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The GMT-CfA, Carnegie, Catolica, Chicago Large Earth Finder (G-CLEF): A General Purpose Optical Echelle Spectrograph for the GMT with Precision Radial Velocity Capability

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ABSTRACT

The GMT-CfA, Carnegie, Catolica, Chicago Large Earth Finder (G-CLEF) is a fiber fed, optical echelle spectrograph that has undergone conceptual design for consideration as a first light instrument at the Giant Magellan Telescope. G-CLEF has been designed to be a general-purpose echelle spectrograph with precision radial velocity (PRV) capability. We have defined the performance envelope of G-CLEF to address several of the highest science priorities in the Decadal Survey[1]. The spectrograph optical design is an asymmetric, two-arm, white pupil design. The asymmetric white pupil design is adopted to minimize the size of the refractive camera lenses. The spectrograph beam is nominally 300 mm, reduced to 200 mm after dispersion by the R4 echelle grating. The peak efficiency of the spectrograph is >35% and the passband is 3500-9500Å. The spectrograph is primarily fed with three sets of fibers to enable three observing modes: High-Throughput, Precision-Abundance and PRV. The respective resolving powers of these modes are R~ 25,000, 40,000 and 120,000. We also anticipate having an R~40,000 Multi-object Spectroscopy mode with a multiplex of ~40 fibers. In PRV mode, each of the seven 8.4m GMT primary mirror sub-apertures feeds an individual fiber, which is scrambled after pupil-slicing. The goal radial velocity precision of G-CLEF is $\partial V < 10$ cm/sec radial. In this paper, we provide a flowdown from fiducial science programs to design parameters. We discuss the optomechanical, electrical, structural and thermal design and present a roadmap to first light at the GMT.

Keywords: Echelle spectrograph, precision radial velocity, high dispersion spectroscopy, exoplanets, G-CLEF, GMT

1. INTRODUCTION

The GMT-CfA, Carnegie, Catolica, Chicago 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. The G-CLEF collaboration consists of the Smithsonian Astrophysical Observatory, Pontificia Universidad Católica de Chile, University of Chicago, Harvard University and the Observatories of the Carnegie Institution of Washington.

G-CLEF has been designed to simultaneously satisfy the need for a general purpose high dispersion spectrograph meeting the requirements for a high resolution visible spectrograph (HRVS) and a precision radial velocity spectrograph (PRVS). These requirements are set forth in GMTO documents #1987[2] and #1982 [3].

While G-CLEF is designed to be a powerful instrument for a broad range of astrophysical investigations, we have defined the performance envelope of G-CLEF to address several of the highest science priorities in the most recent Decadal Survey. These are:

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- A census and characterization of the most metal poor halo and Local Group dwarf galaxy stars
- The discovery and characterization of exoearths and exosolar systems, especially habitable planets
- Abundance in and evolution of galaxies in the Local Group and beyond
- Probing the IGM and ISM at high z

While G-CLEF will be a powerful tool for many scientific programs, we have chosen to focus on programs that are specifically enabled by the large GMT aperture, where G-CLEF on the GMT crosses new thresholds of discovery space.

In Table 1, we illustrate how these science goals translate into instrument performance parameters:

Table 1: G-CLEF performance parameters required to achieve key science objectives.

Science Goal	Required Performance Parameter
Abundance studies Detection and census of metal poor stars	High resolution Extended blue response to 3500Å
High z IGM and ISM/Gamma Ray Bursts	Rapid instrument changeover Extended red response
Exoearth science	Very high resolution Long term wavelength stability
Detailed chemical composition beyond the Local Group	Long slit length for multiobject capability

A final, non-scientific design consideration is cost. While it was possible to include deep UV and NIR capability to G-CLEF, it was determined at a fairly early phase in the program to limit the passband of G-CLEF so as to control cost. The top-level properties of the G-CLEF design are listed in Table 2.

Table 2: Top-level G-CLEF properties and rational. †As compared with a four camera design.

Spectrograph Property	Motivation
Fiber Feed	PRV stability
Asymmetric White Pupil Design	PRV resolution, reduce technical risk and cost†
Two Camera Design	Good red and blue response, reduce cost
Vacuum Enclosure	Thermal/ambient index of refraction stability
Short Fiber/Simple Feed	Good blue response

The Australian Astronomical Observatory (AAO) is developing a multi-object feed for the GMT called the MANy Instrument FibrE SysTem (MANIFEST)[4]. The G-CLEF team has maintained an interface to MANIFEST since the beginning of concept design. G-CLEF will have a multiobject capability with a multiplex advantage in the range of 40 simultaneous objects with MANIFEST.

2. G-CLEF SYSTEM DESIGN

The conceptual design for G-CLEF was informed by several considerations. G-CLEF was to satisfy the requirements of both the HRVS and PRVS instruments described in the call for proposals[5] for conceptual designs for GMT instruments.

The requirements for a PRVS capability drove the positioning of G-CLEF to the only gravity invariant, co-moving location on the GMT, the Coudé Platform. G-CLEF will only be fiber fed (see Figure 1). After several attempts to design a Coudé-like feed that would enable a slit feed at this position, the design team concluded such a feed would drive cost and complexity to a level that would exceed the funding available for a first light echelle spectrograph, while providing only a small performance boost.

To maximize throughput at the blue end of the passband, we minimize the G-CLEF fiber run by locating the telescope interface (the front end) on the Instrument Platform (IP). A second fiber run to a multiobject spectroscopic (MOS) feed, the MANIFEST, at the Gregorian focus is being studied in collaboration with the AAO instrument team to provide a MOS capability for G-CLEF.

A paramount consideration in the design of G-CLEF was preservation of good blue and red response. As we have previously discussed, several key stellar astronomy programs require high efficiency to a blue limit of 3500Å, while many cosmology programs are enabled by good red response. Given the dense complex telluric absorption features that dramatically reduce atmospheric transmission between 9400Å & 9800Å, the red performance limit is chosen to be 9500Å. This broad operational passband drives the spectrograph to a two-camera model with a red and blue beams split with a dichroic in the parallel beam.

