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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) will be part of the first generation instrumentation suite for the Giant Magellan Telescope (GMT). G-CLEF is a general purpose echelle spectrograph operating in the optical passband with precision radial velocity (PRV) capability. The measurement precision goal of G-CLEF is 10 cm/sec; necessary for the detection of Earth analogues. This goal imposes challenging stability requirements on the optical mounts and spectrograph support structures especially when considering the instrument's operational environment. G-CLEF's accuracy will be influenced by changes in temperature and ambient air pressure, vibration, and micro gravity-vector variations caused by normal telescope motions. For these reasons we have chosen to enclose G-CLEF's spectrograph in a well-insulated, vibration-isolated vacuum chamber in a gravity invariant location on GMT's azimuth platform. Additional design constraints posed by the GMT telescope include; a limited space envelope, a thermal leakage ceiling, and a maximum weight allowance. Other factors, such as manufacturability, serviceability, available technology, and budget are also significant design drivers.

G-CLEF will complete its Critical Design phase in mid-2018. In this paper, we discuss the design of G-CLEF's optical mounts and support structures including the choice of a low-CTE carbon-fiber optical bench. We discuss the vacuum chamber and vacuum systems. We discuss the design of G-CLEF's insulated enclosure and thermal control systems which simultaneously maintain the spectrograph at milli-Kelvin level stability and limit thermal leakage into the telescope dome. Also discussed are micro gravity-vector variations caused by normal telescope slewing, their uncorrected influence on image motion, and how they are dealt with in the design. We discuss G-CLEF's front-end assembly and fiber-feed system as well as other interface, integration and servicing challenges presented by the telescope, enclosure, and neighboring instrumentation.

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1. INTRODUCTION

G-CLEF is the GMT-Consortium Large Earth Finder. It will be one of the first light science instruments on the GMT. G-CLEF is an optical-band, fiber-fed echelle spectrograph with a working passband of 3500Å-9000Å. 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 PRV measurement 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 telescope structure. The spectrograph features an asymmetric white pupil design[2] with a 300 mm diameter beam that is reduced to 200 mm with a pupil transfer mirror after dispersion by the echelle grating. We are currently in the Critical Design phase. The instrument's Preliminary Design Review was held in April 2015. Critical Design Review will occur in mid-2018 and science operations are planned to begin in 2023.

The GMT is a 25.4 m diameter optical and near infrared (NIR) telescope under construction in Las Campanas, Chile. 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 filled aperture, optical-NIR 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 OPTO-MECHANICAL REQUIREMENTS

2.1 G-CLEF Operational and Performance Requirements

GMT Instrumentation and Science Requirements flow down into the G-CLEF Instrument System Design Requirements. To meet the multiple science objectives, G-CLEF must have a broad passband, high resolution, high throughput, and PRV capability. G-CLEF will support four different resolution modes using two science cameras, one for the blue wavelengths and another for the red.

A brief summary of G-CLEF's performance requirements is shown in Table 1. Expected throughput is illustrated in Figure 1.

Table 1- Summary of Primary G-CLEF Operational and Performance Requirements

Requirement	Requirement Statement
Instrument Passband	3500Å to 9000Å simultaneous wavelength coverage (goal of 9500Å)
Measurement Modes and Spectral Resolution	Optically Scrambled Precision Radial Velocity mode (PRV) – Spectral Resolution = 108,000 (Pupil Sliced) Non-scrambled PRV Mode (PRV-NS) - Spectral Resolution = 108,000 (Pupil Sliced) High Throughput (HT) Mode - Spectral Resolution = 19,000
PRV Measurement Precision	Capable of making single PRV measurements with a radial velocity single measurement precision of 40 cm/second; 10 cm/second with averaging.

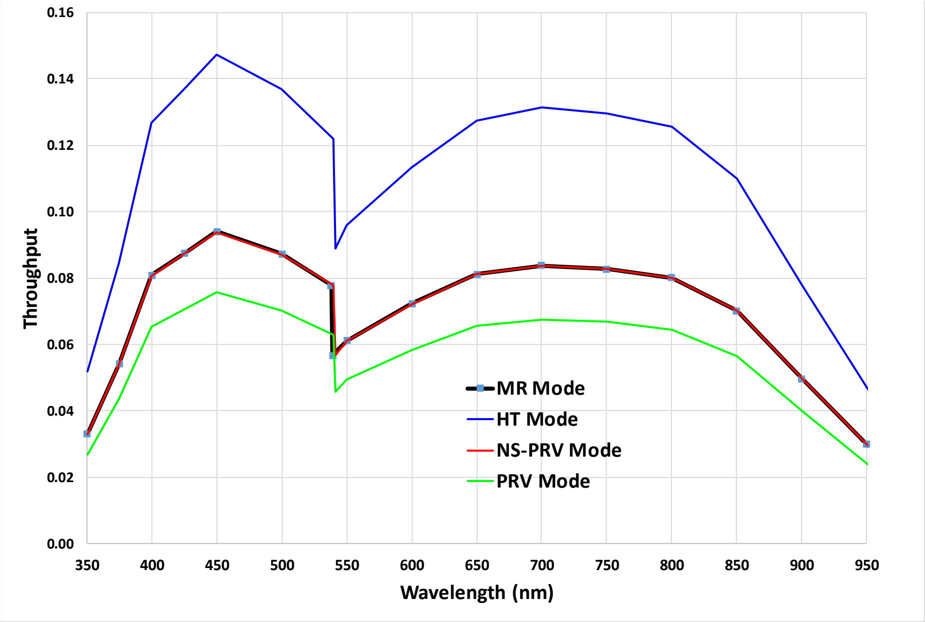


Figure 1 – Current Estimate of G-CLEF Throughput

2.2 G-CLEF Physical Requirements

A summary of G-CLEF's physical requirements is shown in Table 2.

