SOFIA Flies to the Stars
Exploring the universe from the stratosphere

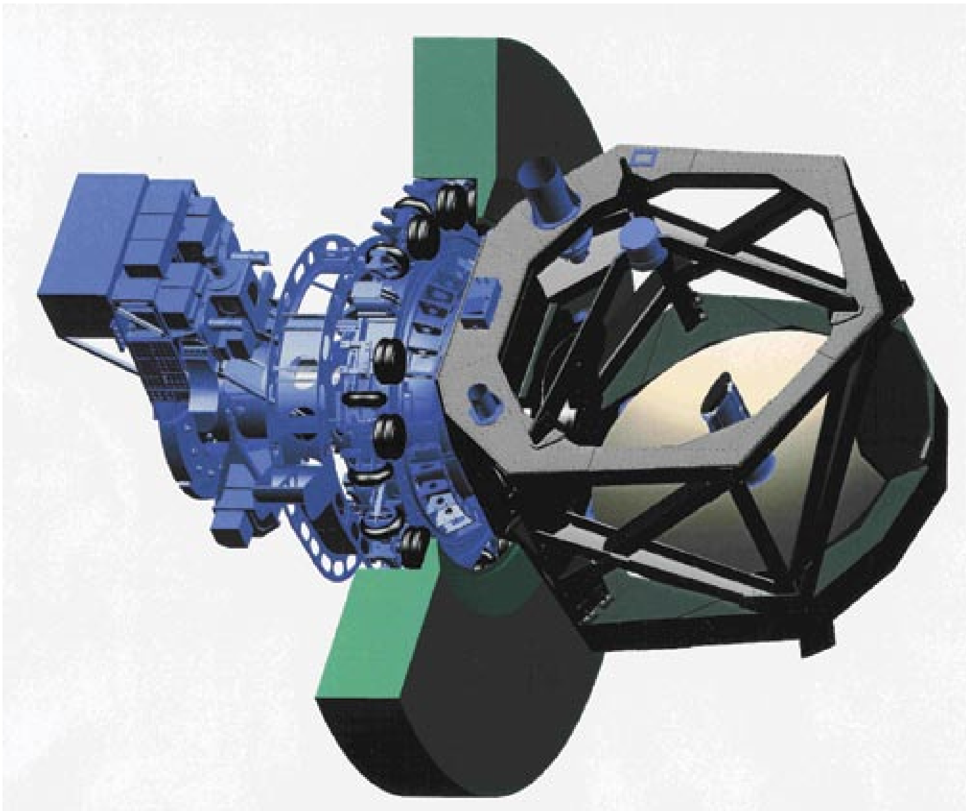
by **Trudy E. Bell**

It's 1986. Your mission from NASA astronomers, should you care to accept it, is: to develop the largest possible telescope to fly on the largest existing aircraft capable of cruising at 41,000 feet or higher for the longest possible time, specifically to explore the universe in the far infrared from above 99.8 percent of the atmosphere's water vapor.

Oh, yes, the telescope can't look out through a windowpane. It must sit within a cavity in the airplane with its optics naked to the sky, at brass-monkey stratospheric temperatures down to -50°C (nearly -60°F) and at stratospheric air pressures as low as 14 percent that at sea level. But the detectors at the telescope's receiving end must be inside the pressurized and heated passenger cabin where astronomers in shirt sleeves can tweak settings as needed. Moreover, despite the facts that air is whipping by the end of the telescope at 85 percent the speed of sound and the plane may encounter turbulence, these picky astronomers want the telescope to remain as rock steady as if it were mounted on the ground. Is meeting such an extraordinary combination of engineering specs even possible?

Fast forward to 2010. Not only is meeting those specs possible, it's been done—and the resulting telescope is now starting to fly its first science missions.

