The SOFIA Telescope

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ABSTRACT

The Stratospheric Observatory For Infrared Astronomy SOFIA[1] is a major milestone in the prospering wavelength range of the infrared. As a successor of the tremendously successful Kuiper Airborne Observatory (KAO) it will be the biggest astronomical airborne observatory ever build, comprising a 3m-class telescope onboard a Boeing 747SP. I present an overview on the telescope as the heart of SOFIA, discuss some of the requirements, describe the optical and mechanical design and give an update on the current status of construction.

Keywords:

INTRODUCTION

The American – German SOFIA project is opening a new era in MIR/FIR astronomy. Starting in early 2005, SOFIA will offer regular access to the entire MIR and FIR wavelength range between 5µm and 300µm part of which is otherwise inaccessible from the ground. SOFIA's 2.7m-size mirror together with it´s optimized telescope system combines the highest available spatial resolution with excellent sensitivity. SOFIA can operate in both celestial hemispheres, will always fly the latest instrument technology, and will be available for the next two decades.

SOFIA, jointly managed by NASA and DLR (German Aerospace) on an 80/20 shared basis, is currently being build by the Universities Space Research Association (USRA) in the US and by MAN and Kayser-Threde in Germany. A recent overview over SOFIA can be found in Krabbe (2000). Meanwhile, SOFIA has successfully passed it´s critical design review and is now in the construction phase. First light is being scheduled for 2004, science operation will start in early 2005.

REQUIREMENTS

Some of the top-level requirements for the SOFIA telescope are listed in Table 1. Among those, the requirement for the optical performance of the telescope - 80% light circle diameter of 1.5″ - is rather moderate and relatively easily to achieve. For wavelengths shorter than 3 µm, the local seeing at 13 km altitude will be about 2″ to 4″. Beyond 15 µm, SOFIA will then be diffraction limited.

The image stability requirement of 0.2″ during flight (Table 2) presents the major challenge to the telescope design. It turns out that this requirement is the hardest to meet. Aeroacoustic noise in the open cavity as well as the residual vibrations of the aircraft during flight excite vibrations in the structure of the telescope. These vibrations are dominated by resonances with discrete eigenvalues in the range between 10 and about 110 Hz. From current simulations a rms image stability as good as about 1 arcsec can be expected at the time of operations readiness review. During the following 2 years of operations and based on operations data and telescope testing, those vibrations will be characterized and actively minimized and the pointing performance of the telescope controller will be improved towards the required 0.2".

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[1] http://www.dlr.de/SOFIA, or http://www.sofia.usra.edu/

One of the design goals of the SOFIA observatory was to make every component as light as possible in order to maximize the useful observing flight duration. Saving weight on the telescope itself is particularly important, since it eventually saves not only the counter weight, but also the ballast weight in the front of the aircraft. In addition to be very light, the telescope structure has to be very stiff as well. Consequently, most of the telescope´s structural elements, including the mirror support, the star frame, the truss work, the front ring and spider, and the Nasmyth tube, are made of carbon fiber reinforced plastic (CFC). The lowest eigenfrequencies of the telescope, the Dumbell bending modes, are above 35 Hz.