Table 2- Summary of G-CLEF Physical Requirements

Requirement	Requirement Statement
Bench/Optics Thermal Stability	±0.001 deg K assuming a low CTE composite bench (derived from PRV accuracy requirements)
Detector and CCD cold head stability	±0.004 deg K (derived from PRV accuracy requirements)
Internal Vacuum Levels	Spectrograph = 4 X 10^{-4} Torr or better to meet PRV budget (7.5 X 10^{-7} Torr desired for 80000 hour ion pump operational life) Red and Blue Detectors = 5 x 10^{-6} Torr or better
Fiber Feed	17 meter maximum length from front end to spectrograph. Must accommodate -2 to +62 degree telescope elevation change.
Location	GMT Gravity Invariant Station (GIS) on rotating Azimuth Disk. Self-Leveling and Active Isolation will be implemented.
Seismic	Must withstand Operational and Survival Level Earthquakes (OLE and SLE) with minimal damage.
Operational Temperature Range	-10 to +25 deg C. Maximum thermal emission into dome to be less than 5 Watts/m^2.
Mass allocations	15000 kg @ GIS (Spectrograph) 1500 kg @ GIR (Front End)

3. G-CLEF OPTO-MECHANICAL DESIGN

3.1 G-CLEF Spectrograph Optical Design

The spectrograph optical layout is shown in Figure 2 and follows the following optical path.

1. Beam emerges from the fiber feed through a focal ratio converter converting from f/3 to an f/8 beam
2. Beam reflects off an off-axis parabolic collimator, f = 2400mm with 300mm beam size
3. Reflected and dispersed from the Echelle grating, 31.6 lpm, 306mm X 1258mm
4. Reflected (2nd pass) off the off-axis parabolic collimator and focused
5. Reflected off a cylindrical Mangin fold mirror
6. Reflected and collimated off a pupil transfer mirror (M2), f = 1600mm with 200mm beam size
7. Red wavelengths are transmitted, blue reflected by a dichroic (split at 5400Å) into separate red and blue camera systems
8. Each band passes through separate red or blue cross-dispersers and multi-lens cameras
9. Each band is imaged by an STA 1600 95.04 mm X 95.04 mm CCD

A more comprehensive description of the optical system is described in "New Features in the Optical Design of the GMT-Consortium Large Earth Finder".[2]

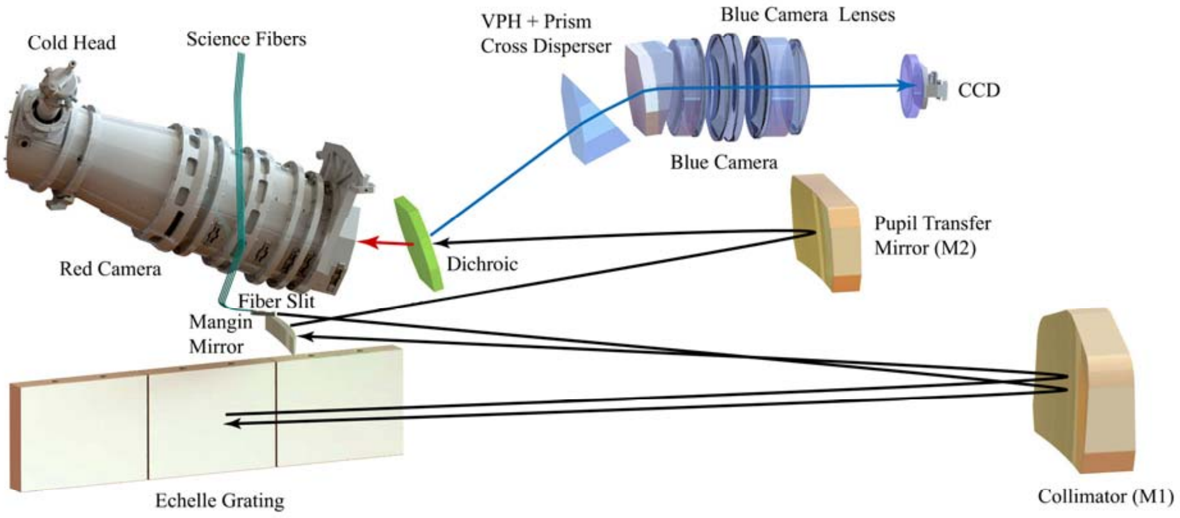


Figure 2 - Spectrograph Optical Layout

3.2 G-CLEF High Level Instrument Architecture

The overall system and its placement on the telescope is shown in Figure 3.

