Performance and control of the MMT thermal system

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ABSTRACT

We present results from a study of the performance of the MMT thermal system. The 6.5-m MMT primary mirror consists of a borosilicate honeycomb structure that is thermally controlled with a forced-air ventilation system. We will give an overview of both the measurement and control systems. Our goal is to define an algorithm for control of the ventilation system such that the primary mirror temperature closely tracks ambient while minimizing thermal gradients. Future work will include a study of correlations between the thermal state of the primary mirror and both seeing and wavefront errors. The thermal system is currently controlled by the telescope operators, but the results from this work will assist in fully automating the system.

Keywords: MMT, thermal control, ventilation

1. INTRODUCTION

The primary objective of any large astronomical facility is to provide the highest quality data products while maximizing the observing efficiency. The data quality may depend on many system and environmental parameters. Although some of these parameters cannot be controlled, in general the data quality can be improved by continuously monitoring and tuning the system. However, observing time on large telescopes is a precious commodity and therefore the time required for these system adjustments should be balanced against the benefits realized.

The thermal state of a large telescope can have a significant adverse effect on the image quality if the system is not controlled properly. Three effects that can be particularly apparent to observers are:

1. Focus changes resulting from temperature changes in the optical support structure (OSS).
2. Degradation of the image quality resulting from thermal gradients in the primary mirror.
3. Poor seeing resulting from differences between the ambient temperature and primary mirror temperature (mirror seeing).

In an effort to reduce these effects at the MMT, we have undertaken a study to fully characterize the thermal system. The products of this characterization will be an automatic temperature dependent focus routine and a concise algorithm or set of guidelines for controlling the ventilation system. These guidelines will be used by the telescope operators to minimize wavefront errors and mirror seeing that result from thermal gradients within the primary mirror and between the primary mirror and ambient air, respectively.

For an complete overview of the current state of the upgraded MMT, see Blanco et al.\textsuperscript{1} in these proceedings.

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2. THERMAL SYSTEM DESIGN SPECIFICATIONS

Fabricant et al.\textsuperscript{2} present a set of optical specifications for the converted MMT. The optical error budget was specified to provide an image quality that would match the best seeing conditions expected at the MMT site. This requires the telescope to deliver images of 0.23\textquoteright full width at half maximum (FWHM) and for the combination of the telescope and atmosphere to produce a detected image of 0.32\textquoteright FWHM. Thermal sources are allotted a fraction of the error budget. The result was a set of specifications for the forced-air ventilation system. The design of the ventilation system was largely driven by similar requirements provided in Cheng & Angel.\textsuperscript{3} One goal of the current study is to understand how well those specifications have been met during the three years the system has operated. The following sections describe the specifications provided in Fabricant et al.\textsuperscript{2}

2.1. Optical Support Structure Temperature and Focus

The current operating procedure at the MMT requires the overhead of manually refocusing when the temperature of the optical support structure (OSS) changes. Following the upgrade of the MMT, there has been an ongoing effort to reduce this overhead by implementing an automatic temperature-dependent focus routine (tempfoc). However, attempts to collect the necessary empirical data have been largely unsuccessful, hindered by a number of factors including poor weather during the limited number of dedicated engineering nights. Accurate measurements of both OSS temperature and the telescope defocus are required but have not always been available. Our most recent efforts are discussed further in Section 6.1

Fabricant et al.\textsuperscript{2} calculate the following theoretical temperature dependent defocus values for the three MMT secondaries:

1. f/5: $-54 \mu m/\degree C$
2. f/9: $-64 \mu m/\degree C$
3. f/15: $-65 \mu m/\degree C$

These values include focus changes resulting from temperature variations in the OSS, the primary mirror, the secondary mirror, and the back focal distance. The image quality error budget requires a defocus of less than 2.7 \mu m in the wide-field configuration. Therefore, focus corrections need to be applied when the OSS temperature changes by $\sim 0.05 \degree C$.

