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## AMES RESEARCH CENTER

## SYSTEM ENGINEERING REPORT (SER) EWD-001

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**SUBJECT:** SOFIA SEEING ISSUES

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# SOFIA Seeing Issues

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9/19/88

This document is a summary of the rationale behind the seeing and image quality related design requirements for SOFIA. Most of the information is derived from the report *Investigation of the Images Formed by the Telescope in the Kuiper Airborne Observatory*, dated February 10, 1987, by E.W. Dunham, et al.

## I. Introduction

From a scientific point of view, good image quality is important for two major reasons. First, there is more information in a sharp image than a blurry one, and second, the S/N ratio of background-limited observations varies linearly with the image FWHM. It is interesting to note that in the background-limited case, which is a commonly encountered one, reducing the image size by a factor of two is equivalent to increasing the telescope aperture by a factor of two. The image quality directly affects our ability to carry out planetary astronomy, where most observations are done at the shorter IR or optical wavelengths, and some astrophysical investigations. Examples include finding the location of subsurface ice on Mars and understanding what happens in a forming stellar/planetary system.

## II. Contributors to Image Degradation

The following items contribute to the final observed image size in the focal plane. These items will be discussed separately in the following sections. We expect that the total image size will be approximately the vector sum of the individual contributions. If ways are found to reduce any of these contributions without significant additional expense, they should be followed up.

| Effect | Estimated Magnitude |
|---|---|
| Optical aberrations | 1-2 arcsec |
| Pointing (tracking and vibration) | 0.2 arcsec |
| Turbulence in the telescope cavity and air bearing path | ~1 arcsec |
| Turbulence in the shear layer over the cavity. | ~1 arcsec |

The item we have the least control over is the shear layer. We expect to obtain a one arcsecond image size from the shear layer by using the aft ramp shear layer control configuration, so the other contributors should be made smaller than this if possible. In comparison, the KAO shear layer degrades the image between 1.3 and 2 arcsec (FWHM) depending on the Mach number.

### Optics

There are two aspects to the optics contribution. First, there are imperfections in the optical surfaces, and second there are unavoidable aberrations that are inherent in the optical configuration chosen, usually causing off-axis coma and astigmatism. I will consider only the first issue here.

The specification in SOF-1011.01 section 3.5.4.1 (as of today) is for the central 2 meters to have 80% of the light enclosed in a circle at most 1 arcsec in diameter at a

wavelength of .633 microns (HeNe laser wavelength), and 80% of the light enclosed in a circle at most 2 arcsec in diameter for the full aperture. This specification is about as loose as it can be without having the optical quality be the major cause of image degradation on SOFIA.

Other factors that can degrade the image quality delivered by the telescope optics include focus resolution and stability, optical alignment or collimation and vibrational distortion of optical surfaces or their alignment. It should be noted that the performance of the KAO telescope optics is limited not by the quality of the optical components themselves but by errors in the alignment of the components, a characteristic it shares with most groundbased telescopes. The focus resolution specification in section 3.5.8 of SOF-1011.01 is such that the focus resolution corresponds to an image blur significantly smaller than 1 arcsec, as it should be. Alignment is discussed in sections 3.4, 3.6.21.5, 4.2.4 and 4.4 of SOF-1011.01, where the alignment precision is specified in terms of the image quality and the required fixtures and procedures are also discussed. Finally, vibration is discussed in sections 3.3.4, 3.5.4.1, 3.5.19.2 and 4.2.3 of SOF-1011.01.

## Pointing

The pointing stability specification in SOF-1011.01 section 3.6.3.3 is tighter than image quality considerations alone require. It is driven by the anticipated use of superresolution (deconvolution) techniques to improve the resolution of maps. Such work requires that the pointing be very stable over the time period during which the map is made. It makes additional demands on the pointing accuracy and offset pointing precision (Sections 3.6.3.1 and 3.6.3.2) that are not issues for the image quality alone. The pointing specifications are derived from experience with superresolution techniques on the KAO. The main systems affecting the pointing accuracy are the vibration isolation system, the gyrostabilization system and the optical tracking system. For more information on the pointing requirements, contact Paul Harvey at the University of Texas at Austin.

## Cavity

Temperature fluctuations in the cavity and air bearing regions are important sources of image degradation on the KAO, and would also be on SOFIA if we let them. Analogous "dome seeing" is the dominant source of image degradation in ground-based telescopes, where the rule of thumb is one arcsec of image degradation per degree C of temperature difference between the air and the warmest component near the optical path. On the KAO, this rule appears to be one arcsec per two degrees C, the difference being most likely due to the lower air density at altitude. The major offending components on the KAO, owing to their long thermal time constants, are the metal "tub" containing the primary mirror and the mirror itself. In addition, it is clear that considerable image degradation occurs in the region of the air bearing due to the large temperature gradient there. Also, if an air leak from cabin to cavity is present, the image quality suffers, but this effect has not been quantified. Finally, we expect that the heat injected into the cavity due to imperfect insulation on the walls, gyro package and TV cameras are also factors in degrading the image quality, although controlled experiments verifying this have not been made.

In the case of SOFIA, we have the opportunity to eliminate this problem in the design phase. The thermal imbalance between the telescope assembly and the air is addressed in numerous places in the SOF-1011.01 document where a temperature deviation between +2 and -10 °C is specified. We have found that it is helpful to have the mirror and "tub" cooler than the air on the KAO, which is the reason that the range includes negative values. The lower limit of -10 °C probably reflects the fact that no test data exists for more negative values. As far as we know now, the lower limit may be set by the dew point at altitude. The upper limit of +2 °C corresponds roughly to a 1 arcsecond image degradation. It would be desirable to reduce this if it doesn't incur substantial additional expense. If this

limit were to be reduced to +1 °C, the expected image size would drop from 1.74 arcsec to 1.51 arcsec. For a background-limited observation, this corresponds to increasing the telescope aperture from 3 meters to 3.5 meters. In SOF-1011.01, this temperature deviation range should be applied to *every* component, active and passive, in the telescope cavity and air bearing region.