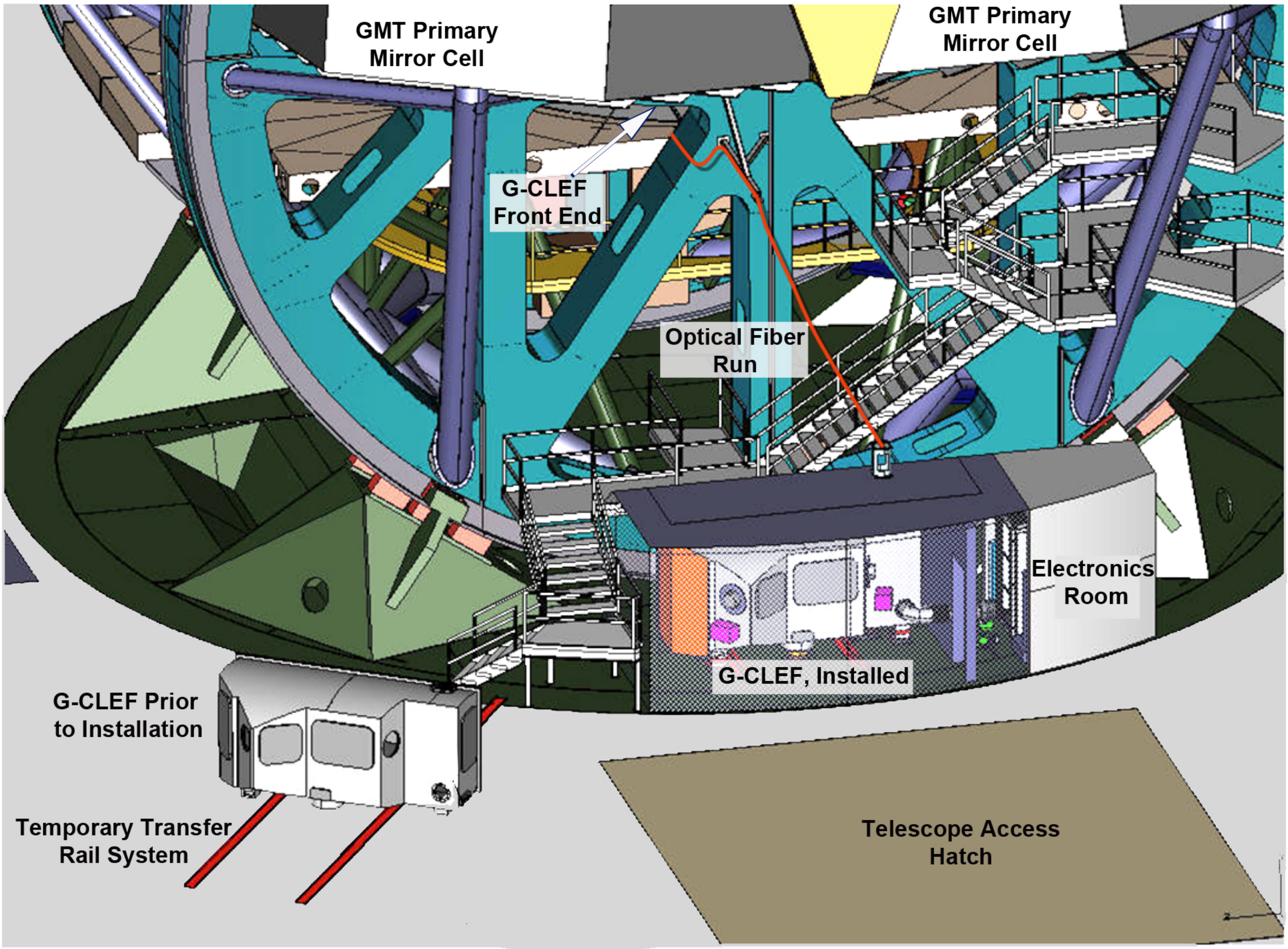

Figure 1: G-CLEF as mounted on the GMT and staged for mounting.

Wavelength scale stability is paramount for many of the science programs to be undertaken with G-CLEF, which implies high thermal and mechanical stability. After a considerable amount of study and debate, the G-CLEF team has decided the only practical way to stabilize the index of refraction of the ambient medium and maximize thermal stability is to enclose the spectrograph in a vacuum (see Section 4.). PRV performance depends on a complex interplay of several parameters, especially spectrograph pupil "whiteness", the slit image anamorphism, resolution, guiding quality and thermal stability, as well as other intrinsic optical design properties. The G-CLEF design will balance these factors, to deliver the most precise velocimetry possible.

A parallel program at CfA[6] to improve calibrators and engineer better fiber systems for high wavelength scale stability observations has been in progress for five years, funded externally. It is our expectation that advances in calibrators and fiber systems will effect significant improvements in wavelength scale calibration precision, thus increasing achievable RV precision[7].

A particularly vexing issue for high dispersion MOS observations is that of calibration. We have been investigating the possibility of applying ultrastable etalons[8], large iodine cell projectors and tunable lasers[9] to improve the quality and speed of MOS echelle calibration. We will continue to evaluate the efficacy and the appropriateness of these calibrators during the design phase of the program, contingent on a MOS feed being selected for first light at the GMT.

Most importantly, our goal is to develop a design that is extremely cost and risk controlled, so we can deliver a first light instrument on a tight schedule and budget. The single most expensive component or components of an ELT echelle is the echelle grating. G-CLEF will have a single echelle grating. A cost emphasis led the instrument team to look critically at the use of aspheres and anamorphs, coating requirement and refractive element substrate size. The current design has several aspheric optical surfaces in the camera optical designs, however the asphere count has been minimized and their form has been simplified to the greatest extent possible.

G-CLEF consists of several major subsystems (see Figure 2):

1. The spectrograph itself, which has several fiber slits that are the optical interface to the telescope.
2. A thermal enclosure and vibration isolation system that are the thermal and mechanical interfaces to the telescope.
3. Several distinct fiber feeds that provide a variety of observational capabilities. One set of fibers runs to the telescope interface ("front end") on the IP, all of which are for single-object observations. A second set of fibers, supplied by the MANIFEST MOS team, run to a MANIFEST feed at the Gregorian focus for multi-object observing.
4. The front end that is the optical interface to the telescope and the calibration system.
5. A calibration system will be an integral part of the G-CLEF design, although it could be trivially shared with other GMT instruments. The IP and Gregorian locations will have different calibration system configurations.

A summary of the top-level design parameters of G-CLEF is presented in Table 3.

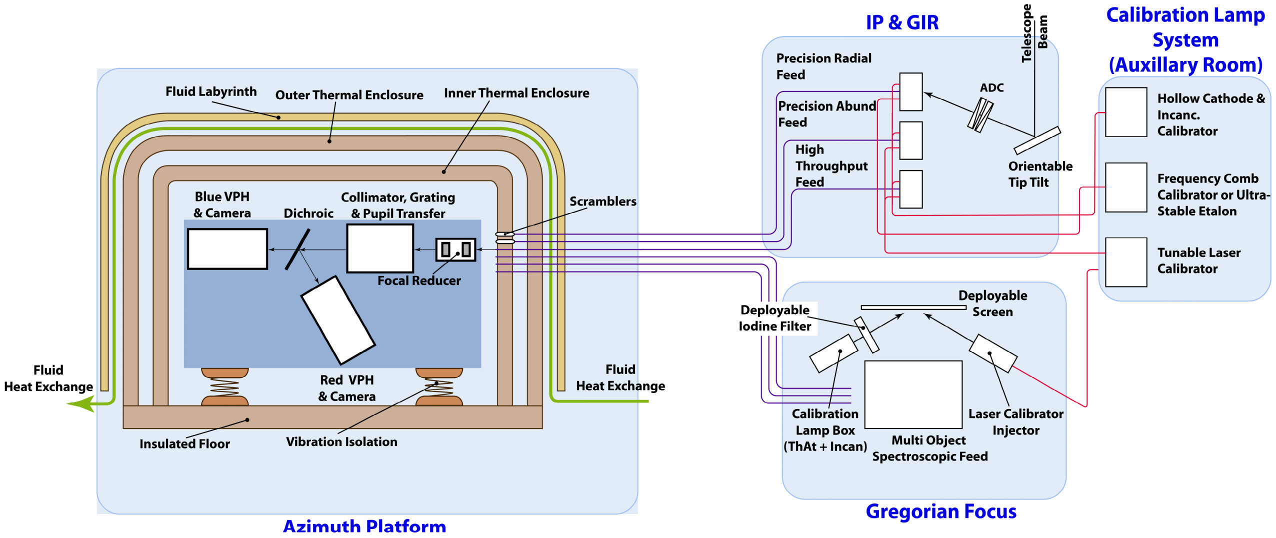

Figure 2: System diagram of G-CLEF

Table 3: G-CLEF Design Parameters

Parameter	Value	Parameter	Value
Modes	HT, PA, PRV & MOS	Cameras	Red & Blue
Res	25k, 40k & 120k	Input f/#	f/8
Peak Efficiency	> 35%	Camera Beam Diameter	200mm
Passband	3500Å-9500Å	Derotation?	No
Calibration	Contin., ThAr, I_2, Ultrastable Etalon	ADC?	Yes
Apertures	25.4m & 7 x 8.4m	Band Limiting Filters?	Yes
Grating	300mm x 1200mm, R4		