Meet SOFIA, the Stratospheric Observatory for Infrared Astronomy. SOFIA is a joint project of the National Aeronautics and Space Administration and the Deutsches Zentrum für Luftund Raumfahrt (DLR, the German space center). The two agencies worked in parallel: while NASA oversaw the task of heavily modifying a Boeing 747SP into an open-port airborne observing platform with U.S. contractors, DLR oversaw the construction of the telescope by German and other European companies. About the challenging task of developing this unique astronomical facility and watching it fly, chief telescope designer Hans Jürgen Kärcher of MT-Mechatronics (called MAN Technologie AG during the telescope development) in Mainz, Germany, declared with relief and delight: "Thanks to the astronomers who create such nice tasks for us engineers!"



Graphic at top shows how SOFIA's telescope assembly is basically a dumbbell, balanced in the middle of a pressure bulkhead (cutaway in green) in the aft section of a heavily modified Boeing 747SP, shown during its first test flight. On the right of the bulkhead is the telescope itself, with its 2.7-meter–diameter primary mirror (gold) and the "metering structure" (open struts) that holds the secondary mirror assembly (small blue cylinder at the top) and the tertiary mirror (tall blue cylinder in the middle of the primary). Left is a horizontal Nasmyth tube (hidden in the cylindrical blue structure) that directs the light path from the unpressurized cold telescope cavity into the heated and pressurized crew cabin. Black rubber donuts around the periphery of the telescope suspension assembly are part of the its vibration isolation system. *Graphic: MAN Technologie AG. Photo: Carla S. Thomas, NASA.*

The primary mirror of SOFIA's telescope is nearly nine feet across—106 inches (2.7 m)—with an effective aperture of 100 inches (2.5 m). Not only is that larger than the 2.4-meter mirror in the Hubble Space Telescope; for historical perspective, it's also larger than the famous 100-inch Hooker reflector of the Mount Wilson Observatory in Southern California, which held the record as the largest telescope in the world during 1917-48.

It is also triple the diameter of SOFIA's predecessor, a 36-inch (0.91 m) reflecting telescope flown in a modified C-141A Starlifter cargo aircraft as the Gerard P. Kuiper Airborne Observatory (KAO), constructed by NASA and operated from NASA Ames Research Center in Moffett Field, CA, during 1974-95. Over those 21 years, astronomers aboard the KAO discovered rings around Uranus and secrets about the birth of stars.

Why air-lift a telescope?

"It was clear with the early success of the KAO that infrared astronomy begged for a bigger telescope," recounted Edwin F. Erickson, first KAO's facility scientist at NASA Ames and later SOFIA's initial project scientist (now retired). In 1980, at the first International Astronomical Union symposium on infrared astronomy, Erickson himself described the potential of a 3-meter–class large airborne telescope with 10 times the light-gathering power of the KAO's telescope. By January 1986, the concept had gained such momentum that Ames established a SOFIA study office; in May Erickson convened the first SOFIA technology workshop at Ames at which engineers from the U.S. and German space agencies, astronomers from both nations, Boeing, potential German telescope manufacturers, and experts from other relevant disciplines explored various engineering designs for both the aircraft and the telescope.

The 1970s and '80s were one thing. But in today's era of NASA spacecraft series, great observatories exploring the heavens from above the atmosphere with telescopes of similar size, and enormous ground-based telescopes 8-to-15 meters wide, what is the 21st-century need for a follow-on airborne telescope?

Because water vapor in the atmosphere blocks most infrared wavelengths from reaching the earth's surface, mountain-top astronomers—no matter the size of telescope—-are virtually blind to what is happening in the universe from the thermal infrared (heat radiation) just beyond visible red at 0.7 micrometer (µm) all the way to millimeter wavelengths (1,000 µm) at the upper edge of short radio waves. At the highest observatories—such as the Keck Observatory at Mauna Kea, HI, which at just under 14,000 feet is above 90 percent of atmospheric water vapor—astronomers can use detectors cooled by liquid nitrogen to observe to maybe 30 µm. NASA's Spitzer Space Telescope, a 0.85-meter (33.5-inch) telescope launched in August 2003, observed from 3 µm to 180 µm. But all observations in the infrared require astronomical instrumentation to be cryogenically cooled so that heat radiated by the telescope itself doesn't drown the data. Because of condensation, ground-based astronomers can cool only their detectors, not the giant telescope optics. In the vacuum of space, Spitzer cooled its whole telescope to just 5°K (-459°F), but only 95 gallons (360 liters) of liquid helium could be carried aloft, the last of which was exhausted in May 2009.

