Automation and control of the MMT thermal system

J. Duane Gibson^a, Dallan Porter, and William Goble,
MMT Observatory^b, University of Arizona, Tucson, Arizona USA 85721-0065

ABSTRACT

This study investigates the software automation and control framework for the MMT thermal system. Thermal-related effects on observing and telescope behavior have been considered during the entire software development process. Regression analysis of telescope and observatory subsystem data is used to characterize and model these thermal-related effects. The regression models help predict expected changes in focus and overall astronomical seeing that result from temperature variations within the telescope structure, within the primary mirror glass, and between the primary mirror glass and adjacent air (*i.e.*, mirror seeing). This discussion is followed by a description of ongoing upgrades to the heating, ventilation and air conditioning (HVAC) system and the associated software controls. The improvements of the MMT thermal system have two objectives: 1) to provide air conditioning capabilities for the MMT facilities, and 2) to modernize and enhance the primary mirror (M1) ventilation system. The HVAC upgrade necessitates changes to the automation and control of the M1 ventilation system. The revised control system must factor in the additional requirements of the HVAC system, while still optimizing performance of the M1 ventilation system and the M1's optical behavior. An industry-standard HVAC communication and networking protocol, BACnet (Building Automation and Control network), has been adopted. Integration of the BACnet protocol into the existing software framework at the MMT is discussed. Performance of the existing automated system is evaluated and a preliminary upgraded automated control system is presented. Finally, user interfaces to the new HVAC system are discussed.

Keywords: Telescope thermal control systems, MMT Observatory, regression analysis, HVAC, BACnet

1. INTRODUCTION

Like other large borosilicate astronomical mirrors, the MMT's 6.5-meter primary (M1) mirror requires active thermal control. From 2001 through 2008, the telescope operators (TO's) directly controlled the M1 ventilation system, including determining the appropriate ventilation air temperature and setpoints for multiple chillers^[1]. Control of this system was as much an art as a science with the fluctuating weather and temperature conditions and the long thermal response times of the system. Through use, several "rules-of-thumb" were adopted by the TO's and thermal control was relatively efficient. Graphical user interfaces (GUI's) were added to allow semi-automatic control of the thermal system by tracking a reference temperature, such as the outside temperature. Even with this semi-automatic approach, the TO's needed to monitor the M1 ventilation control system throughout the night as it responded to changing thermal and environmental conditions.

Automated control of the thermal ventilation system for the M1 mirror began in 2009^[2]. This automated control combines: 1) a simple linear regression control algorithm between the setpoint of the primary glycol-based chiller (manufactured by Carrier Corporation) and the M1 ventilation system air temperature, and 2) a differential air temperature controller for a second methanol-based chiller (manufactured by Neslab, now ThermoFisher Scientific) that further refines or trims the final discharge air temperature of the M1 ventilation system. The thermal control system attempts to drive the M1 glass temperature towards the ambient air temperature while minimizing thermal gradients within the mirror. These algorithms are based upon data gathered prior to 2009.

^a Contact email: jdgibson@mmto.org

^b The MMT Observatory is a joint facility of the Smithsonian Institution and the University of Arizona.

A rich set of environmental and thermal data has been acquired under automated control over the past six years. Preliminary control algorithms for a newly upgraded MMT thermal system have been developed. This automated control software encapsulates much of the control logic developed over the years as well as the necessary safety requirements. Logged telemetry data from this automated system is used in this study for regression analysis of the M1 ventilation system.

2.0 THERMAL SYSTEM EFFECTS ON OBSERVING

Williams *et al*^[1] discuss how the thermal state of a large telescope can have a significant adverse effect on the image quality if the system is not properly controlled. They summarize three effects that can be particularly apparent to observers:

1. Focus changes resulting from temperature changes in the telescope's optical support structure (OSS).
2. Degradation of the image quality resulting from thermal gradients within the primary mirror.
3. Poor seeing resulting from differences between the ambient temperature and primary mirror temperature (*i.e.*, mirror seeing).

An extensive data set has been obtained over the past ten years that allows quantitative analysis of these thermal-related effects at the MMT. Analysis of data associated to these three effects is presented below. These analyses evaluate the performance of the current control software and help guide data-driven improvements to this software.

2.1 Temperature-Focus Relationships

To a first approximation, the change in telescope focus resulting from temperature fluctuations is defined by a linear coefficient that is measured in microns/°C. Correction for this temperature-focus ("tempfoc") effect occurs automatically within the secondary mirror (M2) hexapod control software. The temperatures from six thermistors attached at various locations on the OSS are averaged to control the tempfoc correction. As the OSS temperature changes, the focal length (the "z" direction) of the telescope is adjusted. This coefficient is dependent not only on the OSS, but also on the secondary mirror and instrument, among other factors. For example, the f5 M2 mirror is made of Zerodur glass while the f9 M2 mirror is borosilicate glass, each with a different coefficient of thermal expansion. These different types of M2 mirrors will affect the relationship of focus changes to temperature changes. Likewise, thermal effects on the instrument and its support structure can affect the overall focal length of the optical system. At the moment, the following temperature-focus ("tempfoc") correction coefficients are used at the MMT: -46.7 microns/°C for the f9 secondary mirror, -13.1 microns/°C for the f5 mirror, and -49.0 microns/°C for the f15 secondary. The current instrument on the telescope is not considered in these temperature-focus corrections.