The G-CLEF fiber feeds (see Table 4) will enable the broadest range of G-CLEF scientific missions. At present we envision the following distinct fiber feeds:

The High Throughput (HT) Feed maximizes the light collecting efficiency of G-CLEF. The resolution is currently planned to be 25,000. The HT will not have pupil slicing, image slicing or scrambling. The f/4 input will accept the entire 25.4m GMT aperture in a single fiber, providing a 1.2 arcsec diameter slit on the sky.

The Precision Abundance (PA) Feed provides higher resolution (R~40,000) than the HT Feed, especially designed for stellar abundance investigations by reducing the slit size, hence the light collection efficiency. This will be implemented in the same manner as the HT Feed, with a smaller diameter fiber 0.7 arcsec, set to be slightly larger than the median seeing at Las Campanas.

A Precision Radial Velocity (PRV) Feed will be pupil-sliced into seven 8.4m subapertures. These fibers will provide an R>100,000. The diameter of the fiber has been also set to median seeing – 0.7 arcsec. This channel will be scrambled to maximize wavelength scale stability.

We provide for the possibility of a High Resolution (HR), image sliced feed, where a 1” image delivered by the full primary aperture will be sliced seven-fold to achieve 150,000. This mode may also be scrambled, depending on the outcome of sensitivity analysis during the design phase.

Feeds from the MOS Fiber System will deliver resolution 40,000, and may potentially implement an IFU or Extremely High Resolution Mode.

Table 4: Baseline G-CLEF fiber feed parameters.

Feed	**Resolution**	**Fiber Dia. (μ)**	**Fiber Dia. (arcsec)**	**Comments**
HT	25000	1220	1.2	
PA	40000	711	0.7	
PRV	120000	230	0.7	Pupil Sliced & Scrambled
MOS	40000	711	0.7	

The G-CLEF front end provides an interface to the telescope and G-CLEF calibration system, excluding the MANIFEST MOS feed, which has its own fiber system. G-CLEF will have a dedicated, deployable tertiary that will have tip-tilt functionally to compensate telescope flexure and fine guiding errors. The front end relay optics will feed the science fibers at f/4. They also deliver the telescope focal plane to the guide system. An atmospheric dispersion compensator is also in the front end optical design.

The G-CLEF calibration system is located in the electronics room on the Coudé platform and the calibration beam is delivered to the science fiber inputs on the IP by calibration optical fibers. The calibration beam is injected into the science fiber with deployable folds and the transfer system includes optical relays that match the telescope beam focal ratio and simulate the telescope pupil.

The baseline calibrators will be I_2 cells and ThAr lamps, however we find the potentialities of ultrastable calibrators, tunable lasers and possibly frequency combs are extremely attractive. The calibrator design will include interfaces for these advanced calibrators.

3. G-CLEF OPTICAL DESIGN

3.1 Spectrograph Optical Design

The overarching design choice for the G-CLEF spectrograph is that of an asymmetric white pupil. This design was adopted to minimize the size of camera lenses and achieve a pupil-sliced resolution of R □ 100,000. A particular issue for the manufacture of the camera lenses is the manufacturability of the optical quality glass substrates, since the large sizes required for ELTs are near the outer envelope of global industrial capability. A further consideration is the opportunity this design paradigm offers to optimize cross-disperser angular dispersion to improve overall efficiency. A schematic of the spectrograph layout appears in Figure 3.

The input beam is collimated by an off-axis parabola (M1), dispersed at the echelle grating and reconverged by the collimator, which is used in double pass. A fold then directs the beam to the pupil transfer mirror (M2). The beam diameter is reduced by the ratio of the focal lengths of M1 and M2. In the case of G-CLEF, these are 2400 mm and 1600 mm respectively, effecting a reduction in the beam size from 300 mm to 200 mm. The parallel beam then forms a "white pupil" on a dichroic, which splits the passband of the spectrograph into the red and blue camera. The properties of the spectrograph optical design are summarized in Table 5.

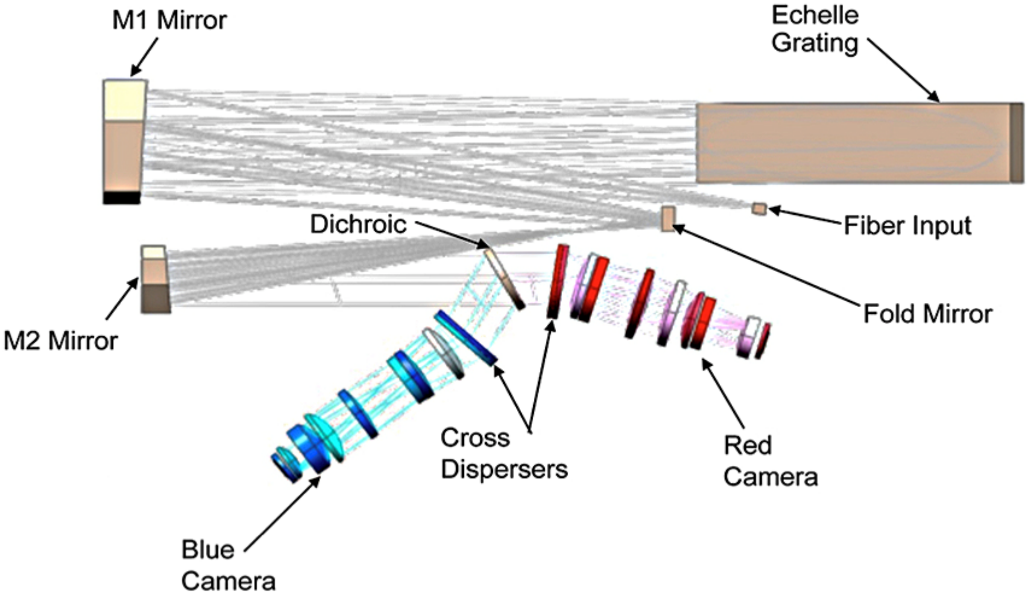

Figure 3: G-CLEF Spectrograph optical layout.

Table 5: G-CLEF spectrograph optical design parameters.

