Daytime use of astronomical telescopes for deep-space optical links

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ABSTRACT

Tests at the 200-inch Hale Telescope on Palomar Mountain have demonstrated this telescope's ability to withstand considerable thermal stress, and subsequently produce remarkably unaffected results. During the day of June 29, 2005, the Hale telescope dome was left open, and the telescope was exposed to outside air and direct sunlight for 8 hours. During this time, portions of the telescope structure in the telescope's optical path experienced temperature elevations of 30 C, while the primary mirror experienced unprecedented heating of over 3 C. The telescope's measured blind pointing accuracy after this exposure was not noticeably degraded from the measurements taken before exposure. More remarkably, the telescope consistently produced stellar images which were significantly better *after* exposure of the telescope (1.2 arcsec) than before (1.6 arcsec), even though the conditions of observation were similar. This data is the first step in co-opting astronomical telescopes for daytime use as astronomical receivers, and supports the contention that deleterious effects from daytime exposure of the telescope can be held to an acceptable level for interleaved communications and astronomy.

1. INTRODUCTION

Astronomical telescopes are almost always designed for use exclusively at night, when the telescope can be kept relatively cool to minimize the seeing conditions that usually limit the telescope's resolution. As a result, there is reasonable skepticism regarding the use of telescopes as receivers for deep-space optical communication links, because these links will be operational during daylight hours, potentially degrading the primary astronomy function of the instruments. These daytime links will also require that the telescope be pointed close to the Sun during periods when the spacecraft is nearing solar conjunction. There are multiple stories of astronomers who have inadvertently allowed sunlight

The Mars Laser Communication Demonstration (MLCD) project[1] had baselined the 200-inch Hale Telescope on Palomar Mountain as the primary receiver for optical communications signals from the Mars Laser Transmitter (MLT) to be placed aboard the Mars Telecommunications Orbiter (MTO). The large aperture of the Hale Telescope was required to collect sufficient signal during high-background daytime conditions to achieve the record-setting Mbps data rates set as goals of the demonstration project. During this project's study phase, several minor studies were undertaken to establish the viability of the approach, considering methods for preventing the primary mirror from being exposed to full solar flux during low-elongation communication links, the likely heating of the primary mirror from exposure to direct and filtered sunlight, the deleterious effects of dome heating from sunlight and air exchange, and safety issues regarding the potential high-intensity spot created when sunlight reflects from the primary mirror. For many of these studies, analytical techniques proved adequate to bound the potential for damage to the structure and facilities. However, there were some classes of problems for which the details of the design and fabrication of the 60+ year-old telescope were inadequate to accurately predict the consequences of daytime operation. For example, concerns over heating of the telescope structure, and its potential for misalignment of the secondary mirror at varying gravity vectors proved very difficult to accurately predict. Also, it has been demonstrated that conditions in which the primary mirror temperature is just a few degrees above the ambient air can significantly degrade astronomical seeing. For the purposes of predicting daytime operational effects on seeing conditions, the level of confidence in fluid-flow and heat transfer analyses was insufficient to draw the relatively firm conclusions desired by the MLCD project as well as the telescope staff. It was therefore decided that the most definitive answers to the questions and the most cost-effective method of obtaining them was to be obtained through a controlled test of the telescope facility under the vigilant watch of the Caltech Optical Observatories staff.

2. EXPERIMENT

2.1 Experiment objectives

The main questions to be answered during the experiment were:

(1) How will the blind-pointing accuracy of the telescope (upon which the MLCD experiment relies for establishing the data link) be affected by sun exposure of the telescope and the resultant differential heating of the mount and structure?
(2) How significant is the warming of the telescope and local facilities when exposed to the typical conditions of an MLCD data pass?
(3) How well do the temperatures of the telescope and associated structures recover after the daylight exposure is completed?
(4) How significantly is the seeing affected by the daytime environmental exposure of a typical MLCD data pass?
(5) How much disruption to the Palomar Adaptive Optics system is observed after exposure to daytime environmental conditions of a typical MLCD data pass?

This last question is important for the potential of 'interleaved operations' in which daytime communication with deep-space assets is interleaved with nighttime astronomical observations with the telescope, essentially allowing the telescope to operate on a double-shift, potentially reducing costs for astronomy and communications. Concerns had been raised that extreme exposure of the telescope and dome to warm daytime conditions would degrade the seeing so significantly that the adaptive optics system would not be able to lock onto a guide star and correct the seeing, rendering the telescope virtually useless for astronomy until it had cooled.

2.2 Experimental procedure

The entire experiment was conducted over a two-day period in 2005 from the morning of 28 June until the morning of 30 June. The initial setup called for outfitting thermal sensors to various structures of the telescope, telescope mount, and dome. The sensors were all connected to a data-logging system in the control room via long wires, to limit RF noise and interference with sensitive instrumentation in the telescope dome. An ultrasonic wind sensor was attached to the head-ring of the telescope to monitor air exchange rates for subsequent convective and forced fluid transfer analysis.

