The Opto-Mechanical Design of the GMT-Consortium Large Earth Finder (G-CLEF)

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ABSTRACT

The GMT-Consortium Large Earth Finder (G-CLEF) is a fiber fed, optical echelle spectrograph that has been selected as a first light instrument for the Giant Magellan Telescope (GMT) currently under construction at the Las Campanas Observatory in Chile's Atacama desert region. We designed G-CLEF as a general-purpose echelle spectrograph with precision radial velocity (PRV) capability used for exoplanet detection. The radial velocity (RV) precision goal of G-CLEF is 10 cm/sec, necessary for detection of Earth-sized planets orbiting stars like our Sun in the habitable zone. This goal imposes challenging stability requirements on the optical mounts and the overall spectrograph support structures. Stability in instruments of this type is typically affected by changes in temperature, orientation, and air pressure as well as vibrations caused by telescope tracking. For these reasons, we have chosen to enclose G-CLEF's spectrograph in a thermally insulated, vibration isolated vacuum chamber and place it at a gravity invariant location on GMT's azimuth platform. Additional design constraints posed by the GMT telescope include: a limited space envelope, a thermal emission ceiling, and a maximum weight allowance. Other factors, such as manufacturability, serviceability, available technology and budget are also significant design drivers. All of the previously listed considerations must be managed while ensuring that performance requirements are achieved.

In this paper, we discuss the design of G-CLEF's optical mounts and support structures including technical choices made to minimize the system's sensitivity to thermal gradients. A more general treatment of the properties of G-CLEF can be found elsewhere in these proceedings[1]. We discuss the design of the vacuum chamber which houses the irregularly shaped optical bench and optics while conforming to a challenging space envelope on GMT's azimuth platform. We also discuss the design of G-CLEF's insulated enclosure and thermal control systems which maintain the spectrograph at milli-Kelvin level stability while simultaneously limiting the maximum thermal emission into the telescope dome environment. Finally, we discuss G-CLEF's front-end assembly and fiber-feed system as well as other interface challenges presented by the telescope, enclosure and neighboring instrumentation.

Keywords: Echelle spectrograph, precision radial velocity, G-CLEF, GMT, optical mounts, vacuum chamber

1. INTRODUCTION

G-CLEF is the GMT-Consortium Large Earth Finder. It will be the first light science instrument on the GMT[2]. G-CLEF is an optical-band, fiber fed echelle spectrograph with a working passband of 3500Å-1µm. It is being built by a consortium of institutions consisting of the Harvard-Smithsonian Center for Astrophysics, Carnegie Observatories, Pontificia Universidad Catolica de Chile, the Korean Astronomy and Space Science Institute and the University of Chicago. G-CLEF is been optimized to have extreme precision radial velocity (PRV) detection capability needed to satisfy a critical science goal of measuring the mass of an earth-sized rocky exoplanet orbiting a solar-type star in that star's habitable zone . In order to maximize mechanical and thermal stability, it is vacuum enclosed and will be operated at a gravity invariant location on the GMT. The spectrograph features an asymmetric white pupil design[3] and has a 300

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mm diameter beam that is reduced to 200 mm after dispersion by the echelle grating. We are currently in the preliminary design phase. The Instrument Requirements Review was held in February and the Preliminary Design Review is scheduled for March 2015. Science operations are planned to begin in 2020.

The GMT is a 25.4 m diameter optical and infrared telescope that is being built in Las Campanas, Chile[4]. The telescope is built around a segmented primary mirror design composed of seven 8.4m diameter mirrors and will have a collecting area roughly three times larger than the largest single aperture telescopes in operation today.

G-CLEF combined with the GMT will be a powerful instrument for a broad range of investigations in stellar astrophysics, cosmology and astrophysics in general.

2. G-CLEF INSTRUMENT DESIGN

G-CLEF's opto-mechanical design is being developed in response to a requirements flow down from the GMT and G-CLEF scientific objectives[1]. These are broad statements of the science drivers for the GMT and G-CLEF. These Level 0 science drivers are quantified into Science and Operational requirements for the GMT and G-CLEF. The GMT overall System Level Requirements reside at Level 2, and the GMT major system (Telescope, Software, Adaptive Optics, Instrumentation and Operations) requirements are at Level 3. The GMT Level 3 Instrumentation requirements and the G-CLEF Science requirements flow down into the Level 4 G-CLEF Instrument Design Requirements[6].

2.1 G-CLEF Instrument and System Engineering Requirements

GMT Instrumentation Requirements and G-CLEF Science Requirements flow down into the G-CLEF Instrument System Design Requirements, which are defined at Level 4 in the GMT Requirements Management System. The resulting document is the G-CLEF System Requirements Specification, which captures the top level G-CLEF design requirements. Table **1** provides a summary of the major requirements for G-CLEF. The requirements reflect the multiple uses of G-CLEF for both PRV measurements and for more general high resolution visible band spectroscopy. To meet the multiple science objectives, G-CLEF must have a broad passband, high resolution, high throughput and a PRV capability. G-CLEF will support four different resolution modes, using two science cameras, one for the blue wavelengths and another for the red. The performance requirements are therefore specified as a function of mode, and the throughput as a function of both mode and wavelength.

Table 1- Summary of Primary G-CLEF Instrument Requirements

Requirement Title	Requirement Statement
Seeing Conditions	Meet requirements at GMT 75th percentile seeing, with a full width half maximum (FWHM) of 0.79 arc seconds
Optical Feed	Provide an Optical Feed which deploys into the telescope beam and relays light into the G-CLEF Fiber Feed System
Flexure and Defocus Detection	Provide an instrument flexure and defocus sensing system which measures flexure-induced telescope to instrument guide and focus offsets. Send these offsets to the GMT telescope Control System for correction
Instrument Passband	3500Å to 1μm simultaneous wavelength coverage
Measurement Modes and Spectral Resolution	Optically Scrambled Precision Radial Velocity mode (PRV) with Spectral Resolution = 100,000 (Pupil Sliced) High Throughput, non-scrambled PRV Mode (PRV-NS) with Spectral Resolution = 100,000 (Pupil Sliced) High Throughput (HT) Mode with Spectral Resolution = 20,000 Medium Throughput (MT) Mode with Spectral Resolution = 35,000

