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**Predicted optical performance of the high-altitude balloon experiment (HABE)
telescope in an adverse thermal environment ¹**

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ABSTRACT

The High-Altitude Balloon Experiment (HABE) telescope was designed to operate at an ambient temperature of -55 °C and an altitude of 26 km, using a precooled primary mirror. Although at this altitude the air density is only 1.4 percent of the value at sea level, the temperature gradients within the telescope are high enough to deform the optical wavefront. This problem is considerably lessened by precooled the primary mirror to -35 °C. This paper describes the application of several codes to determine the range of wavefront deformation during a mission.

1. INTRODUCTION

The 60-cm diameter telescope shown in Fig. 1 is the primary optical receiver in the payload that is used to track targets and acquire optical data. It is located on the gimballed optics bench along with the coarse acquisition camera and the ranger scorer. The telescope images the target onto the infrared (IR) intermediate-tracking and fine-tracking cameras and also images the marker laser beam onto the target. A 1-1/2-in. diameter alignment laser beam also traverses the telescope and is used to reduce jitter between all optics common to the incident fine-tracking wavefront and the exiting marker laser beam. The transmitted wavefront requirement is driven by the required size of the marker laser on the target.

The HABE telescope must operate in an adverse thermal environment that changes during the mission. Prior to launch, the telescope is sealed in the optics canister and the primary mirror is cooled to -35 °C. As the balloon rises, the pressure is reduced in the canister, and when the flight altitude is reached, the canister is opened. The telescope has been designed and fabricated with materials chosen so that it operates similarly to an isothermal system with components that are held in alignment over the temperature range from 20 to -55 °C. To reduce any lateral temperature gradients on the metering structure that would cause misalignment, the metering structure is located between an inner light baffle and an outer radiation shield. Even with this design, there still may exist within the interior of the telescope large temperature gradients that can heat to a varying degree the residual air contained within the optical path. Although at 26 km the density of the air has dropped to 1.4 percent of the standard temperature and pressure (STP) value, there is sufficient density change along the optical path of 1.4 m to distort the wavefront.

This paper describes the models and calculations used to predict the distortion. It describes the input to the thermal models, and the resultant temperature changes of all of the components that affect the air density gradients within the telescope tube. These component temperatures were used to determine the density gradients, the optical path changes, and an optical path difference (OPD) map across the pupil. Wavefront aberrations were extracted and used to calculate the point-spread function (PSF). During the first flight of this telescope, temperatures will be recorded to validate the thermal model.

2. THERMAL MODELS

The temperature as a function of time after launch was predicted for three different cases. In the first case (designated Case A in the tables and diagrams), a relatively simple model was used that only included the temperature of the ambient air, and not the environmental heat fluxes (direct and reflected solar, and earthshine) when the telescope is deployed. The drop in temperatures of the secondary mirror, the main baffle, and the primary mirror are shown in Fig. 2 along with the average temperature of the canister and thermal shield surrounding the telescope. The increase in cooling rate seen at 1.5 hours after

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Figure 1. HABE telescope schematic.

Fig. 2. Temperature profiles for the major components of the telescope only with no other heat sinks or sources. The drop in average temperature of the canister and main baffle occurs when the canister is depressurized and swung open 1.5 hours after attaining altitude.

attaining altitude occurs when the canister is depressurized, opened, and deployed to look at the earth. This initial model was done without access to any of the data of canister and component mass, component layout, and other thermal sources. It represents a worst-case scenario, for it is based on not opening the canister until 1.5 hours after launch. It also assumes there is no thermal shield surrounding the telescope. Later analysis showed that Case A is more representative of the optical seeing immediately after opening the canister at altitude.

As the placement of components became fixed in the design process and other power sources were defined, a more realistic model was constructed. In constructing this model, care was taken to use a sufficient number of nodes to determine the temperature gradients for all of the structural elements that influence the thermal gradients within the telescope enclosure and affect the tilt or decentration of the secondary mirror. Figure 3 shows the internal node numbering for the optics canister and Figs. 4 and 5 show in detail the nodes associated with the secondary mirror support structure and the metering trusses. A total of 196 nodes were used with 4,349 thermal conductances as input into the thermal analysis SINDA¹ code. All calculations were made on a SUN Workstation.

The model predicts the telescope temperatures as a function of time for a number of scenarios. The scenarios included midnight and daylight launch times, with the telescope aimed at various aspect angles to the sun varying from full sunlight shining directly on the primary mirror to the sun shining directly behind the telescope. These results showed that the largest thermal gradients occur in the presence of the sun. The scenario chosen to analyze was a launch at 0900 Hours in the presence of no clouds, with telescope deployment at 1030 Hours. Target engagement would then begin 3 hours after liftoff, or at 1200 Hours, and would occur entirely in the sun. The second aspect of the scenario is the orientation of the sun on the telescope. At no time is it required that the telescope point at the sun. Liftoff locations and times are planned to place the target in an optimum solar-illuminated location with the sun at some angle behind the telescope. An analysis of all targets under consideration showed that during any mission the line-of-sight to the sun was never less than 70 degrees. As the worst probable case, temperature profiles were obtained with the sun orientation at 45 degrees to the telescope axis.