After installation of the various sensors, the dome was opened after sunset, and observations of a variety of stars were made with the PHARO high-resolution imaging instrument on the telescope. The first observation pointed to the SAO-catalog-location of a bright star close to zenith, and an image was taken without adjusting the offsets of the telescope, to establish the initial blind-pointing accuracy of the telescope after several hours of dormancy. Only then was the operator allowed to center the star in the viewfinder, index the telescope (enter the new telescope pointing offsets) and continue pointing to other stars. Subsequent images were obtained for a variety of stars across the sky, concentrating on stars within +/- 30 degrees of the ecliptic, but ranging broadly in hour angle. In no case was the telescope pointing updated or adjusted to center the star in the field of view.

At each star, a set of 10 identical exposures was acquired. In some cases multiple sets were obtained using different filters or exposure times. These multiple images provide the opportunity to observe the apparent image wander resulting from a combination of telescope jitter, seeing and focal plane noise.

As twilight broke on the morning of June 29, the telescope dome was initially closed, the telescope was placed in stow position and the mirror cover was closed. A white shroud was placed over the telescope primary mirror cover to manage the absorption of light at this position that would normally not occur in operation. Once the primary mirror shroud was in place, the telescope dome was opened to a width of 7 meters, and the telescope and dome were set to track a point 45 degrees in advance of the Sun in the ecliptic plane. The telescope tracked this position continuously from before 8:00 AM until the telescope was pointing below the nominal 20-degree elevation angle at which communications operations would be suspended. Throughout this period the telescope and thermal conditions were carefully monitored by the Palomar staff. A thermal infrared imaging camera was used to periodically obtain images of the telescope, mount, dome and structures, both to identify potential hot spots, and to obtain remote readings of temperature on locations that are not monitored directly with thermal probes. Images of some of the thermal probes were also taken for later comparison with the probe data and calibration of the camera.

Once the telescope pointing dipped below the 20 degree elevation angle at about 4:00 PM on the 29th, the dome was closed and the telescope was put into stow position. During the following hour, the primary mirror cover shroud was removed, the cryogen for the PHARO high resolution imager was filled, and an RG850 long-wave-pass filter was placed in the optical path of the Adaptive Optics (AO) wavefront sensor camera to aid in performing adaptive optics during daylight. During this period, though the dome was closed, the air handling and cooling systems were not activated in order to try to hold in the heat that had accumulated during the daylight pass.

At approximately 4:45 PM (local time) the telescope dome was opened and the telescope (with the primary mirror still covered) was pointed to the star Denebula in the southeast. With spotters in the dome confirming that the telescope primary mirror was not in danger of collecting direct sunlight, the mirror cover was opened and daytime observations of stars began. Denebula, Vindemiatrix and SAO 100980 were observed in the eastern sky prior to sunset at 8:01 PM (LT). Attempts were made to establish the performance of the adaptive optics system during this period as well.

After sunset, the infrared filter was removed from the wavefront sensor camera, after which observations continued across the entire sky, both with and without adaptive optics. By design, the same series of stars were observed as for the night of June 28-29 at roughly similar times for more accurate before/after exposure comparison. As the moon rose at the end of the night, attempts were made to observe scattering of moonlight off of the primary mirror at 3 degrees from the moon; however the sky was beginning to brighten noticeably at this time, reducing the value of the data.

2.3 Data analysis

The images from the PHARO camera on the Hale Telescope are 1024x1024 element arrays of 16-bit intensity resolution, stored and transmitted as Flexible Image Transport System (FITS) files. Each pixel covers 0.040 arcsec (194 nrad) for a total field of view of just over 40 arcsec.

Analysis of image sizes was performed by fitting a sub-image centered on the spot to an ideal circularly-symmetric Gaussian blur,

$$b + a\exp\left[-c\left((x-x_0)^2 + (y-y_0)^2\right)\right].$$

The blur amplitude (a), width ($FWHM = 2.355\sqrt{-\frac{1}{2c}}$) and background level (b) are all considered variables along with the blur's center (x_0,y_0) in the non-linear fit algorithm. The sub-image is a square subset of the pixels centered on the blur, with a width ranging from 180 to 240 pixels.

At each sky location, a series of 10 images was obtained. There is variation from image to image resulting from atmospheric turbulence, CCD noise, random photon arrival noise, and telescope drift and jitter. The shortest integration time of the CCD camera is 1.416 seconds, much longer than the turbulence time scale so that exposure-to-exposure the gross blur characteristics of the atmosphere are seen, rather than the 'frozen' speckle pattern produced on the millisecond time scale of adaptive optics. As a result, processing for blur characteristics was accelerated by analyzing the summed set of images.

3. RESULTS

3.1 Exposure conditions

The conditions to which the Hale telescope was exposed are arguably the most severe it has experienced in its nearly 60-year history. Figure 1 shows measured temperature versus local time for four structures of particular concern: the primary mirror cell (which can affect the stresses and ultimately the figure of the primary mirror), the south horn of the right ascension bearing (which can stop the telescope tracking if thermal expansion causes it to go out of round), and the telescope head ring and spider which are directly in the telescope field of view and are expected to significantly degrade the seeing should they warm more than a few degrees above the ambient air temperature.