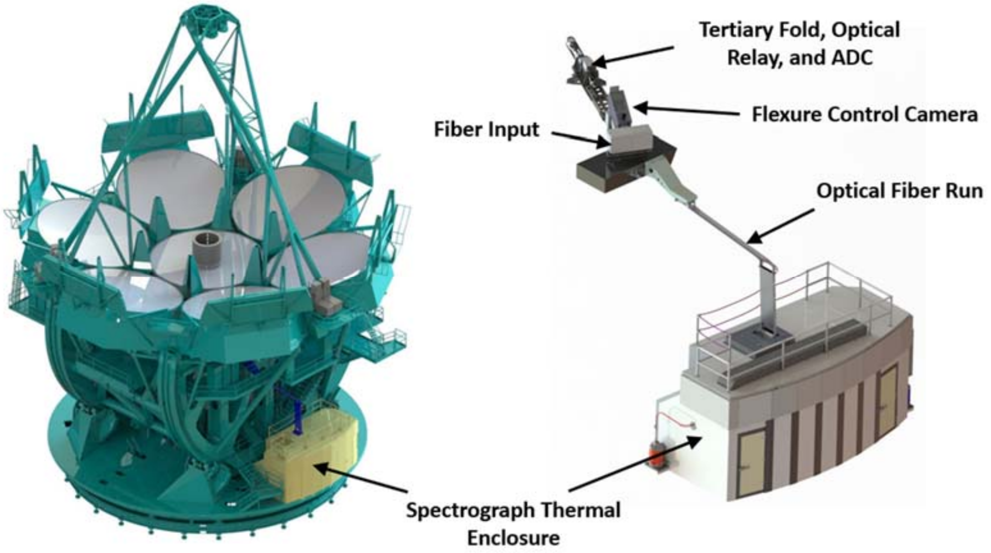


Figure 3 – G-CLEF System on GMT Azimuth Disk

3.2.1 Front End System

The front end subsystem layout is shown in Figure 4. The front end extends into the telescope optical beam, picks off a 1.5 arc minute field of view and relays it to the slit apertures which feed the fiber system. The front end consists of two separate sections. The deployable tertiary portion sits on top of the Gregorian Instrument Rotator (GIR) which resides just below the primary mirror cells. The portion which contains the slit apertures is fixed on the GMT Instrument Platform (IP). The two portions must be aligned to high accuracy during operation.

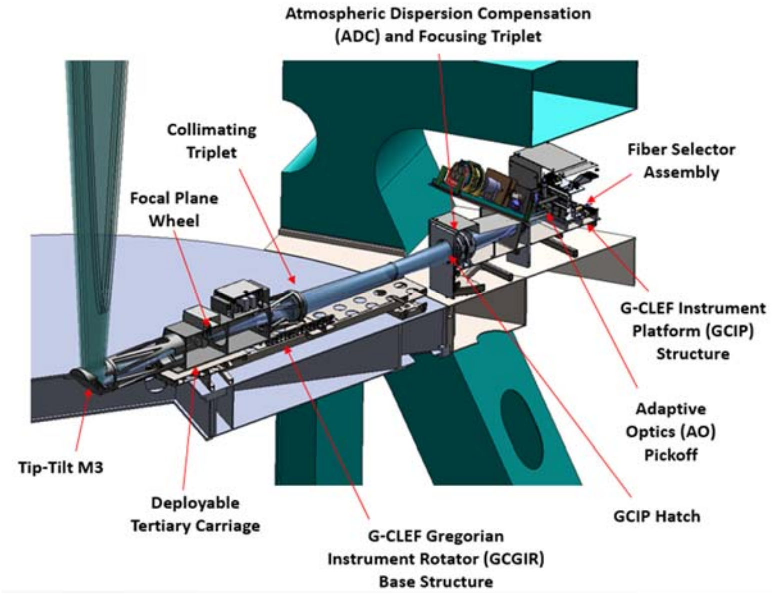


Figure 4 – Front End Assembly Mounted to the Top of GMT's Gregorian Instrument Rotator

3.2.2 Fiber Run and Fiber Link Mechanics

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 using an innovative 2 link system, shown in Figure 4, which minimizes the fiber path length while also accommodating telescope elevation travel from -4 to +64 degrees.

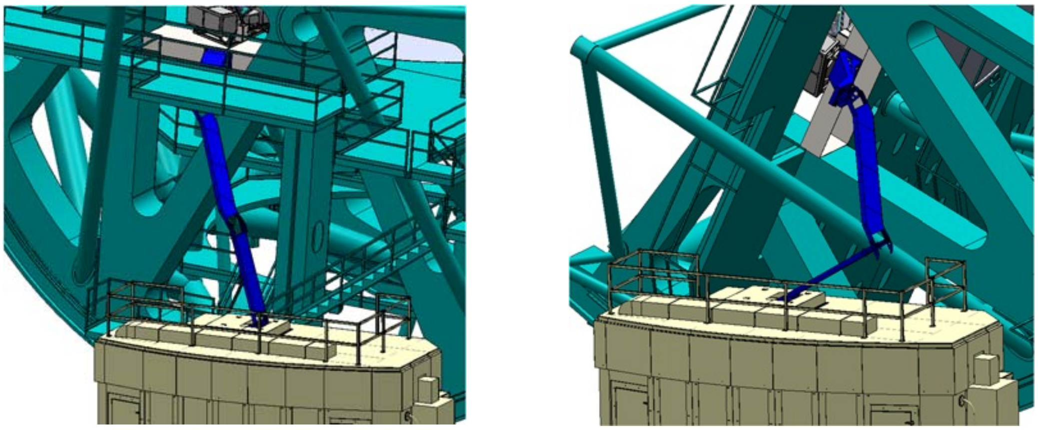


Figure 5 – Fiber Run 2-Link System at Telescope Elevation of -4 Degrees (Left) and +64 degrees (Right)

3.2.3 Spectrograph System

3.2.3.1 Spectrograph Assembly

The spectrograph bench is housed in a vacuum chamber is shown in Figure 6. The sectioned bench with optical assemblies is shown in Figure 7.

