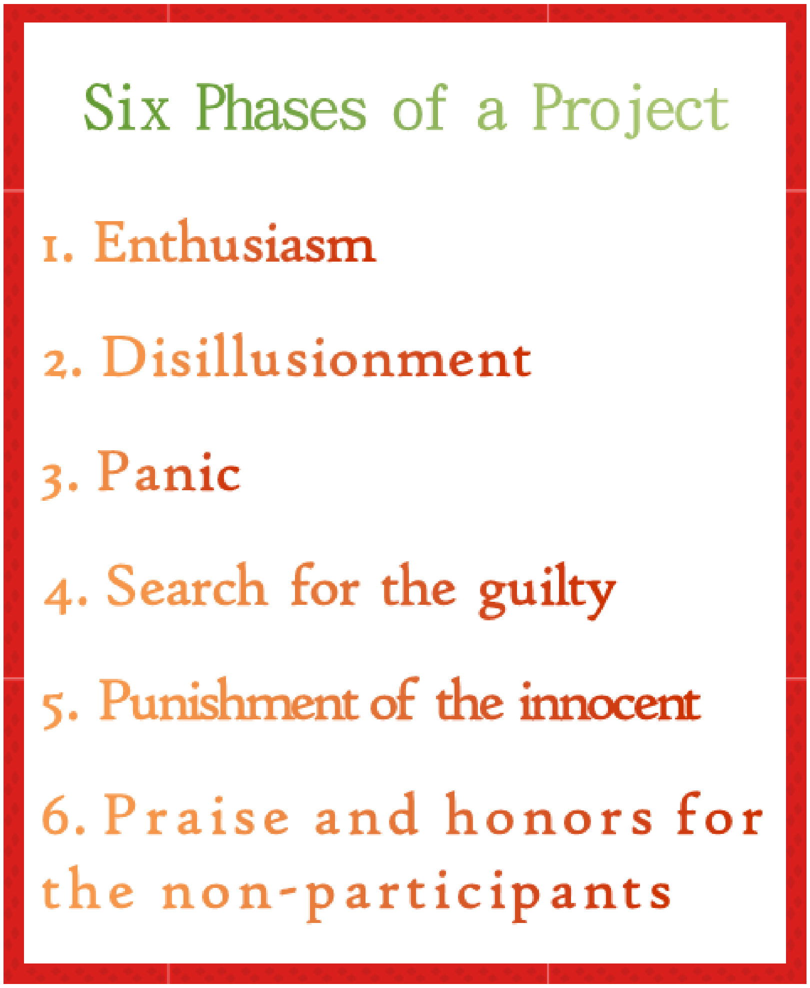


Figure 8.1-12. Back down on the main deck looking aft at the SI and the telescope during the observation − June 12, 2014.

Figure 8.1-13. Drs. Alfred Krabbe and Hans Peter Roeser at the celebration of the 10-year anniversary of the establishment of DSI − 2014.
Professor Krabbe is the director of the DSI, which was formed under the leadership of Professor Röser.



Six Phases of a Project

1. Enthusiasm
2. Disillusionment
3. Panic
4. Search for the guilty
5. Punishment of the innocent
6. Praise and honors for the non-participants

Figure 8.1-14. I remember seeing a poster in the hallway of building N-244 at Ames, where the SPO was located, similar to this and I can't help think how it actually ended up being a fit for how the SOFIA Program ended up.

9.0 CURRENT OPERATIONS, 2015−2016

As this book nears completion (Winter 2015−2016), SOFIA is operational and gathering great science data on a regular basis. With access to wavelengths that don't make it to the ground, mobility to observe the entire sky and ephemeral events, and the ability to fly state-of-the-art SIs with hands on, SOFIA has a capability to do some types of science that no other facility in the world can do. Unfortunately, a lot of people I have spoken to feel like they're trying to do their job with one hand tied behind their backs. I suspect that this has a lot to do with the fact that SOFIA operations are divided into four different locations, in direct contradiction to the lessons learned from KAO operations, which were conducted out of two hangars at Ames (N248 and N211), separated by about 100 yards. As written earlier, the original plan for SOFIA was to have everything in N211. However, currently the science-based operations at Ames is split between N232 and N211 about a 7-minute walk from each other, while flight operations conducted by AFRC down south, about a 5- to 7-hour drive from Ames, is split between two more locations, Palmdale Airport and AFRC (located at Edwards Air Force Base), about an hour's drive apart. Clearly not the most efficient way to run operations.

