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Precision Thermal Control of the GMT-Consortium Large Earth Finder (G-CLEF)

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ABSTRACT

The GMT-Consortium Large Earth Finder (G-CLEF) will be part of the first generation instrumentation suite for the Giant Magellan Telescope (GMT). G-CLEF will be a general purpose optical passband echelle spectrograph with a precision radial velocity (PRV) capability of 10 cm/sec, a requirement necessary for the detection of Earth analogues. The instrument will be particularly sensitive to thermal effects and the necessary stability cannot be achieved through the use of low CTE materials alone. It is the combination of low CTE materials and exquisite thermal control which will enable the instrument to achieve its precision requirements.

G-CLEF will complete its Critical Design phase in mid-2018. In this paper, we discuss the precision thermal control systems which enable milli-Kelvin-level stability of the spectrograph and its red and blue focal planes. The measurement electronics and thermal control strategies used in the spectrograph are described. Of particular importance is the development of a continuous LN2 flow cryo-cooler system used to maintain the focal planes at stable cryogenic operational temperatures. This system has been validated with a prototyping effort completed during the instrument's design phase. We also review G-CLEF's insulated enclosure which simultaneously maintains the spectrograph a stable temperature and limits the maximum thermal leakage into the telescope dome.

This work has been supported by the GMTO Corporation, a non-profit organization operated on behalf of an international consortium of universities and institutions: Arizona State University, Astronomy Australia Ltd, the Australian National University, the Carnegie Institution for Science, Harvard University, the Korea Astronomy and Space Science Institute, the São Paulo Research Foundation, the Smithsonian Institution, the University of Texas at Austin, Texas A&M University, the University of Arizona, and the University of Chicago.

Keywords: Echelle spectrograph, precision radial velocity, G-CLEF, GMT, precision thermal control

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1. INTRODUCTION

The GMT-Consortium Large Earth Finder (G-CLEF) is a fiber fed, optical echelle spectrograph that is being designed as a first light instrument for the Giant Magellan Telescope (GMT). G-CLEF is being designed with a Precision Radial Velocity (PRV) capability with the requirement to detect stellar reflex motion down to 10 cm/s. A key contributor to G-CLEF's ability to achieve state of the art performance is thermal stability of the optics, metering bench structure, and focal plane. Our derived technical requirement is to provide daily thermal stability of the optics to the order of +/- .001 K/day with long term stability of +/- .010 K for the system while exposed to ambient temperature variations within the GMT telescope enclosure. In addition, the focal plane must be maintained at 153 K (-120 C) at a stability sufficient for PRV accuracy of 10 cm/s. These are significant technical challenges and design risks. The goal is to retire these risks through a combination of thermal design, analysis, and risk reduction activities by our Critical Design Review in mid-2018.

2. G-CLEF INSTRUMENT THERMAL DESIGN

The optical system is highly sensitive to relative motion of the optics caused by even minute changes in temperature. In order to achieve our measurement accuracy goal of 10 cm/s, we have allotted 10 Angstroms of image motion at the detector (IMAD) due to temperature variation of the spectrograph, mainly in the form of thermal soaks and gradients. Thermal instability affects the spectrograph in 2 ways. First, it can cause deformation, growth, and/or bending of the bench. Second, thermal variation at the cryogenically controlled focal plane can directly displace the CCD.

2.1 Instrument Stability Requirements – The Need for Precision Control

Even with a bench constructed of a traditional low-CTE material like Invar 36, temperature control of ± 0.001 °C is insufficient to meet our image motion allocation. The image motion breakdown for 3 different bench materials was examined.

When exposed to thermal soaks, and gradients of .001°K, IMAD for different materials is:

- Mild steel bench with optical mounts = 632 Å (316 cm/s) – **63X budget allocation**
- Invar bench with Invar optical mounts = 64 Å (32 cm/s) – **6X budget allocation**
- Carbon fiber bench with Invar optical mounts = 6.5 Å (3.25 cm/s) – **Within budget allocation of 10 Å**

Therefore, for performance reasons, carbon fiber is our material of choice for G-CLEF's optical bench.

2.2 Control of the Bench – The "Onion" Approach

The thermal control strategy is shown schematically in Figure 1. Over 40 aluminum panels with an array of Kapton strip heaters and a layer of insulation surround the vacuum chamber. A typical heater panel is ~1 meter square and all panels are supported on an aluminum and G10 skeleton framework as shown in Figure 2. These panels are controlled to 20 +/- .01 deg C. In addition, guard heaters at the support feet and feed throughs control conductive parasitic losses. A liquid-cooled HVAC system controls the air within the enclosure to a slightly cooler temperature of 17.5 deg C to allow controlled biasing. This approach has been prototyped on a 1/5th scale model and we have demonstrated our target stability of +/- .001 deg C for greater than day-long intervals.