The flight profile consisted of 1.5 hours to ascend, 4.8 hours to float, and 0.8 hours to descend. The specific boundary temperatures used for this flight profile are given in Table 1 and assume that the sky is clear and the balloon temperature varies linearly with altitude.

Table 1. Thermal parameters for SINDA model.

Thermal Parameters	Ascent to Float
Effective Sky Temperature	20 to -269 °C
Ambient Air Temperature	20 to -55 °C
Earthshine (BTU/h-ft ²)	132 (constant)
Solar Heat Flux (BTU/h-ft ²)	132 to 442
Earth Albedo	0.3
Thermostatic control of Optics Bench	20 ± 5 °C

Figure 6 shows the environmental heat fluxes and boundary temperatures at a float altitude of 26 km. In addition to these environmental loads, the power dissipated in several components on the optics payload and in close proximity to the telescope are also included. These nodes are shown in Fig. 7 and are used in combination with the TRASYS² code that determines the environmental heat fluxes and thermal radiation conductances to predict the temperature versus time for all of the major components of the telescope.

HABE Telescope Cannister

DE 03232 WD 52

Fig. 3. The nodes used in SINDA for the interior and upper region of the optics canister.

Fig. 4. The nodes used in SINDA for the secondary mirror, its enclosure, and the support spiders.

Fig. 5. The nodes used in SINDA for the metering structure.

Fig. 6. Exterior thermal environment and loads for the HABE payload at a float altitude of 26 km.

HABE Cameras:

Fig. 7. Thermal nodes and power dissipated into the upper canister and near the telescope. The telescope is not shown in this figure.

3. THERMAL MODEL RESULTS

With the sun shining on only one side of the telescope, one would expect to see a difference in temperature between the trusses. The maximum difference from the model for equivalent positions on the trusses was 0.1 degree where the temperatures are modeled to only a precision of 0.1 degree. This result indicates the efficacy of the design of the telescope that placed the metering trusses between the high emissivity inner baffle and the outer high reflectivity radiation shield. With the metering trusses buried in the shields, there is no side-to-side gradient that would introduce a relative tilt between the secondary and primary mirrors.

A similar null effect is seen in the relative spider temperatures that would introduce a secondary decentration. No temperature difference was computed between any of the spiders. This is as expected because the aluminum spider structures have relatively good thermal conductivity and, except for some minor shadowing of one of the struts by the secondary structure, all of the spiders see the same temperature environment.

Figure 8 shows the temperature as a function of time after attaining altitude for the secondary mirror (node 625) and housing (node 615), the primary mirror (node 603), its inner baffle (node 623), and the main baffle (node 1501).

The density variation within the enclosed volume of the telescope using the fluid dynamics code, FIDAP,³ was determined at two different times during the mission. The earlier time, called Case B, evaluates the performance of the telescope at the specified time of 1.5 hours after reaching altitude. The later time, Case C, occurs 3 hours later or 4.5 hours after reaching altitude. The temperatures of components that affect the thermal gradients of the optical path within the telescope enclosure are given in Table 2.

Table 2. Temperatures of the telescope components that affect the optical path.

Component Description	Node Number	Case A T (°C)	Case B T (°C)	Case C T (°C)
Primary Mirror	603	-45	-36.4	-36.1
Primary Mirror Baffle	623	-20	-30.4	-47.6
Secondary Mirror	625	-5	-20.2	-48.7
Secondary Mirror Struts	616-619	-5	3.6 ± 0.3	-20.5 ± 0.3
Secondary Mirror Housing	614	-5	-31.3	-49.9
Secondary Mirror Housing	615	-5	-19.5	-47.7
Main Baffle at Top	1504	-20	-55.5	-55.7
Main Baffle at 0.7 Height	1503	-20	-55.0	-55.6
Main Baffle at 0.4 Height	1502	-20	-34.9	-55.7
Main Baffle at Bottom	1501	-20	-30.4	-55.6

Note: Case A is a first approximation using worst-case parameters.
Cases B and C result from the final model 1.5 hours and 4.5 hours after attaining altitude.

Fig. 8. The temperature profiles versus time after attaining altitude for the secondary mirror and housing, the primary mirror, it's inner baffle and the main interior baffle.

