Palomar 200” Telescope

Proposal for limiting the heat dissipation of Cassegrain mounted instruments

Summary:

A requirement for maximum heat dissipation is proposed for application to Cassegrain mounted instruments on the Palomar 200” telescope. The proposed requirement is prompted by the planned installation of a new adaptive optics system (Palm 3000) which will likely dissipate four times the heat of the current AO system, and well over ten times the heat of any other Cassegrain mounted instrument. This requirement attempts to address the residual effects of the instrument dissipated heat that is absorbed by the primary mirror and telescope structure and is likely to cause reduction of image quality for the observers in the day(s) that follow the completion of the AO observing run.

The two main detrimental effects of heating the mirror are:
1) mirror seeing; and 2) thermally induce distortion of the mirror.

These concerns are both addressed by defining the maximum allowable increase in primary mirror temperature caused by a Cassegrain mounted instrument, of 0.75ºC throughout the mirror, and a 0.5ºC temperature gradient across the mirror, and defining the maximum heat dissipation allowed for Cassegrain mounted instruments not to exceed 300W under the primary mirror, and 1 kW into the dome air away from the primary mirror.

Introduction:

The facilities of astronomical observatories can often have a negative effect on the natural seeing of the site. Most of these negative effects relate to the dissipation of heat in and around the dome, and near the telescope and optical path. In the case of the 200” telescope at Palomar, facility improvements have been implemented over the years which have resulted in significant improvement of the control of dome air temperature. The advent of newer instruments which produce heat in excess of 10 times the heat of previous instruments has prompted the need to define a limit to the heat that is dissipated and the implementation of methods to mitigate the affect of the dissipated heat.

Background:

In the late 1990’s an adaptive optics system was installed at the 200" telescope. Much of the AO system’s heat dissipating electronics are mounted on the Cassegrain cage below the primary mirror. The total heat dissipation of the current AO system electronics that are mounted on the Cass cage is about 1.5 kW. All other current non-AO instruments mounted on the Cass cage dissipate less than 300 W. The concerns that are raised about the amount of heat dissipated by the AO system electronics and its resulting degradation of image quality are partially rationalized by the ability of the AO system to correct for the reduced image quality characteristics that it may be producing, both transient issues such as local and atmospheric turbulence, and quasi-static issues such as mirror figure abnormalities. Although it is true that the AO can provide corrections for thermally induced image quality degradation while AO is operating, there are concerns that the instruments that follow AO can suffer from the residual thermal effects.

The 200” mirror is a monolithic, honeycomb backed, Pyrex casting. It was the first mirror of its size, and the sectional thicknesses have not had the benefit of optimization for stiffness and heat transfer as compared with large modern mirrors. The thermal time constant of the mirror is estimated to be in excess of 24 hours and recent mirror temperature measurements suggest that it is likely more than 48 hours. If the mirror is not in equilibrium with its environment due to heating by an instrument heat source, the effects of this heating will likely be experienced for days following the removal of the heat source.

A system of eight temperature sensors and data acquisition were installed on the 200" mirror in October 2009. The sensors were mounted at 45º increments along the outer perimeter of the mirror and are covered by the insulating skirt material which isolates them from the ambient temperature. The sensor temperatures are recorded continuously and has allowed one to observe a temperature distribution history of the mirror. A sample of this temperature history is shown in Figure 1. The displayed data is from the period of December 27, 2009 to January 17, 2010. During this period various instruments were installed and running at the Cassegrain position.

The AO system was installed and the electronics switch on mid-day January 3 as noted by the vertical marker on the graph, and AO electronics were switch off sometime during the early morning of January 8. TripleSpec was installed from December 27 through January 3 before AO, and DoubleSpec was installed after AO from January 8 onward. Both TSpec and DBSP dissipate about 300W. The AO system electronics cabinets are located in the west and southwest position of the Cassegrain cage under the primary mirror and are known to dissipate approximately 1500 W of heat combined.

A fairly tight temperature spread among the sensors is observed during the times when the AO system is not running. Shortly after the AO system is switch on, the temperature readings begin to diverge, especially the readings at the sensors located in the west and southwest position of the cage. After the AO system is switched off, the temperature readings begin to slowly converge, but do not fully recover to the pre-AO spread for at least 40 hours. There is a rapid drop in the temperature readings that occurs shortly after the AO system is switched off, and then the readings recover but at a slightly lower value. It was determined that the timing of this temperature drop coincides with the timing that CO_2 cleaning of the mirror was performed. The CO2 snowflakes exit the spray nozzle at about -80 ºC, which would explain the rapid cooling. It is very possible that the recovery of the mirror temperature to its surroundings after the AO electronics were shout off was expedited by the CO2 cooling, and without this cooling, the normalization time could have been significantly longer.