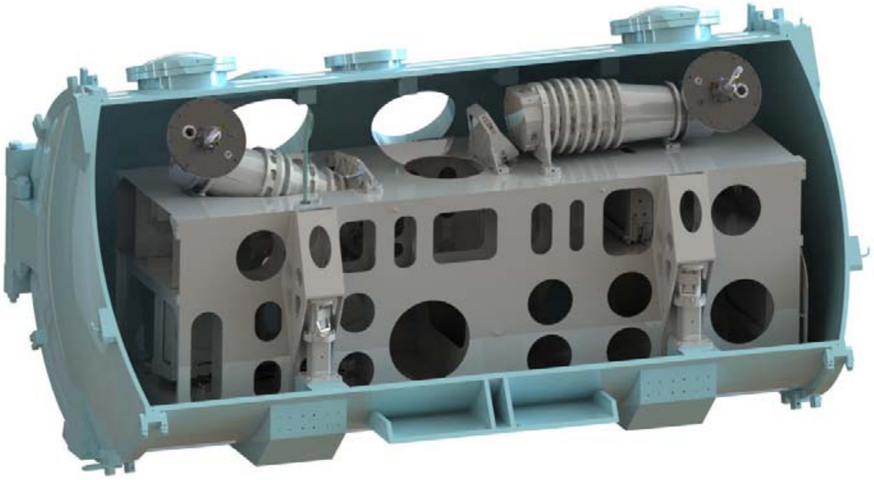


Figure 6 – Spectrograph in Vacuum Chamber

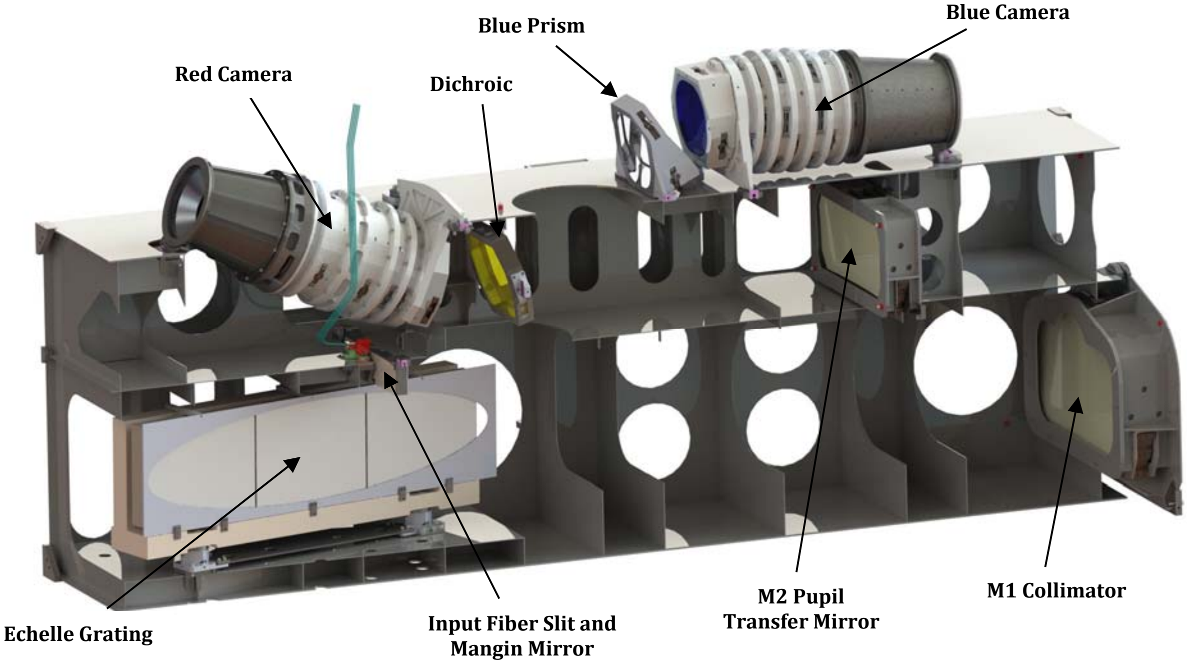


Figure 7 – Bench Sectioned

3.2.3.1.1 Optical Mounts

Most optics within the spectrograph are mounted in rigid bezels with bonded tangential flexures. The exceptions are the science camera field flatteners which also serve as vacuum windows and are preloaded against sealing O-rings. The critical design load condition for each mount is a shipping condition of 5G's and a temperature range of 5 °C to 25 °C. The Red and Blue camera assemblies are shown in Figure 8 below.

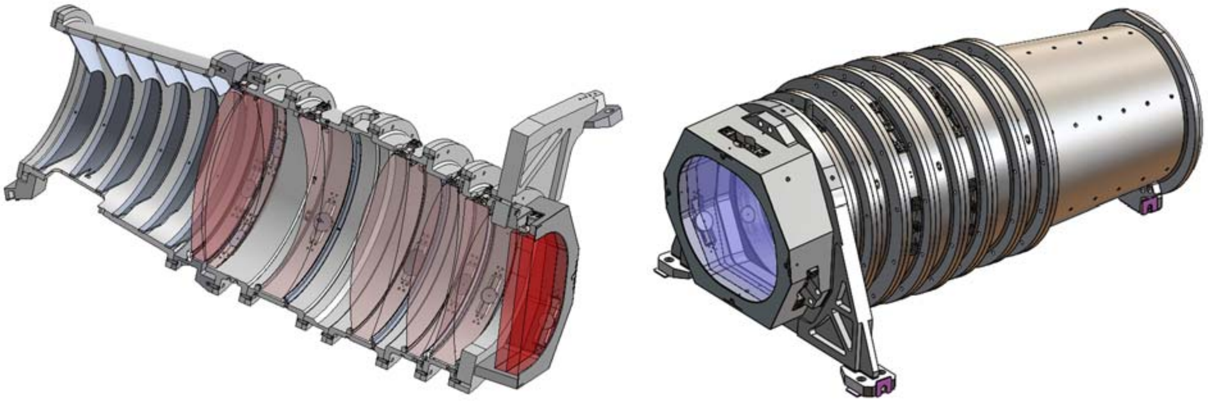


Figure 8 – Red Camera Sectioned (Left), Blue Camera (Right)

The Grating Mosaic, consisting of 3 facets of 400mm X 300mm X 72mm each, preloaded on a monolithic Zerodur structure, is shown in Figure 9. Each end facet is aligned to the central facet to within 1 arc-sec in tip and tilt using adjustable, flexured shims which allow facet adjustment in-situ.

