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SOFIA Optical Design for the Aft Configuration

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Abstract

The Stratospheric Observatory for Infrared Astronomy (SOFIA) is a planned NASA facility consisting of an infrared telescope of 2.5 meter system aperture flying in a modified Boeing 747. It will have an image diameter of 1.5 arc seconds, an operating wavelength range from visible through 1 millimeter, an 8 arcminute field of view, and a chopping secondary. The configuration is a Cassegrain with a diagonal tertiary to direct the beam to a Nasmyth focus. The new choice of a location aft of the wings allows the primary mirror to have about an f/1.4 focal ratio, which is preferable to the f/1.1 previously planned for the forward location.

1. Introduction

SOFIA is a proposed new airborne astronomical observatory to continue NASA's airborne infrared astronomy program[1] into the 1990's as the successor to the Kuiper Airborne Observatory (KAO)[2,3]. The SOFIA telescope requires a 2.5 meter, clear-aperture Classical Cassegrain design similar to the 0.9 meter aperture telescope in the KAO. The Telescope System[4] as currently defined, is supported on an air bearing, inertially stabilized, and vibration isolated. It provides for the mounting, at a Nasmyth focus, of a Scientific Instrument (SI) which is accessible to scientists in flight. The telescope assembly will be required to acquire and track celestial targets to sub-arc second accuracy and stability. A modified Boeing 747 aircraft will provide for operation of the telescope while viewing through an open port at altitudes ≥ 41,000 feet and at -40 °C for periods exceeding five hours per flight.

Design drivers include both facility restrictions and performance requirements. Among the former are the limited mass capacity, limited available volume, stratospheric operating temperature, aircraft vibration environment, and cost. Drivers among the performance requirements are image quality, field-of-view size, and "chopping" (the tilting of the secondary mirror to enable infrared background subtraction). The image quality requirement is that the diameter, on the sky, which encloses 80% of the energy from a point source, be no more than 1.5 arcseconds in diameter at the test wavelength of 0.633 micrometer, exclusive of "seeing" effects. The field-of-view must be 8 arcminutes in diameter, and the secondary mirror must be tiltable to shift the center of the field-of-view by plus or minus 5 arcminutes.

The most obvious place to put a large telescope in a 747 is the enlarged fuselage ahead of the wings, the forward configuration. This location was initially selected for the telescope, however, the SOFIA Project Office concluded that a location aft of the wings, the aft configuration, is actually preferable[5]. Many factors were examined, including results from studies of aircraft structure and internal systems, which later showed the necessary aircraft modifications would be lower in cost. Due to an increase in the cavity depth, the telescope can be longer, which is advantageous to the optical design, and which lowers the risk and fabrication cost of the primary mirror.

2. Performance Requirements

The performance requirements for SOFIA include an image diameter (containing 80% of the energy from a point source) of no more than 1.5 arc seconds on the sky at a wavelength of 0.633 micrometer. This image quality is consistent with the overall system image quality budget which takes into account estimates of the blur circle arising from aero-optical seeing. This kind of seeing results from the signal wavefront propagation through the turbulent shear layer over the open cavity. While the specification is given only at the test wavelength, aberrations should not be worse at the longer infrared observation wavelengths. Diffraction will, however, increase linearly with wavelength. The facility will, in fact, operate over a wavelength range extending to 1 millimeter.

The field of view will be at least 8 arc minutes in diameter, and the chopping throw will be up to 5 arc minutes in any direction. The system aperture stop will be at the secondary mirror. This stop location will result in the primary mirror being oversized as if the field of view were 18 arcminutes in diameter. Tilting of the secondary will then select an 8 arcminute diameter field for delivery to the focal plane. Due to beam movement from tilting, a primary mirror of nearly 2.7 meters diameter will be needed to achieve the 2.5 meter diameter system aperture. The telescope interface must accept the interchange of scientific instruments, each of which is then accessible during flight.