This data suggests that there is a clear relationship between the local temperature of the mirror and the location and magnitude of heat sources below the mirror. The roughly 300 W of heat dissipated by TripleSpec and DoubleSpec electronics do not appear to cause significant local heating of the mirror, but the ~1500W dissipated by the AO electronics cause an approximate 1 ºC temperature rise in the area of the mirror directly above the heat source.

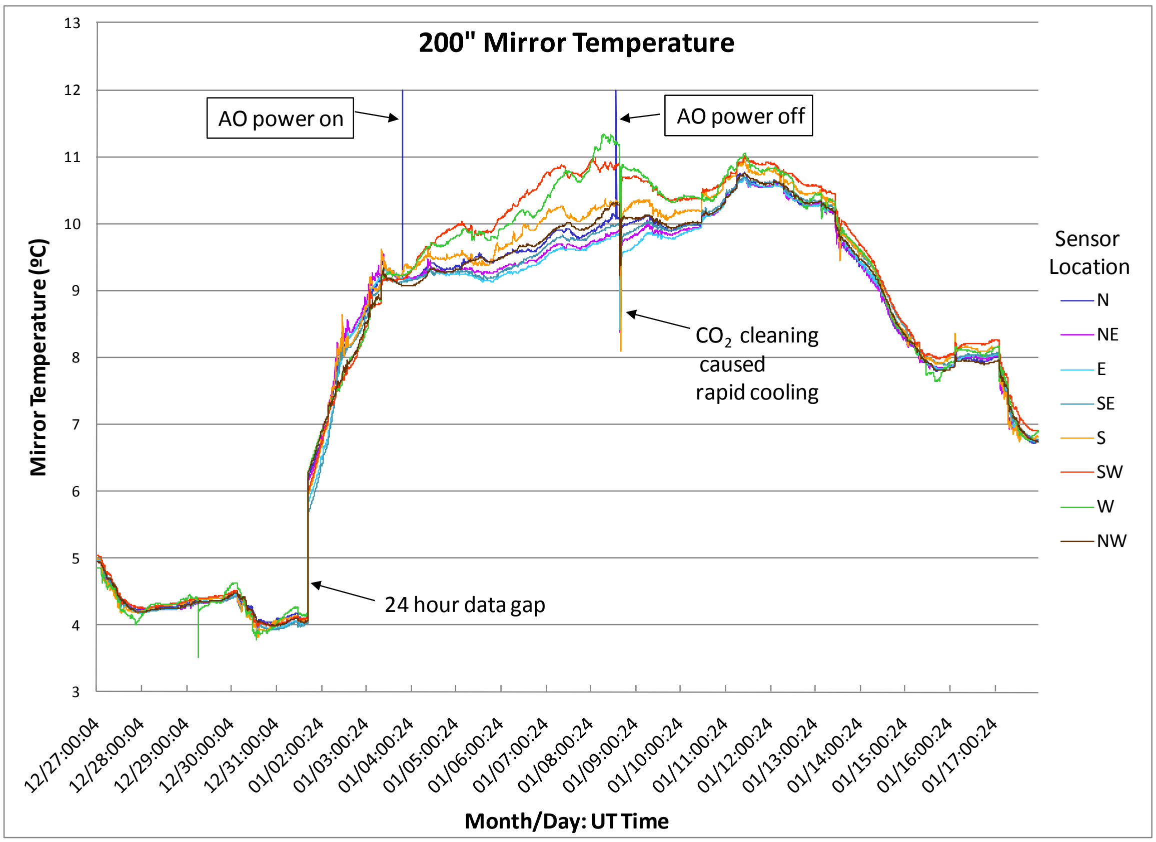

Figure 1: 200" Mirror temperature history; Dec 27, 2009 - Jan 17, 2010

<u>Effects of heat dissipation</u>

There are various effects that are detrimental to image quality caused by the dissipation of heat in the dome, and specifically near the telescope. The focus of this work is to address the sources of heat that have residual effects that are not resolved by the heat dissipating instrument (such as AO) or the current P200 telescope infrastructure such as the facility air conditioning system. For instruments mounted at Cassegrain, the main concern is that of heating the primary mirror. As stated earlier, the mirror has a long thermal time constant and therefore maintains a thermal history of previously absorbed heat.