Parameter	Value	Parameter	Value
Design	Asymmetric white pupil	Configuration	Bench Mounted Fiber Fed
Spectrograph Footprint	1.7 m x 3.6 m	Echelle Grating Pitch	31.6 lpm
Collimated Beam Size	300 mm	Passband	3500-9500Å
Coll. Beam Focal Ratio	f/8	Echelle Grating Size	300 x 1200 mm
Blaze Angle	75.96° (R4)	Pupil Demagnification	1.5
Camera Lens Count	8 lenses	Echelle Geometry	Littrow
Camera Beam Size	200 mm	Camera Focal Length	500 mm
Usable Input FOV	30 mm dia.	Camera Focal Ratio	f/2.5
Cross disperser	VPH	Dichroic Split	5300Å
Blue Camera Passband	3500-5300Å	Red Camera Passband	5300Å-9500Å
Blue VPH Ruling Pitch	925 lpm	Red VPH Ruling Pitch	415 lpm
Blue VPH Diffr. Angle	11.9°	Red VPH Diffr. Angle	8.9°
Blue Echellogram Order Separation (min/max)	3.0/9.7 arcsec	Red Echellogram Order Separation (min/max)	3.3/6.9 arcsec
CCD Size	6k x 6k pixels	CCD Pixel Size	15µ

The collimator mirror is operated in double pass and is an off-axis paraboloid. The focal length is 2400 mm. Since the collimator will be diced out of a 1094 mm parent parabola, we will have the opportunity to get a spare optic if needed (or pick the best subaperture on the parent.)

The echelle grating is R4 with a 36.1 lpm ruling density. The size of the echelle is 300 mm x 1200 mm. Given that the largest monolithic grating that Richardson Grating Laboratory (RGL) can rule is 300 mm x 400 mm, the G-CLEF echelle will need to be a triple mosaic of grating rulings. We are exploring the possibility of having RGL replicate all three rulings onto a single substrate.

The pupil transfer mirror (M2) is an off-axis conic with a conic constant of -0.93, which is almost a paraboloid. The focal length of M2 is 1600 mm. The footprint on M2 is roughly rectangular. We have apodized the clear aperture and envelope of M2 to just fit the beam footprint for reasons of weight and fit to the other spectrograph optical elements.

The dichroic is a flat with a 272 mm diametral clear aperture. We have chosen the wavelength split to be at 5300Å, thus balancing a number of considerations including requirements on the camera designs, interorder spacing in the echellograms and grouping of key spectral features within a single echellogram.

The cross dispersers will be volume phase holographic (VPH) gratings. This choice was made principally based on the size and cost of the alternative prisms that would be required to achieved the necessary dispersion.

The red and blue VPH grating have 415 & 925 lpm ruling densities, respectively. The angles of incidence are 8.9° and 11.9°, respectively. At present a single vendor – Kaiser Optical Systems - has been responsive to our request for quotation.

The red and blue camera optical layouts are shown in Figure 4. The design consists of eight, mostly spherical, elements, with the exception of the first and last element in each camera. In each case the first element of both cameras is a mild, even polynomial asphere. The first element is calcium fluoride in both cameras, so the asphere can be machined rather than polished. We have received quotations from several credible vendors and the cost of these lenses is not exceptional. The last element is plano/toroid. Both this last lens and the focal plane are slightly tilted to compensate non-axisymmetric aberrations produced by the overall design. While this present a challenge during alignment, this sort of design has been executed successfully in many other instruments, e.g. UVES[10] and HARPS[11].

Given the cost of the individual lenses, we recentered the lens barrel and have introduced mild off-axis vignetting to reduce the individual lens sizes. Vignetting starts to cut on at a field angle of 1.8°.

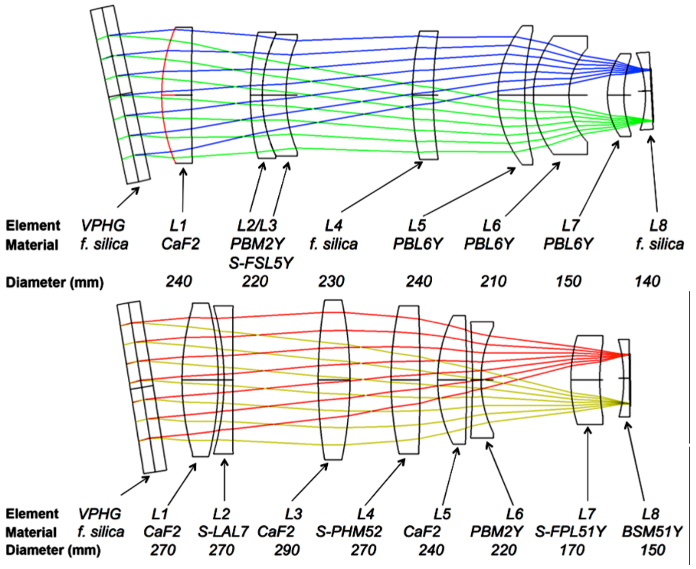

Figure 4: G-CLEF camera lens layout. Top: Blue arm camera, Bottom: Red arm camera.

The red and blue channel echellograms appear in Figure 5. They can be seen to fit well onto the 6k x 6k, 15µ pixel CCD format that is the G-CLEF baseline. The minimum order spacing, at the bluest order of the blue camera is 3.0 arcsec.

This gap is large enough to accommodate the two 1.2 arcsec HT fibers with a clean null between them. The same is true for the PA mode and the PRV mode. In the PRV mode, the telescope pupil has been sliced into seven 8.4m diameter subapertures, thus effectively tripling the interorder spacing. In the case of the MOS mode, order-selecting filters will reduce the bandwidth to one or a few orders at most, making it possible to squeeze many more orders on the format.

The imaging performance of G-CLEF is summarized in a map of the RMS spot diameter over each echellogram, shown in Figure 6. The spots are quite tight (5-7μ) over most of both formats. They only get larger than 15μ in a very limited region of the CCDs. This is to be compared with the 15μ pixel size and oversampling of the resolution elements in all resolution modes.

An important consideration for the calibration of the wavelength scale is the shape of the resolution element, which is perturbed from an ideal circular shape by aberrations and anamorphism. A particular virtue of a Littrow, white pupil design is that it tends to minimize these effects; however some residual distortion of the pupil image is inevitable. We characterize this distortion by the shape factor. This factor is calculated as the ratio of the minimum to maximum elongation, where a shape factor of 1 corresponds to circular slit image and a shape factor of 0.25 indicated a factor of four elongation. Even the worst shape factors are larger than 0.5 and the shape of the slit image is minimally distorted over most of the echellograms.

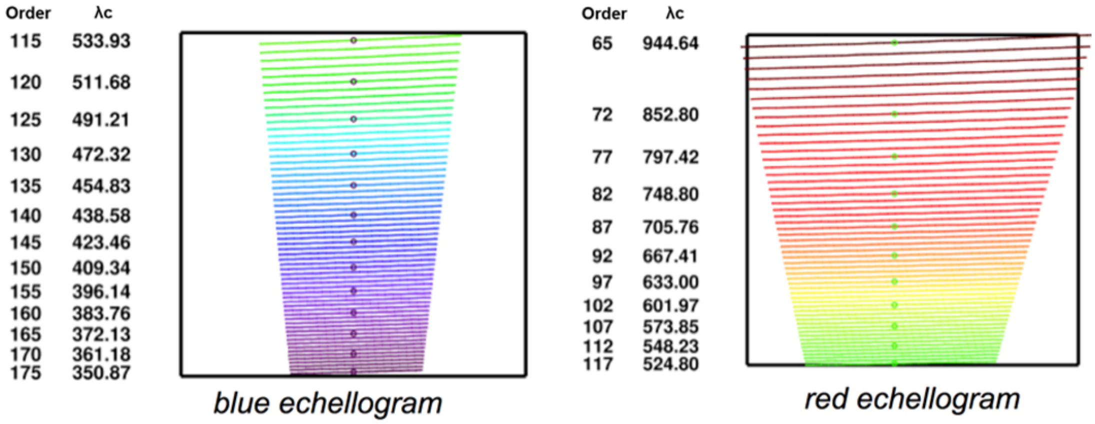

Figure 5: G-CLEF echellograms. The black outline indicates the format of the baseline, monolithic CCD that will constitute the G-CLEF focal plane.