3. ARC Baseline Design

The telescope design chosen for the aft configuration[6] is the same as that developed previously for the forward location (except for reversal of orientation as in Figure 1) and similar to that utilized in the Kuiper Airborne Observatory. The telescope is a Cassegrain-Nasmyth arrangement as depicted in Figure 2, with a concave primary mirror of short focal length, a convex secondary mirror located inside the focus of the primary, and a flat diagonal tertiary located between the primary and the secondary. The tertiary directs the beam to the scientific instrument at a right angle to the telescope axis, approximately along the aircraft axis, through a structural Nasmyth tube supported on an air bearing located in a pressure bulkhead.

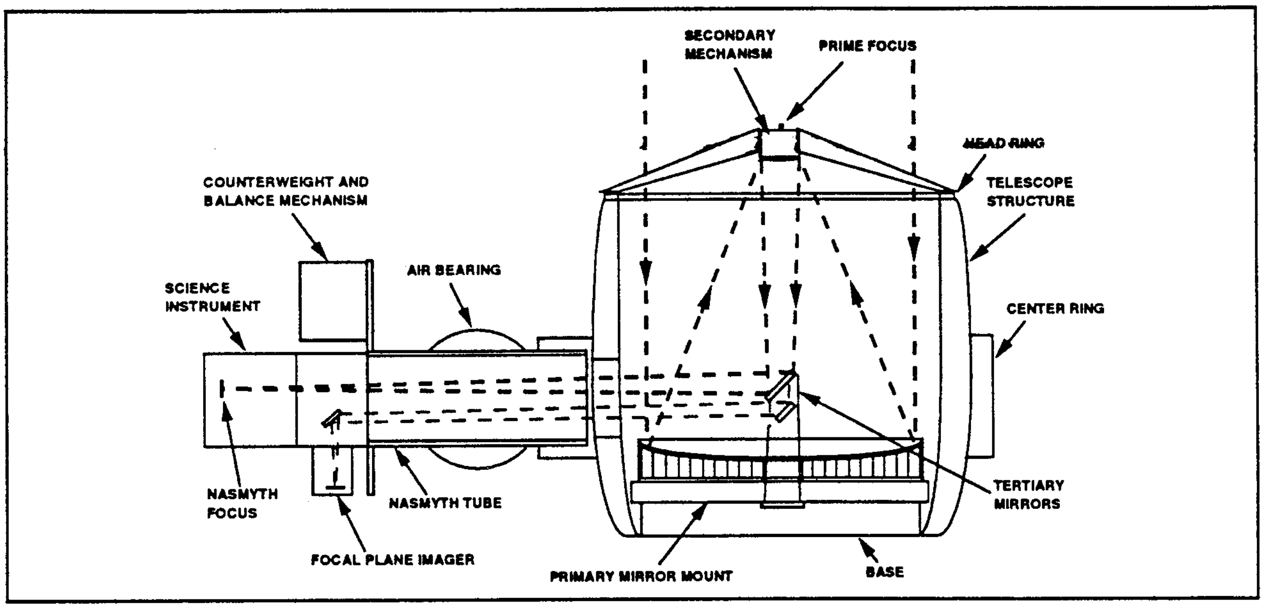

Figure 1. Telescope Assembly

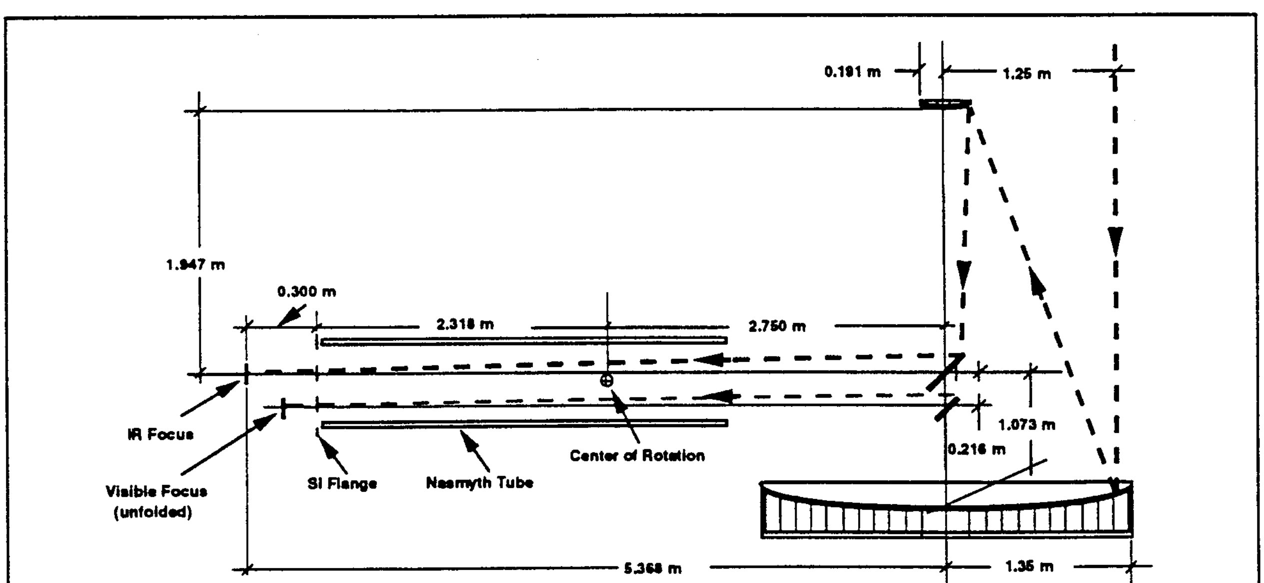

Figure 2. Telescope Optical layout

The primary mirror must be lightweight. It is particularly important because of the need to reach the lowest practical weight for the telescope. Increasing the weight of the mirror in turn drives up the weight of the telescope structure, Nasmyth tube, air bearing, vibration isolator, and counter balance. At the same time, structural stiffness of the telescope is of great importance to the successful achievement of the stringent pointing stability of 0.2 arc second rms. A heavy primary mirror drives up the whole Telescope System weight, which tends to lower the frequencies of the structural modes, particularly the first bending mode of the Nasmyth tube. Thus it is seen, there is a cascading effect on the weight and cost of the whole system from the primary mirror. Recent advances in the technology of lightweight, structured mirrors in the U.S. have made it possible to achieve a mirror weight in the range of 400 kg to 600 kg.

