Advanced Structural Design for Precision Radial Velocity Instruments

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**ABSTRACT**

The GMT-Consortium Large Earth Finder (G-CLEF) is an echelle spectrograph with precision radial velocity (PRV) capability that will be a first light instrument for the Giant Magellan Telescope (GMT). G-CLEF has a PRV precision goal of 40 cm/sec (10 cm/s for multiple measurements) to enable detection of Earth-like exoplanets in the habitable zones of sun-like stars\(^{1}\). This precision is a primary driver of G-CLEF’s structural design. Extreme stability is necessary to minimize image motions at CCD detectors. Minute changes in temperature, pressure, and acceleration environments cause structural deformations, inducing image motions which degrade PRV precision. The instrument’s structural design will ensure that the PRV goal is achieved under the environments G-CLEF will be subjected to as installed on the GMT azimuth platform, including:

- Millikelvin (0.001 °K) thermal soaks and gradients
- 10 millibar changes in ambient pressure
- Tip/tilt due to GMT azimuth axis misalignment with gravity, azimuth track height variations, azimuth platform deformation, and centripetal and azimuthal accelerations due to during telescope slewing.

Carbon fiber/cyanate composite was selected for the optical bench structure to facilitate meeting performance goals. Low coefficient of thermal expansion (CTE) and high stiffness-to-weight are key features of the composite optical bench design. Manufacturability and serviceability of the instrument are also drivers of the design.

In this paper, we discuss analyses leading to technical choices made to minimize G-CLEF’s sensitivity to changing environments. Finite element analysis (FEA) and image motion sensitivity studies were conducted to determine PRV performance for a variety of bench CTEs under a range of thermal environments. We discuss the design of the optical bench structure to optimize stiffness-to-weight and minimize deformations due to inertial and pressure effects. We also discuss quasi-kinematic mounting of optical elements and assemblies, and optimization of these to ensure minimal image motion under thermal, pressure, and inertial loads expected during PRV observations.

**Keywords:** Echelle spectrograph, precision radial velocity, G-CLEF, GMT, composite optical bench, thermal stability, mechanical stability, low CTE
1. INTRODUCTION

G-CLEF$^2$ is an optical-band, fiber-fed echelle spectrograph that will be the first light science instrument on the GMT$^3$, a 25.4 m diameter optical and near infrared (NIR) telescope under construction in Las Campanas, Chile$^4$. G-CLEF 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. The ability to measure the mass of an Earth-sized rocky exoplanet orbiting in the habitable zone of a sun-like star is a critical science goal for the instrument. For thermal and mechanical stability, G-CLEF is housed within a vacuum vessel mounted at a gravity invariant station (GIS) on the GMT azimuth platform. The spectrograph features an asymmetric white pupil design$^5$ with a 300 mm diameter beam that is reduced to 200 mm with a pupil transfer mirror after dispersion by the echelle grating. A Preliminary Design Review was held in April 2015, and the project is currently in the critical design phase. Critical Design Review is scheduled for May 2017, and science operations are planned to begin in 2021.

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 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$^5$. G-CLEF Science requirements flow down into the Level 4 G-CLEF Instrument Design Requirements$^6$. This paper focuses on how the PRV requirements and goals drove the mechanical design of the spectrograph optical bench structure.

2.1 G-CLEF Installation on GMT

The G-CLEF Spectrograph resides at one of the gravity invariant stations (GIS) on the GMT azimuth platform. In order to precisely control instrument temperatures for maximum thermal stability, the spectrograph is mounted inside a cylindrical vacuum vessel which is supported on the GMT azimuth platform. The vacuum vessel is surrounded by thermal control panels which allow the temperature of the spectrograph to be maintained to within a millikelvin. The spectrograph, vacuum vessel, and thermal control panels are housed within a thermal enclosure on the GMT azimuth platform as shown in Figure 1. The vacuum vessel is quasi-kinematically supported at three points on wire-rope isolators (see Figure 2) to isolate the spectrograph and to minimize print-through of GMT azimuth platform deformations into the spectrograph. The wire rope isolators are compliant relative to the stiffness of the vacuum vessel itself, ensuring mechanical stability of the vacuum vessel and spectrograph under azimuth platform deformations experienced during slewing.
Figure 1 – G-CLEF Installation on GMT Azimuth Platform

Figure 2 – G-CLEF Three-point Wire Rope Isolator Support of Ø1.9m x 4.3m G-CLEF Vacuum Vessel on GMT Azimuth Platform
2.2 G-CLEF Spectrograph Optical Design

The spectrograph optical layout is shown in Figure 4. The optical paths for the red and blue channels are both 10.8 meters in total length from fiber feed to CCD detector.

