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Conceptual design of the Giant Magellan Telescope Commissioning Camera

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ABSTRACT

The Giant Magellan Telescope (GMT) Commissioning Camera (ComCam) is an all-refractive, focal reducing camera intended for the evaluation of telescope performance in both natural seeing and ground layer adaptive optics modes across a six arcminute field of view. As the first purpose-built, large imager for the GMT, it also provides unique public outreach functions and scientific research opportunities by enabling both narrowband and broadband imaging and photometric measurements at wavelengths between 360 and 950 nm. In addition to a discrete set of narrowband and broadband filters, inclusion of a deployable Fabry-Perot etalon will greatly enhance ComCam's capabilities. With an image scale of 0.06 arcseconds per pixel, ComCam will be able to take full advantage of the GMT's GLAO-corrected image quality under the best predicted conditions. ComCam has undergone a conceptual design review and is now under development in the preliminary design phase. Instrumental first light will be concurrent with that of the GMT.

Keywords: Giant Magellan Telescope, GMT, ELT, Imager, Camera, Etalon

1. INTRODUCTION

The Commissioning Camera (ComCam) will be the first instrument used with the Giant Magellan Telescope[1] (GMT) during its commissioning phase. ComCam has been primarily devised as an alignment and image quality assessment tool. Its requirements therefore do not primarily flow from a science case. However, since ComCam is the only purpose-built imager planned for early use with the GMT and will provide relatively high spatial resolution, a moderately wide field of view, and narrowband and wideband imaging capabilities, it will also be a useful scientific tool during early operations.

1.1 Objectives

ComCam will provide image quality measurements at the GMT's Direct Gregorian focus over a wide wavelength range. The effects of natural seeing, telescope tracking irregularities, guiding errors, wavefront control errors, wind shake, vibration, flexure, and other behaviors will be monitored simultaneously over its full field of view.

The GMT's Ground Layer Adaptive Optics[2] (GLAO) system will employ wavefront sensors and adaptive secondary mirrors to compensate for the effects of "ground-layer" atmospheric turbulence. The resulting point spread functions within the ComCam field will be evaluated as a function of wavelength and position to qualify the GLAO system performance.

While a fully developed science case is extraneous to the technical development of ComCam as an engineering tool, it is worth considering the advantage of augmenting the instrumental capabilities to increase its scientific utility. In particular, inclusion of a tunable filter will greatly expand ComCam's utility by enabling low- and intermediate-

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resolution integrated spectroscopy, allowing the GMT community to work on cutting-edge research projects. Additional, scientifically useful instrumental augmentations, such as imaging polarimetry, slitless, low-resolution spectroscopy, or high-frequency "lucky" imaging, may also be worth considering.

1.2 Requirements

The ComCam design must deliver image sizes of ≤0.14 arcsec full width at half maximum (FWHM) at λ440 nm, ≤0.12 arcsec FWHM at λ550 nm, and ≤0.10 arcsec FWHM at λ790 nm on the sky. Under the Gaussian limit, this instrumental image quality would limit to 10% the degradation by ComCam of the predicted GLAO-corrected image quality under tenth percentile atmospheric turbulence conditions (i.e. outstanding natural seeing aided by GLAO).

The ComCam pixel width must subtend less than 0.07 arcseconds on the sky. This provides a balance between reasonable sampling of the best, ~0.2 arcsecond FWHM, GLAO-corrected images and maximization of the instrumental field of view.

GLAO performance evaluation requires a moderate field of view to measure image quality simultaneously at a variety of field positions. A minimum corner-to-corner field of greater than six arcminutes on the sky is specified. A hard requirement does not flow from other science or engineering needs.

Exposure time precision sufficient to enable one percent (±0.01 magnitude) photometric accuracy is required. In practice, the actual exposure time will be measured with much higher precision, but the requirement implies that it should be the same for every pixel to within ±1%.

1.3 Derived Characteristics

Some ComCam characteristics derive from practical scientific and engineering decisions based on expected astronomical observing routines.

The minimum allowed exposure time will be 1.0 second and sets the bright limit for stellar observations. While this does not flow directly from a science or engineering requirement, no case for shorter exposure times has been formally proposed. Accurate, uniform shutters capable of significantly shorter exposure times would require deeper engineering and/or impose higher cost and/or risk.

A minimum of five deployable broadband filters should be made available at any time. Typical classical observing programs might require this for ordinary multicolor photometry.

Narrowband filters are used to isolate specific spectral features such as emission lines. Typically, the resolving power R is $\lambda/\Delta\lambda \geq 100$. Scientific programs might use two or three emission line filters and a continuum reference filter. A minimum of three deployable narrowband filters should be available at any one time.

Custom-built interference filters can provide the narrow bandpasses, but because the bandpass of an interference filter shifts with the angle of incidence, preservation of the bandpass shape requires filter placement in a collimated beam, ideally at the location of a pupil. Even so, the bandpass center shifts as a function of field angle. A Fabry-Perot etalon (a.k.a. a tunable filter) may also be included in the same collimated space to provide more generalized wavelength and resolving power access for a greater breadth of narrowband imaging science.

2. DESIGN OVERVIEW

ComCam is an all-refractive, focal reducing camera that will be deployed at the Direct Gregorian (DG) focus of the GMT (see Figure 1) in the narrow field configuration with no wide field corrector or atmospheric dispersion compensator. Only instruments in this location will have access to the telescope field of view beyond three arcminutes in diameter.

2.1 Telescope Mounting

DG instruments are mounted in dedicated instrument mounting frames (IMF) that can be customized within a set of restrictions set by the GMT Organization (GMTO). Up to four IMFs can be mounted in the Gregorian Instrument Rotator (GIR) at any one time, with three laterally stowed toward the GIR perimeter and one deployed to the on-axis, ready-for-use position. The GIR rotates while the telescope tracks in order to maintain field rotation at the focal surface, and can be initialized to arbitrarily orient the on-sky position angle relative to the instruments. ComCam is modestly sized relative to the maximum capacity of an IMF.