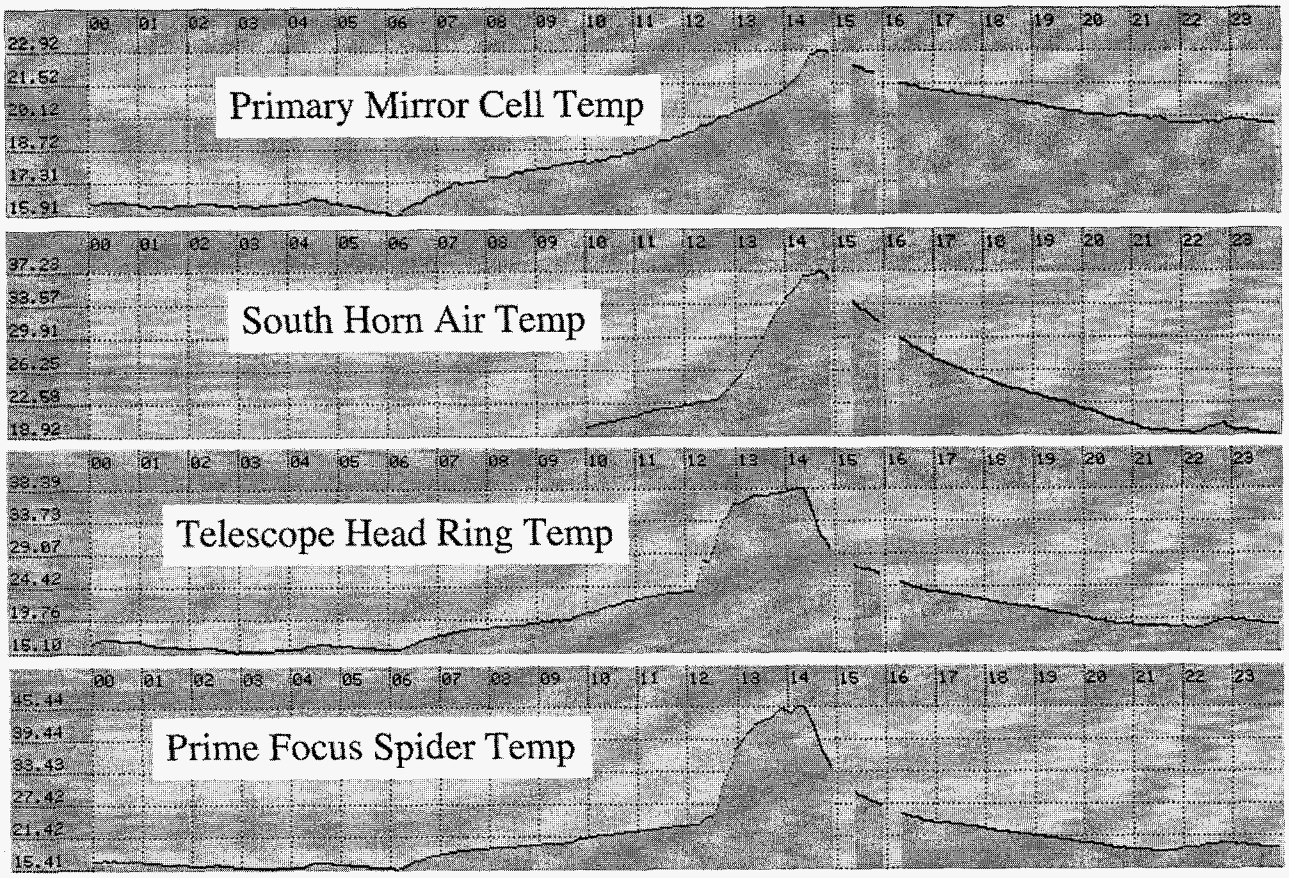

Figure 1 Temperature (deg C) of structural elements of the Hale Telescope during telescope environmental exposure of 29 June, 2005. The horizontal axis denotes local time in hours.

The primary mirror cell rose 7 C above the minimum temperature of the previous night, and was still 4 C above the previous night's minimum during the nighttime operations. Operations personnel at Palomar had never observed such a significant change within a 24-hour period. The south horn of the right ascension bearing experienced direct solar irradiation, and rose almost 15 C in temperature during its 2-hour exposure. It subsequently shed almost all of this accumulated heat, though it took 7 hours to do so. The telescope head ring and the spider (strut) supporting the astronomer's house both experienced a rapid rise in temperature once direct sunlight fell on them, and then appeared to have achieved an approximate equilibrium around 38 C and 45 C, respectively. Both of these structures experienced a more rapid cooling than the primary mirror cell or the right ascension bearing, though they did not reach the low temperatures of the previous night. Throughout the entire sun exposure period and the subsequent observations in the afternoon and night of June 29, the winds were light and variable.

Figure 2 shows a thermal image looking down the 'tube' of the Hale telescope during sun exposure. The enshrouded primary mirror cover is seen to the right of the image, with the baffle tube from the primary mirror projecting out of its center. A small trapezoidal patch of the mirror cover is shown at higher temperature where sunlight has come through the telescope superstructure and illuminated this spot. The left portion of the image shows some of this superstructure which is directly illuminated by sunlight. Some of these structures have risen well above 50C. These points were especially concerning because they were expected to be beneath the telescope FOV during subsequent observations, shedding turbulent cells directly into the telescope's pupil.