Approximately ten years of detailed thermal and telescope focus data are available for the MMT, representing data points under a wide range of temperature conditions and telescope configurations. For this study, it is assumed that the telescope is properly focused and collimated after wave-front sensor (WFS) corrections have been applied for the f5 and f9 M2 mirrors or while the adaptive optics (AO) f15 secondary mirror is in closed-loop mode. The focus and temperature values are retrieved from secondary mirror logs at a few seconds later than the timestamps of the WFS or AO measurements, allowing for any M2 moves to be completed. These temperature-focus pairs should represent typical data under normal observing conditions.

Figure 1 shows results of temperature-focus ordinary least squares (OLS) linear regression analyses for several different telescope secondary/instrument configurations. The observed data are shown as circles in the figure. The regression-fitted data are shown as the central line. This line represents the best linear regression model for the sample data. The upper and lower lines represent the 95% prediction interval. This 95% prediction interval represents the range in which the real value of the dependent value, "telescope focus" in this case, is expected with respect to the independent parameter, "average OSS temperature" in these calculations.

Table 1 presents results of these OLS linear regressions. A temperature-focus coefficient, the slope coefficient in the regression, of around -54 microns/°C is found for the f9/blue and f9/red telescope configurations, with a somewhat higher -62 microns/°C value for the f9/spol configuration. A temperature-focus coefficient of -30.7 microns/°C is found for the f5/hecto configuration while a -32.1 microns/°C coefficient is found for f15/aries. Less scatter is seen in the f9

data than in the f5 or f15 data, as reflected in the relatively high R^2 (*i.e.*, the “coefficient of determination”) values of 0.635 to 0.758, with a R^2 value of 1.0 being a “perfect” fit.

Figure 1. Regression analysis of the average OSS temperature (in °C) versus focus (in microns) for four different secondary mirror/instrument configurations from January, 2006 to May, 2016. These configurations include: 1) f9/blue channel spectrograph (upper left), 2) f9/spol, imaging spectropolarimeter (upper right), 3) f5/hecto, a moderate resolution spectrograph (lower left), and 4) f15/aries, an adaptive optics near infrared-red diffraction limited imager and spectrograph (lower right). See text and Table 1 for additional details.

Table 1. Results of ordinary least squares (OLS) linear regressions of data from January, 2006 to May, 2016 for five different configurations of the MMT telescope. Only data taken after WFS corrections or during closed-loop adaptive optics (AO) operations are included.

Telescope Configuration	Count	Intercept (microns)	Std Err	Slope (microns/°C)	Std Err	R ²	F-Statistics
F9/blue	19923	1035.2	2.65	-54.9	0.259	0.693	4.504e+04
F9/red	5409	989.6	5.05	-53.5	0.533	0.635	1.009e+04
F9/spol	1685	895.5	9.78	-62.1	0.814	0.758	5828
F5/hecto	36943	14470	2.564	-30.7	0.249	0.292	1.523e+04
F15/aries	451189	1244.8	0.726	-32.1	0.072	0.305	1.983e+05

The relatively large F-statistic values suggest that the temperature-focus linear regression assumption is significant. The larger scatter of the f5 and f15 data in Figure 1 suggest that other factors besides OSS temperature changes are more important in changes in focus for these telescope configurations than for the f9 configurations. Future work will expand these calculations to other telescope/instrument configurations, including the f5 MMIRS (MMT and Magellan Infrared Spectrograph) and BinoSpec (a wide field optical spectrograph) instruments. The same regression analysis technique of observational data can also be applied to M2 elevation-collimation (“elcoll”) corrections, a separate automatic correction that is applied during observing. Analysis may also show whether temperature changes affect any other of the six M2 platform axes besides the focus (“z”) axis. The effect of temperature on these other axes is expected to be small.

2.2 M1 Thermal Gradients Effect

Figures 2 and 3 summarize WFS seeing data (in arc-seconds, corrected to zenith) versus root mean square (RMS) glass temperatures within the M1 mirror. These results build upon the work of Williams *et al.*^[1] and Gibson *et al.*^[3]. Thermal gradients can exist within the M1 mirror in any direction and at any scale. The RMS temperature values only represent an overall variability of temperature within the M1 mirror. These values are based upon the E-series thermocouple data from the M1 cell, in which approximately 50 thermocouples are attached to the frontplate, midplate, and backplate of the mirror, giving a three-dimensional temperature profile of the M1 glass.