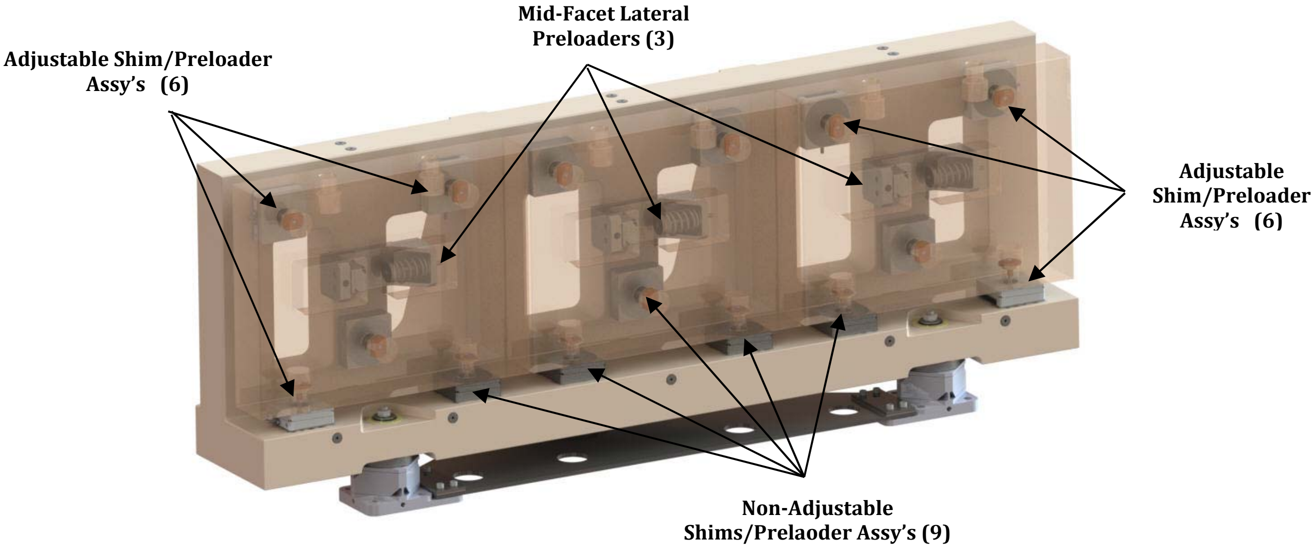


Figure 9 – Grating Mosaic (Grating Facets Shown Transparent)

3.2.3.1.2 Carbon Fiber Bench

The optical system is highly sensitive to relative motion of the optics caused by even minute changes in temperature. Our derived thermal requirement is to control the internals of the vacuum chamber (primarily the bench and supported optics) to a target temperature of 20 ± 0.001 °C. Even with this level of temperature control, 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 (IMAD) would not allow us to achieve our PRV measurement goal of 10 cm/s.

Predicted image motion for different bench materials when exposed to thermal soaks and gradients of .001°K is as follows:

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

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, they absorb ambient moisture and expand as a result. When installed in our vacuum chamber, this moisture will desorb and there will be a corresponding dimensional contraction which will occur over time. We predict that most of this change will occur in the first 100 days. Total dimensional change of the bench over the life of the instrument should be between 12 and 49 microns (.0005” - .002”) which is not enough to affect alignment.
- Temporal effects – 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.

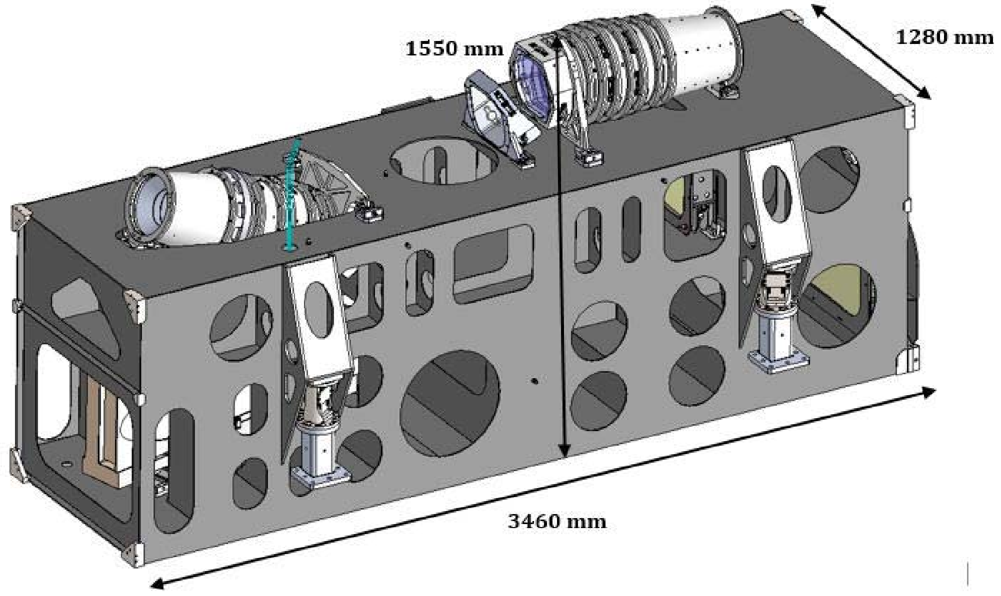


Figure 10 – Carbon Fiber Bench Overall Dimensions

3.2.3.1.3 Science Cameras with Precision Thermal Control at Cryogenic Temperatures

A Janis SuperTran™ [7] continuous flow cryostat provides the CCD cooling in the red and blue detector assemblies. A detail view of a detector is shown in Figure 11. The Janis System is shown in Figure 12.