2.1.1. Primary Mirror Temperature Gradients and Figure

The thermal state of the 6.5-m MMT primary mirror has a direct effect on its figure. Deviations from the prescribed figure adversely affect the resultant wavefront, which degrades the image quality. Fabricant et al.\textsuperscript{2} allow thermal gradients in the primary to contribute an image size of no greater than 0.05\textquoteright FWHM. This limits temperature gradients to less than $\Delta T \sim 0.1 \degree C$ within the primary mirror, either radially or axially (front-to-back). Most of these thermal effects can be removed through wavefront sensing and subsequent corrections. However, there are some instruments used at the MMT that are not equipped with a wavefront sensor. In addition, preliminary results show that thermal states can arise in which the figure of the primary is degraded beyond the correction capabilities of the actuators used to actively control the primary figure.

2.1.2. Primary Mirror Temperature and Seeing

Mirror seeing is a result of convection-driven turbulence produced when the mirror is warmer than the ambient temperature. Fabricant et al.\textsuperscript{2} allow primary mirror seeing to contribute an image size of no greater than 0.04\textquoteright FWHM. This limits differences between ambient air temperature and the primary mirror glass temperature to less than 0.15 \degree C. In general, the mirror should be kept cooler than ambient since mirror seeing is less significant for that case.\textsuperscript{4} The ventilation system should be capable of slewing the average temperature of the primary mirror at the typical mountain top rate of 0.25 \degree C/hr. Fabricant et al.\textsuperscript{2} also specified that the MMT ventilation system should have the capacity of slewing at the maximum rate of ambient near sunset, which can be as high as 2.0 \degree C/hr, but at this slew rate the uniformity specification need not be met.
3. MMT VENTILATION SYSTEM

Cheng & Angel\(^3\) show that an air flow rate of 8.3 L/s from a single nozzle into each cell of a large borosilicate honeycomb mirror could provide cooling rates of 0.25 °C/hr, and therefore, could achieve a temperature stability of 0.03 °C. They used a model of a single hex cell for the study and extrapolated the findings to a full mirror. Miglietta\(^5\) showed that an air-air jet ejector mounted on the top of the mirror cell, which pressurizes the cell plenum, was capable of providing this flow rate. The authors gave a list of advantages over a set of heat exchangers and fans mounted directly to the primary mirror cell. These advantages include a significant weight and volume reduction, less vibration, no heat radiation by electrical fan motors, and no water piping in the cell for the heat exchangers.\(^5\) Their studies led to the design of the ventilation system for the MMT, which is considered a prototype for the Large Binocular Telescope (LBT) system. The MMT ventilation system was installed in the spring of 2001 and has been in operation since that time.

Figure 1 shows a schematic of the MMT ventilation system. Air is drawn into the system through dust filters at the main centrifugal blower located in a support building approximately 50 meters from the telescope dome. The blower is powered by a 50 HP electric motor. A manual lever is available for adjusting the air flow leaving the blower, but the power is remotely controlled by the telescope operators through a graphical user interface (GUI). The blower itself introduces considerable adiabatic heating of air entering the ventilation system. Air leaving the blower is typically 20 – 25 °C warmer than outside ambient air temperature. Much of the task of the rest of the thermal system is removing this heat.

All of the 50 HP dissipated by the blower goes into the intake. The waste heat is removed by a 60 HP Carrier chiller, and therefore, when operating at full capacity, the contribution to the thermal plume is about 110 HP (82 kW). This heat is released to the air on the prevailing downwind side of the site.

The blower air exits the support building through a 24" flexible duct. The duct runs above ground along the west side of the main support building (the “shop”) and into the shop heat exchanger. A chilled glycol coolant, which allows sub-freezing operating temperatures (to approximately −10 °C), is circulated through the heat exchanger. This coolant is supplied by the Carrier chiller. The Carrier chiller is a microprocessor-controlled, air-cooled liquid chiller, utilizing reciprocating compressors and long-stroke electronic expansion valves.

The air exits the shop heat exchanger through another flexible duct that runs underground into the basement (the “pit”) of the telescope dome. The air then enters a second heat exchanger that uses coolant from both the Carrier unit described above and a Neslab chiller located in the pit. The Neslab chiller circulates a methanol coolant. The Neslab chiller was initially intended to provide fine temperature control, but it has been determined that the Carrier provides sufficient cooling capacity under most circumstances. The Neslab is now used primarily during the winter months when additional cooling is required or when the shop heat exchanger is subject to icing.