- **Red Camera**: $f = 500$ mm, single asphere, 7 element, 5400 Å to 9000 Å
- **Blue Camera**: $f = 500$ mm, single asphere, 8 element, 3500 Å to 5400 Å
- **Dichroic** (split @ 5400 Å)
- **Echelle Grating**: 31.6 lpm (300 X 1200 mm)
- **Elliptical Pupil Transfer Mirror**: (f=1600 mm), Beam Size: 200 mm
- **Parabolic Collimator**: (f=2400 mm), Beam Size: 300 mm

Figure 4 - Spectrograph Optical Layout with Red and Blue Light Beam Paths
2.3 G-CLEF Optical Bench Design

A primary driver of the optical bench design is to ensure that 10 cm/s PRV precision is maintained under changes in thermal, inertial, and pressure environments. Apparent image motion at the detectors must be minimized to the order of angstroms in order to meet the PRV design goal. The structure must ensure that milliKelvin soaks and gradients, micro-radian changes in orientation relative to gravity, micro-g accelerations during slewing, and millibar pressure fluctuations do not cause deformations leading to excessive image motion at the CCD detectors throughout the duration of calibrations and observations.

Size and weight are also critical considerations, as the instrument resides on the moving azimuth platform on the GMT. The optical bench is designed to be as small and lightweight as possible while providing adequate stiffness and strength at structural supports for optical components and assemblies. The optical bench structure must provide a stable structural platform for the major optical assembly masses shown in Figure 6.
The optical bench was designed as an internally braced monocoque shell structure to maximize stiffness- and strength-to-weight and to minimize volume without violating the red and blue channel light beam paths. The bench design consists of a rectangular-section outer shell made of four large flat panels with internal ribs and stiffening elements supporting the optical assemblies. A horizontal panel runs the length of the structure and separates the primary structure into lower and upper structural cells. Internal ribs, bulkheads, and longitudinal panels are included in the design to achieve a minimum natural frequency goal of 50 Hz for the assembled instrument.
The instrument is supported within the vacuum vessel on three titanium flexures designed to allow differential thermal expansion rates and to isolate the spectrograph structure from any deformations at the vacuum vessel resulting from atmospheric pressure changes.
Optical assemblies are mounted to invar frames on the optical bench (Figure 10). These frames are supported on flexured mounts which are bonded to the primary bench structures. The flexure mounts are designed to allow for CTE differences between the mounted optical assemblies and the bench metering structure with minimal deformation to the optical bench under thermal soaks and gradients.
The mount/laminate joints are designed to mitigate the effects of high CTE through the laminate thickness and in bondlines (see Figure 12).

Invar frames are mechanically attached to the bonded mounts/flexures. Optical assemblies are aligned and mounted on the frames.

G-CLEF’s mirrors M1, M2 and Mangin Fold will be mounted using bonded flexure mounts (see figure 12).
3. PRV BUDGET, FEA AND IMAGE MOTION ANALYSIS

G-CLEF systems engineering has developed a PRV error budget for environments the instrument will be subjected to during calibration and observation (Table 2). The effects of these environments on translations and rotations of optical assemblies due to structural deformations were analyzed and resulting image motions calculated. Results from these analyses were used to evolve the structural design evolution of the instrument to ensure that PRV performance goals are achieved.