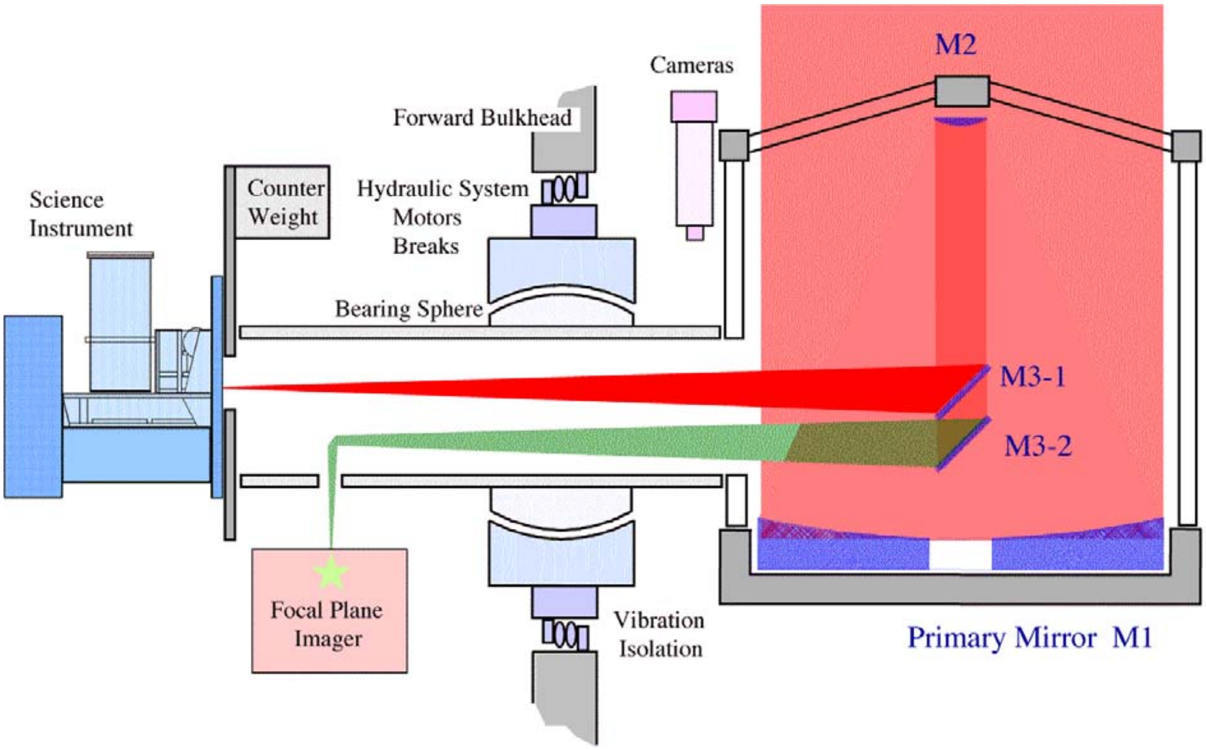

Figure 1 Major components and optical layout of the SOFIA telescope.

THE OPTICAL LAYOUT

The optical layout of the SOFIA telescope is that of a classical Cassegrain used in the Nasmyth focus only (Figure 1). The f-number of the primary is as short as 1.3 in order to let the telescope fit into the aircraft. The total system f-number of 19.7 corresponds to an image scale of 240 µm/″ in the focal plane. The secondary mirror with it´s drive system provides a wide range of chopping capabilities. The planar tertiary dichroic reflects the IR beam into the infrared Nasmyth focus, 300 mm behind the instrument flange. The transmitted optical light is reflected by a second tertiary behind the dichroic and sent to the visible Nasmyth focus and into a guiding camera system. The wide field image and fine field imager guiding cameras are available at the top ring.