Airborne SOFIA finesses both problems of water vapor and limited cryogenics. The entire telescope cavity in SOFIA is insulated and sealed, and before takeoff is pre-cooled with cold nitrogen gas; aloft, the sub-zero stratosphere keeps the entire telescope cold, primary mirror and all. The liquid nitrogen (and other consumables) are readily replenished between flights, giving SOFIA a lifetime as long as the aircraft—projected to be 20 years or more. Moreover, unlike a satellite whose instruments are forever out of reach after launch (especially now that NASA's space shuttle missions are ending), on SOFIA the science instrument at the focus of the telescope can be changed or upgraded between flights. If adjustments are needed in flight, the astronomers are beside their instruments, a luxury not provided at many large ground-based observatories.

Most importantly, SOFIA will have access to wavelengths from the near ultraviolet (0.3 µm) to the millimeter (1,000 µm)—wider than any other ground- or space-based telescope. And uniquely, SOFIA is highly maneuverable: if there is a special astronomical event—an occultation (eclipse) of a celestial object by a solar system object or the unexpected explosion of a star (nova or supernova)—the aircraft can fly anywhere in the world for front-row viewing.

SOFIA's telescope had to be ultralight, yet rigid enough to operate in a highly windy environment. The maximum gross takeoff weight for its modified Boeing 747SP is 696,000 pounds or 348 short tons (316 metric tons)—43 percent of which is fuel, the rest comprising the telescope, scientists, computers, environmental control equipment, and, oh yes, the aircraft itself. That limited the complete main telescope assembly, including detector at the focus, to 19.3 short tons (17.5 metric tons), or 38,500 pounds. What's the weight of an equivalent ground-based telescope? Well, the 107-inch Harlan J. Smith reflector of the University of Texas

A technician inspects a mirror blank of Zerodur glass-ceramic (back-lighted so it glows red) cast by Schott Glaswerke in Mainz, Germany, and fashioned into SOFIA's primary mirror under contract to Kayser-Threde and MAN-GHH (later called MAN Technologie AG and now MT-Mechatronics). As shown in this 1998 photograph, the original blank was about 3 m across and weighed 3,800 kg, far too massive for an airborne telescope. So at REOSC in Paris, France, more than 80 percent of the mirror's mass was removed by machining some 120 hexagonal holes like a honeycomb and then treating the mirror in an acid bath. After the flat front surface was ground into an f/1.28 curve and highly polished, the final mirror weighed only 880 kg. *Photos: Schott AG, top, and REOSC: Kayser-Threde.*

Bearing Sphere

The 1.2-meter precision sphere, top, is made of a proprietary alloy of cast iron because of its remarkable dimensional stability and stiffness. The precision rings that hold it, unseen inside the blue cradle structure, below, are made of an alloy of bronze. The spherical surfaces of both were carefully ground and polished at FAG Wuppertal with curved tools made of art stone (like fine whetstone) using a wet slurry of a proprietary compound, after which a thin coating of chromium was applied and polished. The finished bearing sphere in SOFIA now floats, nearly frictionless, within the rings on a thin, 35μm layer of hydraulic fluid. *Photos: MAN Technologie/FAG-Wuppertal*

at the McDonald Observatory in Fort Davis, TX, tips the scales at 160 short tons. In other words, to be able to cruise in the stratosphere aboard a jumbo jet, SOFIA's telescope assembly had to be only 12 percent the mass of a ground-based telescope!

Right from the beginning, the projected cost of developing SOFIA was such that NASA already realized it needed an expert partner with its own separate deep pockets. Meantime, Hans-Peter Röser, a pioneering German infrared astronomer who had observed from the KAO, was instrumental in inspiring DLR and German firms to submit plans for designing and building SOFIA's telescope (Röser now heads the institute of space systems at the University of Stuttgart, which hosts the Deutsches SOFIA institut).