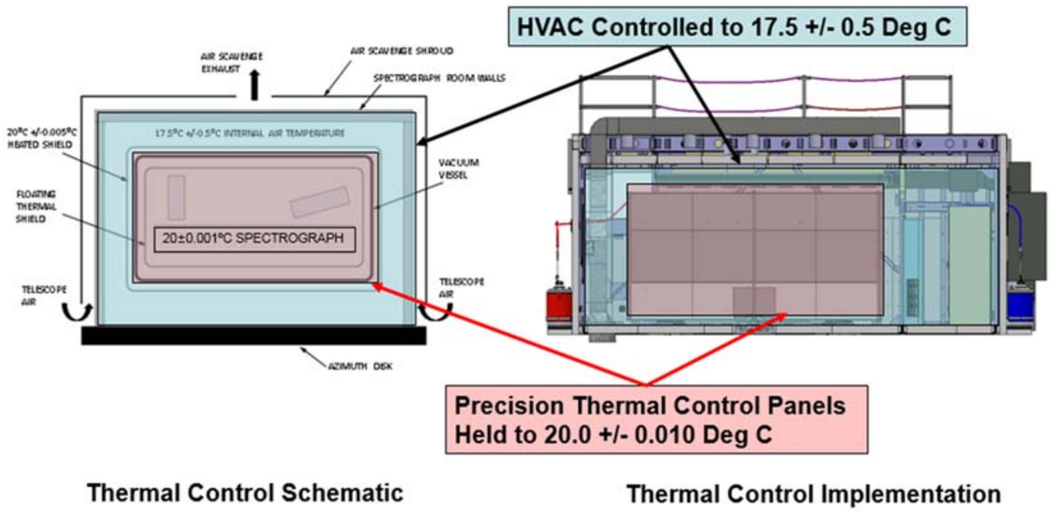

Figure 1 – Spectrograph Thermal Control Strategy

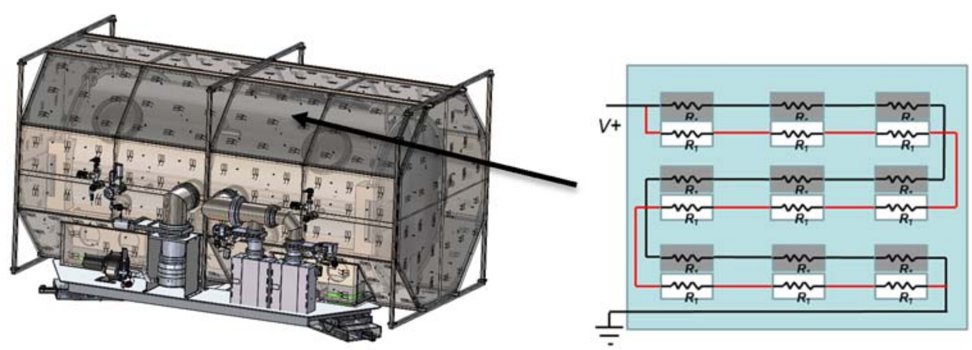

Figure 2 – Thermal Panel Assembly (Left) with a Schematic of a Typical Heater Panel (Right)

2.3 *Continuous Flow Cryo-Coolers for CCD Thermal Control*

We have implemented a Janis SuperTran[6] continuous flow cryostat (shown in Figure 3) to cool our focal planes (shown in Figure 4). The primary advantage of a continuous flow system is that the dewar and its associated variable volume of LN2, can be located farther from the CCD and bench, therefore, any thermal drifts associated with a changing volume of LN2 or from variations in atmospheric pressure occur farther away from the focal plane. It also allows the supply dewars for the system to be located outside of G-CLEF's thermal enclosure. We have developed a novel fill system which allows the dewar to be quickly filled with minimal disruption of LN2 flow to the focal plane. This minimizes the thermal disruption caused by LN2 fills which would otherwise adversely affect focal plane and bench stability.

Figure 3 – Janis SuperTran™ Continuous Flow Cryostat

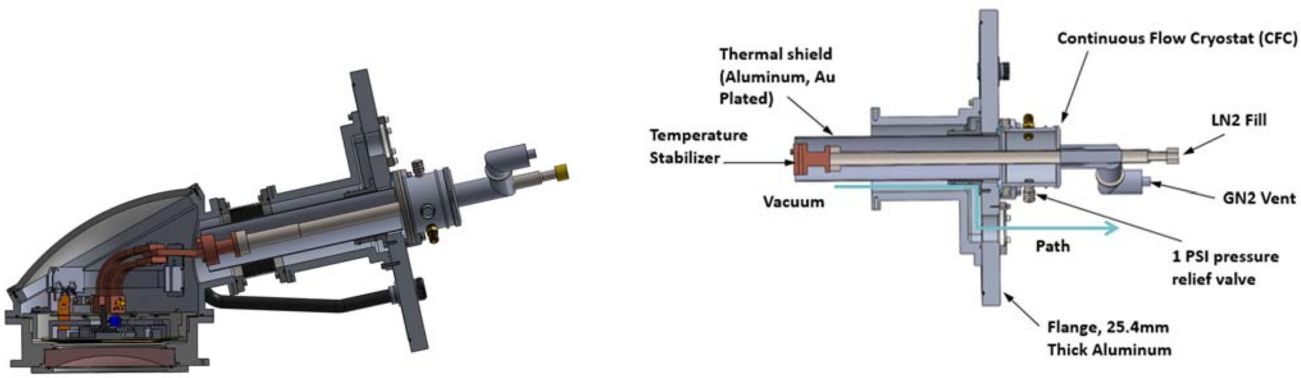

Figure 4 – Continuous Flow Cryostat (CFC) Connected to Focal Plane

2.4 HVAC System

A commercial air handler system from Johnson Controls is used to control the temperature of air within the thermal enclosure to a target temperature of 17.5 deg C. The unit selected is liquid-cooled (water/glycol mixture) using telescope-supplied coolant. This method was chosen over a traditional refrigerant based system to avoid both the heat rejection and mechanical vibration associated with a refrigerant cooling loop at the point of use.

2.5 Air-Scavenge System

GMTO has imposed a thermal emission limit on heat allowed into the telescope dome of 5 Watts/square meter or ~ 580 Watts. Analysis has shown that with a completely passively insulated system, G-CLEF could violate this limit on the coldest days (temps below 5 deg C). We mitigate this by "vacuuming away" the thermal plume using an air-scavenge system.

3. Thermal Analysis

Several thermal desktop models were created to determine steady state power requirements as well as predicted motion at the focal plane.

3.1 Heater Panels

A simple models of the heater panels (Figure 5) were created to help us optimize heater number, sizing, and placement, as well as panel and insulation thickness.