For the ARC baseline primary mirror, a compromise weight at around 584 kg was estimated for a structured mirror shown in Figure 3. It can be fabricated from a combination of technologies. The core can be cut in a single piece by waterjet, the face and back plates formed from sheets, and the three parts joined by frit bonding. Web and plate thicknesses were assumed to be 12 mm.

The secondary mirror will be about 38 centimeters in diameter, of lightweight construction, and tiltable at frequencies up to 35 Hertz, though at varying amplitudes. The required chopping performance is considered within the state of the art, as evidenced by the chopping mechanism designed for the Keck Observatory; however, the SOFIA airborne application will still present challenges to the optomechanical and controls designers.

There will actually be two tertiary mirrors: the first one a dichroic, which reflects the infrared beam to the scientific instrument, but transmits visible light; and a second fully reflective mirror which will direct visible light to the focal plane guidance sensor. (For some observations the dichroic will be replaced with a fully reflective tertiary. At these times tracking will be accomplished using an attached guide camera.) It was recently determined that it will be advantageous if the second tertiary is cropped at the upper and lower ends of the full elliptical shape. (Formerly it had been assumed that all vignetting would be at the top, by the dichroic tertiary, or that the Nasmyth tube would simply have to be large enough to accommodate both beams in their entirety.) This shape will produce a somewhat smaller visible light beam, which will be below the infrared beam. The Nasmyth tube, and the air bearing on which the entire telescope rests will thus be smaller and less expensive. The attendant loss of light in the shaped visible beam for focal plane guidance is acceptable; further, this symmetric shaping of the effective visible aperture utilized will retain a symmetric image for ease in centroiding.

