

A high-precision differential-thermocouple temperature measurement system for the 6.5m MMT primary mirror

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1.0 Overview

Following the primary mirror integration tests in the SO mirror lab, it was clear that the thermal measurement system needed improvement. The original system incorporates a large copper “isothermal” junction block (IJB), where the individual type-E thermocouple wires (chromium and constantan) are converted to copper for input into the system’s electronics. The absolute temperature of this IJB is measured at a single point with a solid state AD 590 sensor. The accuracy of this system is dependent on the implied isothermality of this rather large block, and the stability of the electronic MUX for extremely small signal voltages. Attempts to calibrate the offsets and characterize the stability of the system while in the thermally managed polishing lab proved problematic.

The MMTO decided to place an additional and more precise temperature measurement system into the primary mirror optimized for measuring temperature differences.

2.0 New System

2.1 Design goals

The new system concentrates on temperature measurement in 3 areas:

- the radial temperature profile with attention paid to the temperature of the mirror blank edges.
- the temperature difference between the mirror front and back plates (bi-metallic effect).
- the temperature difference between the mirror and ambient air (thermal servo).

Our goals for improving the original temperature measurement system included:

- eliminating the IJB.
- obtaining higher measurement accuracy and increased stability.
- replacing the electronic MUX with a mechanical switcher optimized for extremely small voltages.

- providing better isolation of the thermocouples (attached to the glass) from the forced-air stream of the thermal control system -- including the effects of conduction through the thermocouple wires.

In addition, we wanted to overlap sections of the two measurement systems for cross checking.

2.2 Thermocouple circuits

Thermal information important to controlling the mirror figure and local seeing are dependent only upon temperature differences and not absolute temperatures. Therefore, we want to create a system that inherently measures temperature differences to high precision by using differential pairs of thermocouples. Furthermore, we wanted a flexible system that would allow changing the configuration of thermocouple connections as the mirror thermal properties become better understood.

After carefully studying two successful measurement systems, we decided on wiring geometries that use differential pairs of thermocouples (Figure 1)[1,2,3]. The thermopile

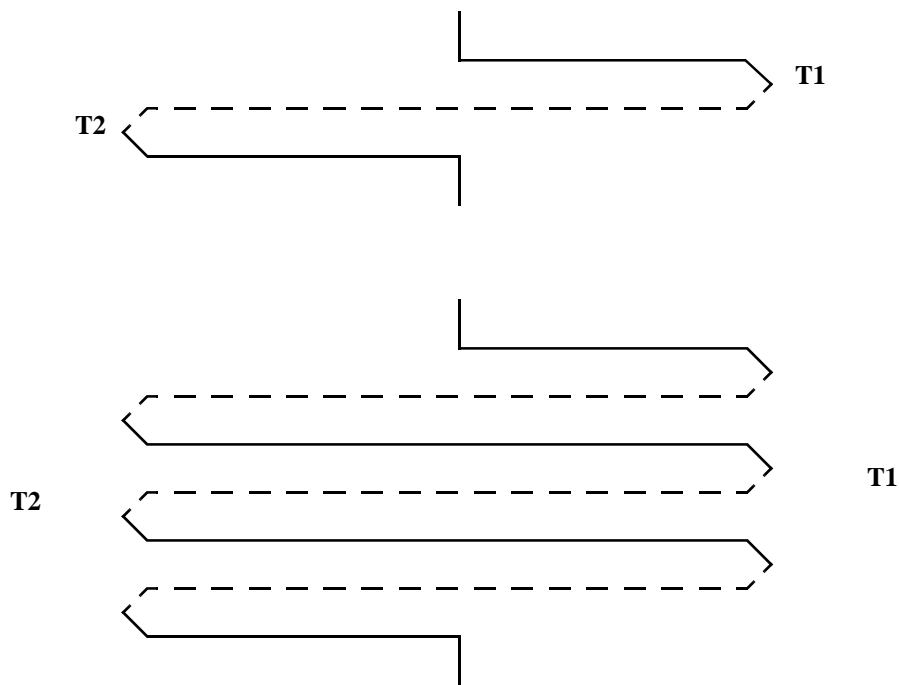


FIGURE 1. Two ways to measure temperature differences using thermocouples. A differential pair of thermocouples (top) and the thermopile which consists of differential pairs wired in series. For a given temperature difference, the output voltage of the pair is proportional to $(T1 - T2)$, while the output voltage of the pile is $N(T1 - T2)$, where N is the number of pairs incorporated. For type-T thermocouples, solid lines are copper and dashed lines constantan.