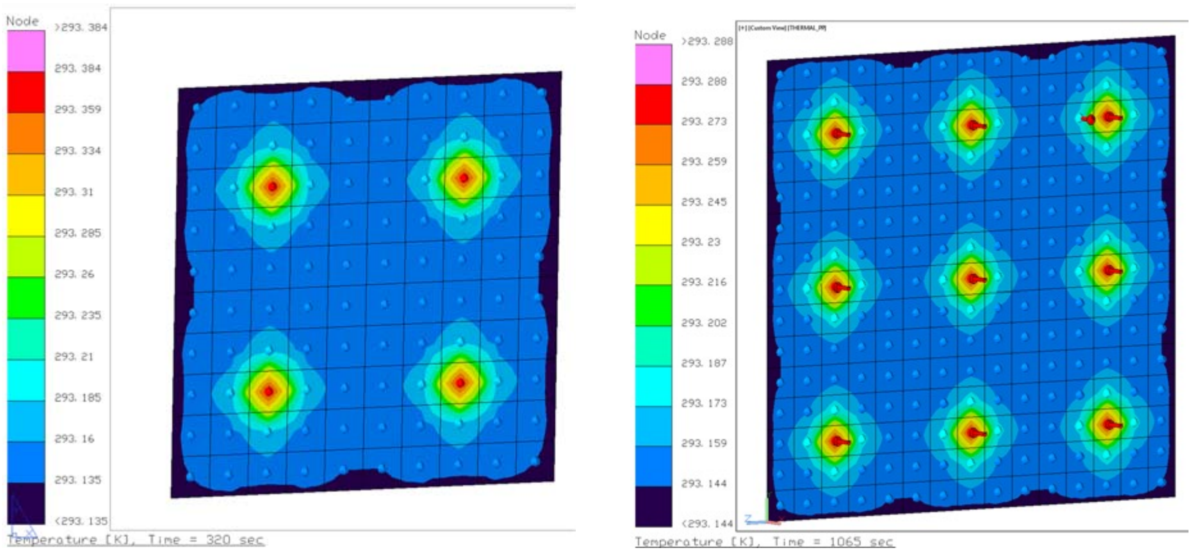

Figure 5 – 4 and 9 Heater Panel Analytical Models

Foam insulation over the outside of each panel enhances temperature uniformity across the panel. We chose a 1/8" panel aluminum thickness as it offered the best balance between temperature uniformity, weight, and cost. 9 heaters vs. 4 was chosen for greater temperature uniformity. Minco 75mm X 75mm Kapton heaters (44.4 ohms each) are used (9 in series). Predicted steady state power consumption is ~2 Watts per panel.

3.2 Focal Plane

A thermal/structural model of the focal plane was also constructed to examine the expected change in temperature of the focal plane due to 2 different power states of the CCD; integration and read-out. The model is shown in Figure 6.

Temperature profiles of the 2 operational states (at steady state) were mapped onto the structural model and CCD motion at the detector in the dispersion direction was obtained. It was found to be 8 Angstroms (see Figure 7), which is below our 28 Angstrom requirement with significant margin. In addition, we determined that, in actual observations, the CCD would likely never traverse the entire temperature extreme from one steady state condition to another. More typically an observation would be ~1/10th of this change. Therefore, this motion prediction is very conservative.