Other points of great concern to the Palomar staff were the dome shutter facings, which have the potential for significant warming and subsequent shedding of turbulent cells across the telescope fields of view. During operations, IR images of the shutter facings indicated they had warmed to over 42C, high enough to cause concern.

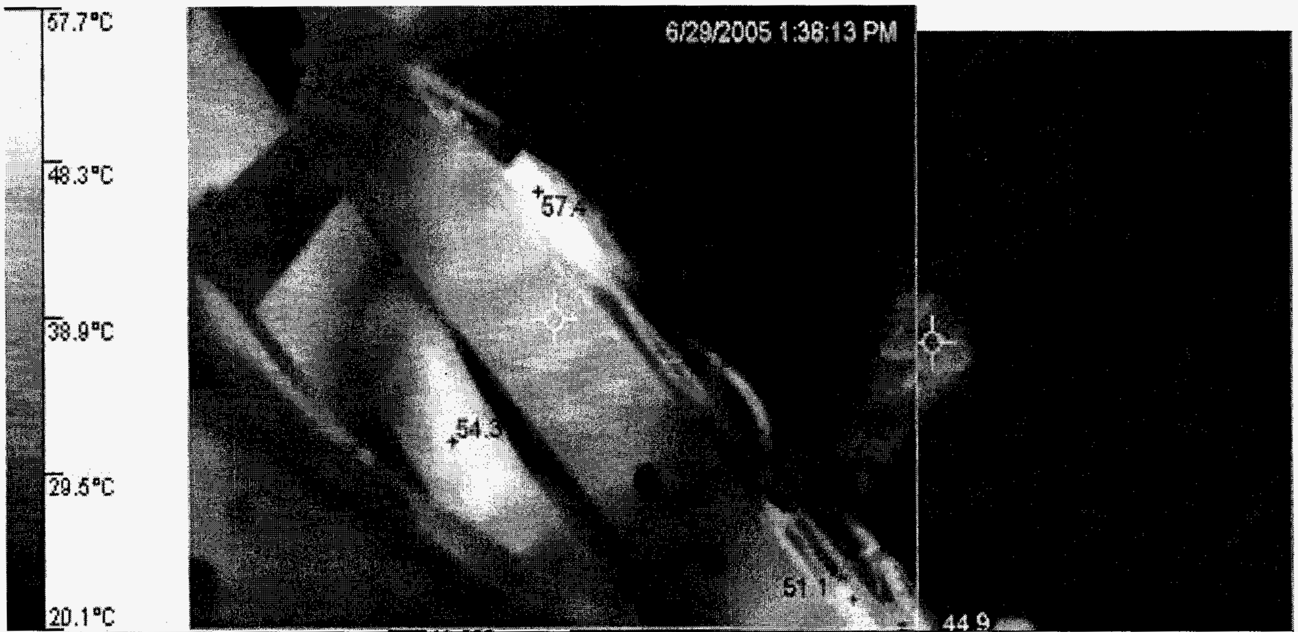

Figure 2 Composite thermal infrared (8-13 um) view of Hale telescope structure during solar exposure. Telescope tube structure is shown on left, while the enshrouded primary mirror cover is shown to the right. Indicated temperatures are in degrees Celsius.

3.2 Blind pointing measurements

The radial blind pointing accuracy of the Hale Telescope as a function of its hour angle is plotted in Figure 3 for the same stars before and after telescope exposure. Both of the data sets are referenced to their nearest Zenith position from when the data was collected. It can be seen that as the hour angle moves away from the reference position the pointing error increases. Both test cases showed similar dependence of pointing error on telescope hour angle.