"Lightweighting" the mirror

In December 1996, a memorandum of understanding was signed between NASA and the DLR: NASA would undertake the structural and aerodynamic challenge of designing and installing a cavity in the side of a Boeing 747SP for the enormous telescope. In parallel, DLR would fund and build the telescope itself, a commitment amounting to 20 percent of the cost of the SOFIA program, in exchange for a guarantee of 20 percent of time on the telescope after it began flying. Two German firms were responsible for the detailed design, based on specifications from NASA Ames: MAN Technologie (today called MT-Mechatronics, known for boosters for the European Ariane 5 rocket and mechanical parts for radio telescopes) and Kayser-Threde GmbH (an aerospace company known for satellite subsystems, especially optics and instrumentation of European research satellites), but "a lot of the work was subcontracted all over Europe," said Alois Himmes, DLR's program manager for the development of SOFIA.

The primary mirror needed to be able to hold its precise optical figure through wide temperature changes. The Germans chose Zerodur: an inorganic non-porous glass-ceramic manufactured by Schott AG. Not only does Zerodur have very low thermal expansion over a wide range of temperatures, but it also can be precisely polished like optical glass. Even better, in the 1990s, Schott already had made test castings of various sizes while working up to casting several 8-meter Zerodur mirror blanks for ground-based telescopes. So it happened that one test casting about 3 meters across "was already available at a relatively low price," Himmes said.

Just one problem: that available Zerodur mirror blank weighed in at a hefty 3,800 kg (8,360 pounds)—far heavier than would work for SOFIA's weight allowance. That meant one thing: getting rid of most of the mirror's mass by cutting the blank to size and drilling holes all over its back. At that time, "lightweighting" using a mechanical cutting process had been done before for several smaller mirrors, but had not been tried for a mirror 2.7 m across. "This was the single hardest job," exclaimed Himmes, "especially since we knew the mirror was crucial to SOFIA, and we had no contingency, no alternative, no spare mirror!"

Dumbbell on a sphere

The 2- to 3-year painstaking task fell to the only company in Europe with the tools and skills, the REOSC product unit of SAGEM SA in Paris. REOSC carefully machined a honeycomb of 120 rounded hexagonal hollows from the back (Himmes: "the idea is to make them round and to etch away all microcracks so a crack doesn't 'know' where to start"), and then ground and polished the front surface to the deep curve needed for an ultrafast focal ratio of f/1.28. When the job was done, more than 80 percent of the mass had been removed. SOFIA's final lightweighted mirror was a trim 880 kg (1,940 pounds or less than 1 short ton).

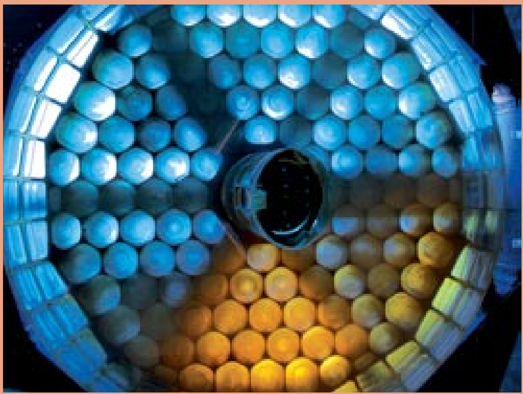
Wanting to stick with a winner, the basic design of the mechanical parts of SOFIA's telescope assembly is similar in principle to the KAO's: it is basically a dumbbell supported in the middle by an aircraft pressure bulkhead. The telescope cavity, just aft of the 747SP's wings, is also aft of the cabin with the astronomers and flight crew. On the aft side of the bulkhead, in the unpressurized and unheated telescope cavity open to the stratosphere and the heavens, is the telescope itself. Open trusses form what is called a "metering structure," which holds all the mirrors in precise alignment in separation and tilt. At the bottom of the telescope, the 2.7-m primary mirror captures infrared light from the heavens and focuses it upward a smaller secondary and then down again to a tertiary mirror (both about 30 cm across); the tertiary then directs the beam forward (along the plane's axis) into the detector of a science instrument. The detector—which may be a spectroscope, faint-object camera, or other astronomical instrument—is on the forward side of the bulkhead, inside the pressurized and heated cabin with the astronomers. Yes, you read right: the light path goes through the aircraft's pressure bulkhead.