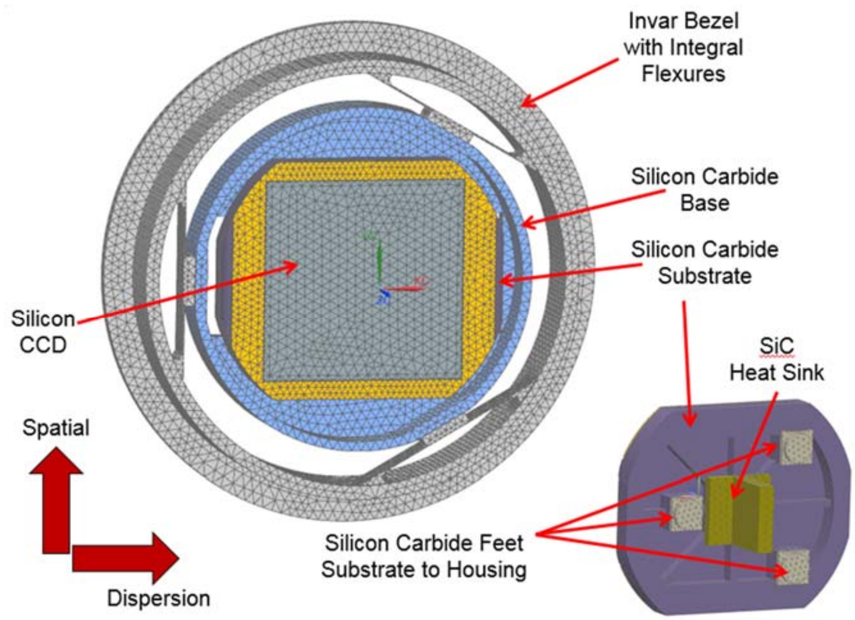

Figure 6 – Thermal/Structural Model of the Focal Plane

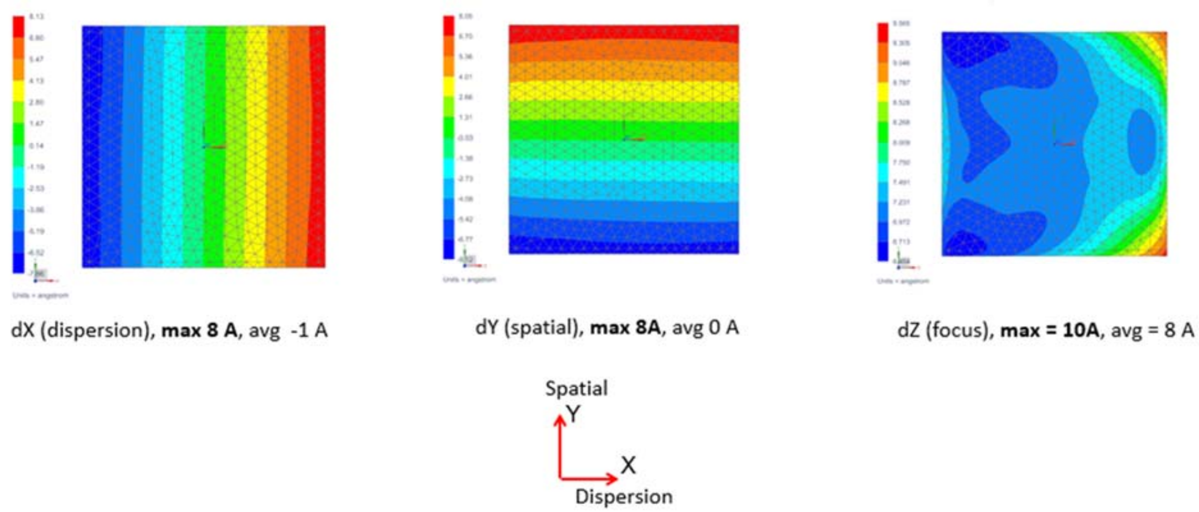

Figure 7 – CCD Displacement Results from Structural Model Using Temperature Mapping from Thermal Analysis

3.3 Penetrations

The G-CLEF vacuum enclosure is surrounded by a thermally controlled ”box” to provide a stable 20 deg C environment. Penetrations from outside of the thermal panel assembly (in HVAC controlled air at 17.5 deg C) are interruptions to the continuous nature of the control system and have to be “guarded” to preserve the 20 deg C surround. Vacuum penetrations are large (10-inch pipe). Thermal modeling was done to answer several questions, including; how much power would be required for the guard heaters at the transition between the 17.5C and 20C zones? The thermal model created for this analysis is shown in Figure 8.

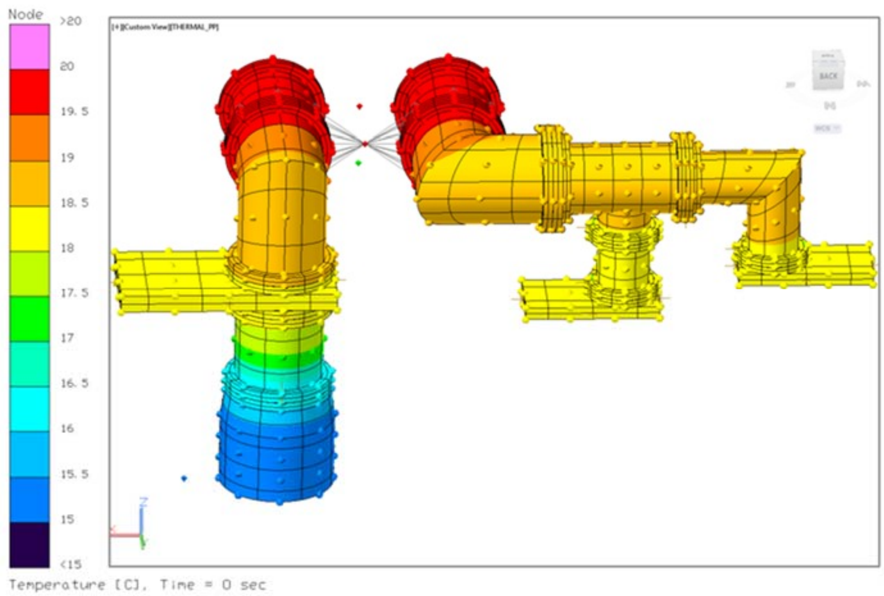

Figure 8 – Thermal Modeling of Vacuum Feedthroughs

Lessons learned from this analysis includes the following:

- Power required at the pipes to balance parasitic heat loss is ~ 1.7 Watts at each pipe. A manageable amount nearly equal to our heater panels.
- Temperature of the “view” into the pipes from inside the chamber is 19.51 to 19.65 deg C. A radiation shield should help any “view” of these pipe to the bench. An additional shield at the aperture could be added if necessary.
- No other issues seen and the other penetrations should be fine.

4. Risk Mitigation Activity

4.1 Phase I Testing

Using a 1/5th scaled prototype, with a nested control loop, we demonstrated that a realistic test mass within a vacuum chamber could be controlled to 0.25 milli-K/day stability levels. The test provided strong evidence that we can meet the 1 milli-K per day specification with the G-CLEF instrument.

This prototype also provided for development of control algorithms and testing of the control scheme(s), including the use of high-accuracy sensors on the control loop. We evaluated several implementations of heater control loops including; “bang-bang” control, PID on the heater panel and nested PID control. Best control was observed with a nested PID control loop.

The Phase 1 test hardware is shown in Figure 9 and test strip results are shown in Figure 10.