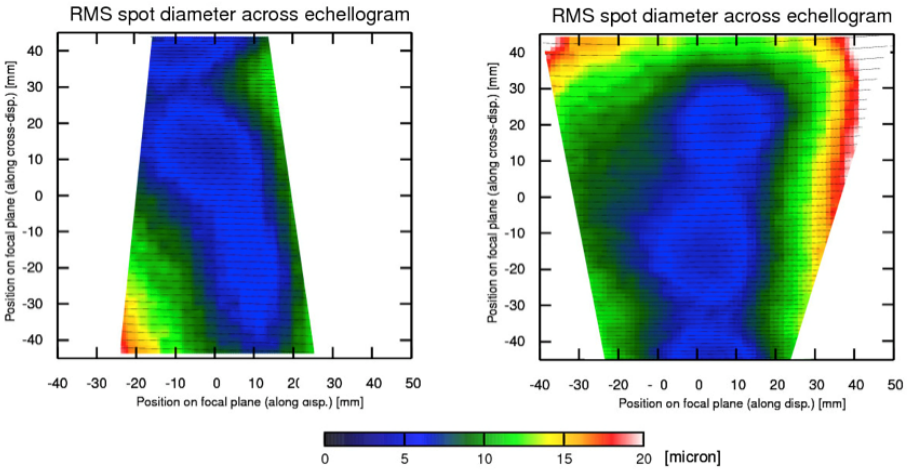

Figure 6: Predicted imaging performance of the G-CLEF cameras, i.e. maps of the PSF across the focal plane.

A positive aspect of a two-camera spectrograph design is that red and blue optimized CCDs can be used in the red and blue arms, thus increasing the overall efficiency of the spectrograph.

The overall efficiency of the spectrograph is plotted in Figure 7. Both the spectrograph alone and the spectrograph efficiency with all attendant losses (e.g. slit losses for a 0.7 arcsec slit, telescope reflectivity, etc.) are plotted.

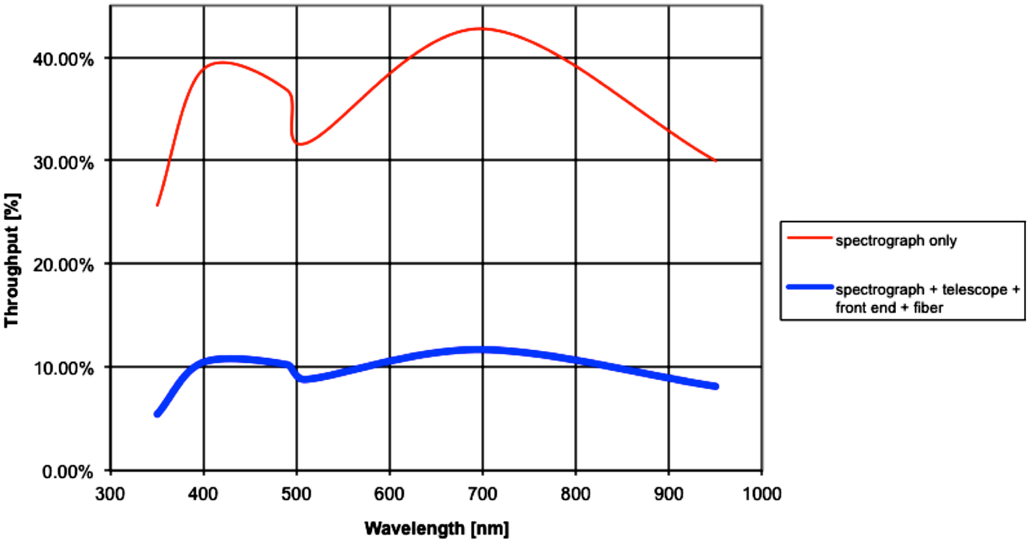

Figure 7: Efficiency of the G-CLEF spectrograph (red/thin line) and with the losses associated with the telescope included (blue/thick line).

3.2 Front End Optical Design

The G-CLEF Front End, i.e. the interface between the GMT and the G-CLEF fiber system, is shown in Figure 8. The Front End is mounted on the GMT IP, just below the primary mirror. The f/8 telescope beam is folded through 90° by a flat tertiary. The tertiary is mounted on a fast tip-tilt stage to compensate flexure of the IP and guiding errors.

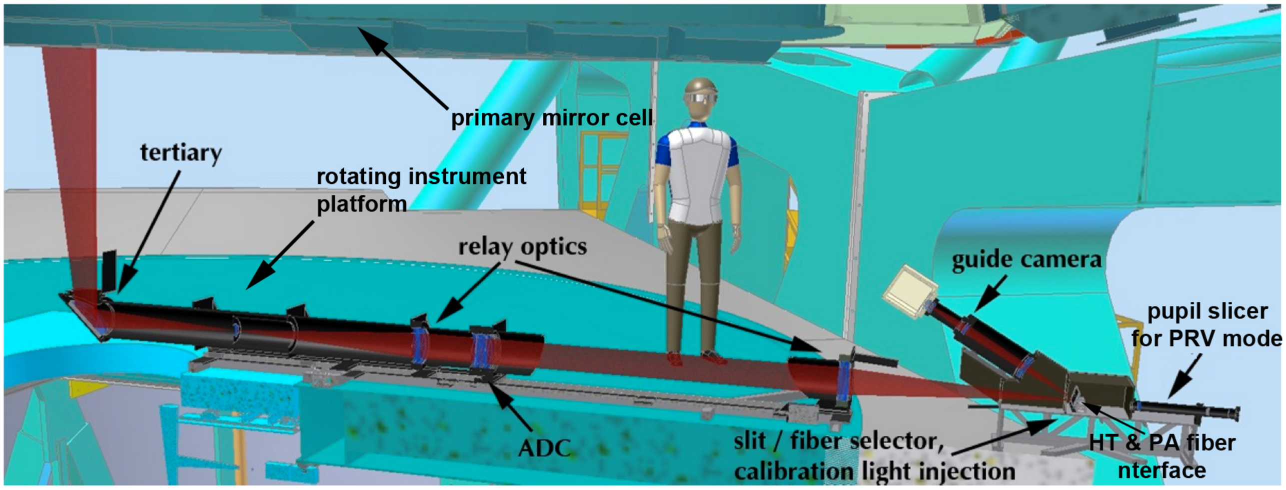

Figure 8: Overall Front End optical layout.