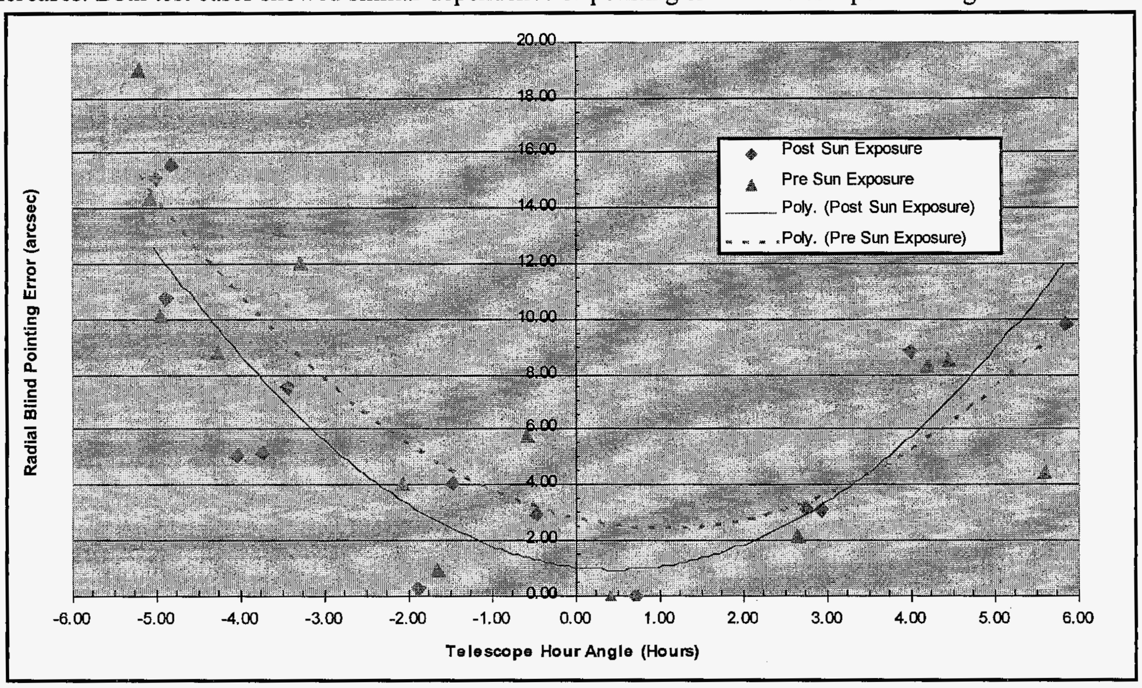

Figure 3 Hale Telescope blind pointing accuracy dependence on telescope Hour Angle. The three test runs are included. The blind pointing accuracy has a strong relationship to the telescope's hour angle.

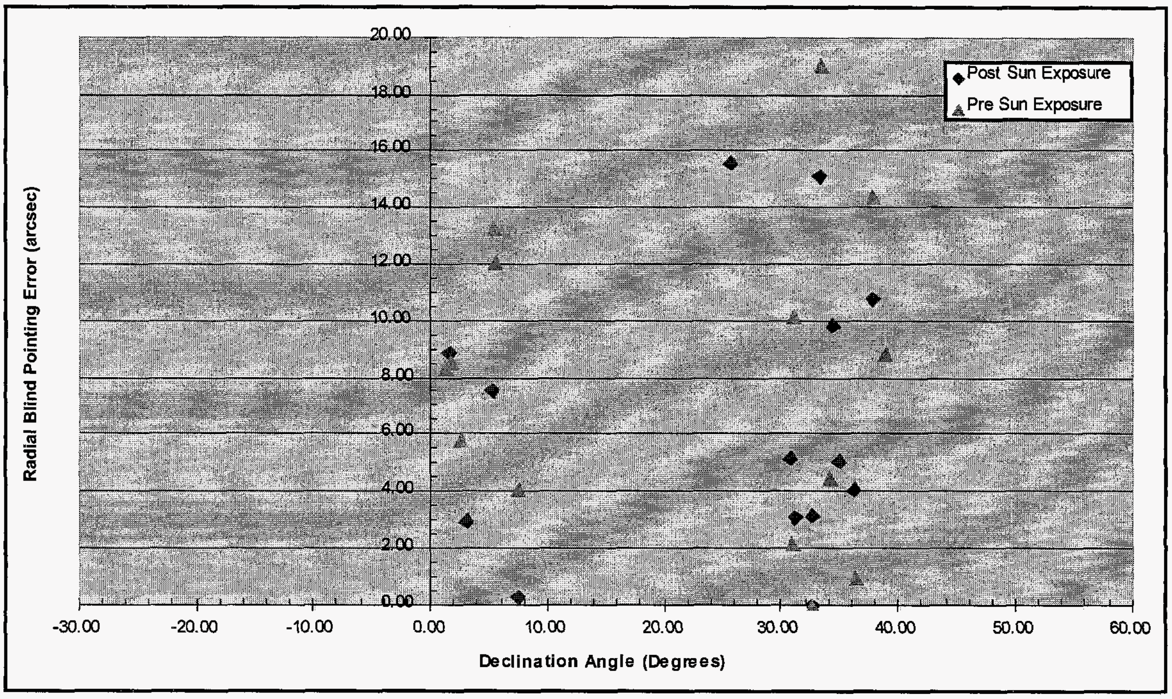

Figure 4 Hale telescope blind pointing dependence on telescope declination angle both before and after telescope exposure. The blind pointing accuracy has a negligible correlation to declination angle.

The radial blind pointing accuracy dependence on the telescope's declination angle is plotted in Figure 4. As with the hour angle, both of the data sets are referenced to star position closest to Zenith. There appears to be little dependence on the declination angle.

3.3 Seeing measurements

A series of 11 stars in different locations on the sky was measured on the night prior to exposure of the telescope to daylight operations, and then repeated on the night after exposure. The results of the Gaussian fits to the data are shown in Table 1. The observations for each star are taken at approximately the same time on successive nights in an attempt to normalize conditions (e.g. airmass, gravity vector, diurnal seeing variations, etc.) as much as possible. Observations the first night were all made with the 1% ND grism, varying the integration time to maintain the stellar image intensities in the linear range of the detector array. During the second night, the 0.1% ND grism setting was primarily used, resulting in changes to the total amount of light recorded at the focal plane. Filter calibration factors from a previous telescope run[ii] were applied to correct for these differences.

As seeing changes, the product of the amplitude of the Gaussian fit and the square of the Gaussian width should remain relatively constant, since the total amount of power arriving at the focal plane does not change. As a check, a 'volume' of counts (amplitude × width^2) was calculated for each image each night, after correcting for variations in integration time and grism transmission. Finally, the ratio of the volumes calculated before and after telescope exposure were calculated. Significant deviations from unity in the volume ratio indicate a case in which the Gaussian fit to the blur (on which the volume is calculated) is not very representative of the actual blur. All stars shown had volume ratios within 20% of unity, indicating relatively good fidelity to the Gaussian fitting procedure.