Another contribution to the frustration of the SOFIA science community is that the current culture of operations has the aircraft management mentality dominating many aspects of this science program. This is exactly what we were trying to avoid, both from the lessons learned from KAO operations and from the original intent of privatization. The requirements set for the SIs and the data-gathering infrastructure are almost the same as if they were flight-critical safety related. Of course, this all leads to less science data gathered per NASA dollar spent, which of course is a big concern. As mentioned above, mothballing SOFIA was considered for FY15, motivated no doubt in part by the high cost of operations. Not surprising: there is always competition for NASA science dollars, requiring tough decisions by the SMD Director.

Lesson 14:

If the production of world-class science is the goal of the program, then scientists should lead the operations phase and have authority for budget, staffing, and scheduling decisions. Safety should never be compromised, but neither should it be the primary criterion for these program decisions.

Earlier, a Senior Review was scheduled for 2016 but has currently been delayed for a couple of years. The concern of a lot of people who are involved with or care about SOFIA is that this review might be the first step to try to shutdown SOFIA operations again, which would be shameful on multiple fronts. One of course is not keeping up our side of the agreement with our German partners; another is shutting down such a spectacular and capable facility that can do science that no other facility in the world can do, and in which we have invested so much time and money. Perhaps the purpose of the Senior Review could be to investigate the operation to determine how it could be done more efficiently while avoiding center management politics. In my opinion, which I am sure would be considered biased, there is a clear solution which would be to move all operations into building/hangar N-211 at Ames Research Center. In addition to being able to co-locate everyone involved with SOFIA operations within the same building, there are multiple other advantages to locate it at Ames. These include proximity to three major international airports, several major universities and colleges, Silicon Valley technology, better weather, less restricted airspace, and of course the tropopause, which is lower at higher latitudes. There are of course other things that can be done to improve operational efficiency as well.

10.0 POSTSCRIPT / LESSONS

As we reach the end of this book, hopefully it's found useful on multiple fronts, from those interested in the history of the making of SOFIA, to engineers and managers perhaps working on other projects, to finally current and future SOFIA staff members. I want to reiterate that I recognize DFRC, now AFRC, has a lot of very skilled and capable people and that it appears that I blame them for a lot of the setbacks of getting SOFIA operational, but I recognize it was just the center management doing their job to maximize the money flow to their Center. Hopefully, operations can be optimized such that SOFIA's future viability is no longer in jeopardy, allowing SOFIA to live the long and productive life for which it was designed.

To review, the *Making of SOFIA* occurred in three basic phases:

Planning: The necessary planning and engineering for SOFIA benefitted enormously from the 21 years of operation of the KAO at Ames, during the last 10 years of which we did our homework to define how to build and operate SOFIA successfully. This included the participation of our German partners, who have been staunch allies during the entire project.

Development: SOFIA's technical development incorporated most of the features evolved during the 10-year planning phase which preceded the formal start of the project. So, the physical facility—including the German telescope—turned out as desired. However, the detailed plan for development of the aircraft and mission systems which had been prepared by the SPO was not implemented because of two decisions by top-level NASA management: First, the decision to privatize the development with a prime contractor who had neither the opportunity to participate in early (phase A and B) studies of the project, nor the experience of managing a big facility development. Second, the 2006 decision to transfer the completion of development to DFRC. FOC was scheduled to occur in under 2 years (from the date of the transfer) by the NASA Ames (not USRA) project management, whose IMS was being successfully implemented. FOC was finally declared 8 years later.

Operation: The NASA HQ decision to operate SOFIA at DFRC (AFRC) was also extremely detrimental to the program. In the N-211 hangar at Ames, all the necessary infrastructure had been completed to enable co-location of the entire operation—a primary lesson for efficiency learned from the operation of the KAO. Most personnel who had done the planning and engineering of SOFIA were at Ames. AFRC had neither the facilities nor the experienced personnel to operate the observatory.