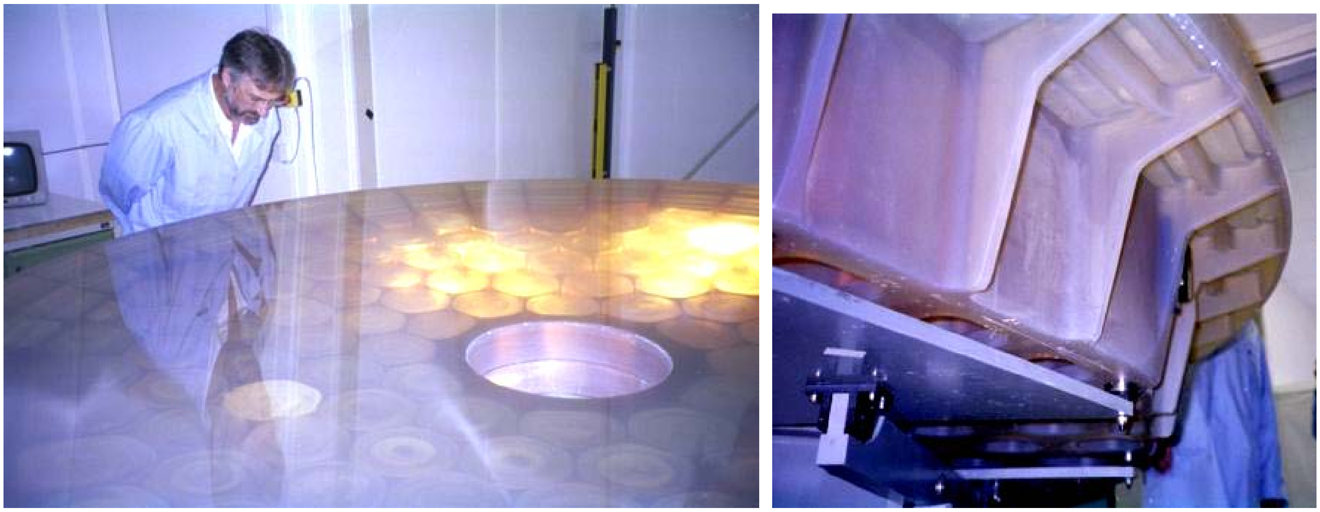

Figure 2. SOFIA´s 2.7m primary mirror after polishing ready to be accepted at SAGEM, France. Left: The pockets of the honeycombs are visible through the front surface. A light underneath the mirror illuminates part of the back structure. The 40mm central hole provides the space for the tertiary mirrors tower. Right: View on the back side. The geometry shown for the outer zone was optimized to minimize the weight and retain the required stiffness. One of the axial mounting pads is also visible.

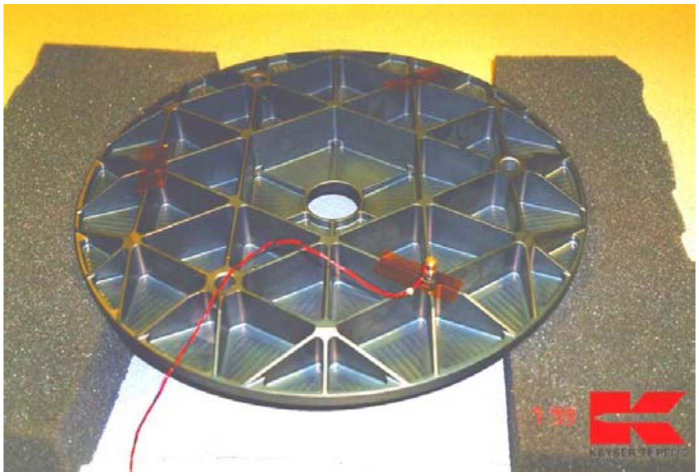

Figure 3. Back side of the secondary mirror. The mirror is made out of sintered SiC and has been CVD coated with a dense layer of SiC in order to minimize stray light. The diameter is about 350mm. The rips on the back side are 2mm thick. The central hole can hold a reflective button, to radiate away the emission of the central hole in the primary.

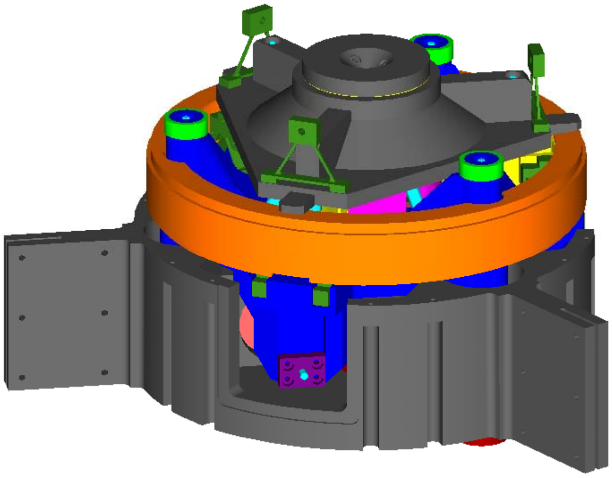

Figure 4. CAD view of the secondary drive system without the mirror and the upper housing. The mirror is attached to the 3 hexapods, which are visible above the counterweight ring. The hexapods connect to the interface plate, which has one central bearing and is driven by three linear motors.