<table>
<tr><td>Instrument Throughput
(Includes all pre-optics and fiber run, excludes the telescope. Assumes 75% seeing or 0.79” and a Gaussian PSF)</td><td><table>
<tr><th>Wavelength(nm)</th><th>HT</th><th>MT</th><th>PRV</th><th>PRV-NS</th></tr>
<tr><td>350</td><td>5.2%</td><td>3.2%</td><td>3.0%</td><td>3.4%</td></tr>
<tr><td>500</td><td>12.7%</td><td>7.9%</td><td>7.5%</td><td>8.6%</td></tr>
<tr><td>700</td><td>12.9%</td><td>8.0%</td><td>7.6%</td><td>8.7%</td></tr>
<tr><td>800</td><td>12.0%</td><td>7.4%</td><td>7.1%</td><td>8.2%</td></tr>
<tr><td>1000</td><td>1.9%</td><td>1.2%</td><td>1.1%</td><td>1.2%</td></tr>
</table></td></tr>
<tr><td>Brightness Limit</td><td>Function with target brightness of M_R = 6 (or fainter)</td></tr>
<tr><td>Atmospheric Dispersion Compensation</td><td>Provide on-instrument atmospheric dispersion compensation</td></tr>
<tr><td>Operating Air Mass</td><td>Operate in all modes with air mass ≤ 2</td></tr>
<tr><td>PRV Measurement Precision</td><td>Capable of making single PRV measurements with a radial velocity precision of 40 – 50 cm/second with a goal of 10 cm/second.</td></tr>
</table>

2.2 G-CLEF Spectrograph Optical Design

The spectrograph optical layout is shown in figure 1. Emerging from the fiber feed and passing through a focal ratio converter, an f/8 beam follows the following optical path:

1. Reflected off an off-axis parabolic collimator
2. Reflected and dispersed from the Echelle grating
3. Reflected (2^{nd} pass) off the off-axis parabolic collimator and focused
4. Reflected off a cylindrical Mangin fold mirror
5. Reflected and collimated off an elliptical transfer mirror (M2)
6. Red wavelengths are transmitted, Blue reflected by a dichroic into separate Blue and Red camera systems
7. Each band passes through separate Blue or Red cross-dispersers
8. Each band passes separately through a 9 lens camera (Blue or Red)
9. Each band is imaged by a CCD (Blue or Red)

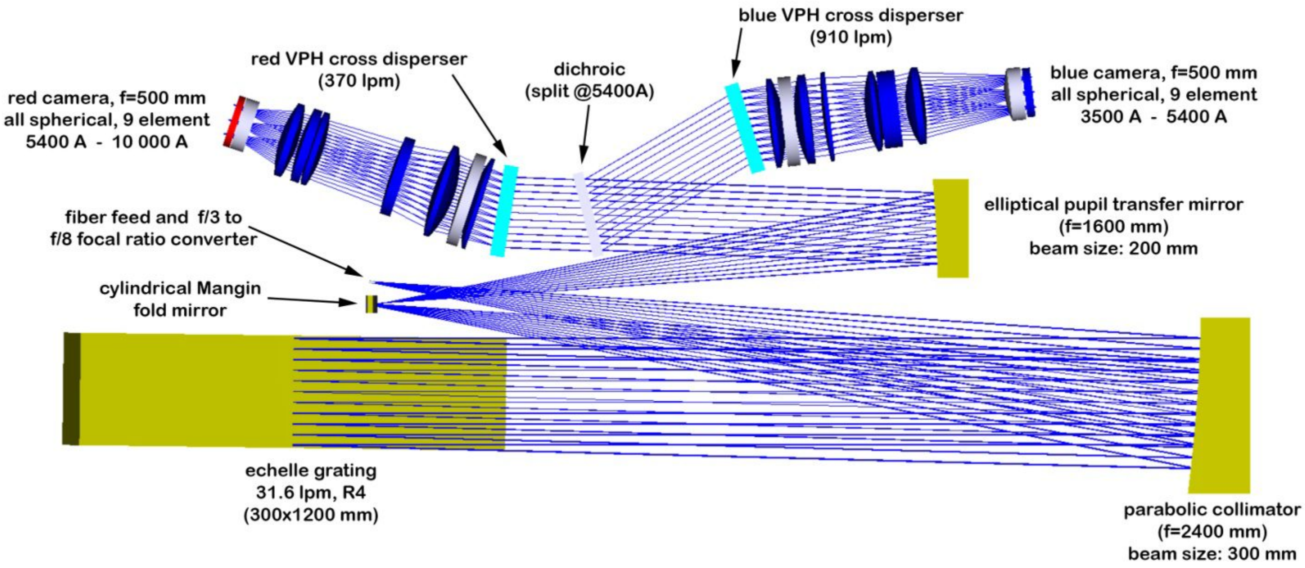

Figure 1 - Spectrograph Optical Layout

2.3 Major Instrument Subsystems

1. Front End System

The Front End subsystem layout is shown in figure 2. The function of the Front End is to extend into the telescope optical beam, pick-off a 1.5 arc minute field of view and relay it to the slit apertures which feed the fiber system. The Front End sits on top of the Gregorian Instrument Rotator which resides just below the primary mirror cells.

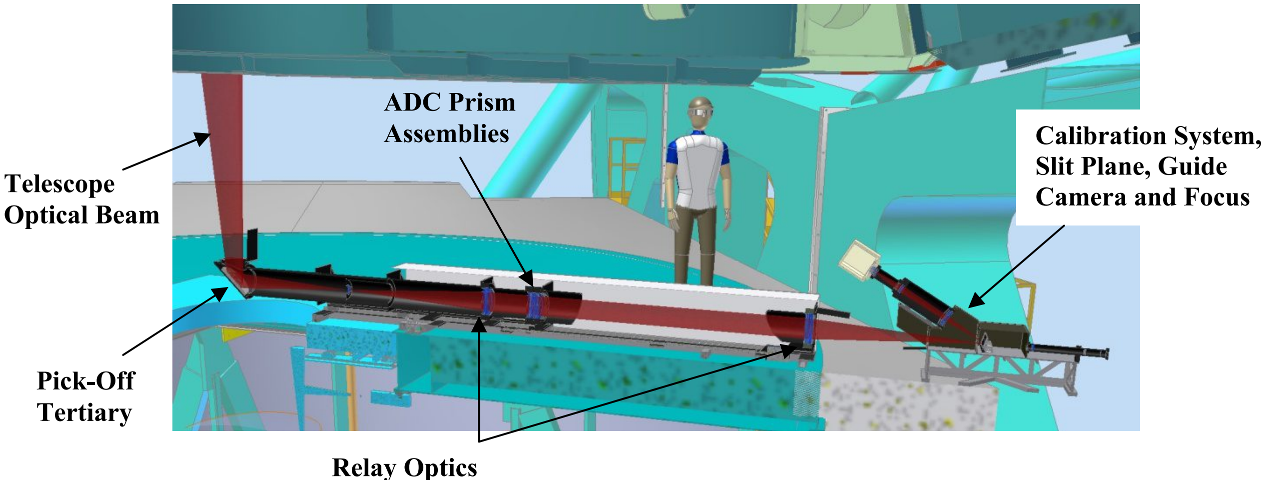

Figure 2 – Front End Assembly Mounted to Top of GMT's Gregorian Instrument Rotator