I recognize that top-level NASA managers may have priorities other than the efficiency of development and operation of its programs, such as assuring adequate work for its personnel at different Centers, and responding to pressures from elected officials. However, from an engineer's perspective, the inefficiencies resulting from such decisions in the case of SOFIA resulted in a shameful waste of resources, an excessive, avoidable delay in reaching FOC, and significant inefficiency in operating the observatory.

10.1 A Look Back at Lessons Learned

Here is a compilation of lessons cited previously that I think should be learned from our SOFIA experience.

10.2.1 Lesson 1: Keep A Log of Progress; Section 1.0, page 1

Especially when working on a major project, record highlights, take photos as you go, and file them in chronological order. You may not realize from the start that you could be heavily involved in a project for over 20 years.

10.2.2 Lesson 2: Privatization; Section 6.15, page 79

Don’t write the Call for Proposals for a major project in such a way as to *force* all the phases of development to be bid in a single proposal. This forces different types of organizations to team together to make a proposal, and you may therefore end up with the prime contractor managing major elements of the program for which that prime has no prior experience. Example: USRA, a science and science mission operations organization, was selected as the prime, managing a major systems development contract—modification and integration of the aircraft system—as well as aircraft operations.

10.2.3 Lesson 3: Privatization; Section 6:15, page 80

Privatization is not always the best choice, and each case should be evaluated logically looking at available data. Many NASA Projects are very unique, and NASA internal organizations and employees may actually be more experienced, and skilled, and therefore better choices for related development activities to provide the desired end product more efficiently than external private contractors. Moreover, the structure of any privatization approach should be carefully evaluated with respect to the kind of experience required.

Corollary to the above: Putting a science-based organization in charge of a major systems development makes no sense unless that organization has previously and successfully demonstrated the ability to manage such a development.

10.2.4 Lesson 4: Privatization; Section 6.16.7.3, page 83

An unprecedented procurement approach that initially sounds like a bad idea probably is. At the least, NASA HQ should have insisted that the procurement approach be reviewed by experienced project manager(s), instead of just lawyers and procurement officials. It’s not enough to be legal; the procurement approach must also *make sense* from a systems management perspective.

10.2.5 Lesson 5: Work Products; Section 6.16.7.3, page 83

Don’t put a contractor in charge of approving government-provided products, especially on a cost-plus contract. This rewards the contractor for schedule delays that they can blame on the Government-Furnished Equipment (GFE). Examples: contractually, the German Telescope was GFE to the U.S. contractor – a source of considerable friction and inefficiency; work products from NASA work packages were evaluated by the contractor.

10.2.6 Lesson 6: Realistic Status Assessment and Reporting; Section 7.5.5, page 99

For oversight: external review teams can be misled. They should have the means and the authority to dig as deeply as necessary to truly understand the project status.

For Project Managers: hiding reality or not dealing with the issues at hand usually does not work in the long run. The NASA project manager must develop an open and honest working relationship with the prime contractor project manager. Without this level of trust, there will almost certainly be nasty ‘surprises’ to deal with.

10.2.7 Lesson 7: Center Responsibilities; Section 7.6.1, page 104

The Center with primary responsibility for the project should carefully monitor the progress of the project, and not just pay ‘lip service’ through some generic review. When necessary (and it is incumbent on Center management to be on top of this), the center should provide help, guidance, and mentoring, especially when the project and/or program manager lacks the appropriate level of experience. That assistance should come directly from a project manager who has managed a large, complex systems contract. If the Center lacks such an experienced senior manager, then they should use all means to hire one *before* the project gets deeply in trouble. A good model for this is how JPL oversees projects there.

10.2.8 Lesson 8: Aircraft Modification; Section 7.9, page 182

If your project involves making a modification of a used airplane, consider getting the routine maintenance up-to-date prior to the start of the modification even if the modification involves altering the parts of the airplane affected by the maintenance.