The two main detrimental effects of heating the mirror are:
1) mirror seeing; and 2) thermally induce distortion of the mirror.

Mirror Seeing

There has been significant work in the area of mirror seeing and understanding its effects on image quality. Most notability a study given by [Racine et al (1991)] involving the 3.6 m telescope at CFHT analyzes the various sources of seeing degradation, and specifically of interest, develops a relationship between mirror temperature to dome air temperature and its effect on mirror seeing. A function is developed which represents the contribution of mirror seeing on reduced image quality when the mirror is warmer than the dome air as: FWHM = 0".4 / C$^{o\ 6/5}$. This provides for a +1°C temperature difference between the mirror and dome air, the resulting image quality reduction is 0.4 arc sec. The image size increase is very rapid when the thermal contribution to the image size approaches the intrinsic seeing size. Several other publications reference the findings of Racine et al and use it as a basis of defining performance targets for thermal management and seeing improvement initiatives. Below are a few links to publications which relate to controlling mirror temperature and its effect on image quality, and general telescope thermal management. It is not the aim of this document to determine the exact relationship of temperature variation and its effect of on image quality of the 200" telescope. The depth of knowledge in the field should prove as sufficient justification for addressing this issue on the 200" and other astronomical instruments where image quality is an important product.

http://lbtwww.arcetri.astro.it/tech/ua9502/ua5.htm

http://www.noao.edu/noao/noaonews/jun96/node29.html

http://www.eso.org/gen-fac/pubs/astclim/papers/lz-thesis/node58.html

http://www.pha.jhu.edu/~atolea/WAS/thermal_management_newtonians.pdf

http://www.cruxis.com/scope/mirrorcooling.htm

Knowing that thermal issues degrade image quality, how should we define the limits of thermally induced degradation that we would allow? Here is one proposal:
If we assume that the best seeing at Palomar is 0.8 arc sec, and we define a goal to not let mirror seeing degrade image quality in the best seeing by 10%, we then want to determine the mirror seeing contribution that constitutes a 10% reduction in image quality.

0".8 + 10%(0"8) = 0".88

Assuming that the seeing error would follow Kolmogorov turbulence principles, image degradation caused by different turbulent layers would add by the 5/3 power law:

$\omega^{5/3} = \omega_1^{5/3} + \omega_2^{5/3} + \ldots.\ \omega_N^{5/3}$

$0.88^{5/3} = 0.8^{5/3} + \omega^{5/3}$, where ω = mirror seeing contribution

$\omega = (0.88^{5/3} - 0.8^{5/3})^{3/5}$
$\omega = 0.28$ arc sec

This allowable mirror seeing contribution of 0".28 corresponds to a 0.74ºC mirror to dome air temperature difference as referenced by the relation: FWHM = 0".4 / $C^{o\ 6/5}$ from Racine et al.
For reference, a 1.0 ºC dome air to mirror temperature difference would correspond to an 0."4 image quality reduction which results in a 18% reduction from the 0."8 best seeing using the same 5/3 power method.

Thermally induced mirror distortion

Thermal gradients within the mirror will lead to distortions. Significant attention was given to quantifying the thermal gradients, the resulting distortions, and their effect on image quality in a paper by J.M. Hill, "Mirror Support System for Large Honeycomb Mirrors", 1994. The results of this work showed that borosilicate (i.e. Pyrex) honeycomb mirrors must remain in close thermal equilibrium to prevent exceeding a wavefront distortion of r_0 = 180 cm which corresponds to 0.056 arc sec FWHM for a 8 meter mirror. "A simple summary of this work is that a borosilicate honeycomb mirror must remain in temperature equilibrium within 0.1 °C. Some large scale gradients can be larger without exceeding the error budget --- a radial temperature gradient of 0.25 °C is required to generate a r_0 = 180 cm wavefront error. Regardless of the expansion coefficient of the honeycomb, the face of the mirror must be within 0.2 ° C of ambient to control mirror seeing."

An FEA model of the Palomar 200" mirror was constructed to assess the distortion due to a uniform axial temperature gradient (parallel to the optical axis). It was found that when the back of the mirror was uniformly heated to 0.5ºC warmer than the front face, the resulting distortion was 6µm with the figure distortion increasing with distance further from the center. The response is linear with temperature as a 1ºC gradient resulted in a 12 µm distortion. Distortions of these magnitudes would result in significant spherical aberrations as well a shift of focus. After the heat source is removed and the mirror would slowly normalize, it is expected that the focus would shift with time and anyone observing during this period would be plagued with the timing consuming task of "chasing focus".