As seen in Figure 2, data from 2006 to 2016 suggest that the best seeing conditions occur when the M1 RMS values are between 0.05 and 0.15°C. Overall seeing worsens with increased M1 RMS temperature values. There are many factors affecting astronomical seeing, with thermal gradients within the M1 mirror being only one factor. Figure 3 shows the distribution of M1 glass RMS temperature values from the same 2006 to 2016 period. M1 RMS values from 0.0°C to 0.6°C are plotted into 60 bins (0.01 °C/bin) in the histogram (Figure 3, left). A mean value 0.150°C is found for the data with a standard deviation of 0.087°C and a kurtosis value, a measure of skewness, of 5.744. Although this median temperature variation is not as low as the MMT design specifications of 0.1°C^[4], Figure 2 shows that overall seeing is typically only slightly worse at the 0.15°C RMS level. Ideally, the RMS for the M1 mirror would be 0.1°C or less.

Figure 2. Median seeing (in arc-seconds, corrected to zenith) as measured by the f5 and f9 wave-front sensors from January, 2006 to May, 2016. The best seeing occurs when the M1 glass root mean square (RMS) temperature is between 0.05°C to 0.15°C. Overall seeing worsens with increased RMS temperatures.

M1 glass RMS temperatures, resampled for a 3-month (*i.e.*, seasonal) mean, are shown in Figure 3 (right). Seasons are defined as: 1) winter (December through February), 2) spring (March through May), 3) summer (June through August) and 4) fall (September through November). The lowest seasonal RMS values are seen between 2011 and 2013. The data suggest somewhat worse overall seeing data during the winter compared to other seasons. This may result from any heating of the telescope chamber during daytime activities, which would have the greatest effect in the winter. The cause of lower annual RMS temperatures from 2011 to 2013 is not known. It should be noted that the RMS temperatures during automated control of the MMT thermal system, from 2009 onwards, is as low or lower than during previous years.

2.3 M1 Glass-Air Temperature Contrast Effect

Figures 4 and 5 present WFS seeing values (in arc-seconds, corrected to zenith) versus the M1 glass-air temperature contrast from 2006 to 2016. As seen in Figure 4, the best seeing at the MMT over the past ten years has been when the glass temperature is 0.0°C to -1.0°C below the chamber air temperature. These results are similar to those in Williams *et al.*^[1] and Gibson *et al.*^[3]. This low temperature contrast minimizes air turbulence or eddies at the front face of the mirror. Seeing is worse when larger temperature differences occur in both the positive and negative directions, but the worse situation is a warm mirror adjacent to cold air, as seen in the data on the right side of Figure 4.

Figure 3. Histogram (left) and time-series (right) plots of M1 glass RMS temperatures (in $^{\circ}\text{C}$) from January, 2006 to May, 2016. Data points are taken at the time of f5 or f9 WFS corrections with a 10-minute median filter applied to the data. A mean M1 glass temperature of 0.150°C is found for this ten-year period. The seasonal mean RMS values are shown as a time-series to the right. Seasons are defined as follow: winter (December through February), spring (March through May), summer (June through August) and fall (September through November).

Figure 4. Mirror seeing at the MMT as found from median seeing values for f/5 and f/9 combined seeing data from January, 2006 to May, 2016. The total number of seeing values is 108083. The minimum seeing value is found when the mean M1 glass temperature is 0.5°C to 1.0°C below the chamber air temperature. Seeing is worse when the glass-air contrast is either higher or lower than this temperature range. Data are restricted to M1 glass RMS temperatures $\leq 1.0^{\circ}\text{C}$.

Figure 5 investigates the frequency of glass/air contrast values at the time of WFS measurements over the past ten years. The mean of the resampled values is -0.026°C (Figure 5, left), within the target zone of 0.0°C to -1.0°C temperature difference for the M1 ventilation system. The standard deviation is 0.87°C with a kurtosis value of 4.84. Figure 5 (right) indicates a seasonal trend of increasing glass-air temperature contrasts over the past ten years, with a decrease in the past couple of years. These conditions of glass warmer than air temperatures are not desirable. At the time of

implementation of the automated system in 2008-2009, glass temperatures were colder than chamber air temperatures. However, worsening thermal conditions are seen in 2010 and subsequent years. Several factors may be involved in this trend. The distribution of flexible tubing that disperses air within the M1 mirror cell is quite complex. This tubing was completely removed for the 2010 re-aluminization of the M1 mirror. The tubing may have not been reinstalled optimally. In addition, more and more glycol coolant has been diverted over the years for other cooling requirements. Improved (*i.e.*, more negative) seasonal mean glass-air temperature contrasts are seen for 2015 and early 2016 in Figure 5 (right). These improved glass-air temperature contrasts may correspond to the new HVAC system with its larger glycol pumps and a more powerful glycol chiller. Details of this upgraded HVAC system are given below.