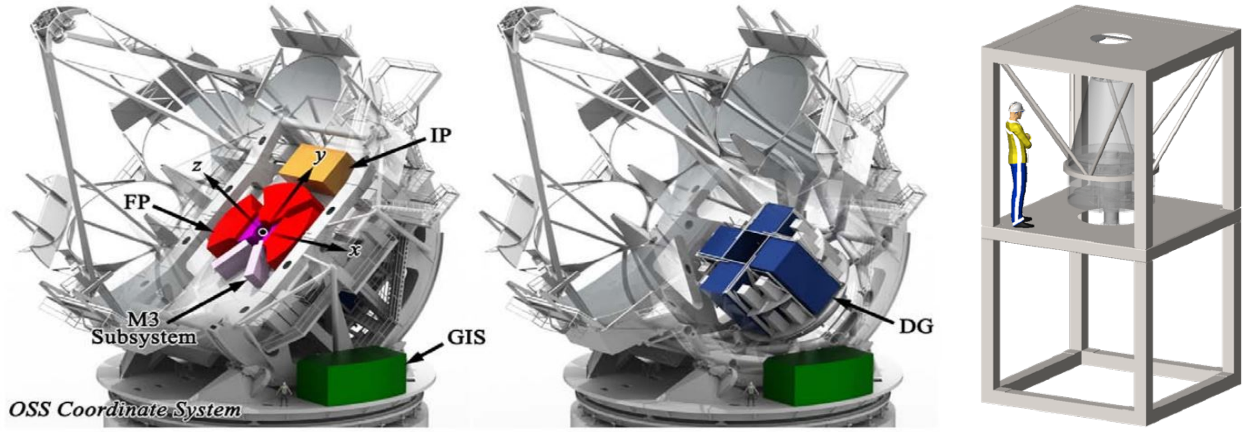

Figure 1. The various GMT instrument ports are shown in the left and middle panels. ComCam, shown at a different scale on the right, will mount at the DG position in its own dedicated IMF.

2.2 Imaging Modes

ComCam has three imaging modes: broadband, narrowband using filters, and narrowband using an etalon. For broadband imaging, a filter is inserted in the converging beam in front of the CCD cryostat. For narrowband imaging, either a filter or an etalon is also inserted, but in the collimated beam, resulting in a change in the effective optical path length. To accommodate this change, the camera and collimator move axially with respect to each other, and the telescope's secondary mirror is adjusted to fine-tune the focus.

2.3 Filter Deployment

Broadband and narrowband filters will be mounted in removable holders and deployed into the beam using filter wheels. There is space for two wheels to accommodate a total of ten broadband filters with one blank in each. The "blank" space will in fact be a window in order to preserve the optical path length and remove the need to focus the detector independently. The narrowband filter wheel will accommodate five filters and will have one empty position.

The etalon is significantly larger than a narrowband filter and will therefore be deployed linearly on its own actuator. A suitably sized cutout in the narrowband filter wheel will accommodate this.

2.4 Detector

CCDs are the only practical visual light detector for the GMT's image scale, even when de-magnified. The largest single CCDs currently available include devices with as many as 10560x10560 9µm pixels and as few as 6144x6160 15µm pixels. 9µm pixels are unnecessarily small, so the decision was made to use a Teledyne e2v CCD231-C6 back-illuminated sensor in the latter format.

The CCD will likely be cooled by liquid nitrogen held in an attached dewar with a hold time of at least twenty four hours. The CCD will be controlled using an Archon[3] from Semiconductor Technology Associates, Inc (STA).

The CCD camera will mount to the exterior of the instrument, which in principle would make it relatively simple to remove and replace with alternate detector packages for other potential, specialized future applications.

2.5 Flexure and Focus

The GMT's guide system expects updates from the instrument on thirty second intervals about offsets in guiding required to compensate for instrument flexure, and also focus adjustments required of the secondary mirror. Measuring these effects is best done as close to the CCD as possible using feedback from on-sky images. Two smaller detectors adjacent to the primary CCD, one slightly in front of focus and one slightly behind, will monitor focus and flexure using two stars (one on each).

2.6 Operations Concept

ComCam is first an engineering tool designed to analyze GMT imaging in ways intended to optimize telescope performance. Low level control of most parameters will be available to engineers and observers so specific tests of telescope functions can be done efficiently.

There will be relatively few configurable elements in the instrument, so operation will be fairly simple. Observers will choose filters, exposure times, and perhaps CCD binning and readout clock rates so that most of the commissioning effort will be in understanding and adjusting telescope subsystems and the GLAO.

Focus adjustment and acquisition of flexure/focus monitoring stars will be necessary, but could perhaps be relatively automated during the commissioning period and via observation planning software so that they do not require concerted and active interaction by the observer. Advance identification of suitable stars should be enabled by the existence of sufficiently faint catalogs produced by upcoming surveys.

While hands-on operation will be fairly simple, observing scripts could in principle be set to allow use of ComCam with minimal human intervention.

Daytime calibrations, including flat field observations, will be necessary. ComCam will be available almost 100% of the time in its "Ready" state, capable of observing immediately after deployment into the DG beam.

3. OPTICAL DESIGN

3.1 Overview

The GMT's native image scale is about one arcsecond per millimeter, which is large relative to a CCD pixel. In order to meet the instrument requirements, re-imaging optics are needed to de-magnify the image. ComCam's optical design is fully dioptric, which allows for excellent throughput and naturally matches the Petzval curvature of the collimator to the telescope's Gregorian focal surface.

GLAO needs require wavelength coverage from 500 to 900nm, but significant scientific utility is enabled by extending to shorter wavelengths. The ComCam design has excellent imaging performance down to λ360 nm, which allows coverage of, for example, the Ca H&K absorption lines and [O II] λ373nm emission.

Reflective optical designs were discounted. While use of a reflecting catadioptric system for the camera might ease optimization for the near-UV and allow an even faster focal ratio for greater demagnification, the GMT pupil's relatively small central obscuration would demand an off-axis, folded reflecting system. This would complicate packaging, increase sensitivity to alignment errors, and likely be less efficient.

The optical design ultimately includes ten lenses made from Ohara i-line glasses, CaF_2, and fused silica, all of which have excellent transmissivity at near-UV wavelengths. Two are bonded as a doublet and six are bonded into two triplets. Bonded lenses were preferred to minimize the number of air-glass interfaces in order to improve throughput. The final lens flattens the field and also acts as the vacuum window for the CCD cryostat. All but two surfaces are spherical.