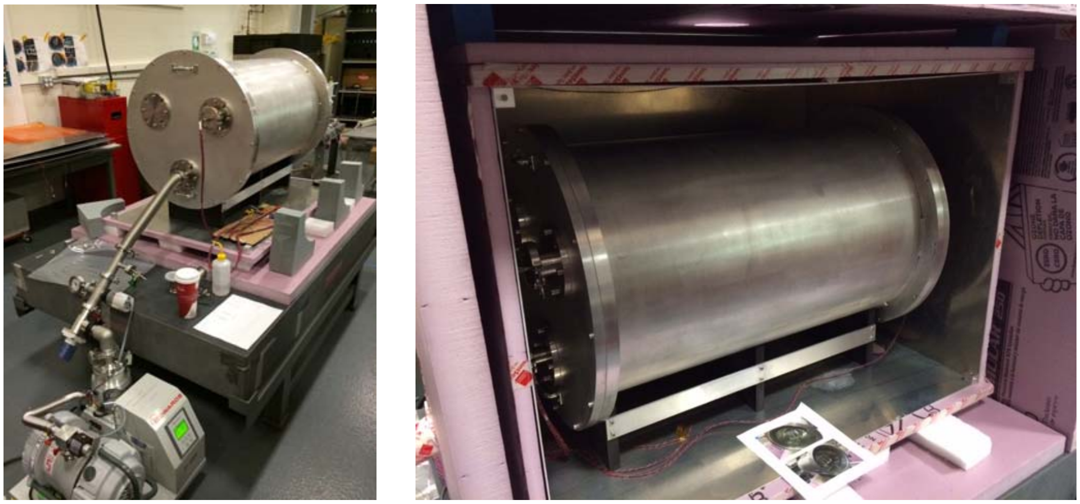

Figure 9 - The Phase 1 Test Hardware

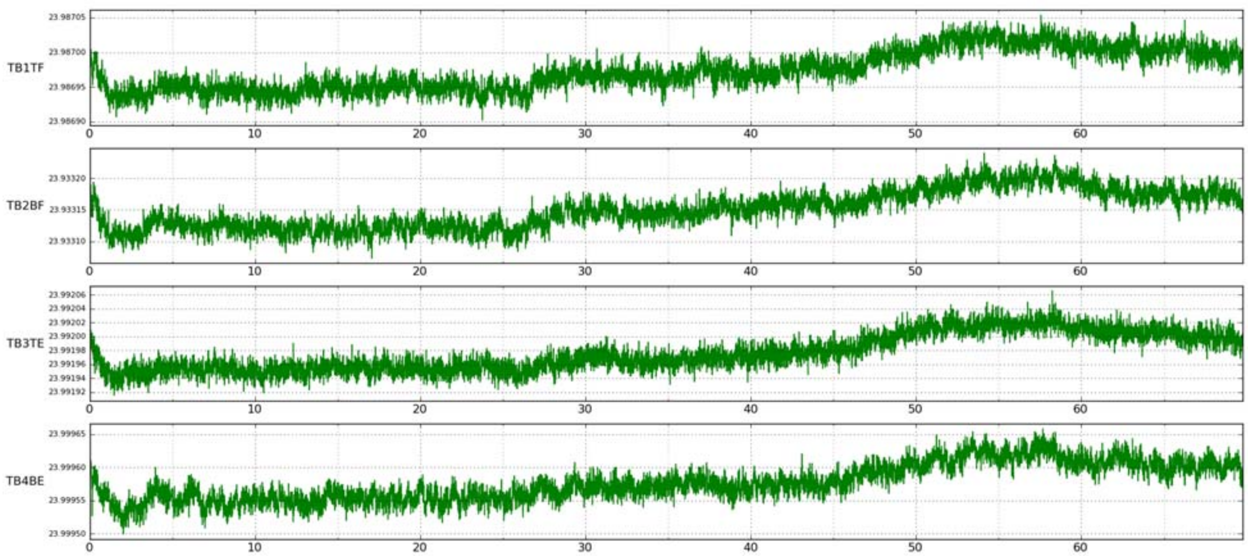

Figure 10 - Close up of data strip showing test mass control within a 0.15 milli-K band for 70 hours. Ambient temperature varied approximately +/- 1ºC during this run. X-axis is hours, Y is ºC.

4.2 Lessons Learned from Phase 1 Testing

- We have demonstrated that with Isotech[5] electronics, temperature can reliably be measured down to about 50 micro-K (the measurement noise floor).
- With a nested control loop we have demonstrated that a less than ideal system (known parasitic losses due to conduction were still present) could be controlled to better than 0.25 milli-K-per-day stability levels. With refinement, we believe that stability levels much better than this are feasible.
- The system validated our measurement system selections and control algorithms, and provided useful data on the heat loads for the insulated panels and important information

for establishing temperature, power, and insulation requirements for the G-CLEF instrument.

- Control of parasitic losses must be addressed on the full sized instrument. Well engineered solutions to control conduction through mounting feet and vacuum hoses are a must.
- This scaled system appears to be tolerant of bias temperature (ambient) variation in excess of 2ºC. This sets the control range of the AC system which controls the layer of air surrounding the heater panels on the full sized instrument.

4.3 Phase II Testing

In Phase 2 of this risk reduction activity, we have incorporated a Janis SuperTran[6] continuous flow cryostat to cool a CCD simulation mass adjacent to our test mass. We sought to demonstrate 1 milli-K per day stability for the bench while simultaneously achieving CCD thermal stability sufficient for extreme PRV. The cold finger hardware is shown in Figure 11.

With the set-up described above, we have demonstrated long-term bench stability of better than .001K/day for the bench and focal plane thermal stability of +/- .004K. This level has been shown through analysis as sufficient to meet our PRV requirement.

The prototype also enabled development of nested thermal control algorithms for the bench, systems enabling precision LN_2 flow control to the CFC, and systems and procedures for rapid refill of the LN_2 supply dewars.