MAJOR COMPONENTS OF THE TELESCOPE

The primary mirror, made of Zerodur, has just been finished at SAGEM (former REOSC), France (Figure 2). Pockets in Honeycomb shape have been milled into the backside of the mirror reducing it´s weight by 80% to about 870 kg. The wall thickness of the remaining hexagonal structure inside the pockets is only 7 mm. The central hole in the primary will take the tower, which supports the two tertiary mirrors. The optical quality of the mirror is diffraction limited at optical wavelenghts and was optimized for an elevation angle of 45°. The secondary mirror (Figure 3) is made of sintered silicon carbide (SiC) and it´s backside has been optimized for weight and momentum The front side of the blank has been CVD coated with a dense layer of SiC prior to polishing in order to minimize straylight. Currently this is the largest secondary made of SiC. It´s eigenfrequency is about 2 kHz and the mass is 2.2 kg. The mirror is completed and has been delivered in July this year.

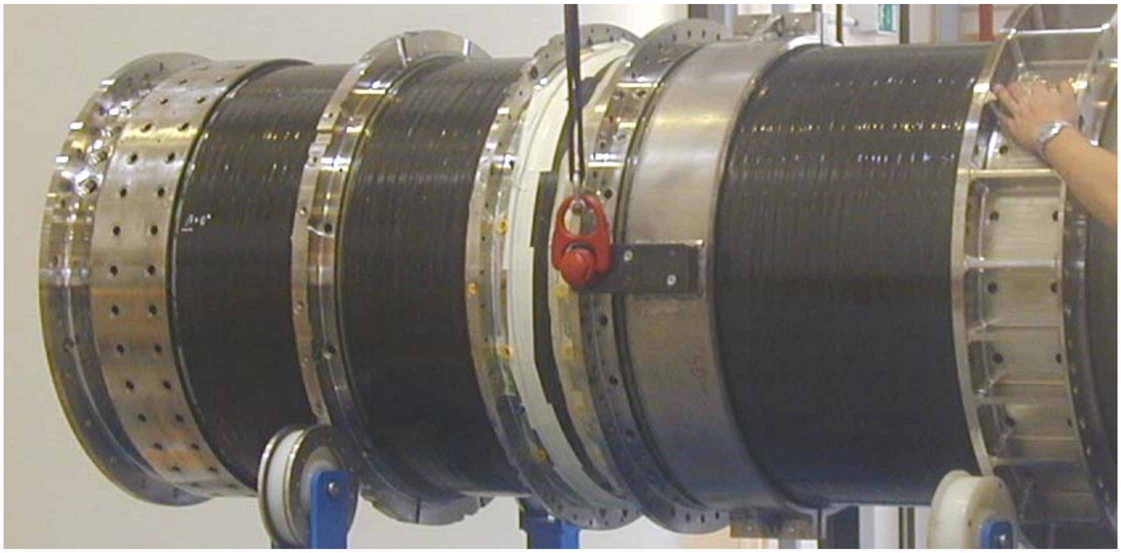

Figure 5. The Nasmyth tube (in black) made of carbon fiber reinforced plastic with interface rings being attached to it at MAN (Germany). The instrument adapter will be mounted to the leftmost interface, the bearing sphere will be supported by the two flanges at the right. Compare with Figure 1.

Figure 6. The bearing sphere ready to be integrated. The bearing races are the upper and lower shiny surfaces. Their deviation from a sphere is less than 10 micron.