is the most attractive for our purposes. For a given temperature difference, an arbitrarily

large signal can be generated that overwhelms any noise from the measurement electronics and switching circuits. For example, a single channel proportional to the average mirror temperature minus the average ambient air temperature is created if the pair ends of a single pile are distributed throughout the mirror and ambient. Such a high-signal channel is ideal for a single setpoint thermal servo. Another pile could easily measure the average difference between the mirror face and back plates indicating bimetallic bending of the blank. A disadvantage of the pile is wiring the interconnections for widely separated points.

Additionally, the selection of Type-T thermocouples has the advantage that both signal wires are copper, and therefore the thermocouples can be connected to the electronics *without using an isothermal junction block*.

Spatial resolution can be obtained by using multiple pairs of thermocouples (Figure 2).

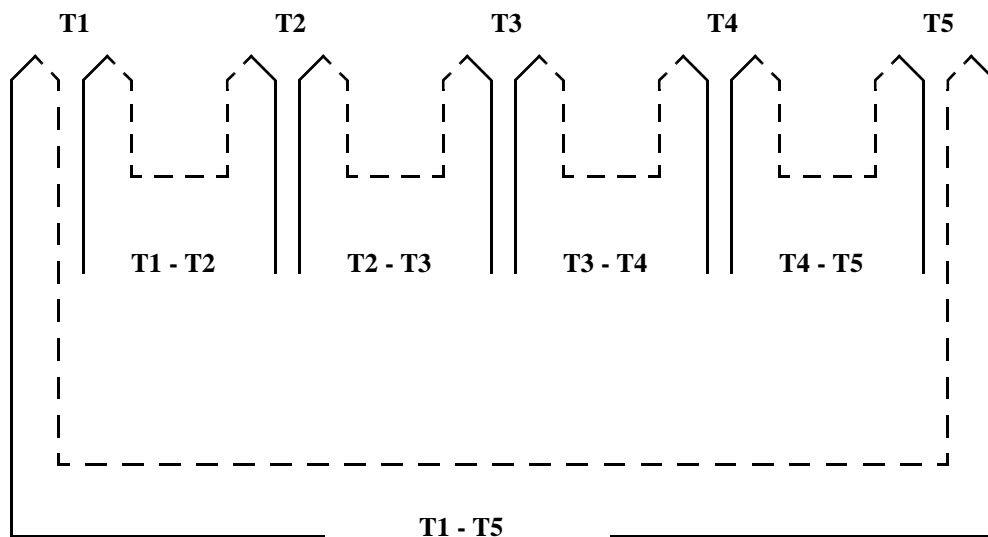


FIGURE 2. Schematic showing how accurate spatial resolution information may be obtained by using multiple differential pairs of thermocouples.

The thermocouples at a given location (*e.g.* T2) are placed in close proximity so that they read the same temperature. The final pair connecting the segment ends acts as a checksum to control error accumulation.

2.3 Attachment of thermocouples to the mirror blank

Figure 3 shows the assembly details of installing the thermocouples into a hex core of the