The air exits the pit heat exchanger and passes through a rotating duct that encircles the telescope pier. The rotating duct connects to two large “elephant” hoses that run into the telescope chamber. These flexible hoses are connected to PVC pipes mounted to the bottom of the mirror cell. The PVC piping splits out into an air distribution manifold inside the cell that feeds each of the 150 jet ejectors.

Figure 2 illustrates the design of an individual jet ejector and the location of the jet ejectors within the mirror cell. The jet ejectors are attached to holes in the upper-plate of the cell. Pressurized air from the ventilation system is directed through the jet ejector nozzle. This draws air from the upper plenum, the area between the cell top-plate and the mirror back-plate, through the jet ejector where it mixes with the conditioned air. The lower plenum fills with pressurized air, which is forced through the ventilation nozzles into the 1020 honeycomb cells of the primary. The air circulates through the honeycomb cell and exits into the return plenum. A set of six exhaust ejectors allow for a fraction of the air to be exhausted from the cell; 90% of the air is recirculated. Additional details on the design of the jet ejectors and model analyses are given in Miglietta.\(^5\) Additional data on the exhaust ejectors is provided in Benjamin & Callahan.\(^6\)

4. TEMPERATURE MEASUREMENT SYSTEM

4.1. OSS Temperature Measurements

Until recently the MMT OSS temperature was measured with E-series (Chromel/Constantan) thermocouples taped to the structure. We found that this configuration was not providing an accurate measure of the OSS
Figure 1. A schematic representation of the MMT ventilation system.

Figure 2. Drawing of one of the 150 jet ejectors used in cooling the MMT primary mirror (left). Cut-away of a section of the MMT primary mirror showing the location of the jet ejectors (right).
temperature. The thermocouples were not insulated and therefore were returning a combination of ambient and metal temperatures rather than just metal temperatures. We replaced the E-series thermocouples with six heavy duty thermistor probes, each housed in a rugged stainless steel tubing. These probes are connected to a Sensatronics Model E8 TempTrax base unit that is ethernet-accessible. The probes have a resolution of 0.05 °C and are capable of measuring absolute temperature to an accuracy of 0.25 °C.

The new probes have been affixed to both the secondary mirror and primary mirror ends of the main trusses of the structure. There are four probes on the secondary end: one each on the northeast, northwest, southeast, and southwest sides. There are two probes on the mirror cell end: one each at the east and west sides. There is also one probe mounted in the secondary hub. The probes were affixed to the metal using thermal grease, insulating foam, and aluminum tape to better insulate them from the ambient air.

4.2. Primary Mirror Temperatures
Temperatures in and around the MMT primary mirror cell are monitored with E-series thermocouples. There are 72 E-series thermocouples placed throughout the primary mirror. They have been arranged to measure the temperature of the mirror’s front-, mid-, and back-plates. There are 24 thermocouples on each of the plates.

West et al. express concerns with the stability of the MMT E-series thermocouple network. The system uses a large copper “isothermal” junction block (IJB) where the individual thermocouple wires interface to copper. The temperature of the IJB is measured at a single point with a solid state AD 590 sensor. The accuracy of the E-series network is dependent on the isothermality of the IJB and on the stability of an electronic multiplexer (MUX) when measuring small voltages. In addition the thermocouples are not well insulated to the glass, and therefore, they measure a combination of conditioned air and glass temperatures. The current stability of the MMT E-series network is not known because there is no published empirical data.

These concerns led to the addition of a new set of 64 T-series (Copper/Constantan) thermocouples within the primary. The design, presented in West et al., will be much more accurate and stable than the E-series network. The T-series are also insulated from the conditioned air stream, and therefore, provide more accurate glass temperatures. These thermocouples have not yet been integrated into the system but will be soon.

4.3. Ambient Temperatures
The outside and chamber ambient temperatures at the MMT are measured by several types of probes including E-series thermocouples, TempTrax thermistors, a Rainwise weather station, and two Vaisala weather stations.