The secondary mirror is animated by a two-stage secondary drive system. A stiff hexapod driven base plate provides 6 degree of freedom slow movements for the secondary, which will be used for focussing and optical alignment as well as for optimization of the image quality during operation. On top of the hexapod a 3-unit linear drive provides fast rotation movements of the mirror around its center of gravity. The linear drive system will be used for chopping, for user defined image motion as well as for image motion compensation of up to about 35 Hz. An interface plate provides stress-free acceleration of the mirror itself. The secondary mirror drive system has been designed as a very compact unit in order to fit into the limited space between the secondary and the cavity door, which is part of the aircraft. The manufacturing of the drive unit is ongoing.

The Nasmyth tube provides the mechanical center piece of the telescope (Fig. 5). With a length of 6m and 3 cm wall thickness and suspended by the bearing sphere, it carries all the weight of the telescope on one side and the counterweight and science instruments on the other.

The bearing sphere embraces the Nasmyth tube and carries the dynamical weight of 9 tons of the telescope. Made of cast iron with an outer diameter of 1.2 m, it represents the inner part of the hydraulical oil bearing. The fitting of such bearings is rather tight since oil gaps around 40 µm have to be achieved. The bearing sphere has been polished to an accuracy better than 10 µm. The bearing rings, surrounding by the bearing sphere, are shown in Fig. 6.

Figure 7. Bearing rings surrounded by inner and outer cradle and the elevation drive mounted on a test setup at MAN (Germany). The fine drive rotates the inner (blue) structure against the outer (blue) structure.

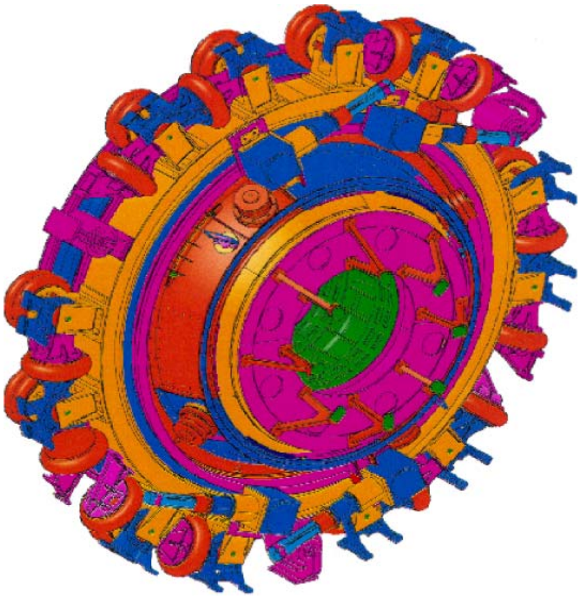

Figure 8. The vibration isolation bumpers are arranged along the outer circumference of the telescope coarse drive as shown in this CAD drawing.

The coarse and a fine drive (Figure 7) of the telescope provide a free elevation range relative to the aircraft of 20° – 60° during operation and 0° - 180° for maintenance. The telescope can be rotated in cross-elevation by ± 3° to compensate for aircraft movements. Rotation of the third axis by ± 3° provides a means of compensating image rotation during at least 12 to 15 minutes. An optional instrument rotator at the instrument flange will also provide image rotation compensation. Positioning of the SOFIA telescope is based on spherical sensors (position sensitive devices, PSDs), located at the bearing, and an high resolution inertial three laser gyro system, which is updated regularly by the focal plane tracker camera. The gyros were specially developed for SOFIA to provide extremely low drift rates and noise. Each of them includes 3km of glass fiber providing an angular increment of 0.0008".

The vibration isolation system (Figure 8) consists of pressurized rubber bumpers, which are radially and axially arranged between the telescope drive and the forward bulkhead and represent the structural interface between the telescope and the aircraft. They can be adjusted to accommodate different altitudes and have been successfully tested.

Figure 9. Mirror cell of the SOFIA telescope ready to be integrated at MAN Augsburg.

The telescope is currently being assembled at MAN, Augsburg (Germany) (Fig. 9).

According to the current schedule, the telescope will be integrated into the aircraft cavity during 2003 in the USA. First light is then expected for 2004. Regular astronomical observing will begin early 2005.

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