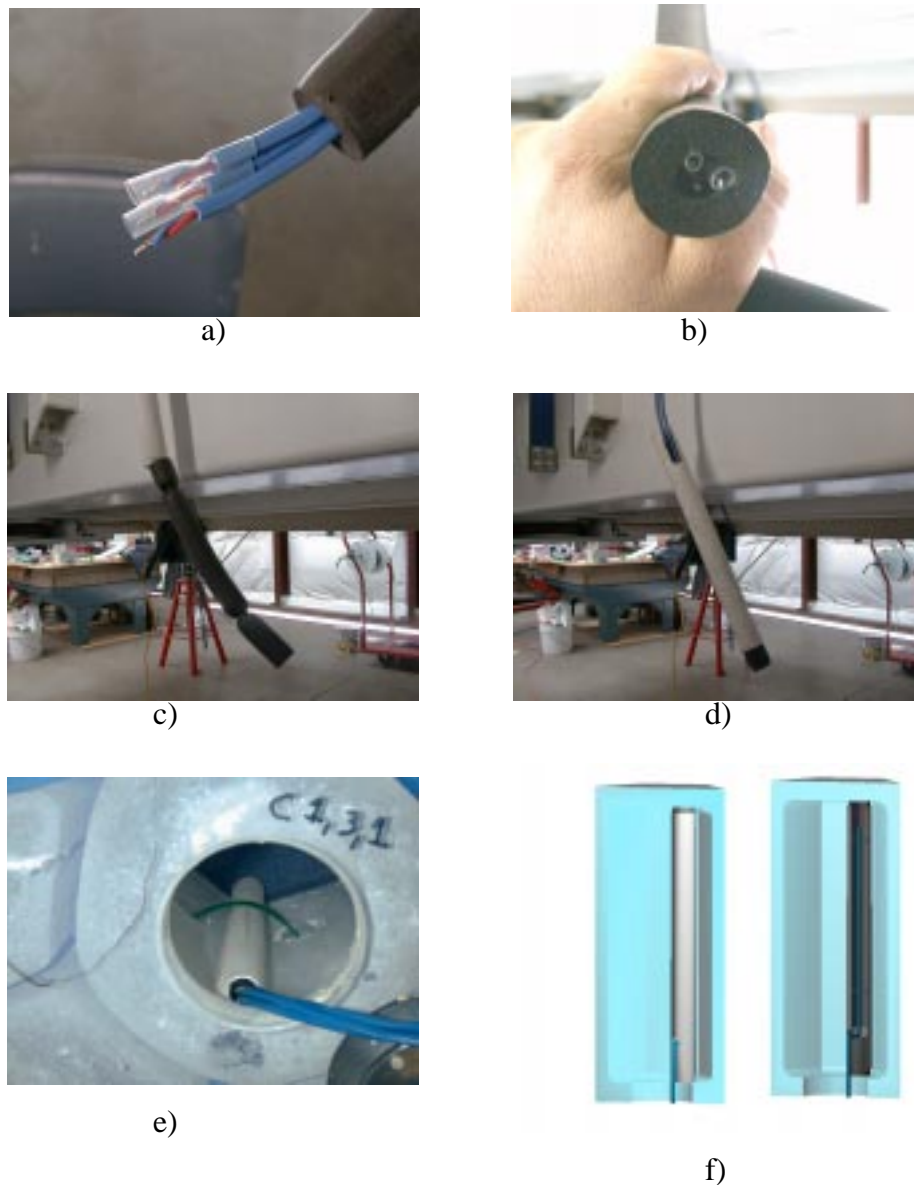


FIGURE 3. Assembly details showing how the new thermocouples have been placed into the mirror hex cores in order to measure glass temperature. a) and b) Three thermocouples are slid into a 12-inch insulating neoprene tube and electrically isolated to prevent shorting. c) The neoprene tube is clamped in two places to hold the cables and prevent air from the ventilation system travelling through the tube center. d) The neoprene and thermocouples are slid into a PVC tube with 3/4-inch of neoprene foam extending out of the tube to contact the underside of the mirror faceplate. Additional foam is inserted into the rear of the PVC tube to contact the mirror backplate (not shown). e) and f) show the tube installed into a hex core. The foam on both ends of the PVC tube is adjusted to give the stackup slight compression. Loctite 404 bonds the foam to the PVC tube to prevent creep and RTV bonds the foam to the glass at the ends of the tube. Finally, e) shows a plastic retainer that lightly clips into two cross-pin holes.

mirror. As Figure 3b shows, the thermocouples are not attached to the glass, but instead

they are inside the air pocket of an “igloo” that itself is sealed to the glass and insulated from the forced-air stream of the thermal control system.