Table 2 – PRV Error Budgets

<table>
<thead>
<tr>
<th>Environment</th>
<th>PRV Error Budget</th>
<th>Dispersion Image Motion at Detectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001 °K Soak</td>
<td>2.7 cm/s</td>
<td>5.4 Å</td>
</tr>
<tr>
<td>0.001 °K Vertical (X) Gradient</td>
<td>1.6 cm/s</td>
<td>3.2 Å</td>
</tr>
<tr>
<td>0.001 °K Lateral (Y) Gradient</td>
<td>3.9 cm/s</td>
<td>7.8 Å</td>
</tr>
<tr>
<td>External Pressure Change</td>
<td>10 cm/s</td>
<td>20 Å</td>
</tr>
<tr>
<td>Microtilt</td>
<td>7 cm/s</td>
<td>14 Å</td>
</tr>
<tr>
<td>Moisture Effects</td>
<td>10 cm/s</td>
<td>20 Å</td>
</tr>
</tbody>
</table>
3.1 Finite Element Model

A system-level model of the G-CLEF optical bench and optical assemblies was created using NX Nastran. The purpose of this model was to accurately represent mass, stiffness, and coefficients of thermal expansion (CTE) of the assembled instrument in order to determine deformations resulting from thermal, inertial, and pressure environments. Finite element displacement results were used to determine image motions at the detectors (IMAD).

Figure 13 – G-CLEF System Level Finite Element Model

3.2 Image Motion Analysis Using CfA/SAO Bisense Software

Bisense was developed by SAO engineers for the purpose of quickly evaluating the optical response of complex instrument systems subject to mechanical loads and deformations. A Zemax (optical design software) input file is read to define the optical system. The optical sensitivities for each optical surface in the system are read from a second Zemax file. The finite element geometry, deflection data, and group data defining the optics are read from a punch output file generated by finite element analysis software. A text file is read by Bisense that relates the Zemax data to the finite element output data. For evaluating image motion at the detector (IMAD) for a complete instrument system, the software determines the spatial, dispersion, and focus displacements of the beam at the detector for each selected optical surface resulting from its translational and rotational displacements as calculated by the finite element analysis. The total displacements at the detector are determined by summing contributions from all the optics. In G-CLEF image motion analysis, individual optical elements are considered to be rigid, and higher-order effects on PSF, aberrations, and wavefront errors are not considered.

3.3 Thermal Soaks and Gradients

The instrument will be maintained in a vacuum with thermal controls ensuring constant temperature of the bench and all optics within 0.001 °K for the operational life of the instrument. Finite element analyses (FEA) were conducted with
thermal soaks and gradients applied to the model. Analyses were run with CTE values for the composite optical bench ranging from -0.4 to +0.3 ppM/°K to determine IMAD sensitivity to optical bench CTE.

Figure 14 – Vertical (X-axis) and Lateral (Y-axis) Thermal Gradients Applied to G-CLEF System-Level Finite Element Model

FEA displacement results were input into Bisense software which calculated image motion at the detectors (IMAD) for the thermal soak and gradient load cases. Results show that the design is most sensitive to optical bench CTE when subjected to a lateral (G-CLEF Y-axis) thermal gradient. This gradient induces bending in the instrument structure which causes the greatest amount of image motion at the detectors in the critical dispersion direction (see Figure 15).

Figure 15 – Instrument Deformations, 0.001 °K Lateral (Y-axis) Thermal Gradient, Optical Bench CTE = +0.3 ppM/°K
Dispersion image motion as a function of optical bench CTE with a lateral thermal gradient is shown in Figure 16. In order to maintain image motions within budgeted allowable for PRV performance allowable under a 0.001 °K lateral thermal gradient, bench CTE is must be within a range of -0.15 to +0.20 ppM/°K. This sensitivity of PRV precision to optical bench CTE precluded the use Invar 36 as the material for the metering structure for the G-CLEF optical bench, as it has a CTE ranging from +0.8 to +1.8 ppM/°K. The narrow range of CTE required is achievable for a quasi-isotropic carbon fiber cyanate laminate with high-modulus carbon fibers and well-controlled fiber volume fraction. The sensitivity of PRV performance to optical bench CTE was a major consideration driving the selection of carbon fiber cyanate composite as the primary material in the optical bench structure.