3.2 Field of View and Pixel Scale

The ComCam optics were not originally designed to a well-documented set of formal requirements, but rather guided more by a set of principles motivated by a desire to achieve excellent performance characteristics without unnecessarily driving costs. The most expensive components in an instrument are normally the optics and the detector(s). The largest available single CCDs are now greater than 90x90mm. Attempting to save costs by designing the optics to produce a clear aperture inscribed within the active area of the detector would seem wasteful of the detector itself. On the other hand, fully respecting the cost of the detector and designing the clear aperture to completely circumscribe the detector would drive the size and cost of the optics perhaps unnecessarily. A compromise was therefore struck to produce the unvignetted field of view (FOV) shown in Figure 2, and the merit function was defined to optimize image quality within that region. The detector is an e2v CCD231-C6, which has a 92.2 x 92.4 mm image area filled with 15µm pixels.

Ideally, the pixel scale should be fine enough to take full advantage of the best images that the GLAO system can provide. Achieving that requires a demagnification of the native telescope plate scale by a factor of almost four. The resulting FOV was roughly six arcminutes along each side of the CCD, and so an effective focal length with modest weight was added to the merit function in order to set this FOV explicitly. The resulting scale is 3.919 arcsec/mm, or 0.058 arcsec/pixel.

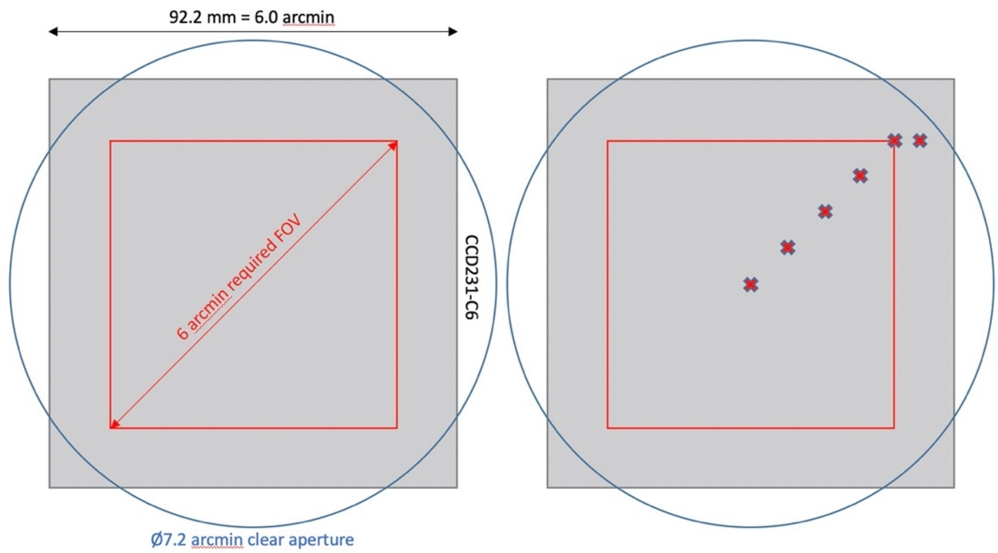

Figure 2. Optimization and clear aperture relative to both the CCD and the required FOV. The right panel shows the field positions corresponding to the image quality evaluation numbers given in Table 2.

3.3 Optical Design Description

The ComCam optical layout is shown in Figure 3. The five central field positions represent the full required diagonal FOV (6 arcmin), and the outermost field positions show the full clear aperture (7.2 arcmin).

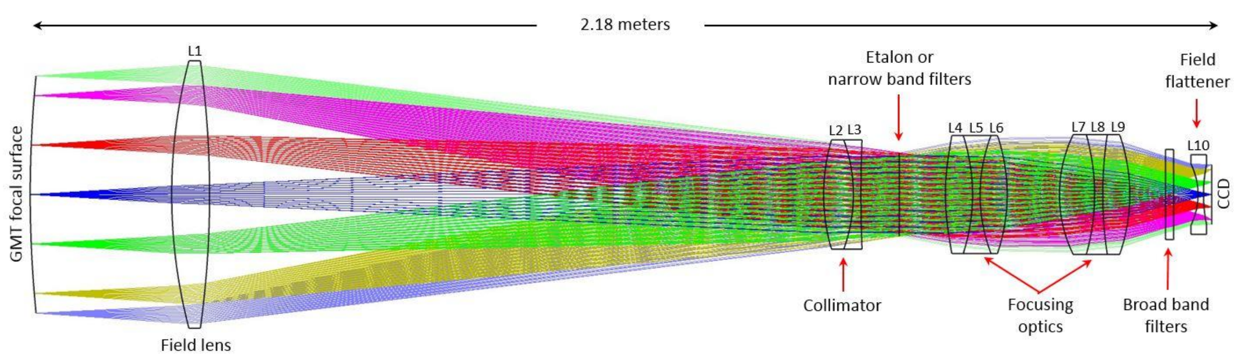

Figure 3. ComCam wideband optical layout.

The design is fully dioptric. To control the sizes of most of the lenses, a field lens redirects all field positions toward the optical axis. The light is then nearly collimated by a cemented doublet. Collimation was not strictly enforced in the merit function, but weighted modestly to allow both the collimator and camera to compensate for each other in producing good final image quality. The focusing elements, or camera, consist of two cemented triplets and a field flattener that acts as the entrance window to the CCD cryostat. There are two aspheric surfaces, and the rest are spherical. Broadband filters will insert in the converging beam near the CCD window. The merit function included a restriction to make the chief rays for all field positions telecentric relative to these filters.

Narrowband filtering will be done in the pseudo-collimated beam. Either discrete narrow band filters or a tunable Fabry-Perot etalon can be inserted. While Figure 3 shows the optics in wide band imaging mode, Figure 4 shows narrow band filter and etalon modes. In order to switch between the different imaging modes, the camera optics must be moved axially relative to the collimator optics for a total travel between narrow band and etalon modes around 40mm. The optical design was optimized with a plano-plano glass in the collimated region that was about half the thickness of the etalon in order to balance imaging performance between all of the modes.

In order to accommodate the size of a specific etalon from IC Optical Systems, both the pupil diameter and axial spacing in the collimated region were restricted.