Figure 5. Data for mean glass minus chamber temperature contrast (in °C) at the time of f/5 and f/9 WFS corrections from January, 2006 to May, 2016. A mean of -0.026°C is seen in Figure 5 (left), a histogram with 100 bins between -6.0°C and 6.0°C. An overall increase in this glass-air contrast is seen in the time-series plot of the same data in Figure 5 (right) with a decrease since 2014.

Figure 6 (left) illustrates the linear regression during 2015 of Carrier setpoint (in °C) versus ventilation system air temperature (in °C) data as measured at the midpoint of the Pit heat exchanger, the last point at which the glycol coolant directly influences the ventilation air temperature. Figure 6 (right) shows annual coefficients of these same regression

Figure 6. Ordinary least squares linear regression of Carrier Setpoint (x-axis) to Pit Heat Exchanger midpoint temperature (y-axis) (Figure 6, left). Annual trends for regression coefficients are seen in Figure 6 (right). This midpoint is the final location that the glycol from the Carrier chiller can directly influence the M1 ventilation air temperature.

results from 2006 to 2016. The R^2 values are 0.9 or higher for all annual regressions, suggesting that the linear regression model is a very good fit for the observed data. The intercept parameters vary from 7.7 in 2006 to 4.4 in early 2016. This is a variation of over 3.3°C during the ten-year period - a significant variation given how tightly the sample

data clusters. An overall trend of decreasing intercept value to a minimum of 5.1°C is seen from 2006 to 2009, followed by an increasing trend to 2014 and a subsequent decrease to 2016. This may be a similar trend as seen in Figure 5 (right) and may be related to modifications to the glycol circulation system.

As described in Williams *et al.*^[1] and Gibson *et al.*^[2], the methanol-based Pit Neslab chiller provides additional conditioning of the M1 ventilation air system in the second portion of the Pit heat exchanger and uses the difference between observed air temperature and the target air temperature to further control the ventilation system air temperature. This chiller can, at least partially, compensate for any changes in the glycol cooling system. The Neslab chiller, which is also connected to the main glycol coolant system, is capable of internal setpoint temperatures down to -25°C, although it can only reduce the M1 ventilation air temperature by up to 8-10°C. Perhaps the biggest advantage of the automated control is the elimination of continuous human monitoring of the M1 ventilation thermal system rather than a significant improvement of ventilation system thermal behavior.

3.0 THERMAL SYSTEM UPGRADE

3.1 Thermal System Hardware Upgrades

Figure 7 shows the extensive hardware improvements of the thermal system that began in 2015. The hardware upgrades include: 1) two new 10-hp glycol pumps, 2) two new three-way, Belimo bypass valves that modulate the amount of glycol coolant through M1 ventilation system heat exchangers, 3) two variable frequency drives (VFD's) for control of the main ventilation system centrifugal blower, 4) upgrades of Carrier chiller #1 to BACnet communication, using an OpenUPC Carrier Comfort Network-to-BACnet communication module, 5) a second, larger Carrier chiller #2, which also uses BACnet and a separate OpenUPC module, 6) four new fan core units (FCU's) in the main MMT enclosure, also controlled by BACnet, 7) two new BACnet/IP controllers used to control the two new glycol pumps, to command the new three-way glycol valves, and to gather thermal data for the Shop and Pit heat exchangers, and 8) three BACnet MS/TP-to-IP routers that communicate with Chiller #1, Chiller #2 and the FCU's.

Figure 7. Schematic of the upgraded MMT thermal system. Air enters the primary mirror ventilation at the left of the figure through the blower intake. Heating of the air by adiabatic compression is removed by the Shop and Pit heat exchangers. Air passes through a rotating duct into the lower plenum behind the primary mirror and is released into the chamber. Four fan coil units (FCU1 through FCU4) provide air conditioning for occupants and instruments within the MMT enclosure. See text and Figure 10 for more details.

The new Chiller #2 and 10-hp glycol pumps increase both the cooling capacity and the glycol flow within the entire glycol system. Additional loads have been added to the glycol system with the installation of four FCUs for air conditioning within the MMT enclosure.

Figure 8 presents a schematic diagram of the modified glycol flow for the Shop and Pit heat exchangers. The system includes a bypass loop and valve that allows glycol to either flow through the heat exchanger or bypass the heat exchanger. Remote control of this glycol bypass valve dictates how much cooling of air is performed by the heat exchanger.

Figure 8. Details of the newly installed glycol plumbing for the Pit and Shop heat exchangers. A 3-way Belimo mixing valve allows glycol flow through or around (*i.e.*, to bypass) the heat exchanger. Commands are sent via BACnet to the Belimo valve, changing the position from 0.0 (0% bypass mode) to 10.0 (100% bypass mode). The valve positions can be changed by ± 0.1 units within this command range.

3.2 Thermal System Upgrade Software Framework

Much of the complexity of the ongoing MMT thermal system upgrade, from a software perspective, is the integration of typical, commercial off-the-shelf (“COTS”) HVAC and building automation system (BAS) components with the existing MMT thermal system. All of the new commercial HVAC hardware uses the BACnet (<http://www.bacnet.org/>) communication protocol. BACnet is specifically designed to allow communication of building automation and control systems for applications such as HVAC, lighting control, access control, and fire detection systems.