The cavity walls present a difficulty unknown to groundbased observatories, namely the fact that they are pressure bulkheads. They will be built using standard aircraft techniques and will therefore leak air. In addition, the insulation on the walls will be imperfect, so they will leak heat as well. Leaks are very easy to create, very difficult to find and nearly impossible to quantify. They are a recurring problem on the KAO, in spite of some major efforts to eliminate them. A possible solution to this problem for SOFIA would be to install a thin aluminum false wall inside the cavity an inch or two from what would otherwise be the inside wall. Note that this false wall is not a pressure seal, so it doesn't need very tight joints. If air was circulated through the gap and exhausted downstream, perhaps by simply running a duct to an area above the wing root where the pressure is low, the need for unusually good sealing of the cavity would be eliminated. This would make work on the cavity easier in the construction phase and would also make work on the cavity during the operational phase less likely to degrade the image quality. In addition, the thermal insulation need not be as difficult to install. A false wall would effectively eliminate the leak problem.

## Shear Layer

The contribution of the shear layer can at present only be estimated based on our image quality measurements on the KAO and the AOA model in the 14-foot wind tunnel. Further work will be conducted as part of the SOFIA wind tunnel test. The KAO shear layer produces an image FWHM between 1.3 arcsec (at Mach 0.64) and 2 arcsec (at Mach 0.82). In the AOA wind tunnel test, we found that an aft ramp configuration was superior to a fence configuration, from an optical point of view, by about a factor of 2, which is the origin of our expectation of obtaining a 1 arcsec shear layer on SOFIA.

In the short wavelength limit, where the linear rms wavefront error corresponds to many radians of phase, the angular image size is given roughly by the ratio of the rms wavefront error to the correlation length of the turbulence. Both of these parameters grow linearly with distance downstream from the forward edge of the cavity (or the fence if one is used), so the image size is essentially independent of position in the shear layer and is therefore also independent of telescope aperture. In the special case where the correlation function of the turbulence is Gaussian, the image size will decrease dramatically with wavelength when the wavelength becomes long enough that the linear wavefront error becomes smaller than a half or a quarter of a wavelength. It is not clear whether this occurs on the KAO because of the presence of numerous additional sources of image degradation. We intend to see if an effect like this occurs in the wind tunnel with the SOFIA model. If it occurs in the actual SOFIA aircraft, we will have images that are limited by the shear layer at optical wavelengths, by optical figure errors at the shorter IR wavelengths and by diffraction at longer wavelengths.

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-- PRELIMINARY ANNOUNCEMENT --

WORKSHOP ON SEEING FROM SOFIA
NASA Ames Research Center
Building 245, Room 141
July 14, 1989
8:15 am - 5:30 pm

## PURPOSE

Existing information and anticipated measurements related to seeing from SOFIA will be reviewed in order to establish (1) is the baseline design satisfactory, and (2) what additional efforts are necessary.

## OPERATING DEFINTION OF SEEING

For this workshop we will define seeing as the diameter of the angular disk containing 84% encircled energy from a point source. This can be compared with the diffraction diameter 2.4 lambda/D, where D = 2.5 meters is the nominal telescope diameter for SOFIA. "Optical" wavelengths will refer to 0.5 microns, unless otherwise stated. For SOFIA the diffraction diameter is roughly 0.1 seconds of arc (") = 0.5 microradians.

## BACKGROUND

Images measured on the KAO and in wind tunnel tests indicate that the seeing on SOFIA caused by the shear layer will be roughly 2" or more. See the attachment by Ted Dunham on "Seeing from SOFIA." The above definition of seeing is practical for astronomical applications because the expected seeing is so much larger than the diffraction limit.

The baseline design specifications for the telescope optical system are 1" optical image quality and 0.2" rms pointing stability. These were selected to be compatible with the anticipated shear layer limit. If this limit is underestimated, or if seeing from other sources (eg cavity effects) is larger, the telescope requirements could be less stringent and the telescope correspondingly cheaper. Optical, pointing, thermal, and shear layer control systems could all be affected. The baseline shear layer control is a passive aft ramp.

Most observations from SOFIA will be made at wavelengths much longer than optical, where the seeing effects are negligible. However, for guiding the telescope and for selected planetary science applications, good optical image quality is desirable. Near infrared (1-8 micron) planetary and astrophysical measurements will also benefit significantly from good image quality, where seeing is still an issue.

## QUESTIONS AND ISSUES

KAO measurements: what have we learned? can we learn more? can these results be predicted with (CFD) models?

AOA measurements: same as KAO questions; does lip blowing significantly improve seeing? (Aft ramp versus fence)

Wind tunnel measurements:

A. Aerodynamic: can planned measurements provide necessary information for seeing models? Are predictions of seeing models reliable?

B. Optical: are they needed? significant?

Wavelength dependence: how does the seeing improve going from 0.3 to 30 micron wavelengths?

Shear layer control: are minimum drag and minimum optical degradation compatible? under what conditions?

Aircraft/cavity configuration: which model 747/cavity location (forward or aft of the wing) would provide the best seeing? How do possible configurations rank in terms of optical seeing?

Future activities: what further work should be undertaken? considered?

## PARTICIPANTS

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