The Front End contains the following components:

a. Pick-off Tertiary Mirror with tip-tilt capability for flexure compensation
b. Relay Optics (Collimating and Focusing Triplets)
c. ADC Prism Assemblies
d. Calibration system
e. Slit plane and fiber/operational mode selector
f. Guide camera
g. Focus Sensor

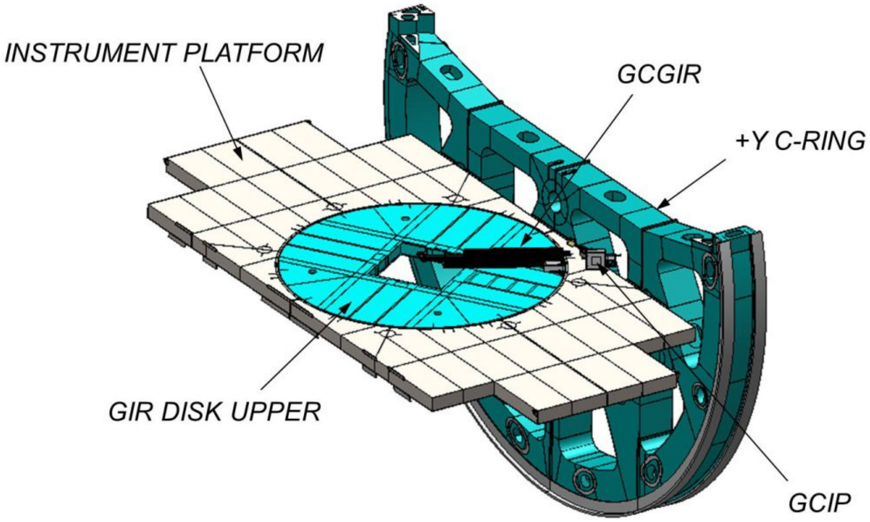

Figure 3 – Front End GIR and IP Portions

The Front End has been allocated a space on the upper portion of GMT’s Gregorian Instrument Rotator (GIR) and Instrument Platform (IP) as shown in figure 3. It shares space with other, yet to-be-defined instrumentation and therefore the front-end design team is working to an interface envelope with a weight budget.

2. Fiber System

The Fiber System includes the optical fibers and associated components which relay the light from the slit aperture into the spectrograph. The Fiber System is routed as shown in figure 4.

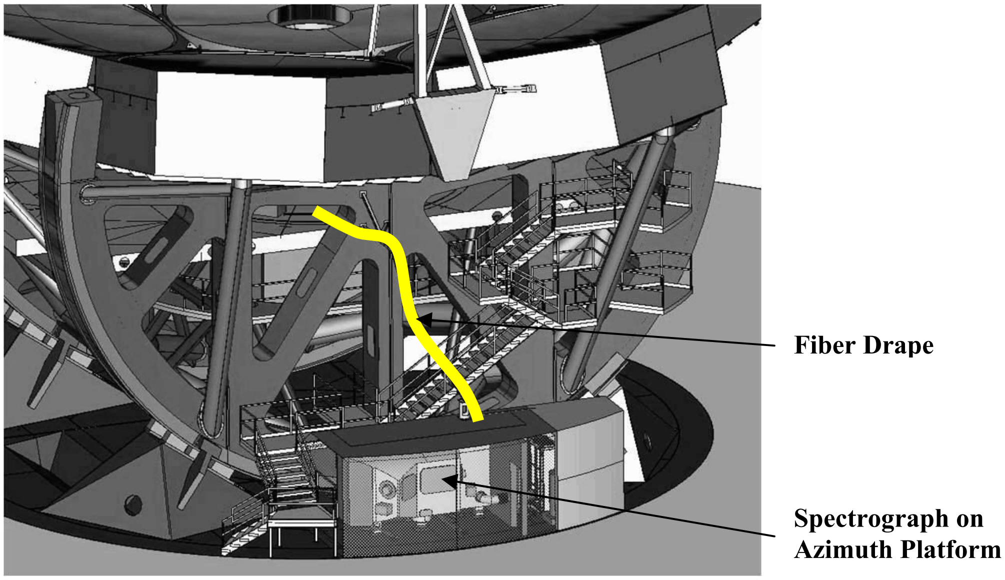

Figure 4 – Fiber Routing

3. Spectrograph

a. Optical system

The optical system shown previously in figure 1 is the heart of the spectrograph and is supported on an optical bench within a temperature controlled vacuum chamber. Because of G-CLEF’s challenging PRV requirement, environmental factors such as temperature, vibration and pressure variation must be controlled to a very high level of precision.

b. Optical Bench

The optical system is highly sensitive to relative motion of the optics caused by even minute changes in temperature. Our thermal requirement is to control the internals of the vacuum chamber (primarily the optical system and bench) to a target temperature (20 °C) ± 0.001 °C. Even with these small temperature changes, system modeling predicts that if the optical bench were constructed of a more traditional low-CTE material such as Invar, image motion at the detector would not allow us to achieve our PRV measurement goal of 10 cm/s. As a result, our baseline material choice for our metering bench is carbon-fiber cyanate composite. Carbon fiber composites are available with in-plane thermal expansion coefficients near zero (roughly an order of magnitude better than Invar). However, there are other considerations with composites that must be considered for our application. They include:

- Coefficient of Moisture Expansion (CME) – Composite structures are hygroscopic. After they are manufactured, these materials absorb ambient moisture and expand as a result. When installed in our vacuum chamber, this moisture will outgas and there will be a corresponding dimensional contraction which will occur over roughly a one-year timeframe.
- Temporal effects[7] – Composites experience a natural temporal shrinkage that decreases asymptotically over time. This effect is present in many materials, including Invar, at similar magnitudes and must be accounted for in order to meet our PRV requirement.