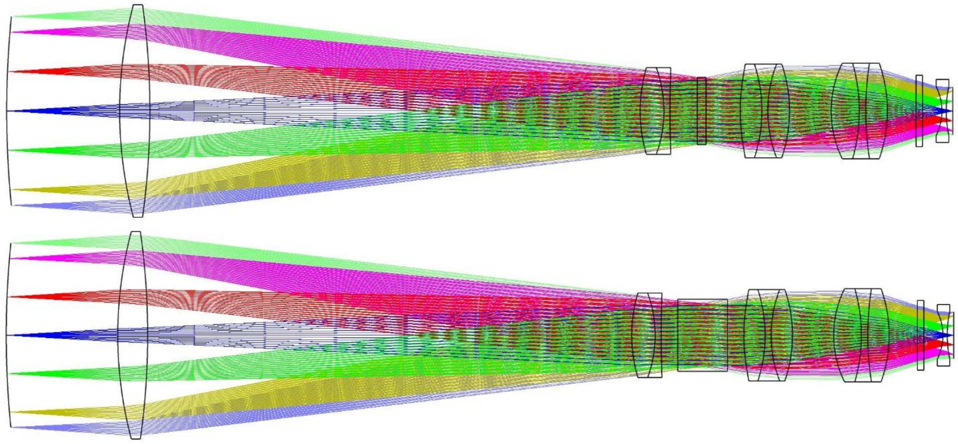

Figure 4. Narrow band filter (top) and Fabry-Perot etalon (bottom) modes.

Optimization was done with a goal to minimize RMS spot diameters relative to the centroid using six field positions evenly spaced from the optical axis out to a radius of 3.6 arcminutes, and with five wavelengths spanning 360 to 950nm. Lens curvatures and spacings were set as variable as were the aspheric coefficients of the two aspheric surfaces. The optical prescription is shown in Table 1.

Table 1. Optical design description in wide field mode. Dimensions in mm.

Item	Material	R1	R2	Thickness	Diameter	Ø Clear Aperture	
						Surface 1	Surface 2
DG focus	Air	2197.2				435.1	
Gap	Air			261.2			
L1	S-FSL5Y	959.2	-1767.8	70.0	490.0	473.3	471.5
Gap	Air			1134.0			
L2	CaF_2	351.7	-290.1	55.0	200.0	190.5	180.8
L3	BAL35Y	-290.1	2704.7	14.0	200.0	180.8	173.8
Gap	Air			156.0†			
L4	CaF_2	Asphere	-350.0	50.0	216.0	189.2	193.5
L5	BAL15Y	-350.0	300.0	14.0	216.0	193.5	202.3
L6	S-FPL51Y	300.0	-334.2	50.0	216.0	202.3	206.2
Gap	Air			96.5			
L7	CaF_2	250.0	-400.0	65.0	220.0	210.5	203.1
L8	BAL15Y	-400.0	717.9	15.0	220.0	203.1	196.5
L9	S-FPL51Y	717.9	-330.2	50.0	220.0	196.5	191.2
Gap	Air			66.1			
Filter	Fused silica	∞	∞	15.0	165x165	139.5	133.1
Gap	Air			45.0			
L10	Fused silica	-Asphere	270.6	10.0	145.8	112.5	109.7
Gap	Vacuum			15.0			
CCD	Silicon	∞			92.2x92.4	110.3	

† For wide band mode only.

3.4 Lens Bonding

The collimator doublet and two camera triplets will be bonded using Dow Corning Sylgard-184. This RTV has good throughput across the ComCam bandpass and is pliable when cured, making it a convenient interface between glasses and crystals with large thermal expansion coefficient mismatches. Sylgard-184 has been used in multiple previous instruments, successfully when the mating lens radii of curvature have been mild, as they are in ComCam, and when temperature departures from the curing state have not been extreme. To enforce the latter, the lenses will be bonded at 15ºC, a temperature intermediate to the anticipated operating range.

3.5 Image quality

The ComCam optical design is required to produce point-source image sizes of ≤0.14 arcsec at λ440 nm, ≤0.12 arcsec at λ550 nm, and ≤0.10 arcsec at λ790 nm FWHM. This requirement corresponds to a 10% FWHM degradation of the predicted single-object, GLAO-corrected image size in 10th percentile seeing conditions.

The field positions used to test this requirement are shown in Figure 2. The required, on-axis field of view is sampled from the center to the corner. An additional field position to the right of the upper corner is included as well; this represents the corner of the required field of view in one possible configuration where the CCD is offset relative to the clear aperture in order to make space for offset guide fields.

The image quality is summarized in Table 2. The optical design software reports RMS spot radius. In the Gaussian limit, the RMS diameter is about 0.85 times the FWHM. Representative spot diagrams for λ550nm are shown in Figure 5. In all cases, the image quality meets the requirements. Note that the optics were refocused for each wavelength using both the collimated space adjustment and piston of the telescope's secondary mirror.

Table 2. PSF size for several field positions and wavelengths. The required FWHM for λ440, λ550, and λ790nm are 36, 31 and 26μm, respectively. FWHM is assumed equivalent to the 50% encircled energy (EE50) diameter.

Field position			**Point spread function diameter (μm)**					
Linear on CCD		**Angular**	**λ440 nm**		**λ550 nm**		**λ790 nm**	
x (mm)	**y (mm)**	**arcmin**	**RMS**	**EE50**	**RMS**	**EE50**	**RMS**	**EE50**
0.00	0.00	0.00	3.72	3.44	9.71	9.38	19.69	19.28
8.12	8.12	0.75	5.20	4.33	8.57	8.75	18.17	18.16
16.24	16.24	1.50	7.24	7.32	5.75	5.77	14.99	14.90
24.36	24.36	2.25	10.56	9.72	5.61	5.13	13.46	10.55
32.48	32.48	3.00	16.02	14.05	10.73	9.97	15.01	11.09
37.49	32.53	3.24	19.23	16.96	13.90	12.72	16.34	12.20

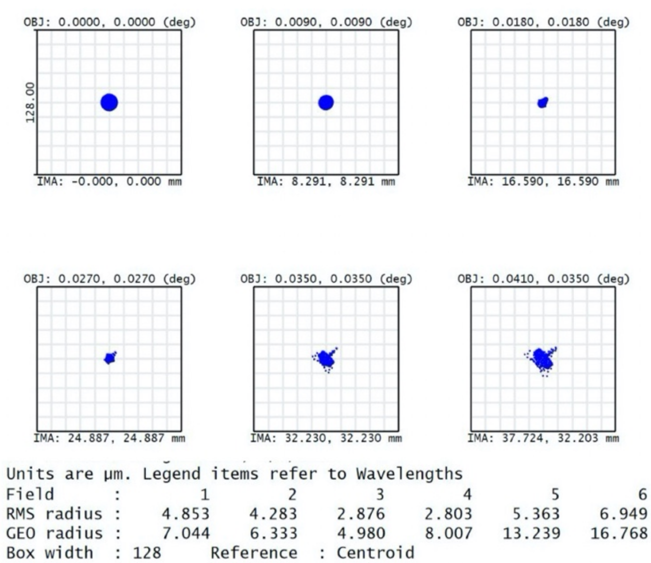

Figure 5. Example spot diagram for λ550 nm in a 0.5 arcsec box. Field positions are shown in Figure 2.