The E-series thermocouples monitor the outside ambient temperature, the chamber ambient temperature, the lower plenum temperature, the heat exchanger temperatures, and the temperature of the air in front of the primary mirror. The TempTrax thermistor probes measure outside ambient, chamber ambient, secondary hub, air in front of the primary, the IJB, and the air exiting the cell through the exhaust ejectors.

There are two Vaisala units: one inside the telescope chamber and the other outside. These measure the temperature, relative and absolute humidity, and dew point temperature inside and outside the dome. This station provides wind speed and direction, a wind gust value, temperature, humidity, wind chill, and dew point temperature. An R. M. Young anemometer also provides wind speed and direction.

5. VENTILATION CONTROL

5.1. User Interface
At the beginning of each night, the operators run a script that brings up eight individual GUIs that allow them to monitor and control the thermal environment of the MMT. These GUIs include temperature measurements and environmental conditions from seven different systems; the TempTrax thermistors, the E-series thermocouples, two Vaisala weather monitors, a Rainwise weather station, and setpoints for the Carrier and Neslab chillers.

*Although there are physical front- and back-plates, there is no physical mid-plate; the mid-plate refers to the diametrical cross section through the middle of the mirror.
†This unit was recently moved to the top of the dome.
Figure 3 shows a screen capture of the main thermal GUI. The upper section of the GUI shows a 14x14 map of the temperatures across the primary mirror. Temperatures for each square are determined by interpolating the temperatures of nearby thermocouples. Although absolute temperatures can be viewed in this GUI, temperature differences, such as the default display of front-plate minus a reference temperature, are emphasized.

There are four tabs in the bottom section of the GUI that allow the operator to modify the information displayed in the temperature map and to control the ventilation system. The first tab, labeled “Plan View”, is used to modify the information that is displayed. The operators can choose from among 8 different temperatures and 14 reference temperatures. The default temperature is the average front-plate temperature minus a reference temperature and the default reference temperature is the value of the E-series thermocouple located immediately in front of the primary mirror. The color scaling can be set automatically, based on the current temperature values, or manually by specifying a midpoint value and a range. The current scale is provided on the bottom of the GUI. The map is updated every second.

The second tab, labeled “Cross-Section View”, displays an axial cross section of primary temperatures. The operator can choose the orientation of the slice from the options of east-to-west, southeast-to-northwest, or south-to-north. The operator can also choose a rotating display that changes the slice orientation every five seconds. There are three layers showing the front-plate, mid-plate, and back-plate temperatures. The relative air temperature in the lower plenum is also displayed. This tab can be used to minimize air/glass temperature contrasts both in front and behind the primary.

The third tab, labeled “M1 Thermal Control”, is used to control the ventilation system for the primary mirror (M1). The operator can adjust the coolant setpoints for both the Carrier and Neslab chillers, together or independently. The new setpoints track a user-specified reference temperature with a specified offset. An ambient slew rate multiplier term, which is applied to the setpoint, can also be set by the user. This multiplier forces the setpoint to change based on the rate of change of outside temperature.

The last tab, labeled “M2 Thermal Control”, is used to set the setpoints for the loft Neslab. The loft Neslab provides coolant to the MMT secondary mirrors (M2).

All of the thermal information which is displayed in the main thermal GUIs (as well as an extensive set of telescope status data) is also accessible through a web browser. The web-based information is an extremely useful resource since it allows the staff to access all the telescope data from any location and any web browser. In addition to the real-time GUIs available to the operators and the web-based data, the entire thermal system data is logged in extensible markup language (XML) format every minute. This data can be accessed at any later date.

5.2. Temperature Control

The goal in controlling the ventilation system is to keep the mirror temperature equal to the temperature of the air that surrounds it. This should be achieved while keeping the thermal gradients within the mirror to a minimum. Cheng & Angel found that this could be accomplished if the temperature at the jet ejectors is equal to the average temperature of the air above the primary. The operators can control two temperatures: the Carrier coolant temperature and the Neslab coolant temperature. One goal of this study is to provide the operators with a set of guidelines for controlling those coolant temperatures to achieve the desired air temperatures at the jets. Currently, the operators must monitor the conditioned air temperatures along the entire ventilation path and the thermal state of the primary to determine which setpoint temperatures to use. The ideal setpoints are also dependent on additional factors such as humidity.