A study was also done to determine CTE requirements of optical assembly structures to determine if a higher-CTE material than Invar could be used for these assemblies. Even within a tight range of CTE for the optical bench of -0.1 to +0.1 ppM/°C, Invar 36 is necessary for the metallic structures in the instrument in order to remain within PRV budgets under a 0.001 °C lateral gradient (Figure 17).
3.4 G-CLEF Tip/Tilt Relative to Gravity Vector and Accelerations During Slewing

Microgravity accelerations ($9.81 \text{ } \mu \text{m/s}^2$) were applied to the G-CLEF system level finite element model independently on x, y, and z coordinate axes to determine deformations and displacements of optical elements. Image motions at the detectors (IMAD) due to these displacements were calculated using Bisense software. The G-CLEF PRV error budget allows 7 cm/sec PRV error for changes in accelerations, equivalent to 14 angstroms IMAD in the critical dispersion direction. G-CLEF sensitivities and allowable accelerations to remain within the allotted PRV budget are shown in Table 2.

Table 3. G-CLEF PDR Design IMAD Sensitivities to Microgravity Accelerations

<table>
<thead>
<tr>
<th>Acceleration</th>
<th>Dispersion IMAD Sensitivity</th>
<th>PRV Budget</th>
<th>Allowable Change in Acceleration for PRV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Red</td>
<td>Blue</td>
<td></td>
</tr>
<tr>
<td>$1 \mu\text{g} \text{ X, G-CLEF vertical}$</td>
<td>$0.094 \text{ Å/μ-g}$</td>
<td>0.047 Å/μ-g</td>
<td>14 Å</td>
</tr>
<tr>
<td>$1 \mu\text{g} \text{ Y, G-CLEF lateral}$</td>
<td>-0.086 Å/μ-g</td>
<td>0.448 Å/μ-g</td>
<td>14 Å</td>
</tr>
<tr>
<td>$1 \mu\text{g} \text{ Z, G-CLEF longitudinal}$</td>
<td>0.499 Å/μ-g</td>
<td>-0.531 Å/μ-g</td>
<td>14 Å</td>
</tr>
</tbody>
</table>

The G-CLEF spectrograph experiences changes in acceleration during telescope slewing due to:
1. GMT azimuth axis misalignment with gravity
2. GMT azimuth track height variations
3. azimuthal and centripetal accelerations.

The GMT azimuth axis alignment tolerance with respect to the gravity vector is 116 microradians. For an observation near zenith with 180 degrees of azimuth sweep, a maximum total of 232 micro-g change in acceleration is possible on either the G-CLEF Y- or Z- axes.

GMT azimuth track height misalignments will cause the instrument to tip and/or tilt as the telescope slews. GMT azimuth track height tolerances allow a maximum of 22.2 micro-g Y-axis, 17.2 micro-g Z-axis changes in acceleration during slewing.

GMT slewing while observing at 1° zenith distance (GMT design goal) through the meridian results in a maximum of 13.5 micro-g centripetal acceleration (G-CLEF Y-axis) and a maximum of 8.7 micro-g azimuthal acceleration (G-CLEF Z-axis), as shown in Figure 18. These accelerations fall off rapidly with increased ZD angle.

$$\Delta a_{Y_{\text{max}}} = 232 \mu\text{g} + 22.2 \mu\text{g} + 13.5 \mu\text{g} = 268 \mu\text{g} \text{ (8.6 X allowable)}$$

$$\Delta a_{Z_{\text{max}}} = 232 \mu\text{g} + 17.2 \mu\text{g} + 8.7 \mu\text{g} = 258 \mu\text{g} \text{ (9.8 X allowable)}$$

The maximum changes in G-CLEF lateral and longitudinal acceleration exceed the maximum allowables to remain within PRV allowables by nearly a factor of 10. It is not seen as practical to increase the stiffness of the spectrograph structure by a factor of 10, so a leveling system was designed for the spectrograph to ensure that instrument orientation relative to gravity is maintained to the accuracy required to ensure PRV performance capability.
Vertical (G-CLEF X-axis) accelerations due to azimuth platform sag between GMT azimuth track support anchors and anchor height variations are in the range of tenths and hundredths of a micro-g and are considered negligible relative to the 149 micro-g X-axis acceleration allowable for PRV.