We conducted a CME analysis on our CoDR system model to determine the effect of hygroscopic deformation of the G-CLEF instrument. This study was conducted on two configurations. The first configuration assumed the entire instrument was to be constructed of composite material. The second configuration assumed composite material for the optical bench only with the optical mount structures constructed from Invar (having no CME effects). The dryout shrinkage was calculated from exposure to a 50% RH environment with a complete dryout over a one year timeframe. Figure 5 shows the deformed shape (grey = undeformed) for the first configuration. The deformation shows the characteristic uniform contraction from the composite material over the entire instrument. Figure 6 shows the deformed shape for the second configuration. The deformation shows “bimetallic strip”-type bending deformation resulting from the composite bench shrinking and the significant Invar optical mount structures not shrinking.

Results from these models were scaled to a one hour estimated observation period. Using *Bisense* software (developed from the Binospec instrument development), the resulting image motion at the detector over an observation period is shown in Table 1. The relatively high values (> 5 Å) for image motion at the detector suggest two design strategies: First, the composite structure of the instrument should be maintained in a dry state; and second, any Invar structure mounted to the optical bench should be flexured to reduce the “bimetallic strip” effect that would be present due to the material mismatch of CME or CTE. For reference, 20 Å of image motion roughly corresponds to our 10 cm/s PRV allowable measurement error.

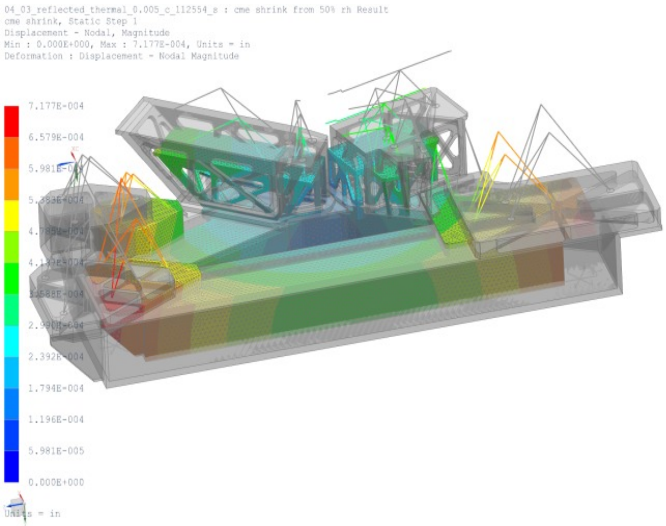

Figure 5. Entire Instrument Dryout

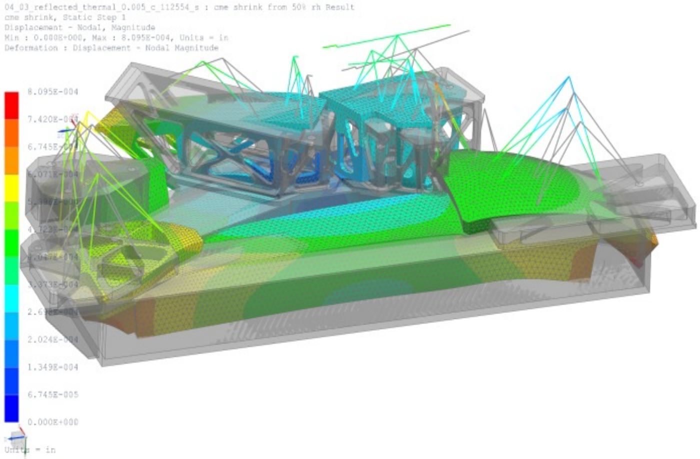

Figure 6. Bench Only Composite Dryout

Table 1. ***Bisense*** **Results for Dryout Stability During a Single Observation**

Load Case	**Motion at Detector, Angstrom**		
	Dispersion	Spatial	Focus
Configuration 1, Entire Instrument Dryout	3.2	-0.3	-9.7
Configuration 2, Bench Only Composite Dryout	-58.1	6.8	-2.3

The bench will be installed in a vacuum chamber for most of its life, therefore the CME effect will have diminished in the timeframe of integration and commissioning of the system. There are also mitigation techniques that can be implemented during shipment, storage and assembly of the bench (storage in humidity controlled environment or dry-nitrogen purge) that can minimize this effect. Relative to the length of a typical exposure, the temporal effects are predictable and small enough to be calibrated out during observation. The weight savings of a composite versus an Invar structure is several thousand pounds. Initial ROM quotations indicate that the cost delta is on the order of a 50% premium when compared to Invar. However, considering the weight and performance advantages of a composite structure, the cost premium is easily justified.

c. Vacuum chamber

The entire spectrograph optical train and optical bench are fully contained within a vacuum chamber. Housing the optics in a vacuum serves a dual purpose. First, in the presence of air, the optical design is sensitive to changes in the refractive nature of air with variations in pressure. This effect is largely eliminated with operation in a vacuum at levels of 4×10^{-4} Torr or lower. Second, vacuum eliminates convection as a mode of heat transfer inside of the vacuum vessel, enhancing our ability to achieve exquisite thermal stability.

Design considerations for the vacuum chamber include:

- Minimizing weight
- Structural rigidity, especially in the areas where the science camera's rear sections interface to the vacuum wall. Although the rear and front camera sections (housing the detectors) are decoupled via a flexible bellows, the bellows does have a stiffness coefficient and changes in vacuum wall displacement with normal atmospheric pressure fluctuations could influence the spectrograph.
- Maximizing access for installation of the bench and optics as well as subsequent adjustment/alignment of optical elements during integration.
- Minimizing o-ring linear seal length such that the chamber can maintain a minimum vacuum level of 4×10^{-4} Torr or lower through an entire observing night with the pumping system off.

Figure 7 shows a tubular vacuum chamber concept inside of the thermal enclosure.