The telescope (in the cavity) and the detector (in the

Getting It Together

SOFIA's telescope assembly came together in the workshop of MAN Technologie AG in Augsburg, Germany, in 2002. In the photographs viewed clockwise from above, all flight hardware is painted NASA blue, and all non-flight assembly jigs are painted red. First, the Nasmyth tube was fastened to the bearing sphere and star frame (red square structure at bottom, which holds the telescope in the telescope cavity). After the bearing sphere was enclosed in the bronze bearing rings unseen inside the blue cradle, the entire fine-drive assembly was lowered (Nasmyth tube downward) into the telescope's outer cradle, consisting of the coarse drive system (silver and blue) and the vibration isolation system (black donut shaped air-springs) to the red dummy bulkhead. Next, the science instrument flange (stainless steel fixture) was fastened to the end of the Nasmyth tube; the interior of the flange is separated from the interior of the tube by a transparent pressure window (not seen). The science instrument flange and balancing system completed the telescope assembly on the cabin side; the yellow in the middle is the insulated interior of the science instrument flange. On the cavity side, the metering structure now was ready to accept its three mirrors, the red structure beneath the metering structure representing a mass dummy of the primary mirror assembly. The finished assembly in three major pieces was flown to the U.S. in an Airbus A300-600 SP Beluga.

Photos: MAN Technologie AG



When the uncoated yellowish primary mirror built for SOFIA was backlighted and partially covered by a blue tarp, the honeycomb lightweighting created a *candy-dish* appearance. *Photo: Ron Strong, NASA Ames Research Center*

cabin) are balanced in the middle of the bulkhead on "what to my knowledge is essentially the world's largest precision ball bearing," said Himmes. Because the single ball has to maintain an absolutely spherical form, stiffness and dimensional stability are imperative. It was made of a highly polished sphere of a proprietary alloy of cast iron with an unprecedented diameter of 1.2 m by FAG-Wuppertal, Schaeffler Group, known for its precision roller bearings.

In the bulkhead, the spherical bearing is supported on two bronze rings, floating on a thin layer of ester basic hydraulic fluid (strictly speaking, not an oil) just 35 µm thick—only the thickness of a sheet of paper. The center of the sphere is the telescope's center of gravity. "The hydraulic bearing is almost frictionless, and the telescope perfectly balanced," said Nans Kunz, SOFIA chief engineer at NASA Ames from inception until 2007; "you can move the 10-ton rotating part of the telescope with your pinky." Running through the center of the bearing sphere is the telescope's optical path: a 30-inch–diameter Nasmyth tube—an optical design named for 19th-century Scottish engineer James Nasmyth, who invented it so that an observer could remain in one position no matter where the telescope points.

Design drivers

Because SOFIA's telescope penetrates an aircraft pressure bulkhead, it "bears two loads that normal telescopes don't have," noted MAN's chief telescope designer Kärcher. "Half of it is on the pressurized warm side, and the other half—including the main optics—is in the unpressurized cold side. The temperature difference between the two sides can exceed 70°C, or about 125°F!" Moreover, the bearing sphere has not only to support the telescope's downward tonnage of its moving parts; it also must handle an equally great horizontal force from the cabin air pressure pushing aft, because the cabin is kept at a standard airline pressure up to 8.9 pounds per square inch relative to the outside, while the cavity is at a stratospheric pressure as low as 2.1 psi. The entire telescope support system is connected to the aircraft bulkhead with a series of inflated donuts (similar to those found in the air-ride suspensions of large semi trucks), which also isolate it from vibrations in all three translational degrees of freedom (fore-aft, left-right, and up-down).