The maximum distortion over the full field of view is 0.68%, and 0.07% over the required field of view.

3.6 Ghost Analysis

Under the simplified assumption of 2% reflectance from each air-glass interface, 1% for each glass-glass surface, and detector reflectance consistent with the inverse of the mid-band sensitivity curve for the e2V CCD231-C6, the relative strengths of ghost images resulting from various combinations of double reflections were analyzed. Relative to a 0.79 arcsec diameter point source image, the strongest ghost image, which comes from a reflection off of the detector, then off of the nearest surface on the field flattener lens, and then back to the detector, is estimated to be 18 arcsec in diameter and twelve magnitudes fainter than the point source image. This is roughly the dynamic range of the detector, so the effects of ghosting should be acceptably negligible except in the case of saturated stars near the center of the field of view, a likely avoidable situation.

3.7 Tolerance and Sensitivity

Tolerance and sensitivity analyses at this stage were performed only for tip, tilt, decenter, and axial spacing of all optical elements. Iterative adjustment of tolerance limits within a "reasonable" range for each of these resulted in a set of very achievable positional tolerances that Monte Carlo simulations indicate will with great likelihood lead to successful reproduction of the predicted image quality to meet requirements.

4. OPTO-MECHANICAL DESIGN

ComCam opto-mechanical designs use successful and proven techniques for mating optics and mounting components in order to minimize risk. Lens cells and barrels make use of "dead-reckoning," the idea that current manufacturing capabilities and fabrication techniques can produce components where features-of-size and other significant geometric accuracies can satisfy tolerances required by the optical design.

4.1 Field Lens

The field lens assembly, shown in Figure 6, consists of a 490 mm diameter, 21.3 kg S-FSL5Y lens mounted in a steel lens cell held radially with Delrin plugs and constrained axially against hardpoints integral to a Delrin shim ring seated against a well-defined, machined surface integral to the cell, a configuration adopted for a similarly sized field lens in the IMACS[4] instrument on the Magellan I telescope at Las Campanas Observatory.

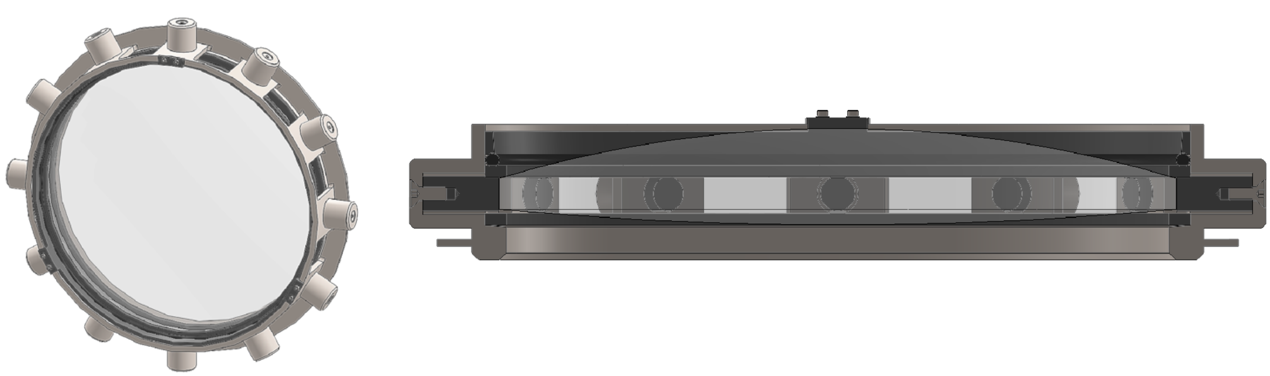

Figure 6. Field lens mechanical assembly in isometric and cross section views, at different scales.

The field lens cell is a steel ring weldment with locating features and surfaces machined post-weld to ensure precise geometric construction, resulting in accurate and measurable placement and positioning of the lens. The cell includes twelve cylindrical features, equally spaced around the circumference, that house components for the athermal design.

The lens is centered in the cell and constrained radially by twelve Delrin posts, mounted in the cell's integral cylindrical housings, centered on the edge thickness. As part of the initial assembly process, Delrin posts longer than the nominal design dimension are installed and then machined down, in situ, such that the mating face has a radius of curvature to match the lens. The assembled cell is heated slightly in order to allow insertion of the lens.

Axial position is defined by three hardpoints machined into a Delrin ring that registers against a flat annular surface machined into the cell, with a location referenced to the mounting face of the cell. Axial contact is ensured by compressing a large O-ring with another Delrin ring that is fixed to the top of the cell. The diameter of the Delrin plugs is selected for the case when only five posts carry the weight of the lens. In the telescope, the assembly will be in a configuration where gravity acts to ensure the lens is properly seated in the cell, so minimal axial constraining force is required.

4.2 Collimator and Camera

The collimator and camera opto-mechanics are similar in design and construction. Cells and barrels will be fabricated from single billets of 6061-T6 aluminum with locating features that rely on precise machining resulting in accurate alignment and placement of assembled components.

Lens groups will be bonded together using Sylgard-184 elastomer adhesive with a bond layer approximately 0.25mm thick. Lens groups will be potted in cells using Dow Corning 3145, injected through the cell radially while the lenses are held temporarily using set screws after having been properly aligned relative to the cells.

The collimator doublet is potted into a cell with a mounting flange at the center of mass. A boss feature adjacent to the flange defines the optical axis of the cell and will engage a bore feature on the mating structure. Twelve elastomer "pucks" equally spaced around the circumference of the lens bond the group to the cell. Retention rings, installed on both end faces, also serve as baffles.