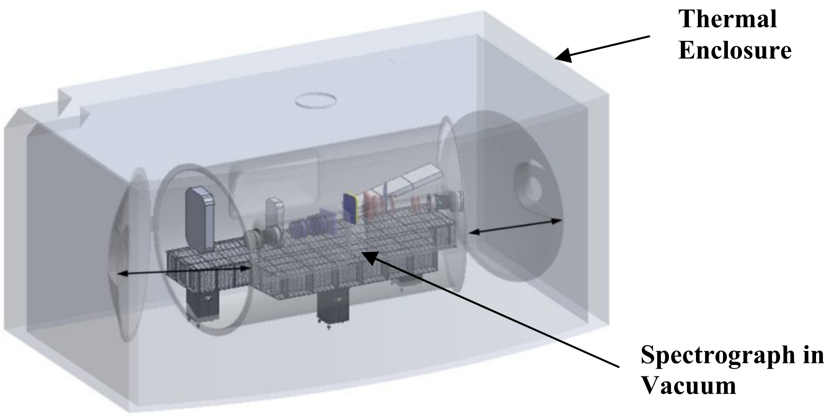

Figure 7 – Tubular Vacuum Chamber Concept (Shown Inside Thermal Enclosure)

d. Thermal control system

The performance goal of the thermal control system is to maintain the bench and all optics to a thermal stability of ± 0.001 °C for the operational life of the instrument. We selected a target temperature close to our expected lab assembly temperature of 20 °C. Accomplishing this by measuring the spectrograph internals directly and attempting to servo heaters to maintain a stable temperature would be very challenging. The mass of the bench and optics is significant and the time-constants large. Controlling the temperature by application of heat to the spectrograph internals would result in an unstable system with significant gradients, completely inadequate for our PRV measurement requirements. Instead, we selected a multi-layer approach as shown schematically in figure 8. The bench and optics reside within the vacuum chamber with an intermediate radiation shield between the bench and vacuum chamber wall. Surrounding the vacuum chamber are the thermal control panels; basically 3mm thick sheets of aluminum covered with Kapton strip heaters. The panels completely surround the vacuum chamber and themselves have a 25mm thick layer of insulation on the side opposite the vacuum chamber. This insulation layer serves to reduce the in-plane temperature gradients across the face of each control panel. The panels are held to 20 °C ± 0.005 °C with commercially available measurement and control hardware. Outside of the thermal control panels is a layer of conditioned air held at 17.5 °C ± 0.5 °C. This serves as a bias temperature ensuring that once steady state temperature is reached, all heat applied to the panels ultimately flows outward. Outside of the conditioned air is a layer of scavenged air drawn away via an additional surround (not shown) by the telescope air handling system into the GMT exhaust system. Its purpose is to ensure that the thermal emission into the GMT dome is minimized.

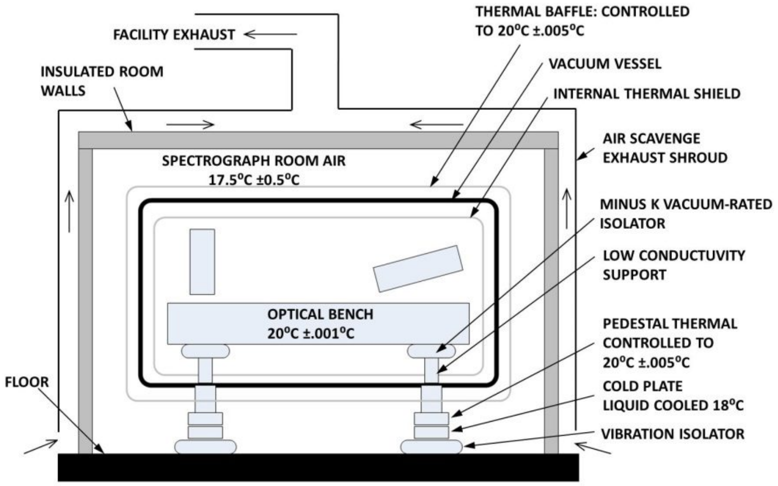

Figure 8 – Thermal Control Schematic

Conduction through the vacuum chamber support legs will be controlled in a like manner, by establishing a lower bias temperature and ensuring that heat flows outward only.

As part of our technology development effort, we are in the process of prototyping this thermal control approach using a small scale vacuum chamber 600mm in diameter X 900mm in length.

e. Optical Mounts

All G-CLEF mounts benefit from operating at a gravity invariant station, at an exquisitely stable temperature. Typically the most challenging load conditions for all mounts are for handling and shipment.

i. Camera Mounts

The baseline mounts will be bonded tangential flexures. We selected shipping conditions of 5G's and a temperature range of 5 °C to 25 °C as our survival load conditions. Our research indicates that international shipment options exist, both by sea and air, for which this is a typical controlled temperature range. Our task will be to design suitable shipment isolation to guarantee that expected maximum shipping loads are attenuated to no more than 5G's. Figure 9 shows the relationship between temperature and bonded-mount shock-load capacity for red camera Lens 3, one of our worst-case lenses. The highlighted area shows the target temperature range for shipment. As shown, for this lens we have additional margin to go colder than 5 °C and still maintain of 5G shock capability if needed.

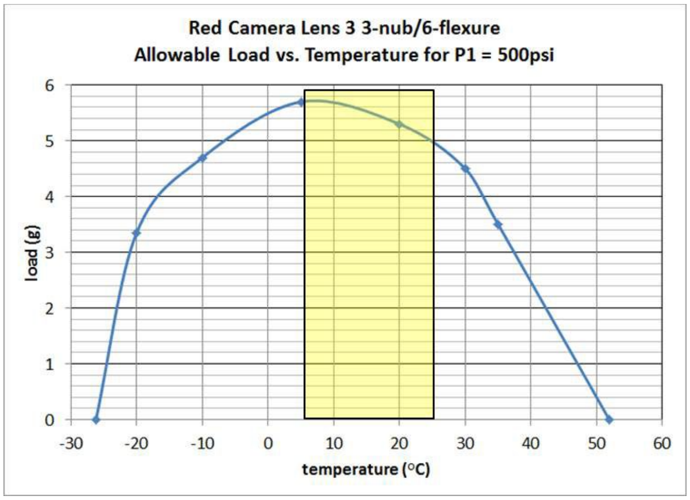

Figure 9 – Shock load capacity vs. shipping temperature for red camera lens 3.

Other mounting options considered were:

- RTV pads – These were rejected out of concerns over RTV's dimensional stability and outgassing properties over long periods of time in a vacuum environment.
- Three point mechanically preloaded mount – These mounts are simple and reversible but the glass is preloaded and the optical surface deformation will not meet performance requirements. In addition, both radial and axial preloading systems are required which complicates packaging of the closely mounted camera lenses.

The current red camera mount design is shown in figure 10 below.