Remarkably, for each star observed, the seeing (as indicated by the FWHM of the blur fit) was better *after* exposure of the telescope than before. In only one case, the observation of SAO 64870 near zenith, is the difference between pre- and post-exposure not significant. This observation experienced much better seeing on the pre-exposure night than any of the other pre-exposure observations, even though the others followed within a few minutes.

Table 1 Parameters of the best fit Gaussian blurs to the stellar images taken across the sky.

Object	Air mass	Amp Pre-expos. (counts)	FWHM Pre-expos. (arcsec)	Volume (counts)	Amp Post-expos. (counts)	FWHM Post-expos. (arcsec)	Volume (counts)	Volume Ratio
SAO 64870	1.01	203091	1.188	1.19E+06	8853	1.163	1.36E+06	1.14
SAO 63676	1.25	64737	1.856	6.17E+05	5085	1.082	6.76E+05	1.10
SAO 62297	2.92	282738	1.846	6.22E+06	29330	1.365	6.21E+06	1.00
SAO 66869	1.05	226495	1.574	4.08E+06	38599	1.042	4.76E+06	1.17
SAO 70467	1.47	209212	1.542	4.13E+06	23346	1.299	4.48E+06	1.08
SAO 71173	1.53	76852	1.552	7.69E+05	3944	1.345	8.11E+05	1.05
SAO 72191	2.02	339120	1.589	7.11E+06	47711	1.222	8.09E+06	1.14
FK5-1511	1.25	62943	1.543	4.36E+06	23237	1.278	4.31E+06	0.99
FK5-800	1.77	207591	1.601	3.09E+06	15128	1.395	3.34E+06	1.08
FK5-516	2.29	77678	1.717	9.51E+05	148198	1.214	9.07E+05	0.95
FK5-3848	2.2	235264	1.658	3.76E+06	304609	1.228	3.81E+06	1.01

Data from the observations of a DIMM/MASS instrument located atop the administration building roughly 500 meters away indicated that there was little difference in the intrinsic seeing of the atmosphere. The DIMM measurements during these observations ranged from 0.9 to 1.1 arcsec centered about 1 arcsec during the pre-exposure night, and 0.7 to 1.3 arcsec, centered about 1 arcsec during the observations taken on the evening immediately following exposure of the telescope.

In an attempt to understand this result, consider the typical images shown in Figure 5. These images show the stellar image with the best-fit Gaussian superimposed in cross section on the left, and a density plot of the residual image (actual image – best fit Gaussian) on the right. Both images are a series of 10 blindly-summed (*i.e.* no offsets applied) frames of long (10-14 second) exposures. The pre-exposure image exhibits an asymmetrical skew that is not present in the post-exposure image. The residual plots show what appears to be mainly astigmatism after exposure, though the pre-exposure image is much less clear.

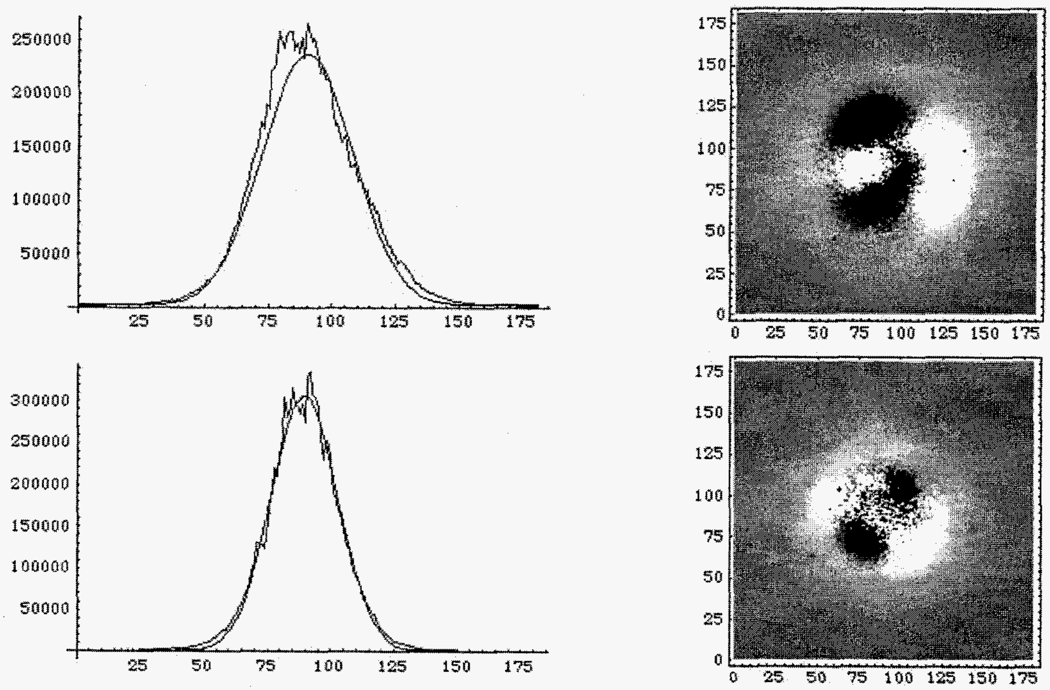

Figure 5 Blur data and fits for star FK5-3848 before (top) and after (bottom) exposure to ambient daytime conditions and sunlight. Images on the left show the data and fits in cross section, while the images on the right are density plots of residuals (data – fit).