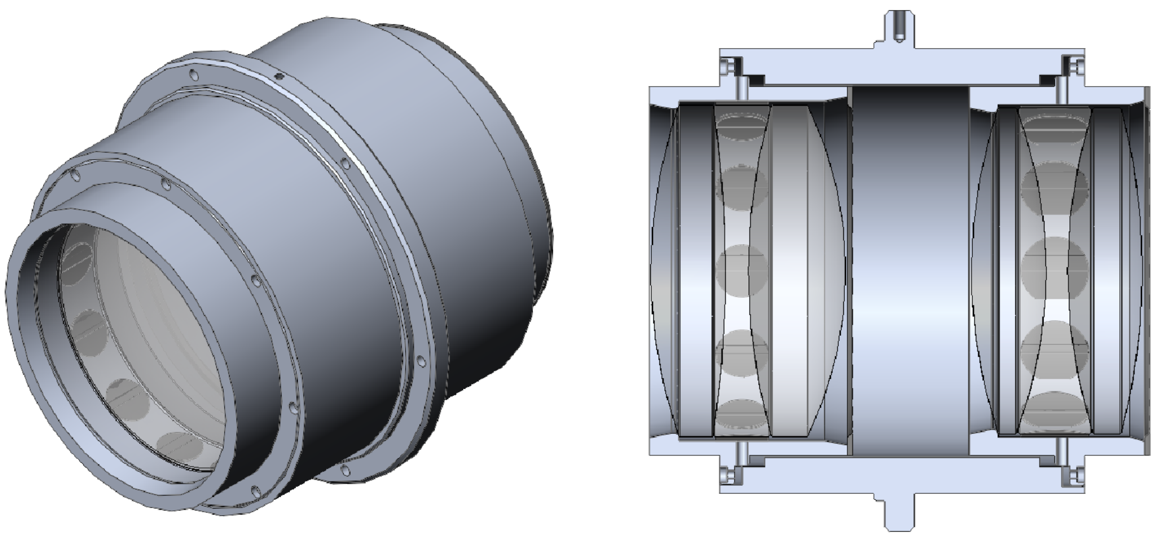

Figure 7. Camera mechanical assembly in isometric and cross section views. The camera triplet lens cells insert into a central barrel. The collimator lens cell is similar in design to the camera lens cells.

4.3 Filters

Filter assemblies are designed to accommodate slight variations in filter dimensions, facilitate quick and simple configuration of filter wheels, and provide versatility, as required.

Narrowband filters are 170mm outer diameter x 20mm thick with a 165mm clear aperture (CA). They seat on three equally spaced Delrin plugs that register against a lip feature machined into an aluminum frame. The plugs are housed in wells and also function to center the filter where adhesive will be applied. A baffle ring will be installed to ensure the filter is retained in the frame assembly. During assembly, the filters will be centered with shims, removed once the adhesive has set.

Wideband filters will be 165mm x 165mm with a 154mm x 154mm CA and require a thickness that results in an optical path length equal to that of 15 mm of fused silica. Wideband filters will be seated in frames with flat surfaces machined into the corners that constrain axial position. Reliefs will be machined into the corners and act as wells for potting the filters into the frame. A baffle, installed on the top surface of the frame, will act as a retaining clip to ensure the filter is fully contained. During assembly, the filters will be centered with shims, removed once the adhesive has set.

4.4 Cryostat Window

The final ComCam lens is a double concave, fused silica field flattener that also serves as the CCD cryostat window. It will register against a machined surface bored into the front of the cryostat's face plate, compressing an O-ring under load provided by the dewar vacuum. A second O-ring, positioned around the upper edge of the lens, will be used under compression to center it in the housing.

5. MECHANICAL DESIGN

The ComCam mechanical design adopts proven mechanical concepts, giving consideration to fabrication, adapting designs of well-functioning mechanisms, and integrating off-the-shelf components whenever possible, with the intent of mitigating risk, reducing design effort, and minimizing operating cost. It relies on fabrication precision provided by current manufacturing capabilities such that lateral adjustment is not provided to make collinear the optical axes of mating components. Axial location of all optical elements may be set by adjusting the nominal thickness of shims incorporated into the design.

5.1 Layout Description

ComCam (Figure 8) includes a fixed, main support structure and a moveable camera support structure.

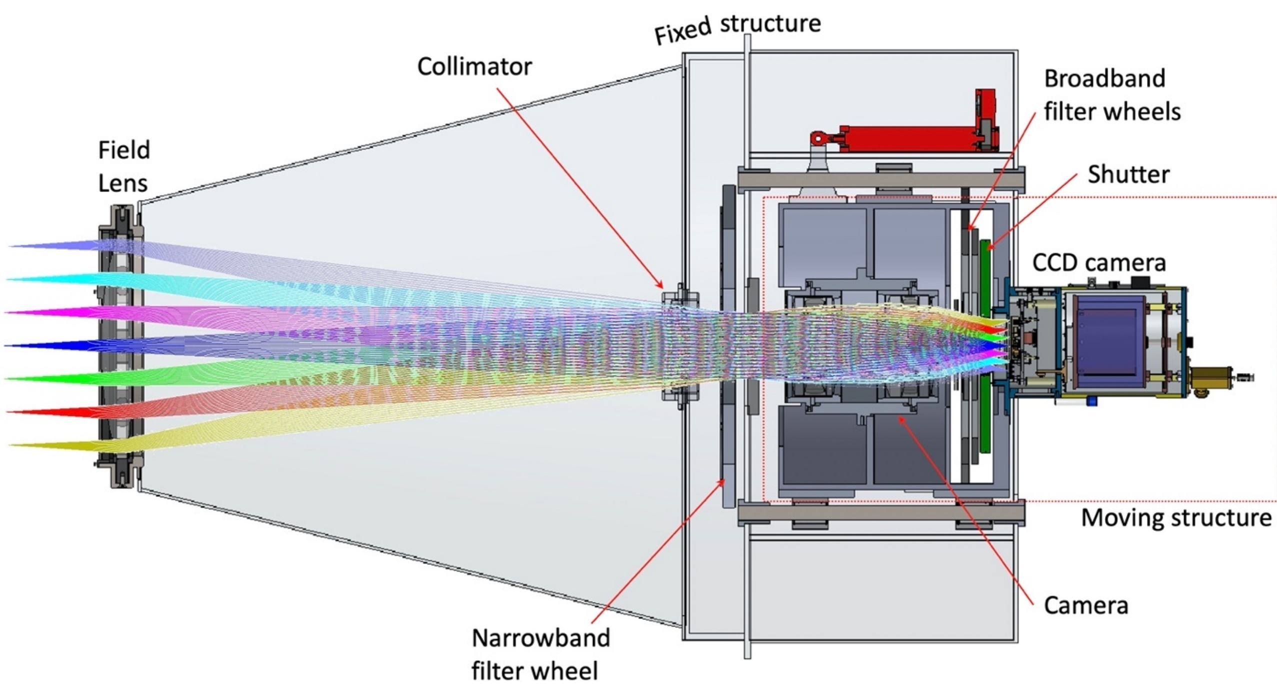

Figure 8. ComCam in cross-section. Light from seven evenly spaced field positions is shown.