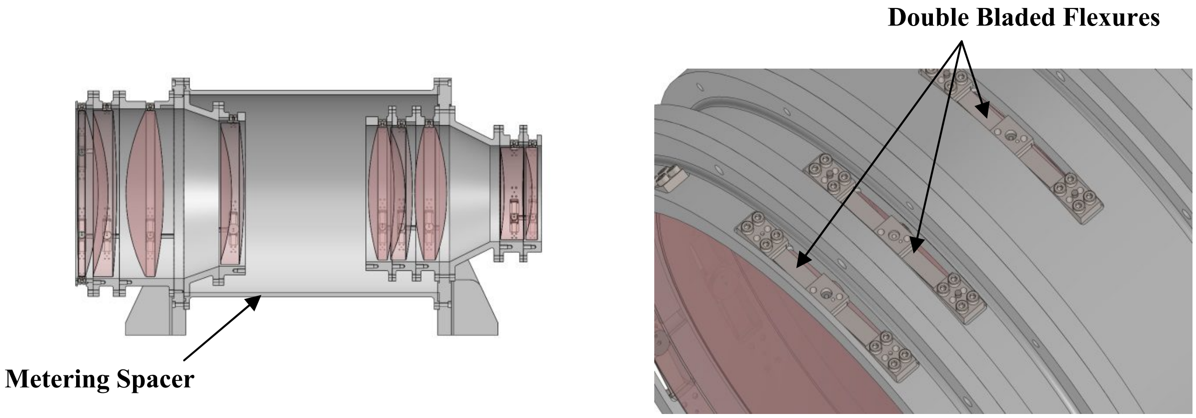

Figure 10 – Red Camera Assembly – Mounted Optics are Stacked in Groups

We will mount G-CLEF optics into their associated bezels using SAO's Opticentric™ lens mounting system. This system was developed and refined during mounting of the MMIRS and Binospec optics. It allows registration of an optic's optical centerline to the bezel's central axis. This eliminates the need to tightly control the relationship between an optic's optical centerline and its physical outer diameter. The system is shown in figure 11.

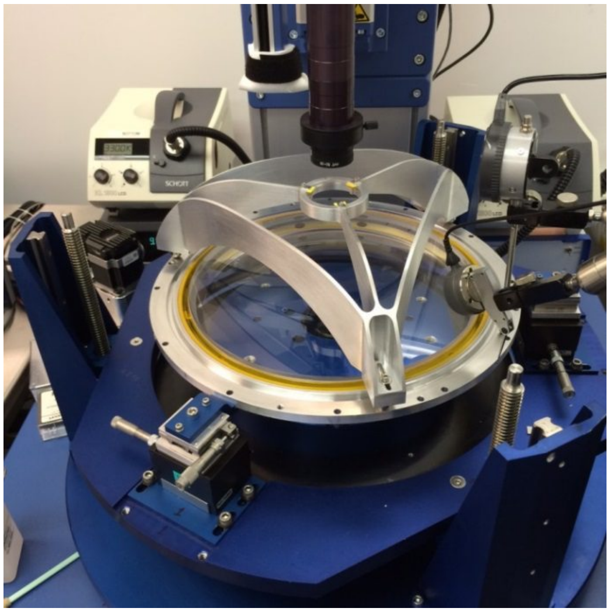

Figure 11 – Opticentric**™** System with Axial Positioning Target

ii. Grating Mosaic

The G-CLEF optical design features a grating mosaic of three 300mm X 400mm grating facets which must be mounted and aligned relative to one another to tight tolerance. Surfaces must be parallel to one another within approximately 1µm, and tip/tilt about axis' normal to the grating surface must also be aligned to less than 1µm across the length of each edge.

We are able to measure alignment of grating facets relative to one another using interferometers positioned at the angle of incidence and also normal to the grating surfaces as illustrated in figure 12.

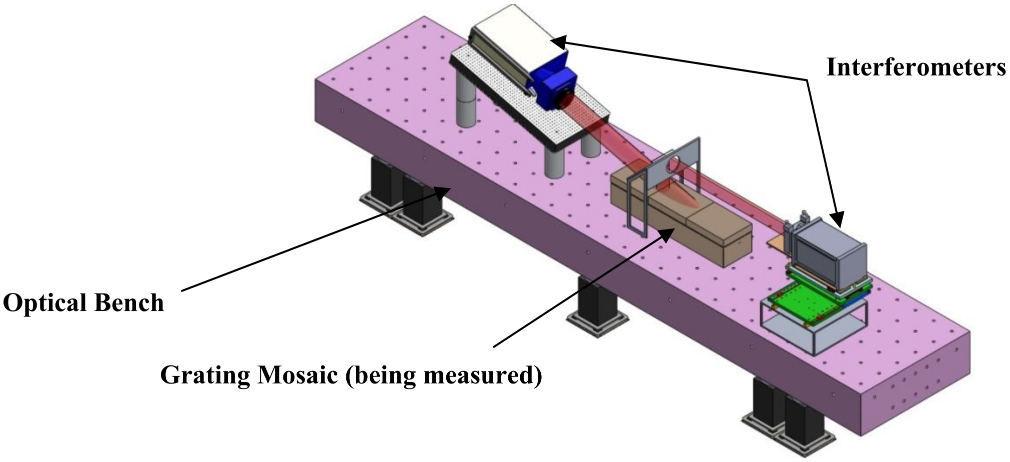

Figure 12 – Grating Alignment Scheme – Interferometer Metrology on Optical Bench

We are evaluating two concepts for mounting. The first is bonding the Zerodur facets to a large Zerodur substrate. This has the advantage of simplicity but the disadvantage of non-reversibility should the facets move out of alignment during the epoxy curing process. The second is adjustment and mechanical preload of each facet on a Zerodur or Silicon Carbide substrate (figure 13). This concept is reversible but would likely require a field alignment capability in the event the facets shifted during shipment or during seismic events. The mechanical concept is our preferred choice at the moment.