10.2.9 Lesson 9: Cost-Plus Contracts; Section 10.7, page 194

When your cost cost-plus work is being done within the same facility as someone else's fixed-price work (with schedule-slip penalties) don't expect to get the first-string team working on your job.

Corollary: Carefully consider the formulas for cost & and schedule incentives. If not properly specified and managed, then at some point, they may hit a floor and then all incentives for the contractor to deliver quicker at a lower cost are gone.

10.2.10 Lesson 10: Integrated Master Schedule; Section 10.7, page 197

For a project of this size, it is essential to have a detailed Integrated Master Schedule (IMS) to clearly identify the critical path and to have enough detail such that the time estimates are credible. This IMS can then be used to help manage the resources and priorities to meet scheduled milestones.

10.2.11 Lesson 11: Incentives; Section 7.11.4, page 205

Incentives are critical. A negative incentive to achieve a milestone can result in an effort to maximize the time required to achieve that milestone. In this case, DFRC (now AFRC)took 8 years to reach the milestone goal of declaring SOFIA fully operational. On the other hand, Ames, a Science Research Center, wanted to begin science operations as soon as possible.

10.2.12 Lesson 12: Major Decision Making; Section 7.11.4, page 206

Involve the right people when making a major decision. There are multiple ways this can or could have been done. By including significantly involved participants, either by delegating the decision or in information gathering discussions, not only can more informed decisions be made, the significantly involved participants are more likely to understand—and possibly to accept—the decision purpose or rationale.

10.2.13 Lesson 13: Mission Computer-System Hardware and Software; Section 7.11.8, page 211

The obvious lesson is for management to retain and value experienced personnel and their contributions. The DFRC-imposed MCCS development excluded the extensive KAO heritage and know-how of the Ames team, as well as that of experienced scientists in the user community.

10.2.14 Lesson 14: Maximizing Scientific Productivity Should Guide Operations, page 231

If the production of world-class science is the goal of the program, then scientists should lead the operations phase and have authority for budget, staffing, and scheduling decisions. Safety should never be compromised, but neither should it be the primary criterion for these program decisions.

11.0 LIST OF FIGURES

12.0 ACRONYMS

AA	Associate Administrator
AFRC	Armstrong Flight Research Center (NASA) – formerly DFRC
AIAA	American Institute of Aeronautics and Astronautics
AOA	Airborne Optical Adjunct
ARC	Ames Research Center (NASA)
AS	Aircraft System
Beluga	Transport aircraft that delivered the telescope from
BMAC	Boeing Military Airplane Company (in Wichita, Kansas)
BMFT	Bundesministerium fűr Forschung und Technologie – Germany’s Federal Ministry of Research and Technology – (1972−1994)
CAD	Computer Aided Design
CCD	Charge-Coupled Device
CDR	Critical Design Review
CES	Consoles and Electronic Systems
CFD	Computational Fluid Dynamics
CFM Schiller	German testing contractor
CFRP	Carbon-Fiber Reinforced Plastic
CG	Center of Gravity (mass)
Cp	Center of Pressure
CPU	Central Processor Unit
Cray	Super Computer (Company)
CSEM	Swiss Center for Electronics and Microtechnology
CTE	Coefficient of Thermal Expansion
CTT	Swedish Contractor, supplier of the desiccant dryer for the cavity ECS
DARA	Deutsche Agentur für Raumfahrtangelegenheiten – German Aerospace Agency – (1989−1997) – formerly DFVLR
DCR12	Document Change Request 12
DFRC	(NASA) Dryden (now Armstrong) Flight Research Center
DFVLR	Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt – German Test and Research Institute for Aviation and Space Flight – (1969−1989)
Dichroic	A mirror that reflects some wavelengths, transmits others
DLR	Deutsche Zentrum für Luft- und Raumfahrt – German Center for Aviation and Space Flight – (1997−Present) – formerly DARA
DRB	Data Review Board
DSI	Deutsche SOFIA Institute
ECR	Engineering Change Request
ECS	(Cavity) Environmental Control System
EIRR	External Independent Readiness Review
EPO	Education and Public Outreach
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FBC	Flexible Body Compensation
FEM	Finite Element Model
FMS	Flight Management System
FOC	Full Operational Capability