The optical designs of the various subsystems of the Front End are shown in Figure 9. The layout of the relay system appears in the topmost panel. A plano tertiary folds the f/8 telescope beam through 90° to a field stop at the focal plane of the telescope. The beam then passes to the first element of the relay system, which parallelizes the beam and transfers it to the second relay element. The atmospheric dispersion compensator, a pair of counter-rotating, zero deviation prisms is located between the two relay system doublets, 300 mm aft of the first element (see Panel B, Figure 9). The relayed beam is restored to f/8 for transfer to the system focal plane. The third panel from top, Panel C show the design of the guide system. The fiber slits will be embedded in a plano mirror that folds the beam and delivers the focal plane "scene" to the guide system. The optical train is 600 mm and images a square guide field 1 arcmin on a side. A filter is included in the guide optical train to improve image quality.

For the PRV mode, it is necessary to slice the GMT pupil into individual 8.4 m subapertures. The design of this optical system is shown in Panel D and the positioning of these optics, behind the system focal plane is also shown in Figure 8.

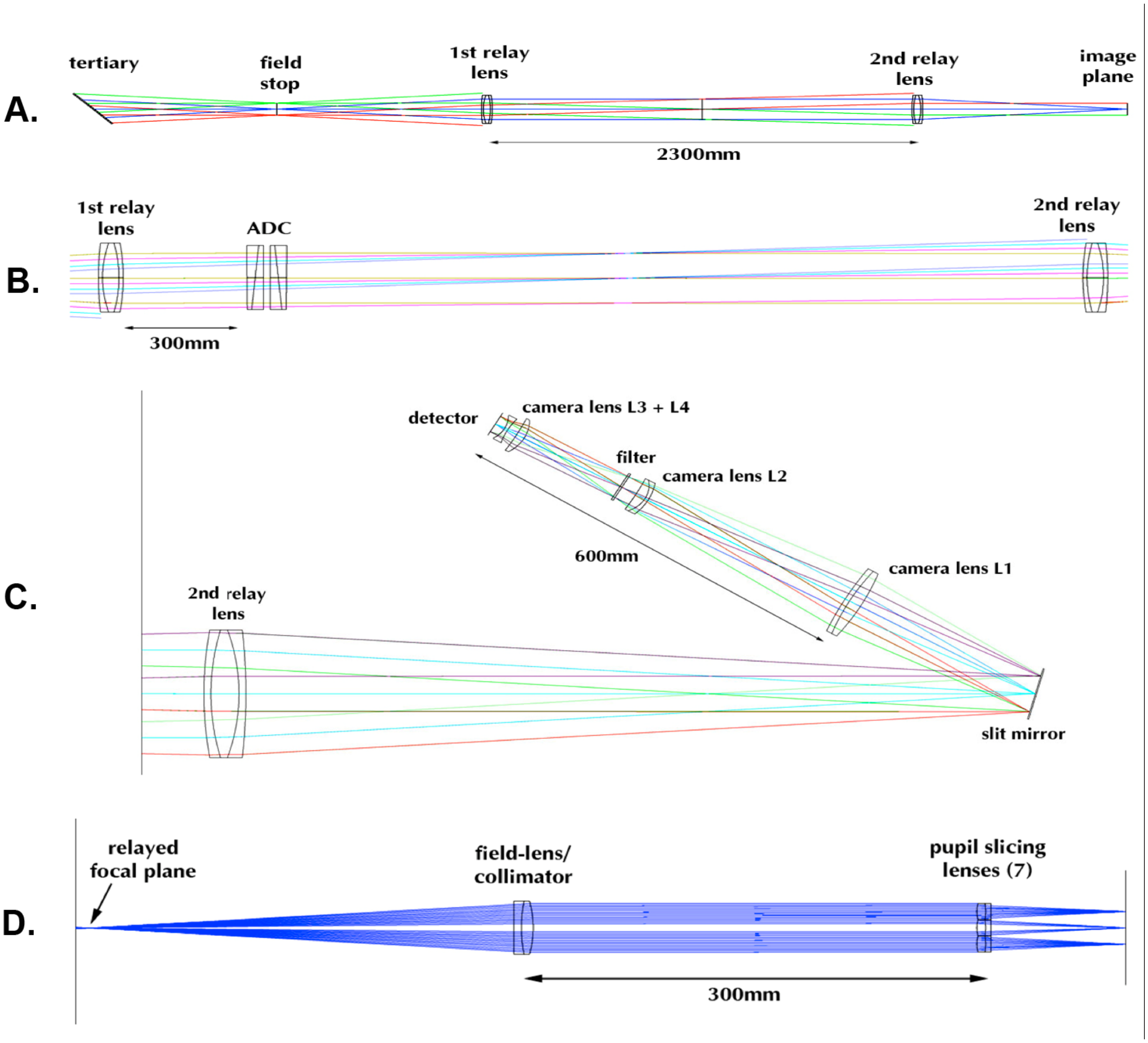

Figure 9: Front End Optical Designs. Panel A. Optical relay from plano tertiary fold to image plane. Panel B. Implementation of atmospheric dispersion compensator. Panel C. Guide system optical design. Panel D. Pupil slicing optics.

4. G-CLEF THERMO-MECHANICAL DESIGN

4.1 Spectrograph Thermo-Mechanical Design

The design of the G-CLEF spectrograph presents several significant design challenges, especially:

1. The stability requirements imposed by the goal of achieving the highest possible radial velocity precision.
2. Arriving at a design for the aperture of the largest optical telescope in the world with an affordable cost envelope.

The G-CLEF target velocity precision of <10 cm/sec implies a stability of the echellogram on the focal plane of ~150Å over decadal operational time scales. Both thermal and mechanical stabilization are paramount requirements. A target thermal stability of ±0.001°C for the spectrograph has been established based on the experience other PRV instrumentation teams, especially the HARPS[11] and PFS[12] teams. G-CLEF, like PFS, will have to be deployed in the telescope dome (see Figure 1). While the spectrograph will have to be operated at single control temperature year-round, the outermost shell of the thermal enclosure cannot leak more than ~100W into the GMT dome irrespective of dome ambient temperature. We illustrate the concept for the multilayer thermal design in Figure 10 that modeling indicates will satisfy these two requirements for internal temperature stability and external heat leakage.

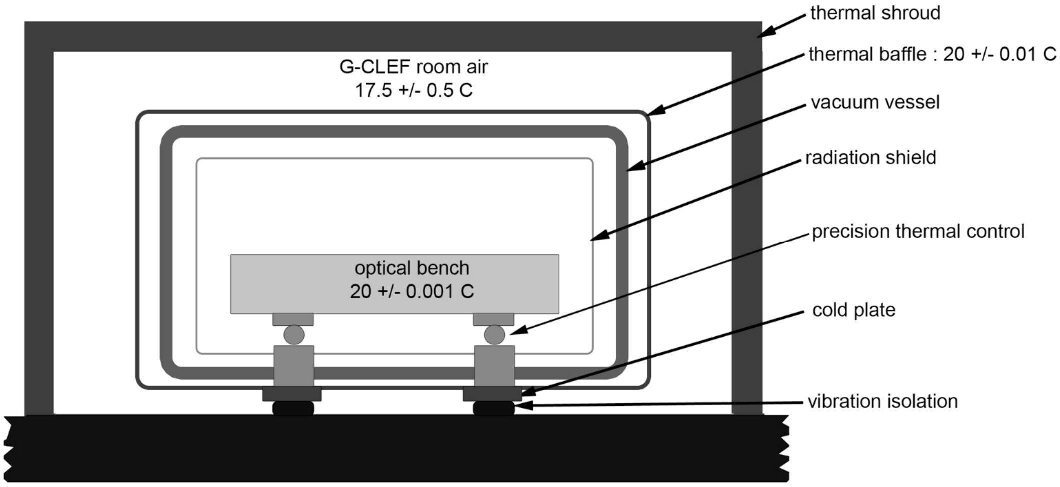

Figure 10: Schematic of G-CLEF thermal enclosure design.