The Palomar staff[iii] has indicated that there are aberrations to the primary mirror which tend to show up under certain circumstances. Astigmatism appears at certain configurations of the telescope with respect to gravity which the mechanical primary mirror support system does not correct. It has also been observed that there is a significant degree of spherical aberration introduced as the telescope changes temperature, apparently a variation in thermal expansion across the primary mirror as it changes temperature unevenly.

4. DISCUSSION

The ability of the Hale telescope to withstand a thermal shock of this magnitude is indeed remarkable. Portions of the telescope structure were directly illuminated by the Sun for hours with no significant consequences to either the telescope's ability to point or its ability to form excellent astronomical images. Though temperatures of various structures in the telescope, the dome and the dome floor rose to alarming levels, the impact on astronomical seeing over the next few hours was not adverse. In fact, it appears that there may even have been an improvement to the functioning of the telescope as a result of this exposure. Given the measures enforced by observatories to guard their telescopes from daytime heating of the dome, structure and optics, this result was unexpected and counterintuitive.

At first consideration, this is very good news for the potential to use this telescope as a communications receiver for deep-space lasercomm signals. Though we would not suggest, based on a single experiment such as this, that there will be no adverse affects on telescopes from their routine use during the day as optical communications receivers for signals from deep-space probes, these results at least indicate that it is not necessarily true that such use will render the telescopes unusable for astronomy for long periods. This experiment proves that there are conditions under which the telescope can be exposed to the daytime atmosphere and even direct sunlight, and not suffer degrading effects.

There are several differences between this test and actual operations, which must be considered in evaluating the ultimate limitations of the telescope. During actual operations the primary mirror would not be covered, and thus could potentially see more significant thermal changes. However, when pointing near the Sun the telescope would employ a side shroud and a reflective filter at the telescope head-ring to limit the amount of sunlight entering the telescope to much lower levels than this experiment admitted. The most significant difference is expected from the relative length of operations; during the communications experiment, the telescope was to be exposed to the external environment daily for periods of up to two weeks. Though it may be that short term exposure of the telescope can be endured relatively benignly, the longer-term exposure of daily operations may well give gradual rise to the temperatures and stresses on all of the structures within the dome, gradually degrading the telescope's performance.

The ability of the right ascension horn to recover to very near the previous night's temperature relieves concerns over the pointing of the telescope, though the temperatures of the other structures monitored did not recover completely. To some extent, residual long-term effects may be mitigated through the use of paint with the proper absorptivity/emissivity (α/ε) ratio, though practical considerations of dew formation limit its application in many circumstances. The magnitude of thermal rise of the primary mirror cell and the persistence of its elevated temperature are of some concern, and may indicate that an active cooling system or convective athermalization system may be necessary in operation.

The causes behind the improvement in image quality after telescope exposure are intriguing, and perhaps may point the way toward methods of improving telescope imagery in general. We briefly consider that the telescope point spread function is a convolution of the telescope's static point spread function (dominated by diffraction or aberrations) and the seeing-induced point spread function. In general, one expects the intrinsic atmospheric seeing (without dome seeing) to degrade as the airmass increases, according to the well-known analysis of Fried[iv]

$$r_0 = \left[0.423\, k^2 \sec\beta \int C_n^2(z)\, dz\right]^{-3/5},$$

in which r_0 is the so-called 'Fried parameter', representing the radius of an area in the telescope pupil over which the wavefront is effectively coherent. The term $\sec\beta$ in this equation is the airmass, and since the FWHM of a blur spot is roughly λ/r_0, we expect to see a dependence like