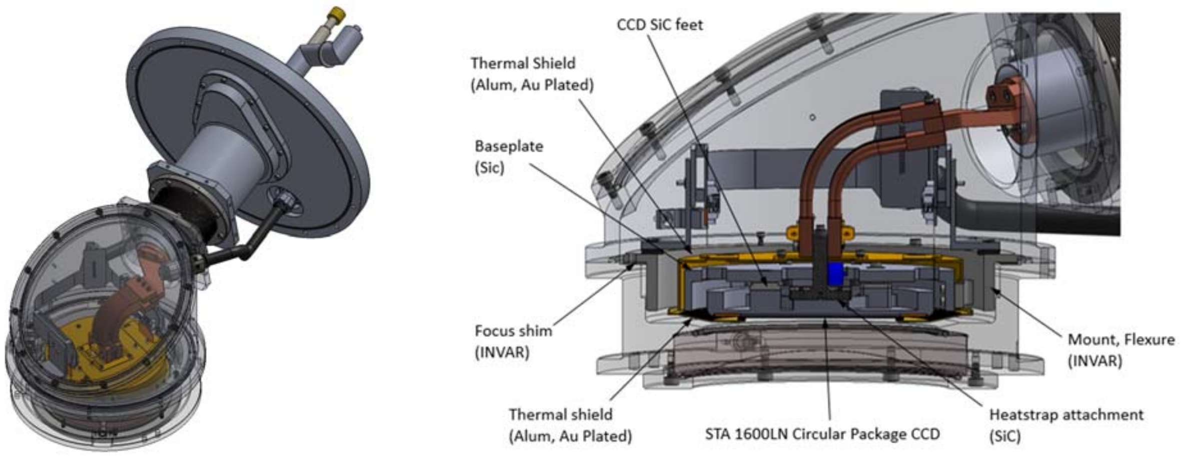


Figure 11 – Science Camera and Focal Plane

Figure 12 – Janis SuperTran™ Continuous Flow Cryostat

3.2.3.1.4 Vacuum Vessel and Vacuum System

The spectrograph is housed in the vacuum vessel shown in Figure 13. The vessel is constructed of 25mm thick aluminum, has an overall size of 2.2 meters in diameter X 4.3 meters in length. It will weigh 2700 kg. The end doors and various access ports are each strategically placed to support bench installation and subsystem servicing. Seals are a combination of O-ring, copper gasket, and wire seal depending on size and expected frequency of use.

Figure 13 – Aluminum Vacuum Vessel

The vacuum system is attached directly to the vacuum vessel and is accessible via removable panels at the rear of the thermal enclosure as shown in Figure 14. The target operation vacuum level is 7.5 X 10^{-7} Torr. A level of 4 X 10^{-4} Torr is required for spectrograph optical performance but the lower level is desired to enable a long ion pump life.

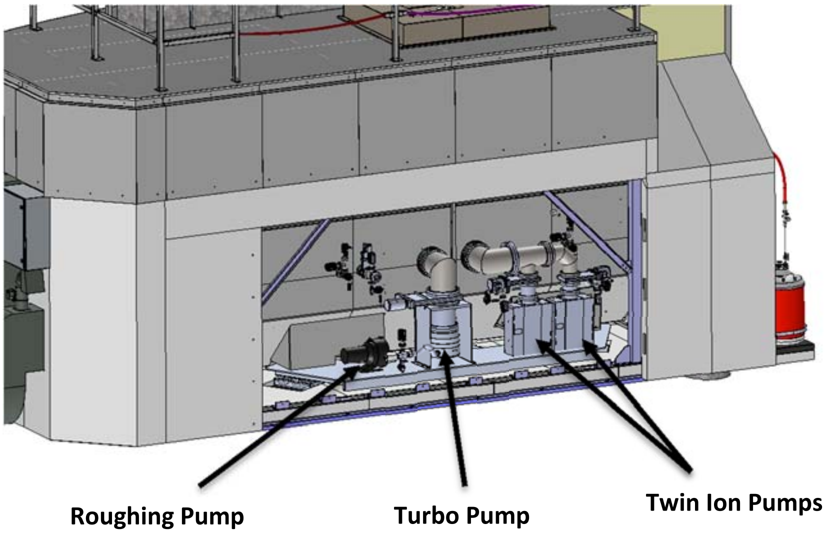
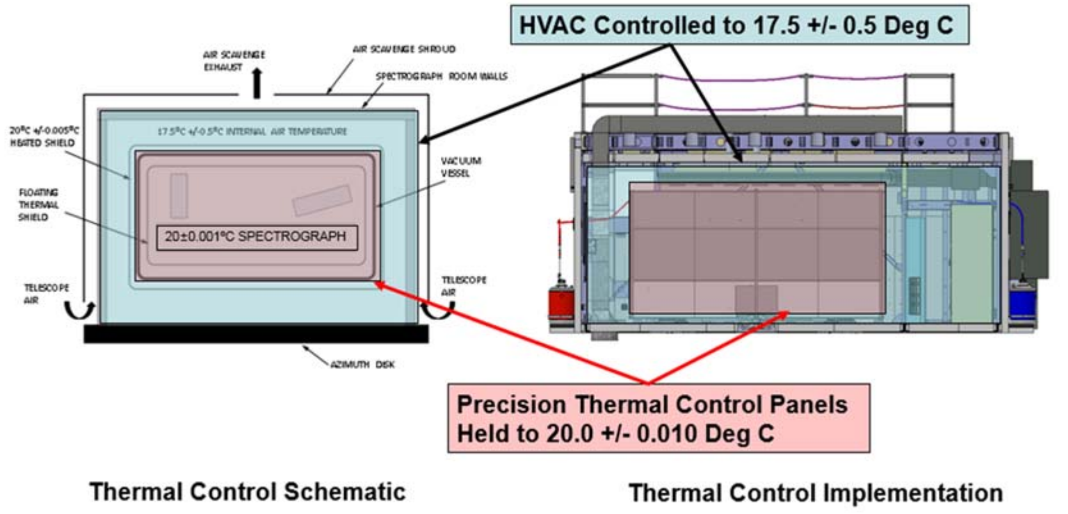