BACnet offers a standardized communication protocol used by hundreds of different commercial vendors, including all the major HVAC manufacturers. The protocol is able to handle a diverse range of applications and hardware, and easily scales to thousands to even millions of devices on distributed subnets, for example, the HVAC requirements for a large metropolitan school district. Advanced capabilities such as scheduling and prioritization are available. The BACnet protocol defines standardized services that communicate between BACnet devices. These protocol services include: “Who-Is”, “I-Am”, “Who-Has”, and “I-Have”, which are used for device and object discovery on BACnet subnets. Services such as “Read-Property”, “Read-Property-Multiple”, and “Write-Property” are used for data transfer. The BACnet protocol defines a number of standardized objects that are acted upon by the services. The objects include “Analog Input”, “Analog Output”, “Binary Input”, “Binary Output”, “Multi-State Value” and many others. The BACnet protocol defines a number of data link/physical layers, including BACnet/IP, Point-To-Point over RS-232, and Master-Slave/Token-Passing (MS/TP) over RS-485 (also known as EIA-485). BACnet routers allow transfer of BACnet objects between data link/physical layers, such as BACnet MS/TP to BACnet/IP, which is used extensively in this HVAC upgrade.

On the converse side, BACnet is a highly complex protocol with a large learning curve. Although the BACnet protocol itself is open-source, the internal controls software of most BACnet devices is proprietary. BACnet has no open source, multi-vendor configuration tool. Most vendors retain custom configuration and controls software tools that are not available on the retail market. BACnet communication typically uses asynchronous UDP (User Datagram Protocol) traffic. Extensive error handling is needed. BACnet data transfer restrictions are also a major software design issue. The maximum BACnet packet size is restricted by the different physical data layers over which BACnet objects are transported. The maximum BACnet MS/TP object size is 480 bytes while BACnet IP has a somewhat larger 1028-byte size. For BACnet object transport over both of these transport layers, the smaller size of the MS/TP portion restricts the maximum packet size. These restrictions can cause the transfer of a complete set of data from a device to take up to tens of seconds, such as the case of the Carrier chillers. BACnet uses a standardized port 47808, although some controllers and routers offer a secondary configurable BACnet port. Only one process can access port 47808 at a time on a single server, making port collision an issue when running multiple BACnet processes on one server. For this HVAC upgrade,

all periodical or “background” logging has been moved to secondary BACnet ports in both controllers and routers. These design factors greatly influenced the final software framework that was adopted at the MMT.

Open-source libraries exist for BACnet communication in several languages, including C, Java, and Python. The C and Python libraries were extensively tested as part of the MMT HVAC upgrade. Of these libraries, the C “BACnet Protocol Stack” library (<http://bacnet.sourceforge.net/>), developed primarily by Steve Karg, has the most active development community. It handles essentially the full range of BACnet protocol requirements, including the BACnet/IP and BACnet MS/TP physical layers. The “BACpypes” library, written in Python, is limited to BACnet/IP communication and is not as fully developed as the BACnet Protocol Stack library. The “BACnet for Java” library was not evaluated in this study.

A hybrid approach has been adopted at the MMT by combining the C-based BACnet Protocol Stack software with scripting languages such as Perl, PHP, and Python (see Figure 9). For single commands, such as a button-click from a graphical user interface (GUI), a system command to a BACnet Protocol Stack “bacrp” (Read-Property) or “bacwp” (Write-Property) command is executed by the scripting language. For background logging at set time intervals, a two-directional pipe is established between a Perl script and a custom BACnet Protocol Stack C program, “bacrp-stdio”, which uses the stdin and stdout file handles. A series of “bacrp” commands are executed through the pipe before closing it. The C executable is run from a Perl script as a subprocess with two-directional pipes for data exchange. The Perl script performs the higher-level database inserts, appends comma-separated value (CSV) log files, publishes data to a Redis key-value store, and other administrative tasks while the C executable handles the low-level BACnet communication. This approach was found to be the most robust. The Perl script is executed at a fixed time interval, *e.g.*, every 60 seconds.

Figure 9. A schematic of the data flow in the upgraded MMT HVAC and M1 ventilation system. See text for details.

A “bacnet” MySQL configuration database was created for the nearly 1000 new BACnet objects that have been added as part of the HVAC upgrade. This database contains all relevant BACnet object names, parameters, and attributes for data telemetry, logging, and device control. A “measurements” MySQL database was implemented with separate tables for each of the BACnet parameters. Data are also logged to comma-separated-value (CSV) text files as a backup for the database. Periodic logging of data began in November 2015. Intervals between logged database entries vary from five seconds to two minutes, depending on the parameter and hardware. It is expected that the number of BACnet parameters will increase with additional of future sensors and controllers.