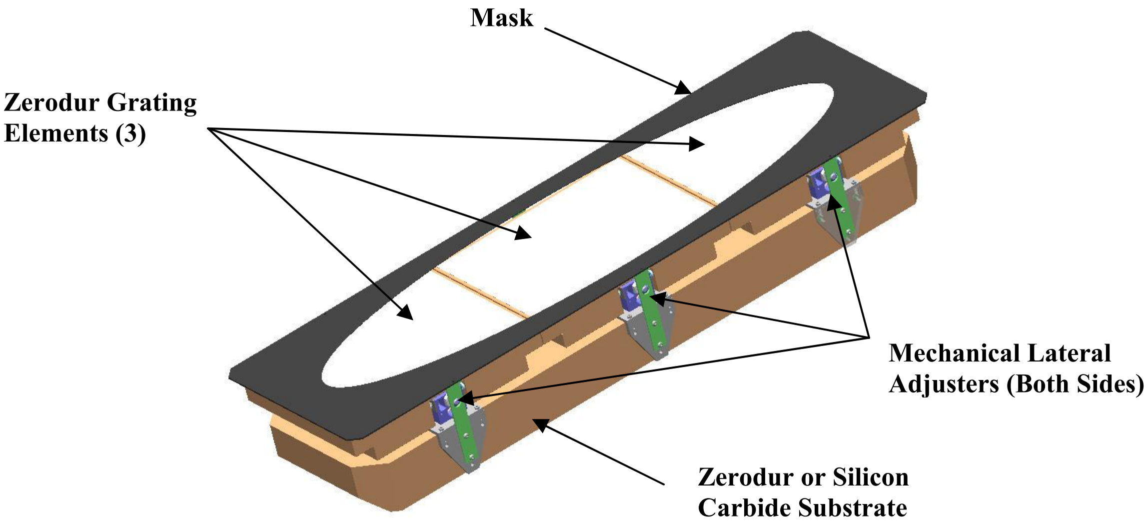

Figure 13 – Grating Concept - Zerodur Elements are Mechanically Metered to a Monolithic Zerodur of Silicon Carbide Substrate[5]

iii. Mirrors

G-CLEF's mirrors M1, M2 and the Mangin Fold, will likely be mounted using bonded flexure mounts (see figure 14). We have used similar flexure mounts on the Hectochelle spectrograph.

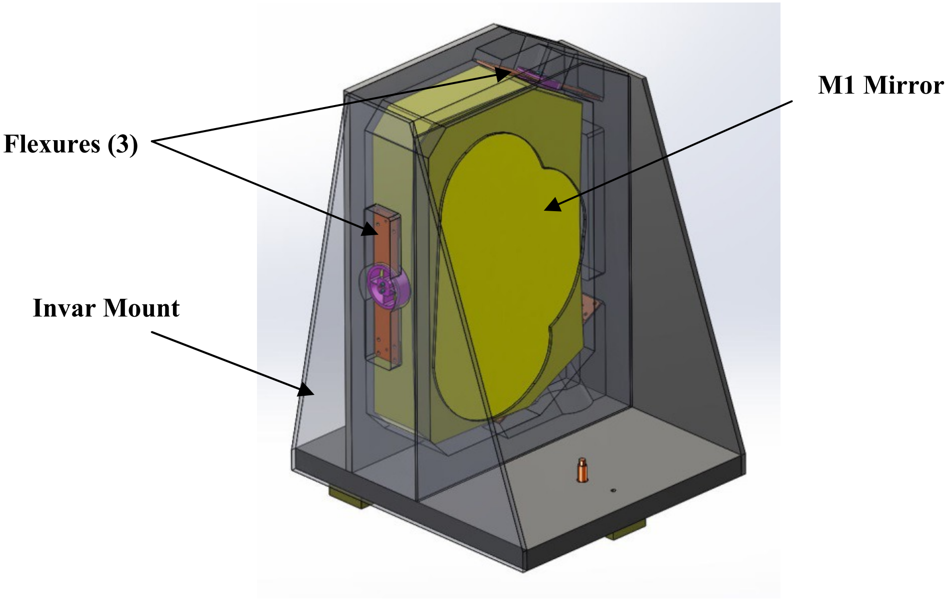

Figure 14 – Typical Mirror Mount – Bonded Flexure Design in Invar Bezel

f. Vibration Isolation System

The bench and optics will be supported within the vacuum chamber on a minimum of three vibration isolators. Our baseline isolator candidate is a product by Minus K® (figure 15). These isolators offer passive isolation and can be made vacuum compatible.

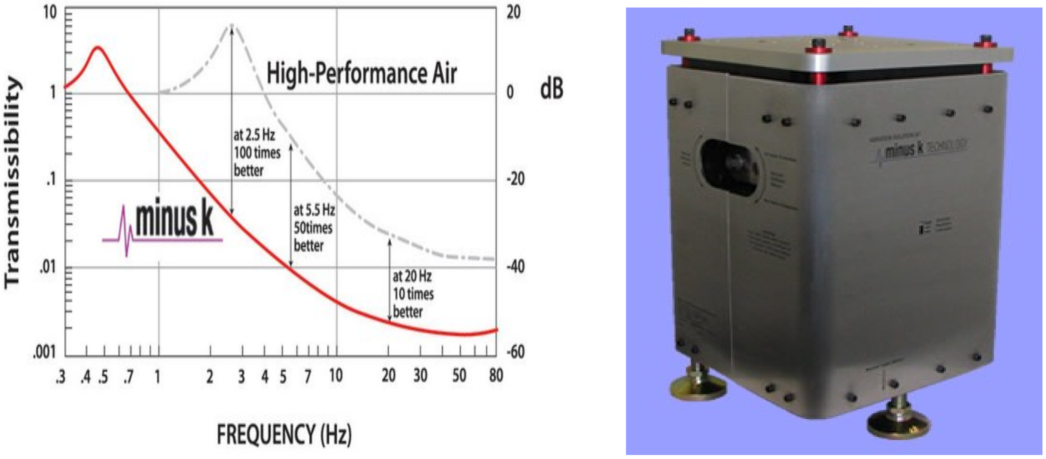

Figure 15 – Vibration Isolator Candidate with Performance Curves

4. Auxiliary Systems

G-CLEF will require several auxiliary systems which will be placed either near the spectrograph or at the Auxiliary Utility Platform just below GMT's Azimuth Disk. These systems include:

a. Power and control electronics
b. Thermal control electronics
c. Dewars and/or cryogen support hardware
d. Vacuum control hardware and electronics

2.4 Significant Design Challenges

1. *Thermal Control*

Measurement errors are present as a result of time varying temperatures in the spectrograph, both in the form of overall temperature and gradients. They cause thermo-elastic distortions of the spectrograph optical system which in turn shifts the spectra on the detector and changes the focus. These errors are low frequency relative to measurement duration and, therefore, are considered calibratable. We allocated a budget for this error and performed a preliminary analyses of these effects using the Concept Design as a basis (figure 16).