A key feature of the thermal design is the vacuum enclosure that houses the spectrograph and a radiation shield. This offers a high degree of immunity to thermal gradients within spectrograph structure and stabilizes the index of refraction of the ambient medium of the spectrograph to that of vacuum. The performance of the thermal control system has been modeled in considerable detail with the Thermal Desktop analysis package. Environmental inputs are thermal time strips at 5 minute sampling obtained for telescope dome environments on La Palma. This environment is very similar to the thermal environment we expect at Las Campanas in the GMT dome. We further impose a restriction that no sources or sinks of heat are present within the spectrograph vacuum enclosure with the sole exception of the subsystems associated with the CCD focal planes. By closely controlling all thermal paths to ground and leveraging on the experience of the PFS and HARPS teams we expect our thermal control goals are eminently achievable.

The mechanical layout and vacuum enclosure of the G-CLEF spectrograph are shown in Figure 11. The optical bench is a custom design that will be fabricated out of Invar plate. The vacuum vessel will be fabricated out of mild steel and has been the subject of extensive thermal and structural analysis. We have used the VacTran Vacuum System Modeling software package to determine how frequently the vacuum system would have to be re-pumped to stay below the 1 millitorr level. The vacuum hold time is ~25 hours, so pumping will only occur when the spectrograph is not in use.

In Figure 12 and Figure 13 we illustrate several of the mechanical subsystem designs that exemplify the overall design approach we have adopted for G-CLEF. The mechanical design of the blue arm camera is shown in Figure 12. Most lenses are mounted in individual bezels with tangential flexures. In both lens designs, there is a closely spaced doublet that is mounted in a single bezel. The bezels themselves will be Invar, the flexures will probably be titanium and the nubs that are bonded to the lenses themselves will be selected based on their match to the coefficient of thermal expansion of the glass used for each lens. The VPH grating cross disperser is mounted at the input end of the lens barrel and is mounted the same way as the lenses.

In the left panel of Figure 13, we show a conceptual design for the focal plane CCD mounting. This mount will interface to a cryostat modeled on the ESO continuous flow cryostat design[13] that is used in both HARPS spectrographs. The expected electrical interface to the CCD is a pair of flexible Kapton ribbons similar to that in use by E2V for their 4k x 4k CCD 231 devices[14].

A particular challenge for the design of a PRV spectrograph for a large telescope aperture is obtaining an echelle grating large enough to meet the size and stability requirements of to achieve the required resolution (R ≥ 100,000) and precision ($\partial v < 10$ cm/sec). The format we require for G-CLEF echelle grating is 300 mm x 1200 mm, which requires a triple mosaic of the 300 mm x 400 mm rulings that are the largest size monolithic surface relief diffraction gratings that RGL can produce. We have adopted a three-pronged approach to obtaining the G-CLEF echelle grating. We are currently studying the possibility of extending the technology RGL has developed for double mosaic gratings used in UVES, HARPS and the SALT HRS[15] to permit triple mosaics. We consider this approach to be the best technically, but also the highest risk. An alternative concept is illustrated in Figure 13, in which individual 300 mm x 400 mm Zerodur echelle tiles are bonded or optical contacted to a monolithic Zerodur substrate with Zerodur spacers. This concept would effectively have an all-Zerodur stack-up controlling the alignment between the individual facets and would eliminate the possibility of thermally-induced misalignment. We regard this option as potentially lower risk than a monolithic mosaic, but potentially lower performance. We have also developed a “zero technical risk” mosaicking scheme that is based on the mechanical metering used to build the HIRES[16] echelle triple mosaic, where registration is achieved with preloaded metering details bonded to a thick substrate. This option would, however, introduce some performance risk.

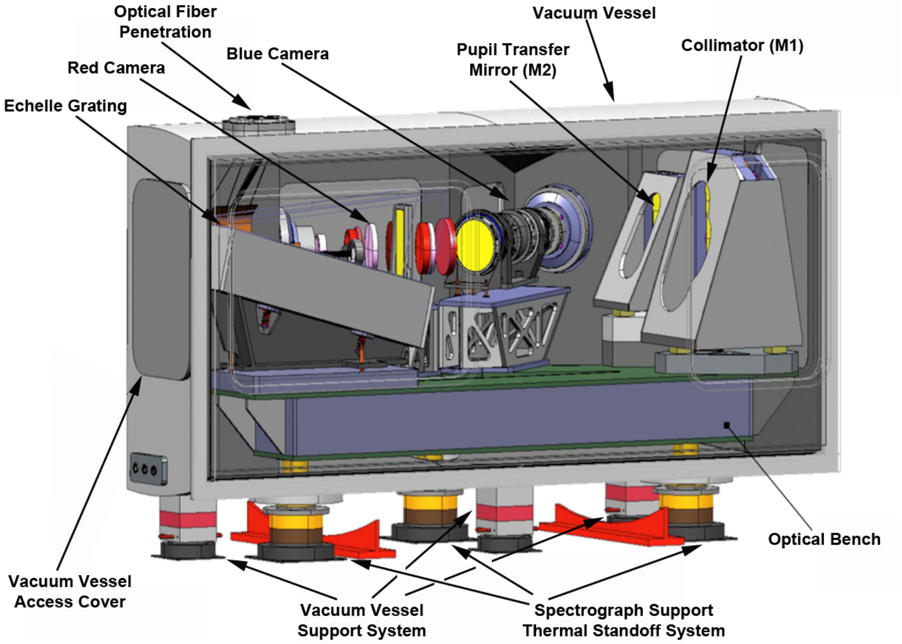

Figure 11: Mechanical design of the G-CLEF spectrograph and vacuum enclosure.