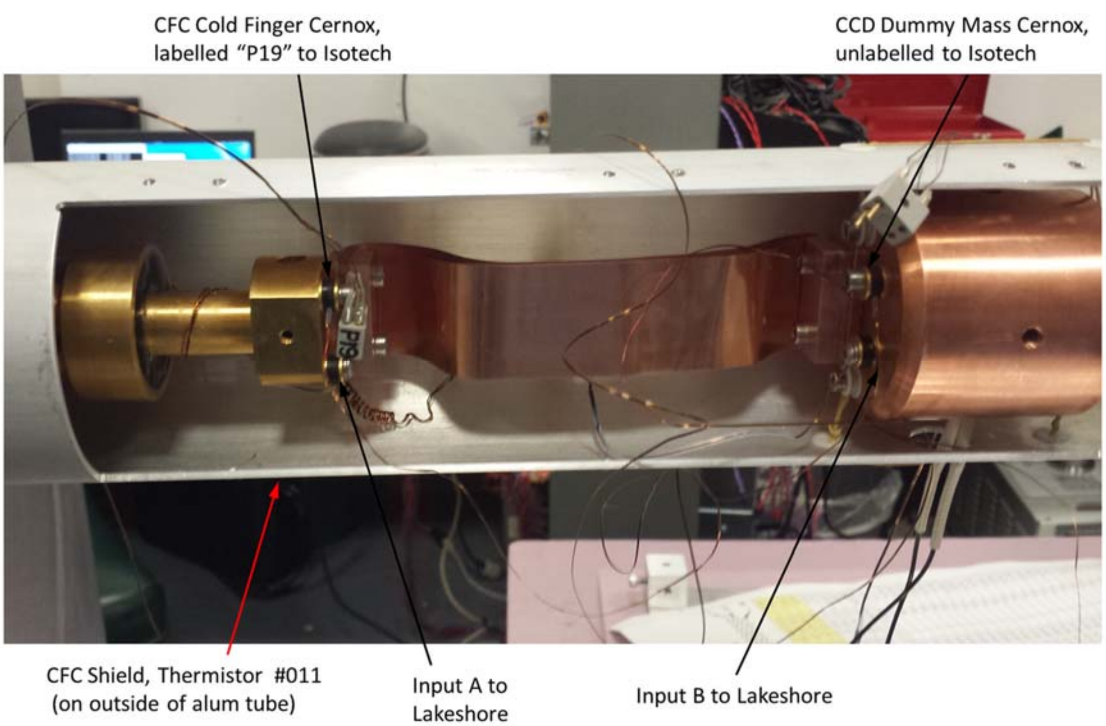

Figure 11 – CFC Cold Finger and CCD Dummy Mass Test Set-Up

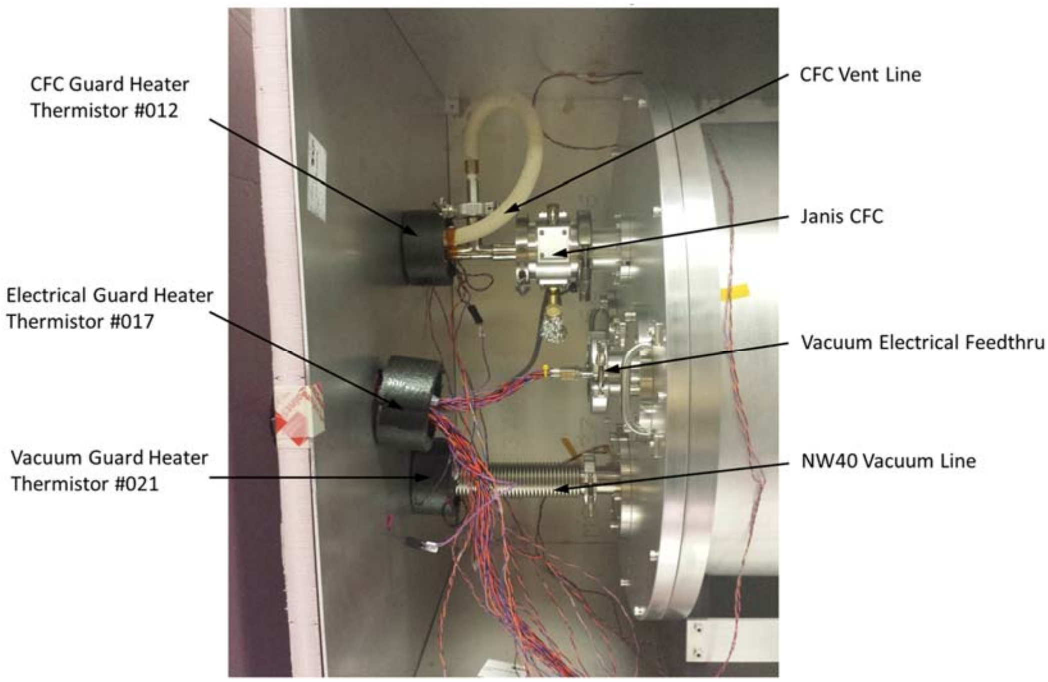

Figure 12 – Penetrations and Guard Heaters

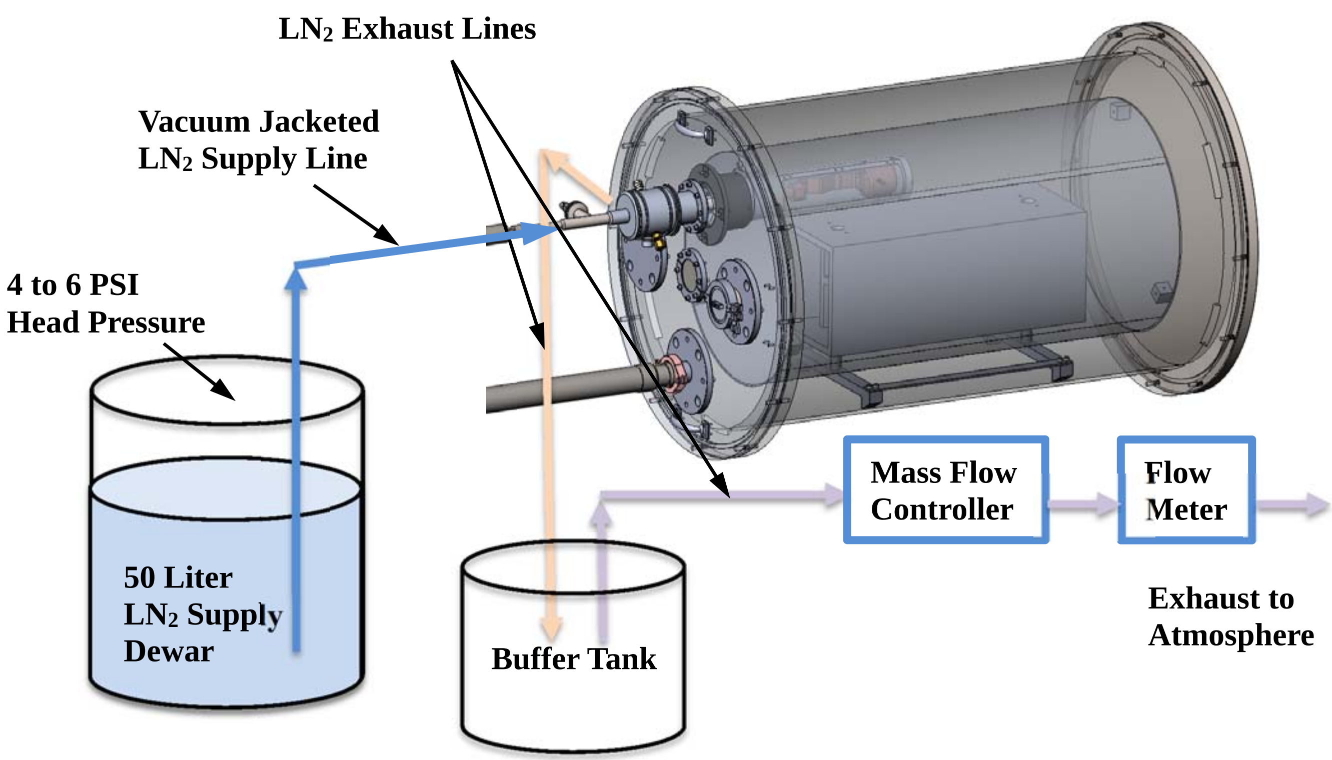

Figure 13 – LN_2 Flow Control Schematic

For phase 2, once we ironed out all of the hardware and software bugs, we were able to log some impressive long term stability runs.