2.4 Performance in a forced-air stream

A test was conducted to determine the effectiveness of the insulation in decoupling the mirror and air temperatures. The tubes insulating the thermocouples were tested by blowing warm air into a core containing both the new and old thermocouples. The results are shown in Figure 4. Warm air was blown into the core until the air temperature rose to 4 C

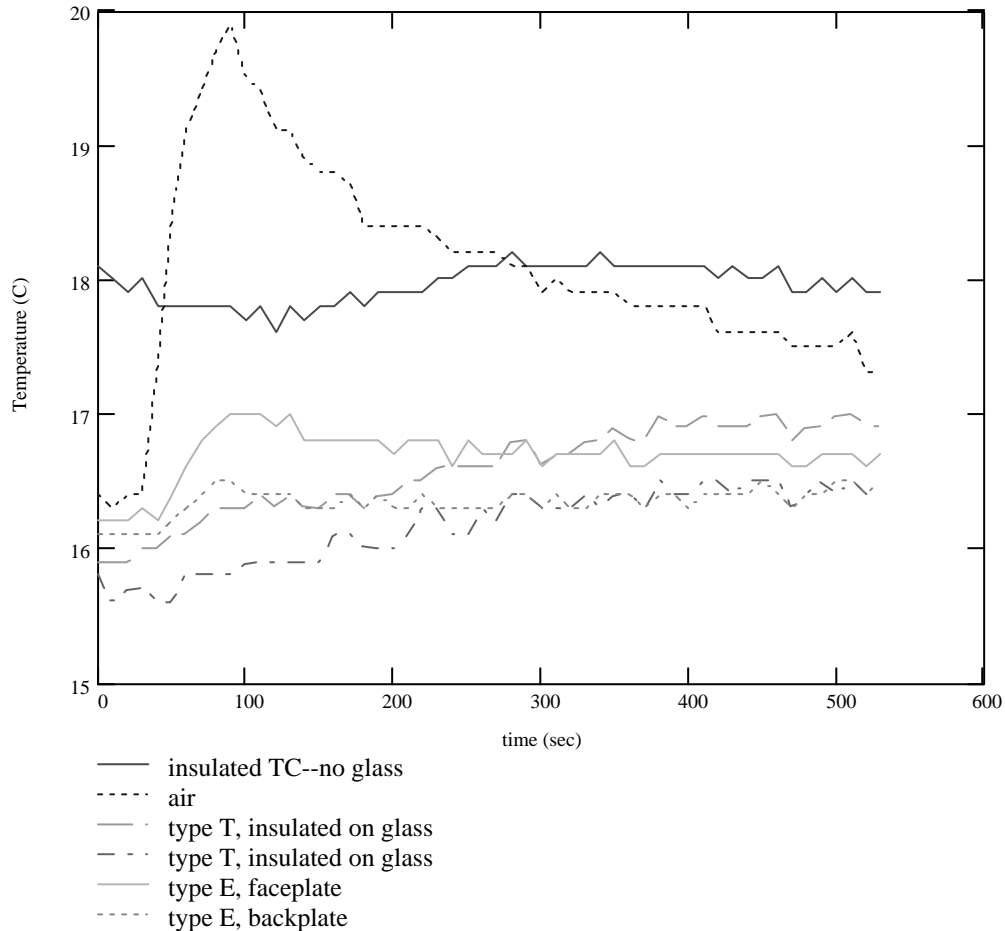


FIGURE 4. Thermal impulse response of thermocouples from the old and new measurement systems. All errors +/- 0.2 C due to cold junction compensation in the electronics. New thermocouple errors will be smaller when they are used in differential mode as intended. See text for more details.

above the glass temperature, and then it was turned off (marked “air” in the legend). The line (near 18 C marked insulated TC -- no glass) is a single thermocouple sealed into the insulated sleeve of the new system without being attached to the glass. It was a control to test for the isolation of the thermocouple from the air stream without the added complication of the glass temperature. (This thermocouple was warmer than ambient due to being recently placed into a new sleeve.) As can be seen, it was slowly cooling toward ambient

before the warm air was injected into the core. The lower two curves are two type-T thermocouples from the new system. The two curves above these are type-E thermocouples from the old system which were pressed against the glass in a glob of thermally conductive epoxy with no other insulation from the air. The type-E faceplate and the type-T thermocouples were directly in the forced-air stream. Clearly, the new system decouples the glass and air temperatures very well.