Each day the ventilation system is started approximately two hours prior to opening the dome for observing. This cools the ventilation ducts and preconditions the primary. The Carrier coolant setpoint is set to 5 – 9 °C below the E-series outside temperature. This setpoint varies according to the humidity or dew point temperature. The setpoint is adjusted slightly, to 4 – 5 °C below ambient, after the dome is opened. The software then automatically modifies the setpoint temperature to follow the ambient temperature with the specified offset.

The temperature of the primary is monitored by the operators throughout the night. When unexpected ambient temperature changes occur or when the mirror temperature is not achieving the desired temperature the operators can alter the setpoint or the multiplier.
Figure 3. Screen capture of the main thermal control GUI for the MMT.
6. ANALYSIS

6.1. OSS Temperatures and Focus

Several hours during three engineering nights in January, 2004, were devoted to collecting data to be used to establish an empirical relation between telescope temperature and focus. During the first night the telescope tracked a single star for approximately three hours until its elevation fell below 40 degrees. The telescope was then repointed to a rising target. Wavefront sensor data, OSS temperatures, and primary mirror temperatures were recorded periodically at approximately five-minute intervals. No corrections were made to the primary or secondary during these measurements.

We found that early in the evening the measured focus change was consistent with the expected contraction of the OSS with falling temperature. However, later in the night, as the cooling of the OSS slowed, we found that there were large deviations in focus which were not correlated with OSS temperature changes. Although the data were corrected for elevation by applying elevation-dependent collimation corrections, we could not rule out that there was an unknown elevation-dependent focus term. Therefore, we chose to repeat the measurements while keeping the elevation constant, i.e., while pointing near the pole.

On the second and third nights, we repeated our measurements while pointing at a star near the pole. Again the relationship between focus and temperature was well behaved for the first few hours of the evening but deviated later in the night.

Figure 4 shows the data from the night of January 8, 2004. There are five values plotted:

1. OSS temperature. (+)
2. Mirror front-plate temperature. (×)
3. The effect of the mirror front-plate temperature in defocus units. (□)
4. Secondary defocus as measured by the wavefront sensor. Converted from wavefront sensor units to secondary defocus and corrected for elevation. (△)
5. The addition of 1 and 3 above, which is the predicted defocus. (◇)

The two curves that should match are the defocus (4 above, △) and the predicted defocus (5 above, ◇). The individual points are connected by lines for those two curves.

Defocus does not follow predicted defocus throughout the night. There appears to be an additional component of defocus with an unknown source. We have attempted to correlate this defocus with other low order Zernike terms provided by the wavefront sensor but have yet to find a correlation. We are still investigating the cause of the discrepancy.

Despite an apparent component other than temperature that causes defocus, we found that the defocus follows the OSS temperature at the beginning of the night. Therefore, we have implemented a “tempfoc” button on the operator GUI. After the initial wavefront sensing, which sets the focus, the operators push a button on the GUI to set a reference position. This records temperature and hexapod position. At a later time the operators can press the tempfoc button, which will change the focus according to the temperature change. This works best at the beginning of the night when the temperature is changing most rapidly. After the first few hours the operators use the button at their own discretion.

6.2. Primary Mirror Control

Section 2 outlines the specifications for the converted MMT ventilation system. In summary, the ventilation system must be capable of keeping the average front-plate temperature to within 0.15 °C of ambient while keeping thermal gradients within the primary to below 0.1 °C.