A uniformly heated mirror is actually a best case. The more likely situation is that the heating will vary with position around the mirror, and the result will be a thermal gradient that has local variation. This is the actual situation that is shown by the data presented in Figure 1. These local temperature variations will cause astigmatism, coma, and other aberrations, and depending on the scale of the gradient, they could be quite detrimental to image quality.

Control of heat dissipation at other observatories

Most modern astronomical observatories have very strict heat dissipation requirements. Below is a sampling of some other major observatory heat dissipation requirements:

Keck 10 meter

3-04.5.3 Uncontrolled Heat Sources Behind Primary Mirror
Uncontolled heat sources from the active control system behind the primary mirror shall be limited to 500W total.

3-04.5.4 Uncontrolled Heat Sources in Dome
The sum of all uncontrolled heat sources in the dome shall be under 2kW. In addition, no uncontrolled heat sources above 100W are allowed near the optical path, excluding the primary mirror control system.

Note: The 500W limit is for the mirror active control system only. All Cass mounted instruments must comply with 100W maximum heat dissipation.

Gemini 8 meter

3.2.4 Instrument Heat Sources:
Thermal control is important for Gemini instruments
- Gemini gives a general guideline for heat destinations:
* removed by cryocoolers: well below max capacity
* removed by air to liquid coolers in thermal enclosures: less than 1000 W each rack
* Dissipated into enclosure environment: less than 50 W
* Dissipated into the ISS via air: less than 10 W
* Conducted into the ISS: delta T should be less than 1 deg C between instrument and ISS.

3.2.9.2 Allowable Heat Released from Instrument
- Total heat released to the enclosure air by the instrument
(excluding the electronics in the thermal enclosures) shall not exceed 50 W.
- Total heat conducted into the ISS shall not exceed 50 W.
- Individual elements exposed to the air volume will not attain
a temperature 2 deg C above ambient.

Many modern observatories use closed cycle liquid cooling systems to remove heat that is dissipated from instruments. The goal of these systems is to capture the heat in liquid coolant and then transport the coolant to a place where the heat can be extracted and ejected from the dome. This is typically done with a primary facility chiller in conjunction with a secondary process chiller.

Many observatories also employ a system of air flow management in and around the primary mirror to reduce the temperature gradients of the mirror. Palomar does have a basic air flow management system which is comprised of 12 fans mounted on the bottom of the mirror cell. The intent behind this system is to speed thermal exchange of the steel structure of the mirror cell, and thereby speed the thermal equalization of the mirror itself. Historically, this system has been used by running the fans for 1 to 2 hours after the dome is opened on occasions where a major temperature change has occurred since the preceding night. It is not fully known how effective these fans are at bringing the mirror cell and mirror into equilibrium with the dome air. Now that the entire mirror has been instrumented with temperature sensors, a thorough study is planned to improve the effectiveness of this air flow system. Some observatories use a system of temperature controlled air nozzles which flood air directly into the mirror pockets in order to expedite the heat transfer. Some of these systems are very complex and involve hundreds of air nozzles, with the typical goal of achieving a 1ºC / hour cooling rate.

Proposed Specification

In light of the previous presented information, the main goal of a defining a heat dissipation specification for Cassegrain mounted instruments can be stated as follows:

Develop a specification which will limit the residual thermal effects caused by heat that is dissipated from Cassegrain mounted instruments that would cause degradation of the optical image quality for non-Adaptive Optics observing.

To this end, the following requirement is proposed:

1. For all Cassegrain mounted instruments, the maximum heat dissipation shall not exceed 300W under the primary mirror, and 1 kW into the dome air away from the primary mirror. If this requirement is met, it is assumed that the following requirements will also be met except under extreme circumstances.

    a. The heat dissipated by any Cassegrain mounted instrument shall not increase the temperature of the primary mirror, locally or globally, by more than 0.75ºC relative to the mirror baseline temperature.

    b. The heat dissipated by any Cassegrain mounted instrument shall not induce a temperature gradient in the mirror of more than 0.5ºC measured between any two points on the mirror.

        i. Evaluation of items 1a. and 1b. to be made by comparing values using a 12 point moving average of data taken at a 5 minute sampling rate.
        ii. The baseline temperature is defined as the average of the primary mirror temperature measured at the north and northeast temperature sensor locations.