The huge temperature and pressure differentials were "main drivers for the design of the telescope's mechanical parts," declared Kärcher. As a result, his team decided that both the metering structure and the Nasmyth tube should be made of carbon-fiber–reinforced polymer (CFRP), "same stuff that is commonly called *graphite* in light-weight golf club shafts, or high-end bicycle frames," added Kunz. The right mixture of fibers and epoxy gives essentially zero thermal expansion similar to Zerodur, important for minimizing changes in distance between the telescope mirrors with changes in temperature—with the added bonus of being exceptionally lightweight and stiff. Although the bearing sphere itself is part of the warm side, the optical path running through it is part of the cold side. The 100-inch–long Nasmyth tube, which has CFRP walls fully 30 mm thick and lined with insulation, is the only structural component connecting the unpressurized cold side with the pressurized warm side, separating the two with a transparent pressure window (which may be open or closed, depending on the science instrument).

'Hurricane and earthquake'

"In principle, the telescope is an altazimuth, but it has two drive systems: coarse and fine," explained Himmes. For the coarse drive, the telescope can slew vertically to look from 23° to 58° altitude (elevation from horizontal). To scan the horizon in azimuth, the aircraft itself turns to change its heading. "Under autopilot in smooth air, an aircraft typically rolls or yaws maybe 0.2 of a degree of arc in level flight," said Kunz. "But astronomers want to track celestial objects precisely for exposures of up to two or more hours with a factor of 3,600 better accuracy—to 0.2 seconds of arc!"

Airborne in a 747SP, however, the telescope is subject to vibrations from various sources, including engines. Worse, because the instrument is looking out an opening the size of an open two-car garage in the side of an aircraft traveling at 520 mph, the telescope experiences acoustic noise akin to what an automobile driver experiences when traveling at freeway speeds with a window down. The opening was aerodynamically designed to eliminate any blowing-across-a-softdrink-bottle organ-pipe resonances, thanks to heroic computations and wind tunnel tests by William Rose (formerly at NASA Ames and now president of Rose Engineering in Nevada). But some air is still flowing down the sides of the cavity and swirling around the telescope struts, exerting fluctuating pressure on the structure.

"A pointing stability of 0.2 arcseconds is respectable for a ground-based telescope on top of a mountain," exclaimed Kunz. "But in SOFIA, astronomers want the same pointing stability on the aircraft in the midst of the equivalent of a Mach 0.84 hurricane and a mild earthquake!"

Basically, the 10-ton moving part of the telescope is kept pointing in a fixed direction by virtue of its own considerable inertia, with a fine-guidance system that has both passive and active components. "Because the practically frictionless bearing sphere allows it complete freedom of motion, the telescope holds stable in inertial space, with the aircraft rotating around it," explained SOFIA's originator Erickson. It is further cushioned by the passive inflated-donut vibration isolation system. To counteract low-frequency vibrations, the telescope also has the active help of three orthogonal laser-fiber gyros and their associated servo motors and related feedback loops: when the telescope starts deviating, the gyros sense it and send a message to the onboard computers, which calculate how strong a torque must be applied

Author Trudy E. Bell was shown the SOFIA telescope installed in the Boeing 747SP by Deutsches SOFIA Institut structural engineer and telescope operator Ulrich Lampater. SOFIA pilot-consultant Thomas P. Speer took the photograph in March 2010 during Bell's visit to NASA Dryden aircraft operations facility in Palmdale, CA. The aluminum structure in the center of the blue ring is where a scientific instrument will be mounted.

by the spherical servo motors to correct the telescope's pointing. The telescope is also fitted with a focal-plane camera close to the science instrument and two additional guide telescopes on top of the metering structure, which monitor the positions of guide stars to measure and compensate for gyro drift or bending of the metering structure. For higher frequencies, "we do some compensation by articulating the secondary mirror," Erickson said, somewhat like the image-stabilization systems in modern lenses of single-lens reflex cameras.

Will it all work? "We're aiming for a pointing stability of 0.2 arcseconds, but we're not sure we can reach it," hedged Himmes. "We hope to come close to one arcsecond—and we're hopeful: on our first-light flight we were already at 1.2 arcseconds."