3.5 G-CLEF Sensitivity to Pressure Variation

The G-CLEF spectrograph is housed in a vacuum vessel which is subject to changes in atmospheric pressure between calibrations over an observation period. Analysis of barometric pressure data from the Las Campanas Observatory site suggests that a 10 millibar change in pressure over a day should represent 99.9% of statistically likely scenarios. The precision radial velocity (PRV) error budget allocation for atmospheric pressure is 20 Å IMAD in the dispersion direction. Finite element analyses were performed to get translational and rotational displacements of optical points along the red camera optical path due to 10 mbar pressure at the vacuum vessel. Bisense software was used to calculate the resulting image motion at the detector based on optical sensitivities.

The pre-PDR G-CLEF vacuum vessel design was originally designed slightly oval in cross-section (1.9m x 1.7m) to optimize use of space allocated to the instrument on the GMT azimuth platform. Analysis results showed image motions at the detectors from 10 millibar change in pressure in excess of PRV budgeted allowable by a factor of 17. FEA and Bisense analyses were used to optimize vacuum vessel design to minimize image motions due to pressure variations. Image motion at the detector due to vacuum vessel deformations under the 10 millibar pressure change was reduced from 346 Å to 92 Å by implementing a cylindrical cross-section design. A box-beam structure was incorporated into the bottom of the vacuum vessel to provide a more stable platform for the three optical bench support flexures. This further reduced image motion due to pressure variation to 23 Å, very close to the budgeted allowable of 20 Å. Bench mounting flexure orientations were modified and found to have an influence on image motions at the red and blue detectors due to pressure change, as shown in Figure 19. The bench flexures are designed to be adjustable to allow blade orientation to be optimized for IMAD performance.
3.6 G-CLEF Sensitivity to Composite Bench CME Shrinkage

The carbon fiber cyanate optical bench laminates will absorb moisture from the atmosphere, which causes the material to expand according to moisture uptake and laminate CME (coefficient of moisture expansion). When the instrument is installed and the vacuum vessel evacuated, this moisture will be drawn out of the composite laminates causing them to shrink. The rate of shrinkage is initially at a maximum but decays over time. A vendor-supplied relationship for diffusion as a function of time was used to characterize this shrinkage. The laminate dry-out time required to ensure that PRV error due to CME effects is within budgeted allowable was calculated using FEA and Bisense software. For the longest anticipated 12-hour calibration/observation/calibration time span, the dry-out time was calculated to be 123 hours, assuming laminates initially saturated at 50% relative humidity, with 0.15% moisture content. For a 1-hour calibration/observation/calibration time span, the CME effect is within the allowed budget immediately after the instrument is subjected to vacuum in the vacuum vessel, with no dry-out time required.

Figure 19 – Image Motion due to 10 mbar Pressure Variation vs. Spectrograph Mounting Flexure Orientation

Figure 20 – Carbon Fiber Cyanate CME Shrinkage over Time, Initially Saturated at +0.15% Moisture Content
4. CONCLUSIONS

We are designing and building the G-CLEF instrument to meet a PRV precision goal of 10 cm/s. We have identified the major structural design challenges to meet this goal while the instrument is subjected to changing thermal, inertial, and pressure environments at its mounted location on the GMT azimuth platform during observations. The choice of carbon fiber cyanate composite materials as the primary material in the optical bench structure will enable us to meet this performance goal while being subjected to microKelvin soaks and temperature gradients. A leveling system has been designed for the instrument based on analysis results showing that maintaining PRV precision to 10 cm/s during slewing will require maintaining instrument orientation relative to the gravity vector within 26 micro-radians, which is smaller than the GMT azimuth axis alignment tolerance to gravity. Analysis has shown that instrument sensitivity to pressure changes may be easily tuned with bench support flexure orientations, which led to an adjustable design for these flexures. We are confident that the G-CLEF team is on track to present a robust critical design as scheduled in May 2017.

REFERENCES