Figure 10 presents a schematic diagram of the BACnet network topology at the MMT. This figure is similar to Figure 7, but focuses on the BACnet network topology. The BACnet subnets are connected to the existing MMT Ethernet/IP network backbone, shown in the center of the figure. This is somewhat different from most BACnet installations, which typically use a cheaper and easier to install MS/TP backbone. A total of ten BACnet controllers are connected to the MMT BACnet network. Two of these controllers are BACnet IP-based; the remainder are BACnet MS/TP controllers. The Pit heat exchanger controller (C1 in Figures 7 and 10) and the Shop heat exchanger (C2) regulate the three-way glycol valves for the two heat exchangers as well as acquire temperature data (*e.g.*, heat exchanger intake and discharge air temperatures). The Shop heat exchanger controller also commands the new 10-HP glycol pumps. Two Carrier OpenUPC modules, which communicate between the proprietary Carrier Comfort Network (CCN) protocol and the BACnet protocol, are BACnet MS/TP controllers (C3 and C4). These two controllers are connected to the BACnet IP network via individual BACnet MS/TP to IP routers (R1 and R2). The two new VFD’s for the ventilation system blower

are native BACnet MS/TP controllers (C5 and C6) and are connected to the BACnet IP network through a single BACnet MS/TP to IP router (R3).

New HVAC fan coil units (FCU's) have been installed at four locations in the MMT enclosure: 1) the first-floor loading dock/drive room, 2) the second floor west (2W) instrumentation room, 3) the third floor east (3E) computer server room, and 4) control room, located on the first floor. Each of the FCU's has its own BACnet MS/TP controller (C7 through C10). These four controllers are connected to a single BACnet MS/TP-to-IP router (R4). Finally, three servers (S1 through S3) currently interface to the BACnet IP network backbone, providing external process control and logging.

Figure 10. A schematic of the BACnet network topology for the upgraded MMT HVAC and M1 ventilation system. See text for details.

3.3 Thermal System Control Software: “vent_auto2”

Figure 11 shows the preliminary overall control logic for automated control of the upgraded thermal system, referred to as “vent_auto2”. Diverse thermal and environmental parameters are obtained from a central Redis key-value store in Step 1 of the figure. The current time is then used to determine whether daytime or night-time logic should be used. A small open-source C program, “sunwait”, which calculates sunrise and sunset, as well as civil, nautical, and astronomical twilights, is used to determine the transition from daytime to night-time control logic. At the moment, sunset and sunrise are used for the transition between daytime and night-time software control. The criteria for when to transition from daytime to night-time control logic can be significant, particularly if outside temperatures are rising or falling rapidly near the beginning of night-time operations.

If calculations for thermal system control are being made during the daytime, the Carrier Chiller Setpoint Command (“CSP”, Step 2a) is set to a constant value, nominally 2.5°C/36.5°F. This setpoint allows the FCU's to operate properly since they require glycol coolant that is colder than their internal circulation loop setpoints. During night-time operations (Step 2b), the target M1 ventilation air temperature is set to be slightly below, nominally 1°C, the outside air temperature. This offset may be adjusted with further use of the software.

Based upon this CSP, a required chiller setpoint (RCS) is calculated, using the linear regression model of Figure 12. For this calculation, the target M1 ventilation air temperature from Step 2b is set equal to the predicted ventilation air temperature in Figure 12. The RCS is assigned to the Carrier setpoint that corresponds to this Pit heat exchanger (HX) entry air temperature. This step assumes that the behavior of the system remains consistent through time. The regression parameters may need to be adjusted if the glycol system changes significantly. It should be noted that Figure 12 shows that a predicted ventilation air temperature of 0°C corresponds to a Carrier chiller setpoint of nearly -10°C, the lower limit for the chiller's setpoint. This implies that the RCS will commonly be below -10°C, for which the additional cooling capacity of the Pit Neslab is needed (Step 5).

Three different control regimes are used in Step 4 (Steps 4a through 4c). When the RCS is below $-10^{\circ}\text{C}/14^{\circ}\text{F}$ (Step 4a), the ventilation system is delivering its highest level of cooling. The Carrier chiller setpoint is set to its maximum negative limit (-10°C), both the Shop (Step 7) and Pit (Step 8) glycol bypass valves are fully closed for maximum coolant flow through the heat exchanger, and the Pit Neslab is used to actively provide additional cooling to the ventilation air (Step 5).

Figure 11. Logic within the updated automated M1 ventilation system control software: “vent_auto2”. See text for details.

The most common observing case is when the RCS is between $-10^{\circ}\text{C}/14^{\circ}\text{F}$ and $+10^{\circ}\text{C}/50^{\circ}\text{F}$ (Step 4b). In this situation, the system is controlled similarly to the existing “vent_auto” control software where: 1) the Carrier chiller setpoint is varied based upon the target ventilation air temperature (Step 4b), 2) the Pit Neslab chiller setpoint varies to trim the ventilation air temperature (Step 5), and 3) the Shop (Step 7) and Pit (Step 8) glycol bypass valves are also regulated to trim the ventilation air temperature.