The main support structure includes three components that form a structural exoskeleton: the main structural weldment at the aft of the instrument that houses the camera support structure and includes features for mating the instrument to the IMF, a mid-support weldment, which carries the collimator, and a conical field lens support weldment, which mates to features on the mid-support weldment. Each of these steel weldments include important locating and mating features that will be machined post-weld. Finalization of this design will be informed by structural analysis to evaluate flexure during the next phase of instrument development.

The camera support structure will be an aluminum weldment that carries the camera, wide band filter wheels, the shutter, and the detector cryostat.

5.2 Instrument Mounting Frame

The ComCam IMF will be split into three sections (Figure 9) to enable and ease assembly, integration, and testing in the instrument lab prior to delivery to the observatory.

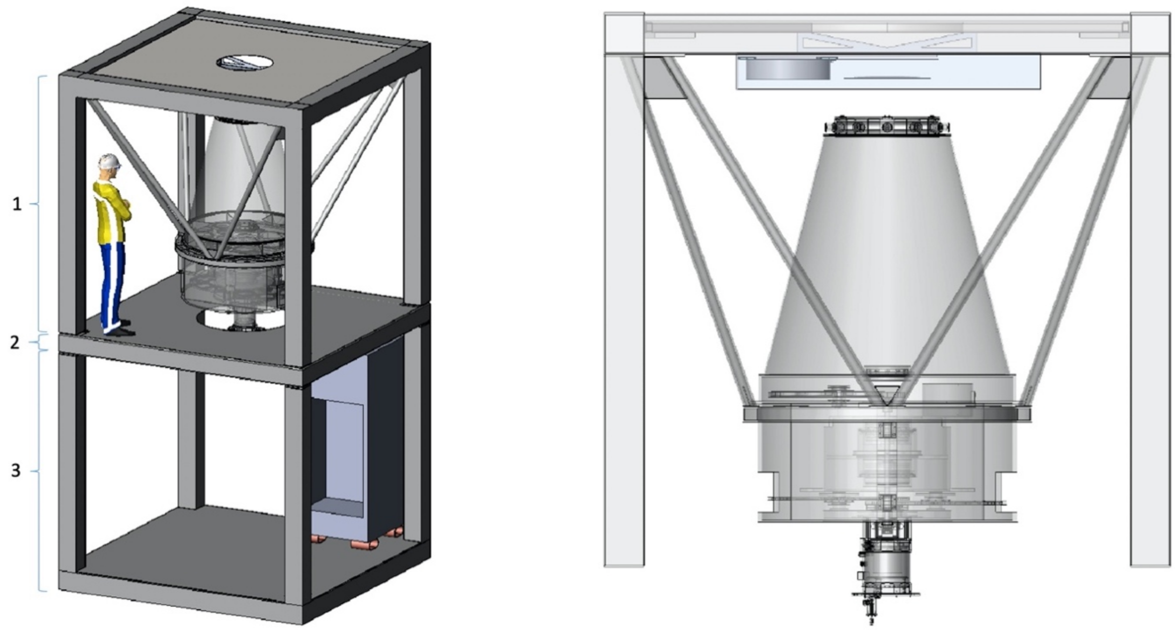

Figure 9. The ComCam IMF is split into three sections, shown on the left. A GMT-standard electronics cabinet is shown on the lower level. The upper section, which includes the ComCam mounting ring and support struts, is shown on the right with the instrument installed. A protective hatch assembly is attached inside the top of the IMF.

The upper weldment includes all mating features and hardware required to kinematically mount the IMF to the telescope when deployed in the observing position, and structural components onto which the instrument mates to the IMF. This instrument interface is a ring section attached to the IMF via eight struts. The upper four corners of the IMF are expected to be clamped tightly to the underside of the GMT's GIR top plate, making these the most stable mounting points for ComCam. Three equally spaced hard points will be integral to the top surface of the instrument mounting ring and define the plane of the mating interface. The top plate of the upper section of the IMF will be removable so that ComCam can be lowered onto the mating ring.

The middle section of the IMF is a platform that provides convenient access to the instrument. The lower IMF weldment satisfies other form and functional requirements defined by the GMT and provides a convenient place to install a control electronics cabinet and potentially other support equipment.

5.3 Collimated Space Axial Adjustment

The camera optics must be moved axially relative to the collimator optics for a total travel between narrow band and etalon modes of around 40 mm. The moving subassembly includes the camera, wideband filter wheels, shutter, and detector. The total moving mass is approximately 285 kg.

The camera support structure will be held between three linear bearings on two one-inch shafts, mounted at both ends to the main support weldment (see Figure 10). The bearing mount points will be designed such that the center of mass is contained within their footprint. Axial positioning is provided by a high precision, high force, ball screw type linear actuator. The actuator is powered by an integrated motor fitted with a power-off brake and mounted to a gusset internal to the main support weldment, with position monitored by a linear absolute encoder.