2.5 Placement in the mirror blank

Sixteen thermocouples in each of four mirror radii have been included in the new measurement system. Of these fifteen measure faceplate temperature from five tubes of the type shown in Figure 3. The sixteenth thermocouple is mounted into an inverted tube in order to measure the backplate temperature. The location of these tubes are shown in Figure 5. Two cores (B130 and E130) have been intentionally overlapped with the old system for cross referencing to the new system.

Two of the thermocouples in each tube are used to obtain the radial temperature distribution of the faceplate as in Figure 2. The remaining thermocouple in each tube is wired as a differential pair to other parts of the system as shown in Figure 6 (e.g. ambient, lower plenum-

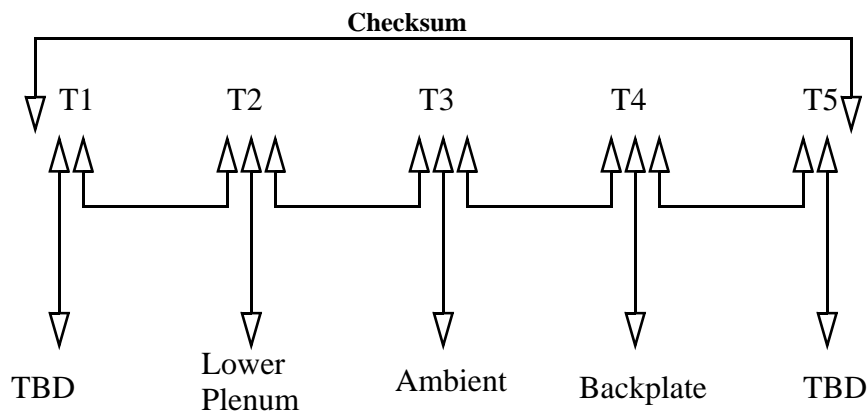


FIGURE 6. Diagram showing the connection of the thermocouple pairs along a single radius of the mirror from the faceplate locations shown in Figure 5. The third thermocouple in each tube is wired as a pair with other parts of the system (TBD=to be determined).

num, upper plenum, and backplate, and as monitors of the ventilation just outside of the mirror edges and cell).

2.6 Wiring and electronics

Each of the four radii of thermocouples has its own wiring distribution box. All pairs of shielded thermocouple wires from a given radius come all the way back to the corresponding box. Inside they are geometrically configured into differential pairs. Once the initial diagnostic period of the thermal system is finished -- and we no longer need a large quan-