SOFIA will provide a pressure window for sealing the SI from the atmosphere present in the aircraft cavity. This seal will allow the SI to be evacuated and cooled in order to lower the emission of optics and for achieving the appropriate temperature for detector operation. Some wavelengths will require special window material which will be supplied by the Principal Investigator who can install it in a standard mounting provision located near the instrument mounting flange. Alternatively, the window may be located as an integral part of the SI.

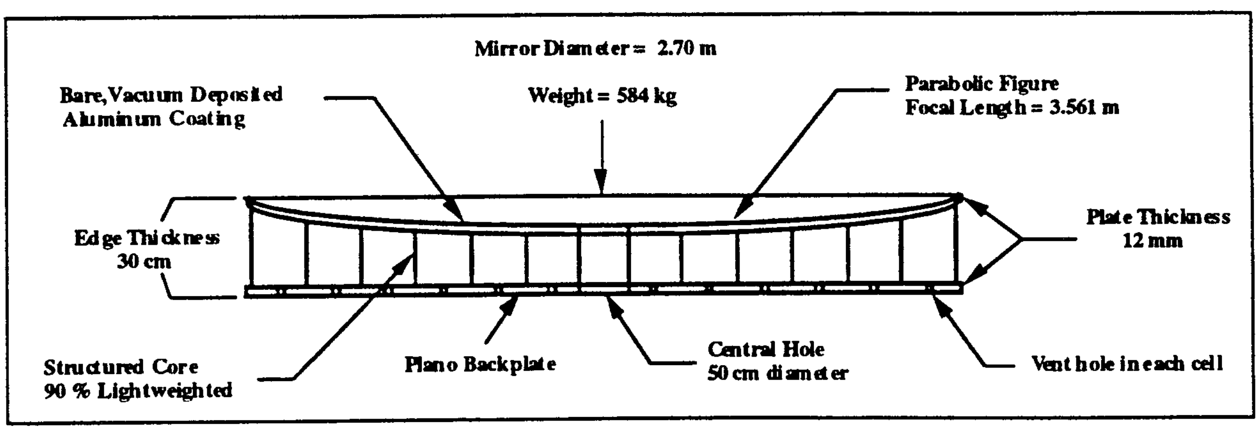

Figure 3. Baseline Primary Mirror

Feasibility of meeting the image quality requirement with this design has been investigated by preparation of a preliminary image quality budget[6] (Figure 4). This budget encompasses high frequency image motion, and focus error, as well as the built in aberrations and gravitational and thermal effects. From this budget, tolerances have been developed. Investigation of a few of the apparently more difficult tolerances from a mechanical point of view indicates that careful design of the structure will enable meeting of these derived requirements.

4. Changes Relative to the Forward Location

Along with choosing the aft location, it was also decided that the straight Cassegrain focus with SI accommodation behind the primary mirror would not be provided, nor would a selection of system focal ratios. Only a relatively small number of investigations require the Cassegrain focus, so the requirement was deleted in the interest of simplification and cost reduction. In a similar vein, changes to the system f/ratio would require, as a minimum, changes of the secondary mirror. It was deemed more cost effective to compromise on a single f/ratio and make the necessary changes to the interface optics of the instruments.

As noted above, one of the advantages of the aft location is that the telescope can be longer. This allows a longer focal length for the primary mirror, about f/1.4, instead of f/1.1 as previously conceived. There is a consequent relaxation of some of the mechanical tolerances (field coma goes as the inverse cube of the primary focal ratio) and an improvement in chopped image quality.