FPI	Focal Plane Imager
FRG	Federal Republic of Germany
G	Gravitational Acceleration at Earth's Surface
GFE	Government Furnished Equipment
GGG	Designation for ductile cast iron
HIPO	High speed Imaging Photometer for Occultations
HQ	Headquarters
Hz	Hertz (cycles per second)
IAR	Independent Annual Review
ICD	Interface Control Document
ICSMR	International Conference on Smart Material Research
IFB	Invitation For Bid
IMC	Image Motion Compensation
IMS	Integrated Master Schedule
IR	Infrared
IRAS	Infrared Astronomy Satellite
iTA	independent Technical Authority
KAO	Kuiper Airborne Observatory
Kayser-Threde	German telescope contractor – part of the telescope consortium
KSC	Kennedy Space Center
L3	Subcontractor for the SOFIA aircraft modifications – formerly Raytheon, formerly E-Systems, formerly Chrysler Technologies – based out of Waco, Texas
LAN	Local Area Network
LAT	Large Airborne Telescope
LFD	Lower Flexible Door
LHe	Liquid Helium
LN_2	Liquid Nitrogen
LOS	Line of Sight
MAN	German telescope contractor – part of the consortium
MCCS	Mission Control and Communications System
MIP	Maintenance Inspection Point
MOU	Memorandum of Understanding
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NASTRAN	finite element structural analysis program – originally an acronym formed from **NA**SA **STR**ucture **AN**alysis, but is now primarily a commercial program
NESC	NASA Engineering and Safety Center
NFAC	National Full-scale Aerodynamic Complex
NRA	NASA Research Announcement
ORR	Operational Readiness Review
OS	Operating System
OSS	Office of Space Science (NASA)
PanAm	Pan American World Airways
PDR	Preliminary Design Review
PED	Partial External Door
PI	Principal Investigator

PM	Primary Mirror
PMC	Program Management Council
PSD	Power Spectral Density
REOSC	French contractor for primary and tertiary mirrors
RFP	Request for Proposal
RIS	Rotation Isolation System (Telescope)
RMS	Root Mean Square
SBIR	Small Business Innovative Research
SCA	Shuttle Carrier Aircraft
SEB	Source Evaluation Board
SESAC	Space and Earth Sciences Advisory Committee
SI	Science Instrument
SiC	Silicon Carbide
SLC	Shear Layer Control
SMA	Secondary Mirror Assembly
SMD	Science Mission Directorate (NASA)
SOF	Prefix, meaning SOFIA, for Project Office Documents
SOFIA	Stratospheric Observatory for Infrared Astronomy
SORT	SOFIA Options Review Team
SP	(NASA) Special Publication
SP	Special Purpose (Boeing 747)
SPIE	International Society for Optics and Photonics
SPIT	SOFIA Pointing Improvement Team
SPO	SOFIA Project Office
SSO	SOFIA Study Office
SSSC	SOFIA Science Steering Committee
SSWG	SOFIA Science Working Group
SUA	Suspension Assembly (Telescope)
TA	Telescope Assembly
TBD	To Be Determined
TESS	Transiting Exoplanet Survey Satellite
TMD	Tuned Mass Damper
URD	Upper Rigid Door
USRA	Universities Space Research Association
VIS	Vibration Isolation System (Telescope)
VMS	Vertical Motion Simulator
WBS	Work Breakdown Structure
ΔCD	Delta (change in) Coefficient of Drag