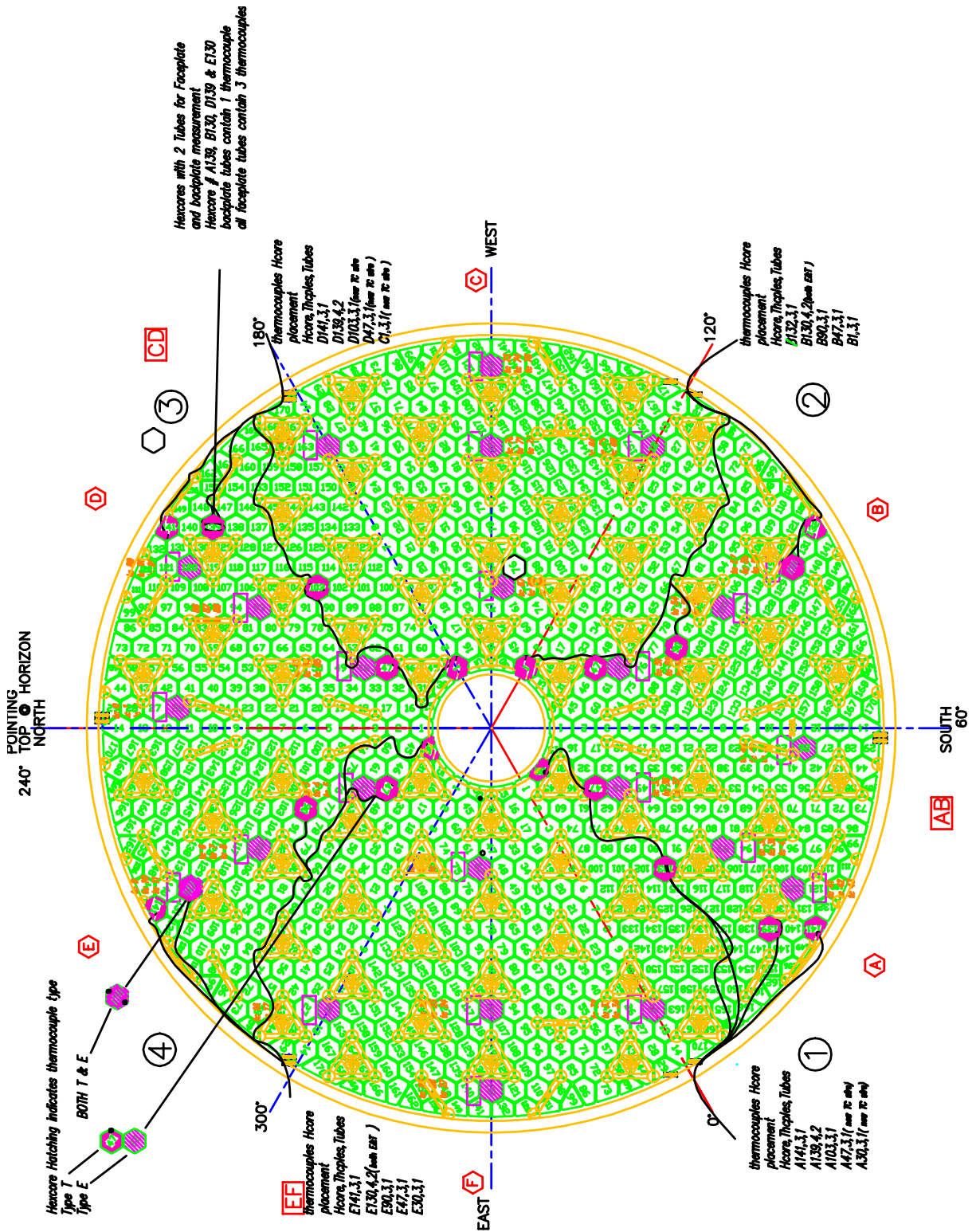


FIGURE 5. Backplate view showing the location of the thermocouples of the original (loose hatch) and new (fine hatch) temperature measurement systems. The drawing is mmt0775.dwg in the archive.

tity of spatial information -- some of the junctions will be wired between distribution boxes into thermopiles. For example, all 4 of the backplate - faceplate thermocouples will be wired into a pile yielding a single high-signal channel of the average bimetallic bending of the blank. Similarly, the ambient pair from each radius will be wired into a pile for the thermal servo.

After consultation with Magellan, we decided to adopt the Hewlett-Packard 34970A Data Acquisition Unit with three 20-channel HP 34901A armature switching boards (Figure 7).



FIGURE 7. Thermocouple measurement electronics consisting of an HP 34970A data acquisition unit (lower) and HP 34901A armature MUX.

Although these MUX boards have integral compensated cold junctions, they are not required for this application. Tests at Magellan have shown that this system is capable of 0.01 C accuracy ($\sim 0.4 \mu V$) using the differential voltage mode and the wiring geometries shown in Figure 1.

3.0 References and Acknowledgments

1. Larry W. Goble 1991, "Temperature control of the 3.5-meter WIYN telescope primary mirror" *Proc. S.P.I.E.* **1532**, p161.
2. M Lloyd-Hart, 1990 "System for temperature sensing and thermal control of borosilicate honeycomb mirrors during polishing and testing," *Proc. S.P.I.E.* **1236**, p844-853.
3. Thomas D. McGee, Principles and methods of temperature measurement, Wiley-Interscience 1988.

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thermocouples, Dave Carr (Magellan) for sharing the results of their testing of the HP data acquisition unit, and Buddy Martin for helpful advice.



FIGURE 8. Team thermocouple next to the 6.5m transportation box: Pete Spencer (left), Shawn Callahan, and Steve West