Figure 14 shows a 160 hour period (6.7 days) where the bench was stable to better than a .001K band (between 20.4975 and 20.4985 ^{0}C). Ambient temperature within our lab varied over this period by ~2°C from a high of 20.5°C to a low of 18.5°C.

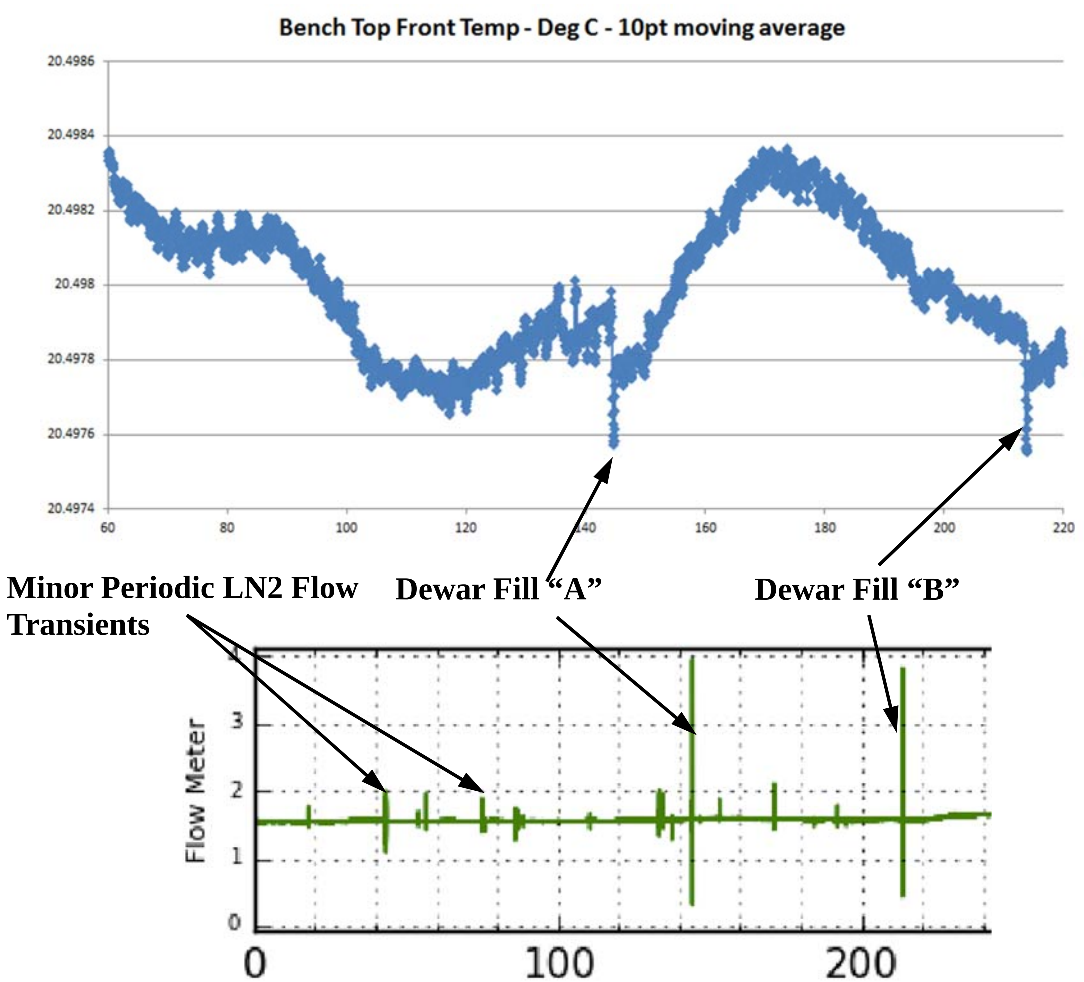

Figure 14 – Bench held within a .001 K band for 160 hours (6.7 days). X-axis for both panels is “hours”, Y is “ºC” for upper panel and “lpm gas” for lower panel. Ambient varied by ~2°C (18.5°C to 20.5°C).