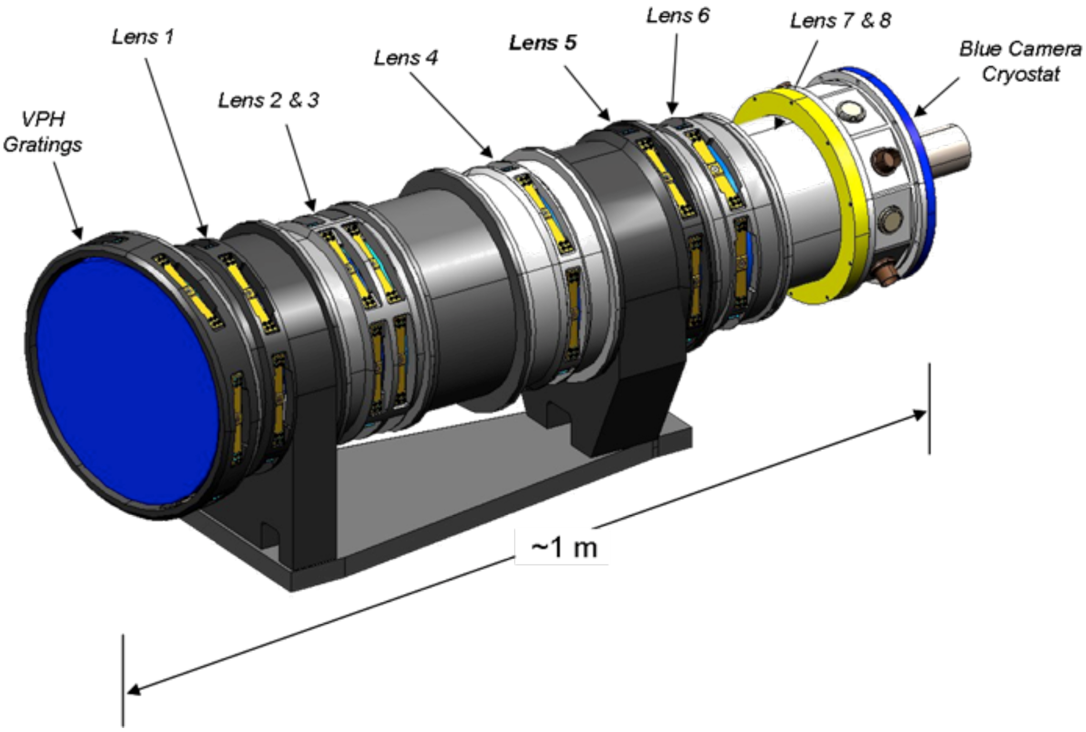

Figure 12: The mechanical design of the blue camera.

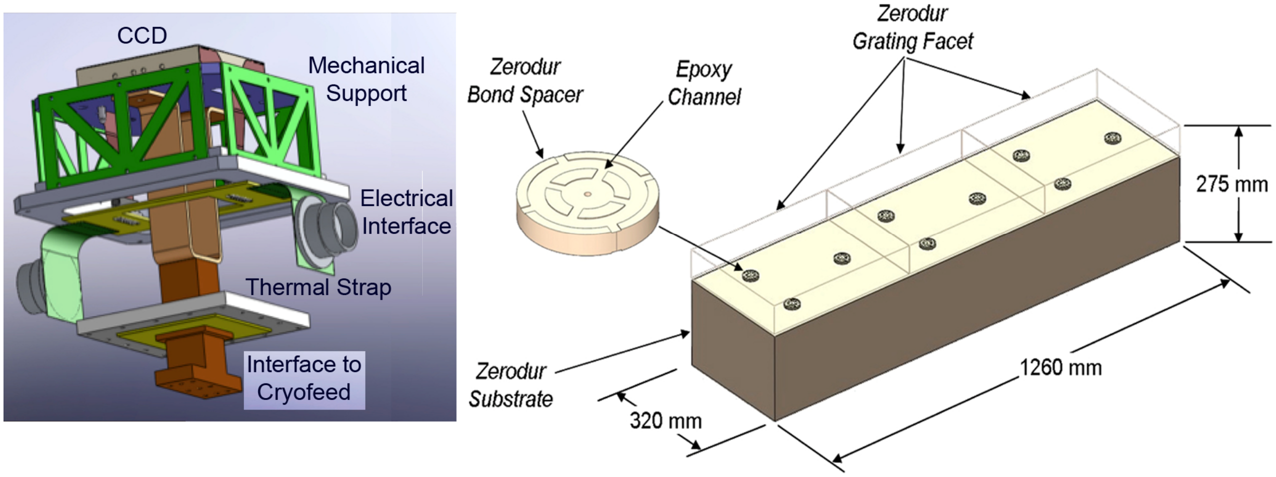

Figure 13: Left Panel - Spectrograph focal plane mounting concept. Right Panel – Baseline echelle grating mosaicking scheme.

5. SOFTWARE

We have developed a concept for a software system. A function diagram appears in Figure 14. We identified requirements for functionality for proposal preparation, operations, real time control, data processing and an interface to an archive. We also envision a spectral and an instrumental database that would facilitate proposal preparation, data reduction and operations planning and execution.

The scope and cost of the G-CLEF software suite has been developed by collaborators in the Chandra X-ray Center Data Systems software group.

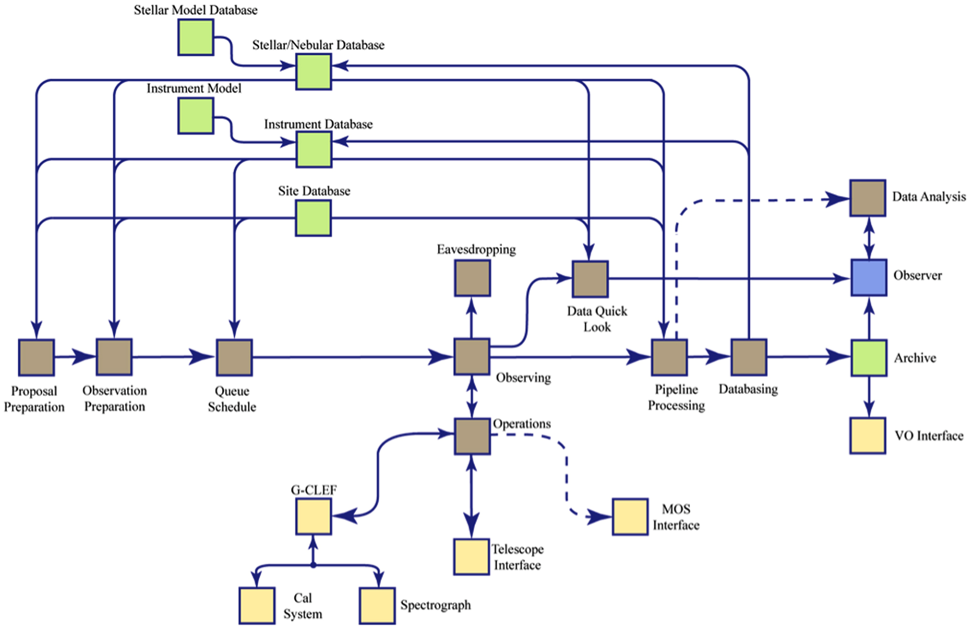

Figure 14: G-CLEF software system function diagram

We have also developed an exposure time calculator with broad, detailed functionality. It can be accessed at http://alerce.astro.puc.cl/gclef.html.

6. SCHEDULE

G-CLEF development plan is laid out over a six year life cycle beginning in early 2013 and ready to integrate with the telescope in early 2019, assuming a timely and adequate funding profile. The schedule follows a traditional multi-phase approach with key decision points at critical junctures in the schedule. Phase B, the Preliminary Design phase, is 12 months. We plan to start Phase B Early 2013. An Instrument Requirements Review (IRR) will be held approximately four months into Phase B and the phase ends with a Preliminary Design Review (PDR). Upon successful completion and acceptance of the PDR, Phase C, Detail Design Analysis, will begin. Phase C includes multiple Critical Design Reviews (CDRs) to allow early procurement of long lead items such as optics and early fabrication of critical subassemblies. Phase C ends with a successful System Integration Review (SIR) which precedes the final phase of development, Phase D, System Integration & Verification. Phase D is a one-year activity bringing major subsystems together and verifying performance of G-CLEF as a system.

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