$$FWHM \propto (\sec\beta)^{3/5}.$$

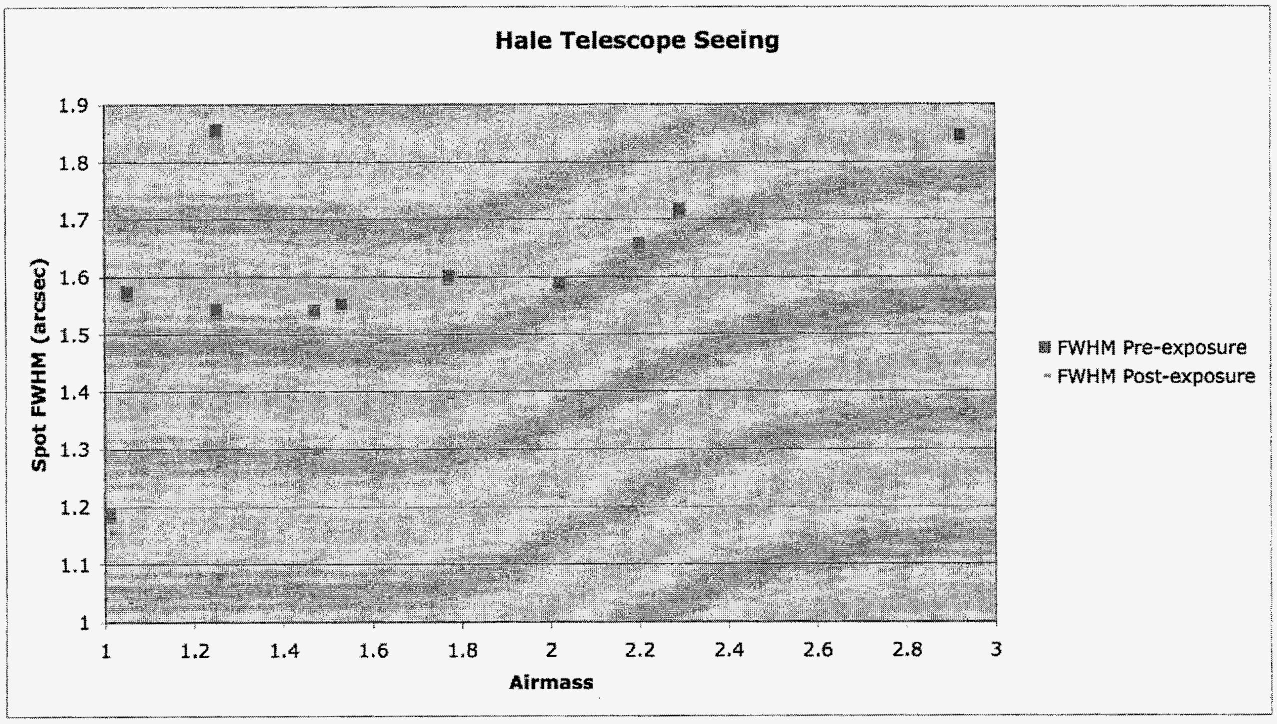

Figure 6 Telescope seeing vs. airmass before and after telescope environmental exposure.

The blur width data from Table 1 is shown plotted as a function of airmass in Figure 6. While it appears that the pre-exposure data may follow this scaling law for higher airmass values (>2), something other than airmass-dependent atmospheric turbulence is limiting the telescope's performance closer to zenith. This could conceivably be dome-seeing which should not be strongly dependent on airmass. The main point arguing against this hypothesis is the anomalously good seeing measurements taken at zenith. More detailed analysis of the 10 FITS images did not reveal any flaws or anomalies in the data that might explain this.

When considered with the post-exposure data however, it appears that if there were another limiting factor working at lower airmass values, it is either not present or is much lower in magnitude during the post-exposure period. Furthermore, there is no apparent dependence on airmass at all in the post-exposure data. Such a factor is likely to be the static aberration in the primary mirror, some of which is believed to be the result of thermal gradients in the mirror. Since the DIMM data from both nights indicates 1 arcsec seeing, it is certainly possible that static aberrations make up the bulk of the residual aberration. The clearly-defined residual images in Figure 5 would appear to support this, especially since the residuals had a much larger magnitude on the night prior to exposure.

5. CONCLUSIONS

The 200-inch Hale Telescope on Palomar Mountain was intentionally exposed to severe environmental conditions during the warm summer da;y of 29 June, 2005, in an attempt to understand the modes of degradation such exposure induces in the telescope, and to bound the magnitude of the effects. The two primary deleterious effects expected were an increase in the pointing errors (a result of thermal gradients in the telescope superstructure and telescope bearings), and a significant increase in seeing (the result of warming of the telescope, the dome floor,. and all structures which might shed turbulent vortices to the cool nighttime air).

The results of the experiment were remarkable, in that no significant degradation of the telescope's ability to perform astronomy was observed, despite the best efforts of the team to perturb it. The blind pointing accuracy of the telescope was checked for many stars at many different hour angle and declination positions, and was found not to have changed in any observable way.

Even less expected, however, was the observation that the results of seeing (measured by observations of the same stars before and after exposure of the telescope) was significantly better after telescope exposure. This result holds, even though most condition, including DIMM measurements of intrinsic sky seeing appear to have been the same on both nights. There is a clear and persistent deviation of the actual blur spots from an expected Gaussian spot, which probably show aberrations to the primary mirror. These aberrations represent a major component of the blurring of the stellar images, and may have been reduced by the environmental exposure, leading to these fortuitous results.

It is clear from this experiment that the environmental exposure of the Hale telescope for a period of several hours does not necessarily degrade its performance, or its ability to collect useful astronomical images immediately after exposure. This may have implications for the potential to allow other 4-5 meter class telescopes to take on a 'dual-use' role in which they are frequently supporting the communications infrastructure of optical communications packages on future deep-space probes, while still performing their main astronomical tasks at night.

Clearly more experiments will be required under varying conditions to determine the full extent to which such telescopes can be employed in this way, and the ultimate limits in time and exposure which can be applied before significant performance degradation sets in. This is but the first of many required tests, but the surprising findings of these tests augurs well for the potential application.

6. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the staff of Caltech Optical Observatories, for their cooperation and assistance with this experiment, access to the telescope, and many fruitful discussions regarding the history, construction, and performance of the facility.

This work was carried out in support of the Mars Laser Communication Demonstration project at the Jet Propulsion Laboratory, California Institute of Technology, under contract the with National Aeronautics and Space Administration.

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