Figure 14 – Aluminum Vacuum Vessel

3.2.3.1.5 Thermal Control and Thermal Panel Assembly

The thermal control strategy is shown schematically in Figure 15. More than 40 aluminum panels each with an array of Kapton strip heaters and an outer 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. These panels are controlled to 20 +/- .01 deg C using precision Isotech[6] temperature measurement electronics and a custom heater driver. 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 significantly longer than the day-long requirement.[3]



Thermal Control Schematic

Thermal Control Implementation

Figure 15 – Spectrograph Thermal Control Strategy

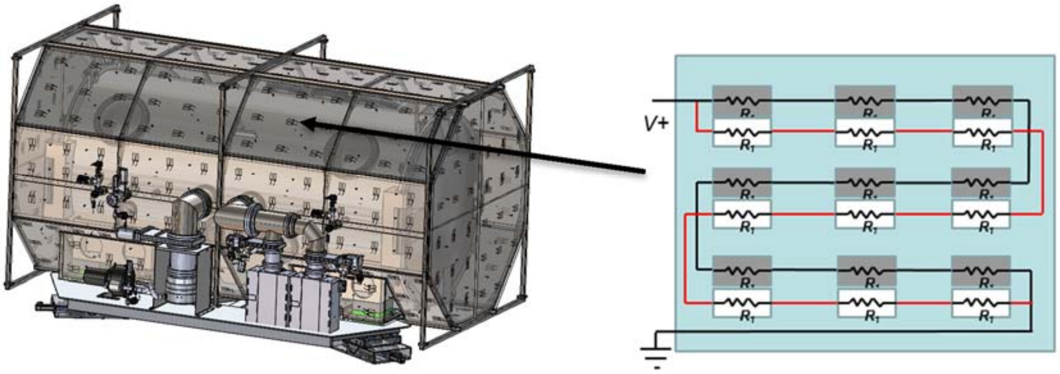


Figure 16 – Thermal Panel Assembly (Left) with Heater Panel Schematic (Right)

3.2.3.1.6 Spectrograph Support Assembly

The Spectrograph Support Assembly serves several important functions:

- It safely supports the loaded 6500 kg spectrograph mass on the GMT Azimuth Disk
- It attenuates ambient vibration using an active isolation system
- It incorporates self-leveling actuators which keep the spectrograph level with respect to the gravity vector

The active isolation system will give the spectrograph a natural frequency of ~2.5 Hz. The “active” part of the system eliminates any resonant peak that would normally occur in a passive mass/spring/damper system. Therefore, the spectrograph will be well isolated from ambient vibration inputs.

Self-leveling is required because system level structural modeling has revealed that the spectrograph cannot tilt more than 5.6 arc-sec and remain within our budgeted error. Tilts of up to +/- 28 arc-sec could be present due to misalignment of the telescope's AZ axis to the gravity vector as well as flexibility of the AZ bearing between its support points. Therefore, self-leveling is required.

3.2.3.1.7 Spectrograph Thermal Enclosure

G-CLEF's thermal enclosure is shown in Figure 17 along with its structural support framework. Its primary purpose is to provide an insulated structure around the spectrograph and isolate it from ambient temperatures ranging from -10 to +25 deg C. Structurally, it consists of a steel frame fastened directly to telescope's Azimuth disk. Insulated panels are fastened directly to this framework and the gaps between panels are controlled via Camlock-type preloaders. This construction methodology is modular which will ease on-site integration. Other features include:

- An insulated drop-type ceiling
- A load bearing, insulated floor
- An HVAC system with liquid cooled air handler
- An air scavenge system which vacuums away any thermal plume, limiting thermal emission into dome
- Removable front and rear panels enabling spectrograph installation and servicing of vacuum system
- Capable of withstanding Survival Level Earthquake loads

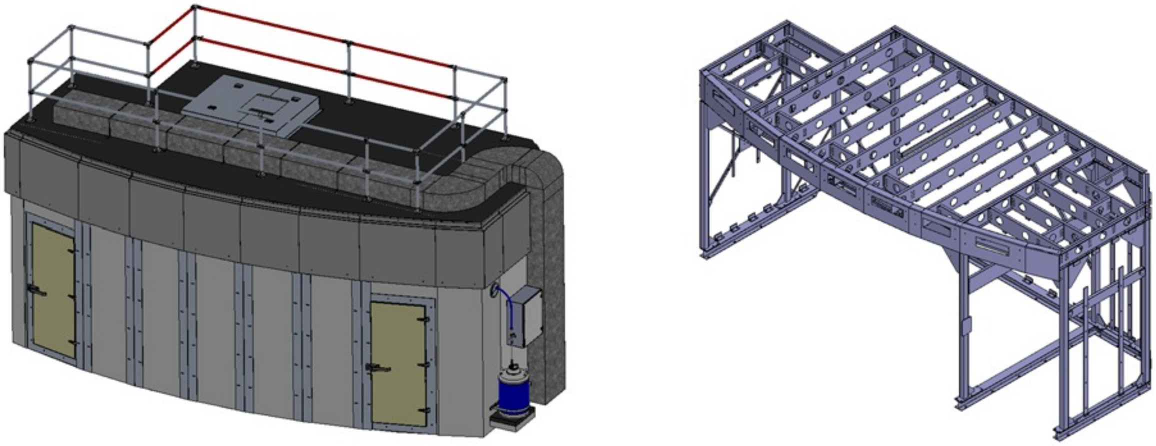


Figure 17 – Thermal Enclosure (Left) and Enclosure Structural Framework (Right)