4. AIR DENSITY CALCULATIONS WITHIN THE HABE TELESCOPE STRUCTURE

Using the temperatures calculated from the initial thermal model for Case A and the final thermal model, Cases B and C (Table 2), the air density distribution in the telescope barrel was calculated using the fluid dynamics analysis code FIDAP. FIDAP is an incompressible code that uses the Galerkin finite element method to solve both the Navier-Stokes and energy equations (Boussinesq approximation). A three-dimensional finite element mesh was generated in the telescope barrel and slightly outside the telescope aperture to accommodate a far-field boundary condition (ambient air temperature at -55 °C). The finite element mesh is comprised of 9,552 27-node brick elements (82,371 nodes). Due to symmetry across a vertical mid-plane, only half of the telescope was modeled.

The FIDAP calculations were performed on a CRAY-YMP. The model calculated variations in air densities for 25 piecewise continuous rays within the telescope traveling from the entrance of the telescope to the primary mirror and then to the secondary mirror. Assuming symmetry about a vertical plane through the telescope axis, only one-half of the pupil is evaluated. Since the rays from the secondary to the prime focus are contained within a relatively small angular extent, the density variations from ray to ray were not determined, but were assumed to be constant for those paths. A cross-sectional view of the air density (in gm/cm³) variations obtained from the FIDAP calculations at the symmetry plane for Case A is shown in Fig. 9. This figure clearly shows the air rising and flowing along the upper surface of the inner baffle, as it is warmed by the primary mirror, and exiting at the upper edge of the telescope. One can also see the cold air entering below the secondary structure and dropping towards the warmer baffle. Figure 10 shows the density variations for Case B where the temperature differences between the telescope structure and the ambient air are not as large as those of Case A. Thus, the flow adjacent to the primary mirror and baffle regions is not as pronounced as in Case A, resulting in lower density gradients and a more stable air environment.

5. OPTICAL PATH DETERMINATION

The OPD in units of waves along the 1.4-m path is determined by numerical integration for each ray using the equation

$$OPD = \sum_i t_i \cdot (d_i - d) \frac{(n-1)0.0139}{\lambda d} \quad (1)$$

where d_i is the density in gm/cm³ calculated at the 75 locations along each ray as described in the preceding paragraph, and t_i is the physical path length at each location in centimeters. The factor 0.0139 is the ratio of densities of air at STP and at an altitude of 26 km.

The index of refraction of air at STP is $n = 1.000292$, and the density of air at altitude $d = 3.45E-05$ gm/cm³.

The expression in Eq. (1) is derived from the Dale-Gladstone relationship, $(n-1)/d = \text{a constant}$, and is applicable to moderate variations in density. The wavelength chosen, λ , is the test wavelength of 0.6328μ .

6. PUPIL ABERRATIONS DUE TO THERMAL EFFECTS IN THE RESIDUAL AIR

The resultant OPD for each of the three cases is shown in Figs. 11, 12, and 13. The view is shown with the top of the telescope located at the top of the view. In each case, the plume of warmer air streaming along the upper inner edge of the baffle causes a drop in the optical path. Here the warm air is so extensive that it introduces global tilt into the wavefront. The symmetry of the pattern is due to the assumption that the density variations are mirror images about a vertical plane through the telescope axis.

To observe the optical aberrations in terms of classical primary aberrations, the 31 OPDs were analyzed to determine the orthogonal set of Zernike polynomials. These values are given in Table 3. The nonsymmetric terms are omitted since they are zero because of the assumed symmetry.

Fig. 9. A cross-sectional view of the density variations within the telescope interior for Case A. The upward flow of hot air as it is warmed by the primary mirror can be seen as well as the cooling of the air by the secondary mirror.

Fig. 10. A cross-sectional view of the density variations within the telescope interior for Case B. The upward flow of hot air as it is warmed by the primary mirror can be seen as well as the cooling of the air by the secondary mirror.

Fig. 11. The OPD in units of waves at 0.63 microns for Case A with the upper edge of the telescope indicated by an arrow. It indicates an overall tilt in the wavefront as well as both astigmatism and coma.

Fig. 12. The OPD in units of waves at 0.63 microns for Case B, 1.5 hours after the payload reaches altitude. The hot plume at the top of the telescope results in a combination of astigmatism and coma.

Fig. 13. The OPD in units of waves at 0.63μ for Case C, 4.5 hours after the payload reaches altitude. The smaller hot plume has minimal effect on the rms OPD of the telescope.

Table 3. Optical aberrations in terms of the Zernike polynomials for each of the three cases.