The new FCU units require that the glycol coolant always be at or below $10^{\circ}\text{C}/50^{\circ}\text{F}$. In the past, glycol temperatures routinely were commanded above this value during the hot summer months. In warm temperatures (Step 4c), the Carrier chiller setpoint is fixed at 10°C . The Shop and Pit glycol valves are partially open, as needed. The Pit Neslab chiller may be used optionally to provide further trimming of the ventilation air temperature (Step 5). As with the other regimes for Step 4, the control software will be modified as needed based upon data from all four seasons.

Step 6 of Figure 11 involves a number of safety checks for both the primary mirror, the heat exchangers, and the chillers. These checks include: 1) keeping the mirror glass temperature below the dew point so that there is no condensation on the mirror, 2) limiting the rate at which the Carrier chillers can change their setpoint values, preventing internal errors that will shut the chillers down, 3) restricting possible ventilation air temperature so that the ventilation air is never warmer than the M1 glass temperature, and 4) constraining the chiller setpoints so that ice does not form on the heat

exchanger coils or on other uninsulated portions of the glycol circulation system. These safety checks can modify the Carrier and Pit Neslab command setpoint values.

Figure 12. A linear regression analysis of recent Carrier setpoint data (in °C) versus the Pit heat exchanger (HX) entry air temperature (in °C). This air temperature also approximately corresponds to the Shop HX exit temperature. The Pit HX entry air temperature is used since it is better instrumented than the Shop HX. The predicted Pit HX entry air temperature is used to infer a Carrier setpoint that would produce a target ventilation air temperature for the upgraded HVAC system.

The introduction of the Shop and Pit glycol bypass valves adds an additional means of varying the cooling capacity (Steps 7 and 8). Commands for opening or closing these valves are calculated based upon whether the measured discharge air temperatures for the heat exchangers are above or below the target ventilation air temperature, respectively. Figure 13 shows characterization of the newly installed Belimo bypass valves using experimental data gathered during January 2016. Figure 14 shows the behavior of the Pit Belimo valve during a single night during April 2016.

The Belimo valves are best characterized by a sigmoidal rather than a linear curve between the open to closed positions. Since the least squares regression technique can be used with many different models (*e.g.*, linear, quadratic, polynomial), using a sigmoidal regression relationship is relatively easy. The general form of a sigmoidal equation is:

$$S(t) = \frac{1}{1 + e^{-t}}$$

The legend of each plot in Figure 13 shows the coefficients used for the sigmoidal regression. These coefficients can be used to predict typical cooling capacity for each heat exchanger, based upon intake and discharge air and glycol coolant temperatures. With colder glycol temperatures, a larger difference will be seen between the intake and discharge air temperatures. This will cause the overall sigmoidal curve to scale as a function of glycol and air temperatures.

As seen in Figure 13 (left), the Shop heat exchanger typically removes a considerable amount of heat from the conditioned ventilation system air. With the bypass valve at 0% bypass, a temperature drop of around 20°C/36°F is seen in the sampled data across the Shop heat exchanger. This roughly corresponds to the amount of heat added to the ambient air temperature through adiabatic heating by the ventilation system blower. The Pit heat exchanger in Figure 13 (right), in contrast, is found to remove around 2°C/4.5°F between the intake and discharge air temperatures. This heat exchanger can be used to trim the conditioned air to the desired temperature. This is similar to the current role of the Neslab chiller, which lies downstream in the ventilation airflow path (see Figure 7).

The curve for the Pit Belimo valve is typical of desired valve behavior with the mean of the sample set lying at a 50% valve position. The desired operating range of the valve is centered in the available range of motion of the valve. The data for the Shop Belimo valve, in contrast, shows skewness with the center of system response at roughly a 70% bypass setting. The valve must be at least 30-40% closed before any significant change in system response is seen. This

reduces the range over which the system can be controlled. Further rebalancing of glycol flow with separate balancing valves may help center the response of the Shop Belimo valve.

Figure 13. Characterization of the Shop (left) and Pit (right) Belimo bypass valves, using a least square sigmoidal regression model. At 0% bypass, the heat exchanger would be cooling the air at its maximum possible efficiency. At 100% glycol bypass, the exit air temperature should be the same as the entry air temperature, with no cooling being performed by the heat exchanger. See text for more details.

Figure 14. Changes in the Pit heat exchanger valve command during normal operations during a night in mid-April 2016. The glycol bypass value is approximately 50% open during much of the night, the preferred location for the valve.

Sending the new chiller and valve commands (Step 9 of Figure 11) is performed primarily through the BACnet protocol previously discussed. The Pit Neslab chiller has its own propriety binary protocol. Data are logged to a Redis key-value store, redundant MySQL relational databases, and to comma-separated value files (Step 10). The control software sleeps for a nominal 60 seconds (Step 11) before repeating the cycle with Step 1.