Gibson provided a quantitative analysis of the performance of the ventilation system during the month of January 2003. He found that the isothermal criterion was never met during that month. However, the peak-to-valley differences for the front-plate were frequently less than 0.4 °C with the larger gradients typically observed
Figure 4. Comparison of the MMT OSS temperature and predicted defocus versus the defocus measured using the Shack-Hartmann wavefront sensor. The two curves that should match are the defocus (Δ) and the predicted defocus (○).
only at the beginning of the night. The RMS differences were repeatedly less than 0.1 °C and were only above 0.4 °C at the beginning of three nights. He also found that the primary mirror was in compliance with primary-to-ambient difference criterion approximately 15% of the time. One caveat is that the stability of the MMT E-series thermocouples is unknown.

Although the ventilation system does not meet the design specifications, the ultimate measure of performance is the image quality. The MMT often delivers good image quality when not meeting the thermal design specifications. There are likely multiple reasons for this. First, the primary-to-ambient requirement was based on empirical results from Racine et al.. Those results did not account for the effect of wind. Zago and Zago found that even a moderate wind could greatly reduce mirror seeing. Second, the isothermality criterion was specified for the very best seeing conditions at the MMT. A seeing histogram for the MMT shows that the best seeing is achieved only 2.5% of the time and that the median seeing is 0.71″FWHM (see http://www.mmto.org/~dblanco/Seeing_Stats/). Finally, since the MMT employs a wavefront sensor and active control of the primary (see Pickering et al. in these proceedings), wavefront errors that result from thermal non-uniformities can be corrected. However, the wavefront sensing is not continuous, and therefore, science observations must be interrupted during wavefront sensing. Therefore, a combination of good thermal control and selected wavefront sensing can deliver very good image quality. We are comparing data on the thermal state of the primary with wavefront sensor data to understand when wavefront sensing is most needed.

As part of the analysis we have used data from the thermal system to create animated gif movies that illustrate the heat flow on the primary mirror front-, mid-, and back-plates. Figure 5 shows an example of four individual frames from one of the movies. The large circle at the top center of each frame is a contour plot of the primary mirror front-plate temperatures. The contours were evaluated using data from 24 E-series thermocouples. The position of the thermocouples is shown on the figure as small squares. The two circles in the lower left and lower right are contour plots of the mid-plate temperatures and the back-plate temperatures respectively. The color in each plot illustrates the absolute temperature; violet being the coldest (-20 C) temperature expected during the year and red being the hottest (+20 C).

The line plot at the bottom center shows the evolution of several system temperatures. The legend for this is shown in the upper right of the figure. The temperatures that are plotted include the front-, mid-, and back-plate average temperatures, the chamber ambient temperature, the OSS temperature, and the outside ambient temperature measured by an E-series thermocouple and a Vaisala unit. Also included on the plots are the two system setpoints that the operators set: the Carrier setpoint and the Neslab setpoint.

The first frame shows the conditions of the primary at the beginning of the night prior to opening the dome. There is a radial temperature gradient that formed during the day. The second frame shows the state of the mirror just 85 minutes later. The front-plate is very nearly isothermal at a temperature that is equal to the temperature of the air surrounding the primary mirror. The third and fourth frames show the conditions during the middle of the night and at the end of the night, respectively. This example illustrates that the primary can be kept nearly isothermal over a large portion of the night. The most difficult time is when the ambient temperature is dropping rapidly at the beginning of the night.

These thermal movies have documented the development of localized gradients that arise during the day. Measurements of airflow around the primary revealed that cold air was flowing out of the cell exhaust ejectors and warm air was being drawn up through the ventilation system. The temperature difference between the air entering and leaving the cell was sometimes as much as 7.5 °C. This lead to the decision to cap the exhaust ejectors during the day. This appears to have reduced the thermal gradients that develop during the day.

7. CONCLUSION

Cheng & Angel and Fabricant et al. provide a set of requirements for the control of the thermal state of the MMT primary and telescope structure. We conclude that the ventilation system is not quite capable of achieving these goals. However, the MMT does deliver good image quality when these specifications are not met. Since there is active control of the primary and wavefront sensing, we feel that the original goals were too stringent for most “normal” conditions.

This work is ongoing with a goal of producing additional quantitative results for the performance of the ventilation system. The data from this study will be used to automate the system in the future.
Figure 5. Four frames from a movie illustrating the thermal evolution of the MMT primary mirror during a single night.
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