SOFIA's mission

It's 2010. SOFIA is now flying the world's largest airborne telescope looking out the world's largest open cavity in the side of a Boeing 747SP. During its first-light flight on May 25 and 26—the first night-time flight for testing the telescope—the new infrared eye on the universe turned to the planet Jupiter and a galaxy designated Messier 82. Both objects were observed by the Faint Object Infrared Camera for the SOFIA Telescope of Cornell University at infrared wavelengths between 5µm and 40 µm—the first time either had been examined with a telescope having as great a diameter and resolution as SOFIA's at the longer wavelengths. Although the data will take time to interpret, already NASA infrared astronomers are thanking the DLR telescope engineers for being, in Erickson's words, "staunch partners in the game."

Acknowledgments

I thank the sources named in both this article and its partner article about the SOFIA aircraft modification in *Air & Space/Smithsonian* for all their time in interviews, commenting on the manuscript, and images. I thank: Thomas P. Speer (a retired long-time United captain of Boeing 747s who is working with SOFIA flight crews and Dryden aeronautics experts to refine understanding of the SOFIA airborne performance) and Ulrich Lampater (Deutsches SOFIA institut structural engineer and SOFIA telescope operator), who together gave me a detailed ground tour of SOFIA; NASA senior photographer Carla S. Thomas (Arcata Associates Inc.) for providing high-resolution images; NASA public affairs specialist Beth Hagenauer (TYBRIN Corp.), who arranged my visit to both Dryden aircraft operations facility in Palmdale, CA, (which maintains and operates SOFIA) and to Dryden flight research center (home of SOFIA flight operations) on Edwards Air Force Base; and reviewers, Ted Brown formerly of NASA Ames and Glenn R. Zwerneman of L-3 Communications.

Notes

Design of the telescope is only half of the SOFIA engineering backstory. An equally heroic story is the pioneering aeronautical engineering involved in heavily modifying the Boeing 747-SP Clipper Lindbergh to carry the 17-ton telescope, especially in determining how to compensate for removing a full quarter of the circumference of the aircraft's fuselage for the telescope cavity. See Trudy E. Bell's upcoming companion article "First Class Upgrade" due in the December 2010/January 2011 issue of *Air & Space/Smithsonian* magazine. See also Nans Kunz's paper "The SOFIA Aircraft and its Modification," Airborne Telescope Systems II (a volume edited by Ramsey K. Melugin and Hans-Peter Röser), Proceedings of the SPIE, Volume 4857, pp. 333-343 (2003).

A fascinating sketch of historical efforts to do astronomy from aircraft is "Milestones in Airborne Astronomy: From the 1920s to the Present," by Wendy Whiting Dolci, at *www.sofia.usra.edu/Edu/docs/97-Whiting_AeroHistory.pdf.* Personal remembrances about the culture of the KAO are gathered in "Kuiper Airborne Observatory Marks 30th Anniversary of its Dedication" on the NASA website at *www.nasa.gov/vision/universe/watchtheskies/kuiper.html.*

A NASA announcement of the lightweighting of SOFIA's mirror is "Airborne Observatory's Telescope Weight Reduced," at *www.nasa.gov/centers/ames/news/releases/1999/99_65AR.html.* More technical details about the machining process can be found in "TIE 38: Lightweighting of Zerodur," Schott AG, March 2008,*www.us.schott.com/advanced_optics/english/download/schott_tie-38_zerodur_lightweighting_v3_march_2008_us.pdf.*

Much of what is involved with keeping the SOFIA telescope aimed at a target is discussed by Nanz Kunz in "The challenges in obtaining 0.2 arc-second pointing stability for a large telescope mounted in an open port cavity on board an aircraft flying in the stratosphere," *Airborne Telescope Systems* (a volume edited by **Ramsey K. Melugin,** *Texas Delta '62*, and Hans-Peter Röser), Proceedings of the SPIE, Volume 4014, pp. 289-300 (2000).

A recent technical update is "SOFIA in Operation: Status of the telescope in-flight commissioning," by Hans J. Kärcher and five coauthors, presented at SPIE Astronomical Instrumentation, San Diego 2010 (9 pages).

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