3.4 Thermal System Control Software: User Interfaces

A new graphical user interface (GUI) (Figure 15) was created to easily interface with all of the new components. The new GUI provides on-and-off and variable control for the VFD blower controllers, the Carrier1 and Carrier2 chillers, the two new glycol pumps, the Shop and Pit glycol flow valves, the four fan-coil units, various fans, and the MMT enclosure perimeter heaters. The chiller and FCU setpoints can be manually input as well. Depending on the state of the entire system, the GUI updates the glycol flow colors, the pump icons, valve arrow positions, and the airflow temperature colors from the blower to the mirror cell.

This GUI gives the operators a visual representation of how the complete MMT thermal system works as a whole in addition to controlling the equipment individually. The GUI provides real-time update of parameters via the socket.io JavaScript library and subscription to parameters within a Redis key-value store through a node.js server. Commands are sent directly from the GUI, through a PHP backend on the web server, to a BACnet Stack Protocol executable. Additional web-based GUI's are available for time-series plotting and for monitoring of all new BACnet parameters. These GUI's interact with the Redis key-value store and MySQL relational databases.

Figure 15. Graphical User Interface (GUI) for manual control of the upgraded HVAC/M1 Ventilation system. This GUI provides control of all the major components of the upgraded MMT thermal system. See text for more details.

4.0 CONCLUSIONS

Three different thermal-related effects on night-time observing at the MMTO are investigated using data that has been acquired over the past decade (2006-2016): 1) the relationships of focus change with temperature variation for assorted secondary mirrors and instruments, 2) the influence of temperature variations within the M1 glass on overall seeing, and 3) the effect of the M1 glass-air temperature contrast on seeing. Temperature-focus ("tempfoc") data pairs are sampled at the same timestamps as when WFS corrections have been applied for the f5 and f9 secondary mirrors and during closed-loop operations for the f15 secondary. Linear regression of these data pairs are evaluated for different M2/instrument telescope configurations. New "tempfoc" correction coefficients are presented that may be used for

automated focus corrections based upon temperature changes. The variation of RMS temperatures within the M1 primary mirror is investigated from 2006 to the present. Seasonal values in the M1 RMS temperatures range from a low of below 0.1°C to a high near 0.2°C, with a mean value of 0.16°C over this time interval. The lowest seasonal RMS values are found during 2011 to 2013. These data suggest that the optimal range for observing is when M1 RMS temperature values are between 0.05°C and 0.15°C. The M1 glass-air temperature contrast from 2006 to 2016 has a mean value of -0.03°C with a low of -0.6°C during 2008-2009, increasing to a high of 0.6°C in 2014, and a decrease to below 0.0°C in early 2016, perhaps related to the HVAC upgrade. The optimal M1 glass-air contrast is found to be -1.0°C to 0.0°C. These analyses are used to evaluate performance of the thermal system under the existing automated control system. Similar analyses will be used to guide future development of control software for the MMT thermal system.

Beginning in 2015, new HVAC equipment is being installed and brought on-line at the MMT. This new equipment includes a larger glycol-based chiller, variable frequency drives (VFD's) for the main M1 ventilation blower motor, larger glycol coolant pumps, multiple three-way glycol bypass valves, extensive new coolant plumbing, and numerous status and temperature remote sensors and controllers. Four new fan-coil units (FCUs) have been installed in the main MMT enclosure to provide air conditioning. This new facilities HVAC hardware must be integrated with automated control of the M1 ventilation system.

The open-source, industry-standard BACnet (Building Automation and Control network) protocol is used to communicate via BACnet objects between devices and computers on different physical data layers. A summary is presented of the BACnet network topology and integration of this protocol into the existing MMTO telemetry and control system, including Redis key-value stores and MySQL relational databases. The new M1 ventilation and facilities HVAC systems require a more complex and robust approach to automation and control. Instead of control solely via adjusting chiller setpoints, the ventilation air will be conditioned through the more widely used approach of mixing warm and cold glycol coolant through multiple three-way valves, each associated with an air/glycol heat exchanger. This approach provides better overall system response.

A preliminary implementation of automated software control for the upgraded MMT thermal system divides software behavior into three regimes, based upon the Carrier chiller setpoint: 1) below -10°C, 2) between -10°C and 10°C, and 3) above 10°C. Requirements for the new FCU's prevent the Carrier setpoint from being increased over 10°C as it has in the past. Details of control of chiller setpoints and glycol bypass valve positions are presented for the three thermal control regimes. This software control is expected to be refined as additional data is acquired through continued operation.

Finally, new graphical user interfaces (GUI's) have been developed to allow the user to monitor and control the upgraded MMT thermal system, including the M1 ventilation and facilities HVAC subsystems. These GUI's allow manual control of the thermal system as well as monitoring of automated control of the system. Real-time updates of environmental and thermal data are provided to users using current web-based technologies.

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