Description of Aberration	Zernike Term	Case A	Case B	Case C
Piston	Z0	-0.363	0.094	0.131
Tilt X	Z1	-0.418	-0.082	0.077
Focus	Z3	-0.259	0.094	0.057
Astigmatism X	Z5	0.159	-0.044	-0.029
Coma X	Z7	0.204	0.034	0.014
Spherical Aberration	Z8	0.272	-0.086	0.018

The 0.418 wave of tilt over the 60-cm aperture is equivalent to $0.37\text{-}\mu\text{rad}$ deviation of the incoming beam. Since both the marker laser and fine-tracking camera use the identical aperture, this tilt does not contribute to the line-of-sight error. It could introduce an error between the telescope line-of-sight and the alignment laser. This alignment laser beam is inserted in a small aperture that may not represent the effective tilt seen over the whole aperture. A decision had been made to locate the alignment beam insertion point on one side to avoid the expected turbulence at the upper and lower edges and to minimize errors caused by non-representative local tilt variances.

7. THERMAL LIMITS TO THE OPTICAL PERFORMANCE OF THE TELESCOPE

The optical aberrations in terms of the extracted Zernike coefficients were introduced at the HABE telescope entrance pupil using the ZEMAX⁴ optical design code. The PSF, the percent of encircled energy within the Airy disc, the rms single-pass transmitted wavefront at $0.63\ \mu$, and the Strehl ratios were determined for each case with and without focus compensation. These are given in Table 4. The rms values given in column 5 can be compared to the specification for the "as-built" telescope of 0.08-wave rms. Column 6 in Table 4 is the root-sum-squared value of both thermal and fabrication errors. The PSF values are plotted with and without focus for Cases A and B in Figures 14 through 17. The PSF for Case C is given in Figure 18. There is no discernable change when the telescope is focused in Case C. The PSF plots and Strehl ratios show a continual improvement in the telescope performance as it cools toward ambient. With focusing, it also indicates that the goal to have an operational and stabilized telescope within 1.5 hours after reaching altitude has been met. It also indicates that within the expected span of an additional 3 hours, the telescope viewing continuously improves, so that the thermal effects are small compared to the specification of 0.08-wave rms of the actual telescope.

Table 4. Strehl ratios, percent of encircled energy enclosed within the Airy disk, and contribution to the rms caused by thermal effects within the telescope enclosure.

Case	Refocus	Strehl Ratio	Encircled Energy (Percent)	Thermal rms Wavefront
A	No	0.18	17	0.62
A	Yes	0.37	28	0.38
B	No	0.84	63	0.20
B	Yes	0.92	70	0.10
C	No	0.95	73	0.06
C	Yes	0.99	75	0.03

Fig. 14. The PSF for Case A without focus compensation. The primary and secondary mirrors and interior baffle temperatures are -45 , -5 , and $-20\ ^\circ\text{C}$, respectively.

Fig. 15. The PSF for Case A after refocusing. The primary and secondary mirrors and interior baffle temperatures are -45, -5, and -20 °C, respectively.

Fig. 16. The PSF for Case B, 1.5 hours after attaining altitude and without focus compensation. The primary and secondary mirrors and interior baffle temperatures are -36.4, -20.2, and -55 to -30 °C, respectively.

Fig. 17. The PSF for Case B, 1.5 hours after attaining altitude and after refocusing. The primary and secondary mirrors and interior baffle temperatures are -36.4 , -20.2 , and -55 to -30 $^{\circ}\text{C}$, respectively.

Fig. 18. The PSF for Case C, 4.5 hr after attaining altitude both before and after focusing. The primary and secondary mirrors and interior baffle temperatures are -36.1 , -48.7 , and -55.6 $^{\circ}\text{C}$, respectively. Refocus increases the Strehl ratio by 4 percent, but there is no apparent change in the PSF.

8. CONCLUSION

The application of codes for thermal analysis, flux and conductance determination, and fluid motion has predicted the three-dimensional density variations within the HABE telescope at several times during a day mission with the sun 45 degrees away from the line-of-sight. The density variations were used to determine the pupil aberrations, their aberration content in terms of Zernike polynomials, and the resultant PSF, rms, and encircled energy values. The results of the model indicate that the wavefront is perturbed by the hotter air flowing out of the upper rim of the telescope, introducing a combination of astigmatism and coma. For the critical Case B, analyzed to determine its capability 1.5 hours after reaching mission altitude, these wavefront aberrations amount to a degradation in the wavefront of 0.20-wave rms and a reduction in the Strehl ratio to a value of 0.84. At this time, i.e., just prior to target engagement, the telescope can be refocused to raise the Strehl ratio to 0.92. These analyses show the validity of precooling the primary mirror, and of using both an inner baffle and an outer thermal radiation shield to protect the metering structure and also show the necessity to refocus the telescope. The goal of obtaining an operational telescope within 1.5 hours after reaching altitude has been achieved.

9. REFERENCES

1. User's Manual for the Aerospace Version of J. Gaski's SINDA 1987/ANSI Code.
2. User's Manual Thermal Radiation Analysis System, TRASYS II ANSI Version 1.0, Martin Marietta, February 1987.
3. FIDAP User's Manual, Fluid Dynamics International, Inc., Revision 6.0, April 1991.
4. ZEMAX Users Manual

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