13.0 CITED INDIVIDUALS

Ackard, Dave
Adeni, Kaiser
Bader, Michel
Belous, Adele
Becklin, Eric
Bullock, Dee
Bonner, Tom
Bremers, Eckhard
Brewster, Rick
Brown, Ted
Caroff, Larry
Carroll, Carol
Casey, Sean
Chee, Desmond
Chin, Ben
Cleave, Mary
Cox, Sylvia
Davidson, Jackie
Dinger, Ann
Dolci, Wendy Whiting
Dunham, Ted
Erickson, Ed
Fitch, John
Fusco, Paul
Gazi, Sami
Geveden, Rex
Gillespie, Carl
Greene, Tom
Griffin, Michael
Haas, Michael
Hall, Warren
Hammes, Heinz
Haslund, Ralph
Hazelrig, Phil
Himmes, Alois
Imprescia, Cliff
Kaluza, Tommy
Kaercher, Hans
Kaindl, Rainer
Kearns, Joel
Keas, Paul
Krabbe, Alfred
Kuiper, Gerard
Kunz, Alex
Kunz, Erin
Kunz, Nans
Martwick, Fred
McDonald, Harold
Melugin, Ramsey
Meyer, Allan
Meyer, Robert
Miller, Walter
Moran, Erin
Roberts, Andy
Rose, Bill
Roeser, Hans Peter
Ruggles, Albert
Sasaki, Glenn
Savage, Maureen
Schubach, Walter
Seuss, Martin
Speers, Tom
Stöffler, Guenther
Strickland, Sandi
Strong, Ron
Szalai, Kenneth
Thorley, Gary
Tu, Eugene
Wallace, John
Weiss, Ulrich
Wilson, Tim
Wiltsee, Chris
Worden, Pete

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That's me, Nans Kunz, former Chief Engineer of SOFIA and author of this SP, on board SOFIA prior to a science observation flight, with the telescope in the background − June 2014.

SOFIA

Stratospheric Observatory for Infrared Astronomy

ABOUT THE AUTHOR

Nans Kunz began work as a Federal Civil Servant at NASA's Ames Research Center in 1978, following his graduation with a degree in Mechanical Engineering from Oregon State University. His entire professional career was spent at Ames. While there, he earned a Master's Degree in Mechanical Engineering at Stanford University, certification as a licensed Professional Engineer (PE), and recognition as an Ames Engineering Honor Awardee. He retired from the Civil Service on 30 October 2015.

Working in the Engineering Directorate during his first 7 years at Ames, Nans supported, led, or had significant roles in dozens of projects involving many research activities and facilities at the center. In 1985, he began technical studies of SOFIA, leading engineering support teams to establish many of the key features of the observatory. In particular, he guided the technical development of the aircraft modification, most notably the design of the critical shear-layer control configuration and large cavity door. As primary technical liaison with NASA's German partners, he managed the telescope/aircraft interface definition and other details to assure that science requirements were met. When NASA planned to cancel SOFIA in 2006, his defense of the project's technical status was instrumental in saving it. He served as the Chief SOFIA Engineer until resigning that role after the first test flights in 2007. His 22 years of expert, insightful professional effort leave a legacy that will always fly with SOFIA.

In 2008, Nans became the Capture Manager for the initial SMEX (SMall EXplorer satellite) proposal to study the Transiting Exo-planet Survey Satellite (TESS) concept; it succeeded in a heavily competed selection. TESS is now in development, and is planned for launch in 2017. In 2009, he became the NASA Engineering and Safety Center (NESC) Chief Engineer at Ames, joining other top engineers from all NASA centers in this prestigious organization to serve as a technical resource for the Agency's most challenging projects.

At his retirement celebration, Ames Director Dr. Eugene Tu said "NASA owes you a debt of gratitude for your work. Exciting projects would not have been completed without your skills, attention to detail, hard work, and dedication." His friends and colleagues valued also his insightful analytical abilities and objectivity, his managerial talents, his easy-going demeanor, his cheerful enthusiasm, and his good sense of humor.

Married with two children, Nans enjoyed many activities such as skiing and camping with his family and friends. He found much pleasure in tutoring junior high "mathletes," coaching youth soccer, mentoring high school robotics teams in national competitions, and leading wilderness outings for a local troop of the Boy Scouts of America. Keeping his commute vehicle, a 1986 Porsche 944 Turbo, in top running condition was a favorite hobby. With such activities, his natural abilities, his affinity for his profession, and his family and friends, Nans seized many of life's wonderful opportunities. He passed away at age 59 on February 23, 2016, a victim of ALS. Those privileged to know him have lost a friend, mentor, gifted colleague, and exceptional engineer. His final professional passion was the completion of this book.

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-0001