During this particular period, we happened to fill the dewar twice (as shown in Figure 14) which caused two very short term perturbations in the bench. They were short in duration and did not cause the bench to go out of its stability range.

Figure 15 shows what is happening at the CCD over this period.

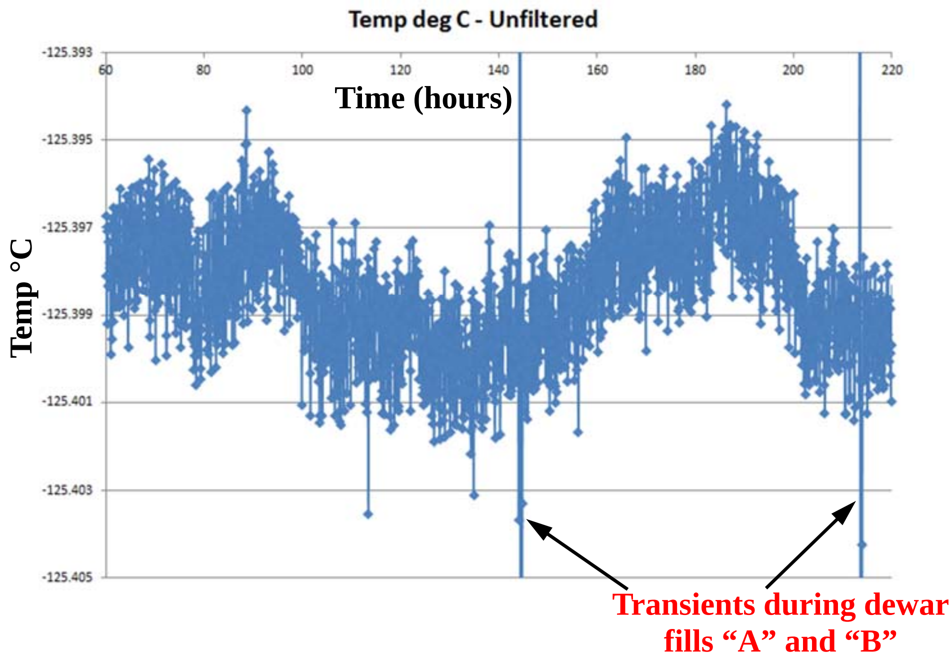

Figure 15 – CCD Simulator Temp – Unfiltered data from Isotech 125

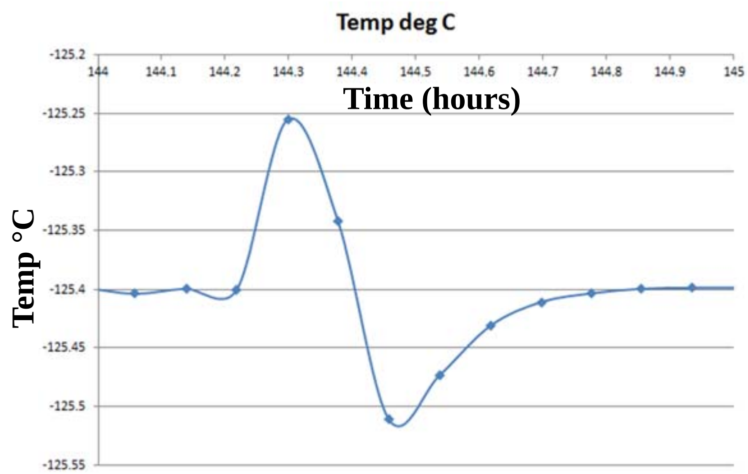

Figure 16 – CCD Simulator after fill event "A" – Temperature recovery in ~1/2 hour

During this test we demonstrated our ability to control the focal plane cold plate to +/- .004 ^{0}C which has been shown through analysis to be sufficient to meet our PRV requirement.

5. CONCLUSIONS

With our risk mitigation activity, we have demonstrated long-term bench stability of better than .001K/day for extended periods and focal plane thermal stability of +/- .004K. This stability has been shown through analysis as sufficient to meet our PRV requirement.

We developed nested thermal control algorithms for the bench, systems enabling precision LN_2 flow control to the CFC, and systems and procedures for rapid refill of the LN_2 supply dewars.

Additional conclusions and lessons learned include:

- Adding a mass flow controller minimizes LN_2 flowrate drift and improves CCD set point accuracy.
- The flow controller also allows consistent flow before and after dewar refills.
- A buffer tank between the CFC exhaust and the flow controller is required for the mass flow controller to function properly.
- Guard heaters are necessary and can be improved with better coupling of the heaters to the vacuum and CFC lines.
- We can control the focal plane cold plate to +/- .004 ^{0}C which has been shown through analysis to be sufficient to meet our PRV requirement.
- There is a transient in focal plane temperature following LN_2 dewar refills – temperature recovers in ~1/2 hour. Since fills are scheduled events, we can perform them with sufficient recovery time before a calibration or observation.
- Random flow rate spikes occur periodically but have minimal affect focal plane stability.
- Need to ensure adequate margin on primary heater amplifiers. Minimum 10X nominal power is planned for the G-CLEF instrument.
- In spite of reduced heater power margin on our test set-up, it was able to tolerate +/- 1.0°C temperature variations of the surrounding air.

Based on the results of our thermal analysis, design, and risk mitigation activities, we have retired most if not all major thermal technical risks associated with the G-CLEF design. This puts this portion of the project on track for a mid-2018 Critical Design Review and most improvements incorporated into the prototype will be implemented on G-CLEF.

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[5] Isotech North America is located at 158 Brentwood Drive, Unit 4 Colchester, VT 05446
[6] SuperTran™ is a product of Janis Research Company, 225 Wildwood Avenue, Woburn, MA 01801-2025 USA