3.2.3.1.8 Electronics Architecture

G-CLEF's overall electrical architecture is illustrated in the block diagram in Figure 18 with the implementation shown in Figure 19. All designs conform to GMT defined electrical standards and operate at available Chilean power (380 VAC – 3 phase). Electronics are housed in a combination of Standard Electronics Cabinets (SEC's) and Non-Standard Electronics Cabinets (NSEC's) and use EtherCAT as the communication protocol between each module and the main control system. Commercial parts are used wherever possible.

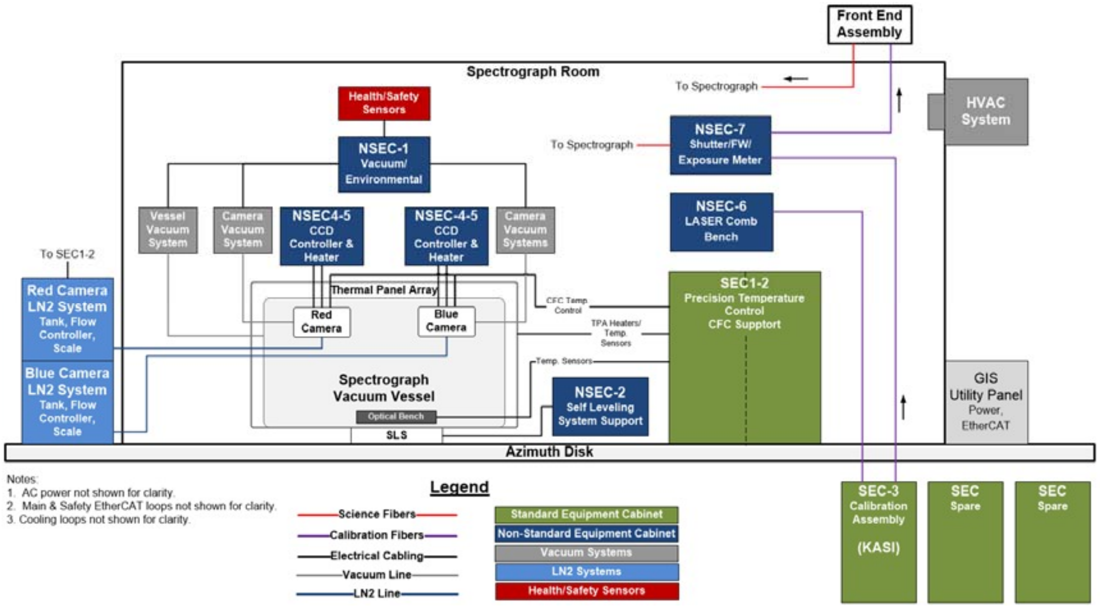


Figure 18 – Overall Electrical Block Diagram

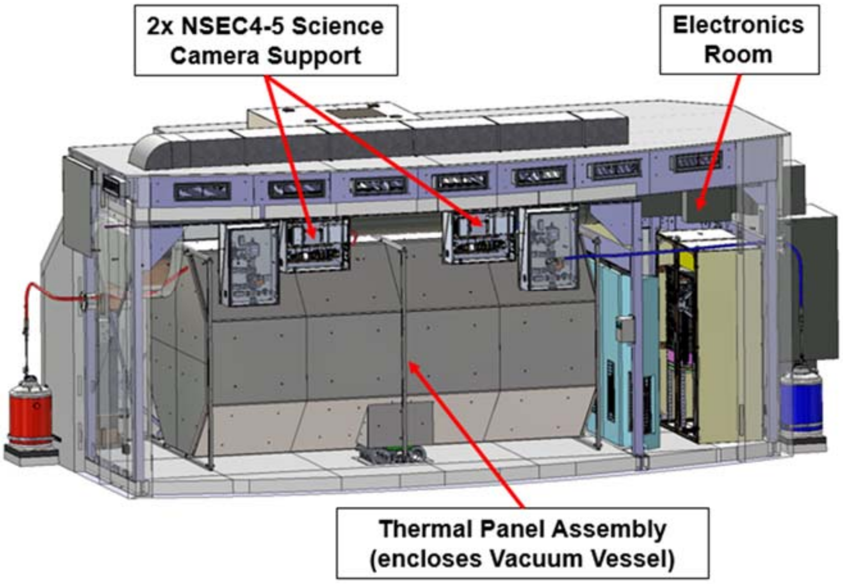


Figure 19 – Electronics Enclosures Located at Points-of-Use in the Thermal Enclosure

4. CONCLUSION

We are designing and building the G-CLEF instrument using current design-engineering best practices guided by rigorous systems engineering methodology. Requirements definition, flow down, verification and error budgeting are integral to 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 critical design as scheduled in July 2018.

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[6] Isotech North America is located at 158 Brentwood Drive, Unit 4 Colchester, VT 05446

[7] SuperTran™ is a product of Janis Research Company, 225 Wildwood Avenue, Woburn, MA 01801-2025 USA