The analysis assumed an Invar bench spectrograph design. Thermal errors assumed were; 1) 0.001 °C bulk temperature and 2) ±0.001 °C gradient in each axis, applied as separate cases. The thermal errors were applied to the FEA model and the resulting optical component motions were input to the SAO *Bisense* software, which computes image shifts in the focal plane (lateral in two axes and defocus). The largest error resulting from the analysis was 118 Å of motion in the dispersion direction, which translates to 59 cm/sec PRV error. We expect to lower this by using low CTE materials (composite bench) and improving thermal control.

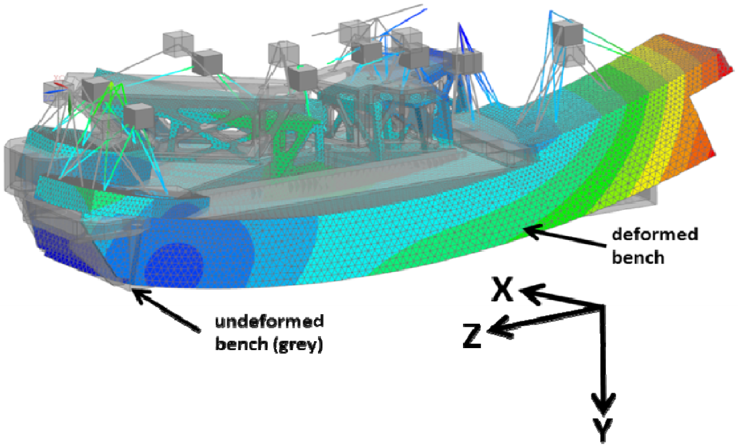

Figure 16. Deformed Plot from ±0.001 C Gradient in the X Direction

Table 1. Invar Optical Bench *Bisense* Results

Load Case	**Motion at Detector, Angstrom**		
	Dispersion	Spatial	Focus
Thermal Soak +0.001 °C	-4	~0	13
X Gradient	8	58	-1
Y Gradient	118	-12	-10
Z Gradient	1	~0	-1

2. *Mechanical Stability*

Mechanical instability of the optical system can be categorized into three types of errors:

a. Changes in atmospheric pressure (external to the spectrograph) cause structural deformation of the vacuum housing which can print through to the spectrograph, resulting in lateral shifts of the spectra as well as focus errors.

b. Motion of the G-CLEF spectrograph support structure (floor) as the telescope moves in azimuth, results in lateral shifts of the spectra and focus errors.
c. Instability of the materials in the spectrograph over the time of a measurement.

These error terms affect both calibration and star light and are expected to be small and vary slowly compared to measurement times, and are thus considered calibratable. These effects are amenable to analysis, which will be done in the preliminary design phase.

3. *Science Camera Cryogenic Systems and Temperature Control*

While we are confident in our overall temperature control scheme, there are two details that must be watched closely. They are:

a. Science camera CCD cooling
b. Thermal conduction through the bench support apparatus

The science CCD must be cooled to an operational temperature of -100 °C (173K). We are considering two methods of cooling. First is LN2 cooling via either a fixed volume dewar or continuous flow system. Second is a pulse tube cryo-cooler. LN2 is well understood but variations in atmospheric pressure and volume of cryogen can cause temperature changes at the dewar on the order of several degrees Kelvin. These components are in close proximity to the bench and, possibly, inside of our control point (thermal baffle plates). Insulating the bench from such changes will be a design priority.

In the case of pulse-tube cryocoolers, the cold tips of these devices can also vary by several degrees. In addition, a significant amount of heat (potentially hundreds of watts) is rejected directly at the vacuum interface of the cryocooler. This heat must be dealt with. Sinking that level of heat into our vacuum chamber will present significant challenges to our precision thermal control efforts.

Thermal conduction is possible at locations where the bench-supports (Minus K® isolators) contact the bench and are anchored to the vacuum vessel. The greatest threat from conduction in this area is the establishment of some level of temperature gradient between the top and bottom bench face-sheets. This would cause bending of the bench and a corresponding image motion at the detector. We will likely employ an attachment scheme which ensures a symmetric conduction path between the top and bottom bench face-sheets and ground such that effects of conduction, if present, will not result in bending of the bench.

4. *Grating Mosaic Mounting and Alignment*

As indicated earlier, G-CLEF's optical design features a grating mosaic of three 300mm X 400mm grating facets which must be mounted and aligned relative to one another to tight tolerance. Surfaces must be parallel to one another within approximately 1μm, and tip/tilt about axis' normal to the grating surface must also be aligned to less than 1μm across the length of each edge. This is a significant but manageable challenge that we will address with a proper measurement scheme, mount design and alignment fixturing.

5. *Optical Mounts*

Optical mounts are never to be taken lightly, however, given the environment that will be established within the spectrograph (temperature and gravity invariant), operational loads are quite benign. The most severe load conditions that the optics will experience are due to handling and shipment. These are well understood and the mount configuration along with all handling and shipping fixtures, will be designed accordingly. Positioning tolerances of optics will typically be in the 12 to 25 micron range. While tight, we have achieved such tolerances regularly on MMIRS and Binospec using our Opticentric™ lens mounting system.

6. *Weight*

The various G-CLEF subsystems must conform to a GMTO defined weight budget. Variances are not out of the question but must be approved. Our current projected and approved weight allocation is as follows:

a. Spectrograph on azimuth disk = 14500 kg
b. Support equipment on auxiliary utility platform = 1200 kg
c. Front end assembly = TBD

7. *System Transport and Shipment*

Shipping conditions (in the form of temperature variation and expected shock loading) are proving to be the design drivers for most critical components, namely the optical mounts. Controlling the shipping conditions will allow us to simplify mount design for a net savings in cost and complexity. Our instrument will have to endure international travel by either sea or air in order to reach the GMT in Chile. We are researching both air and sea options and are finding that a variety of temperature control options are available. Extreme temperature excursions combined with moderate to high shock loads can be dangerous to bonded optical mounts in particular. Also of concern is shipment of the composite bench which combines large size with bonded joints.

We are confident that suitable methods of shipment are available but that we will likely have to break down the spectrograph's major optical assemblies and ship them as discrete items; shock isolated and temperature controlled. A shipment and re-integration plan will be presented as part of PDR.

3. CONCLUSIONS

We are designing and building the G-CLEF instrument using current design-engineering best practices. Requirements definition, flow down, verification and error budgeting are integral parts of the process. This approach is in conformance with the GMT requirements process and is consistent with the approach being utilized to design and build the GMT itself. We have identified the major design challenges and are addressing them with a combination of innovative design approaches, analysis and prototyping efforts. We are confident that the G-CLEF team is on track to present a robust preliminary design as scheduled in March 2015.

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