The introduction of a dual tertiary and a focal plane guidance camera makes it easier to achieve the stability requirements. With the guidance camera and scientific instrument firmly connected to each other, and the two tertiaries firmly connected to each other, the image deflections due to bending of the Nasmyth tube have identical effects in the visible and infrared. The dual tertiary system[6], with the visible light tertiary cropped, is illustrated (Figure 5). An alternative concept, calling for sending a single beam through the tube, and picking off the visible beam later, either introduces another emitting surface into the infrared view, or places the science instrument at a very difficult angle, neither of which are acceptable for scientific or engineering reasons.

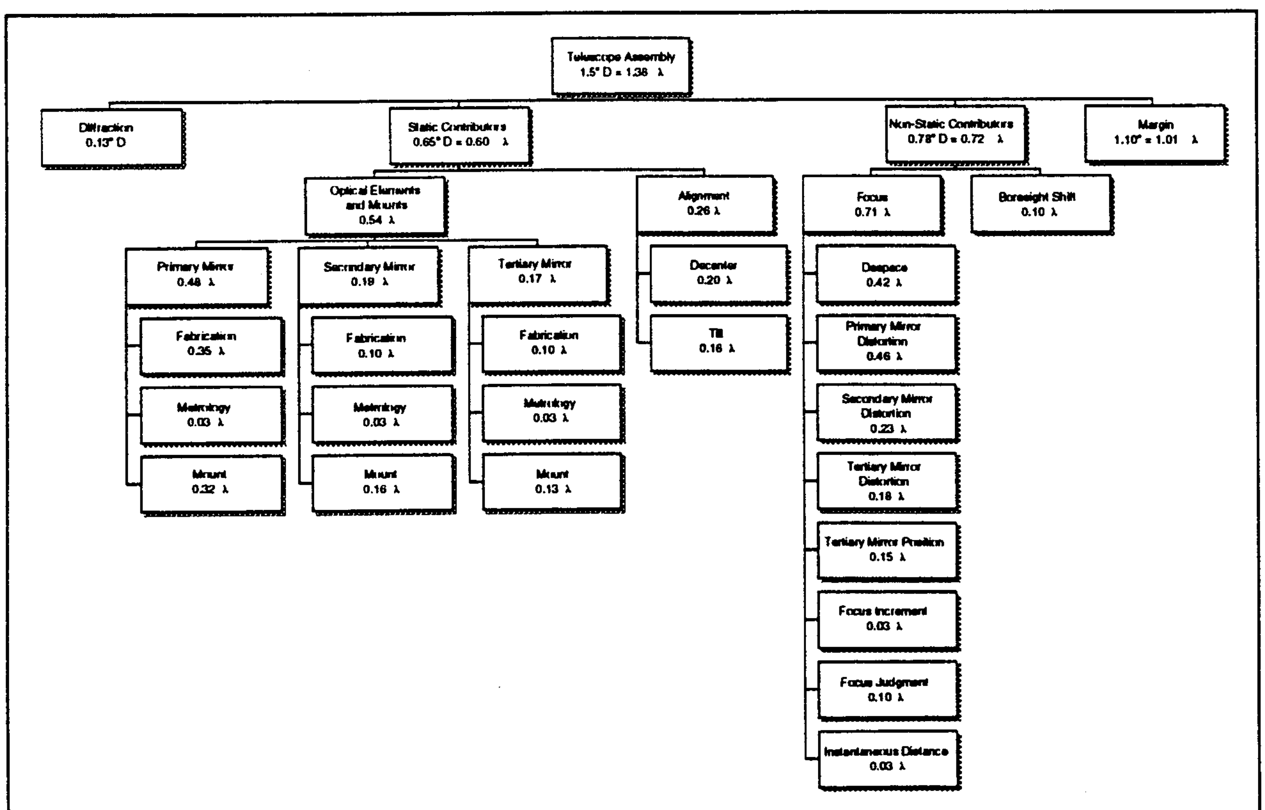

Figure 4. Image Quality/Wavefront Error Budget

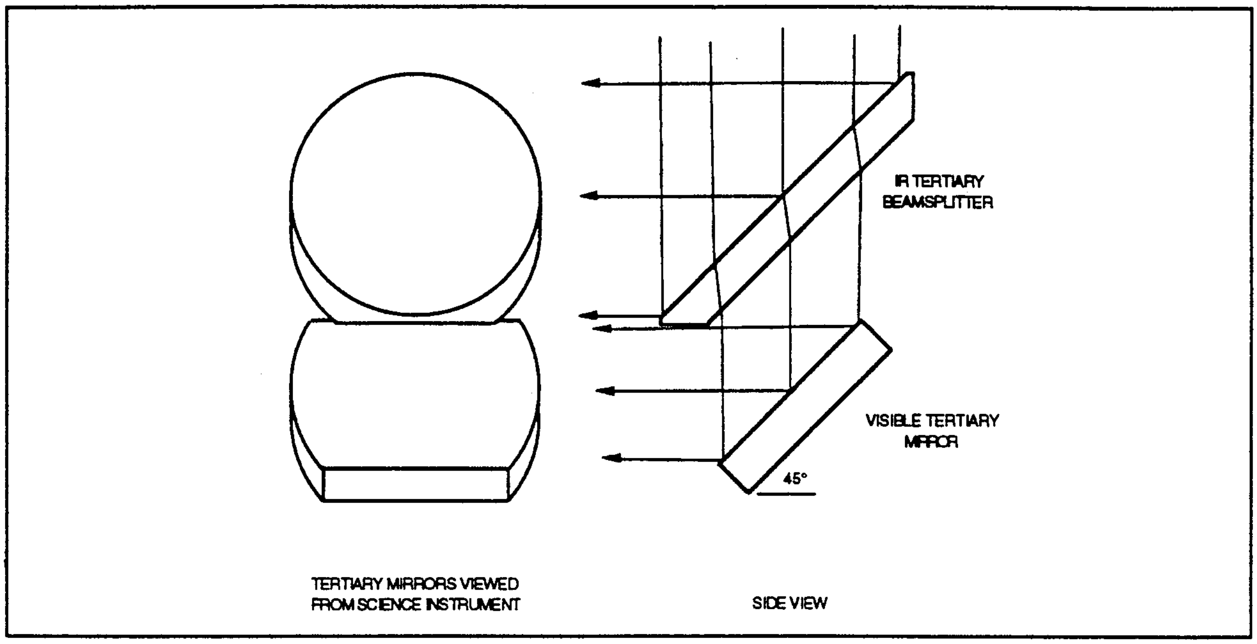

Figure 5. Tertiary Mirrors

The boundary layer over the aft fuselage of the aircraft is thicker than in the front. Analyses and wind tunnel tests have been performed to estimate the boundary layer and shear layer effects on the aero-optical seeing over the aft cavity[7]. Other analyses[8] were performed for the front cavity location. A detailed comparison of these analyses and results is beyond the scope of this paper; however, seeing estimates[9] for the aft cavity reveal a decrease in the resulting blur starting around 2 microns and extending to about 10 microns, beyond which diffraction will dominate.

One potential disadvantage of the aft location, the contribution of thermal radiation from the aircraft engines and exhaust to stray light in the telescope, was investigated in depth. A model of an exhaust plume and its emission was developed to provide an input to an analysis[10] utilizing Program APART/PADE. The analysis showed that only minor restrictions to the operation of the facility are entailed. Only near the telescope's lowest elevation, 20 degrees, are short wavelength observations affected. An additional interesting result was the finding that the plume emission was actually less important as an IR source than the inboard engine exhaust cone, which reaches a temperature near 1000 degrees F.

5. Summary and Conclusion

We conclude that an optical design meeting SOFIA constraints, performance requirements, and mission objectives has been found, which can be manufactured at an acceptable cost. This tentative baseline design is similar to the former design for the forward location, but with a slightly slower primary. It is a Cassegrain with a flat diagonal tertiary for each of two beams (scientific and tracking) directing the infrared and visible light to Nasmyth foci in the aircraft cabin.

6. References

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