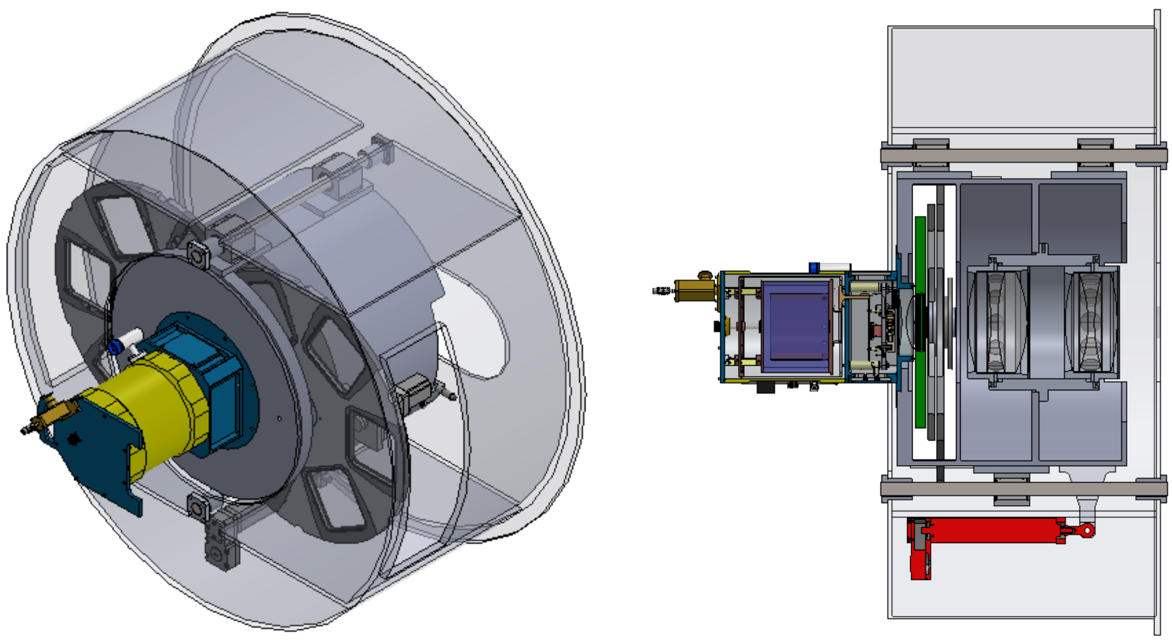

Figure 10. Camera support structure subassembly in isometric and section views. One section of the fixed, main support structure is shown semi-transparent.

5.4 Filter and Etalon Deployment

ComCam is fitted with three filter wheels that accommodate a suite of five narrowband (on one wheel) and ten wideband (on two wheels) filters. The wheels and filter assemblies are designed to allow quick and simple configuration changes. Rotary motion feedback will be acquired with motor encoders, and wheel position will be provided by angle encoders that reference wheel rotation.

Actuation of rotary motion for the filter wheels is provided by a belt/gear drive, fitted with a Parker Bayside 30:1 gearhead and powered by a Beckhoff servo motor. The drives are designed to position adjacent filters in five seconds, with a thirty second maximum between any two positions. The drive assembly for the narrowband filter wheel is contained in a housing mounted to the main support weldment. The drive assembly for the wideband filter wheels will mount to tabs on the moving camera support structure. Solenoid-actuated detents are incorporated into the overall design to guarantee accurate, highly repeatable positioning, with detent stops machined into the circumferences of each wheel. Each wheel is fitted with a hub that contains two low-profile angular contact bearings.

The wideband filter wheels (left panel in Figure 11) accommodate five filters and a clear window, all with a common optical path length. Filter assemblies are an integral part of the wheel; the wheel must be populated with a full complement of filters or at least filter holders for proper operation.

The narrowband filter wheel (right panel in Figure 11) accommodates five filters and has a slot for clearance to allow deployment of an etalon.

Consideration has been given to the integration of an etalon in the future. Solid models have been folded into the current mechanical design and layout to ensure that the appropriate volume will be available to contain an etalon and deployment mechanics without issue. An etalon would be carried in a frame mounted on a linear rail mechanism, driven by a lead screw actuator.

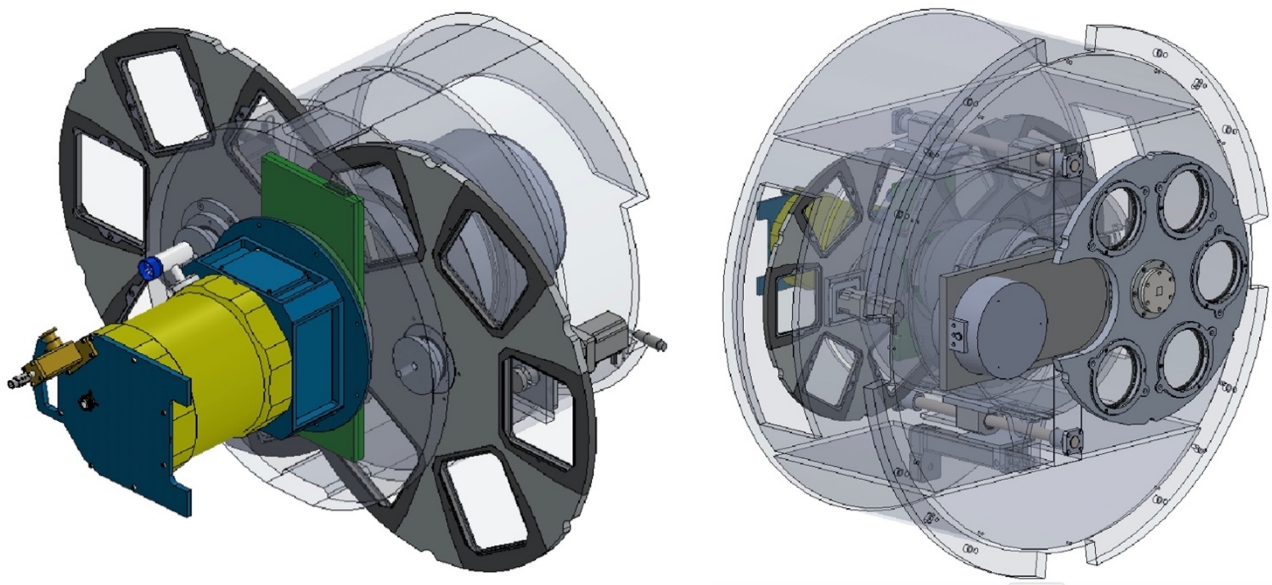

Figure 11. Filter deployment. Shown on the left, two wideband filter wheels, each with six positions, mount just in front of the shutter and detector packages. On the right, from a different angle and at a different scale, the narrowband filter wheel and a block concept for an etalon insertion mechanism are shown.

5.5 Other Mechanical Components

A 125 mm Bonn Shutter will be mounted to the camera support weldment with a simple mounting bracket, positioned as closely to the cryostat window as possible (the green part in Figure 10 and Figure 11).

A pneumatically deployable, sliding hatch will mount to the inside of the IMF above the field lens (visible in Figure 9) and will protect ComCam from falling objects, dust, and debris when it is not in use.

The hatch deployment mechanism may also be adapted to allow insertion of a calibration screen and/or an imaging target at the position of the telescope focal surface that would aid in off-sky instrument evaluation.

6. DETECTOR PACKAGE

The design of the CCD camera draws on heritage from multiple instruments built at Carnegie Observatories over the last several decades, and particularly on recent experience with the Planet Finder Spectrograph[5] on the Magellan II telescope. The e2v CCD231-C6 is mounted on an invar plate (a.k.a. platten), its mounting posts inserted through and held in place with spring washers and nuts. The platten is attached to the tops of three G-10 fiberglass tubes through fine-pitch threaded posts that allow adjustment both of the axial position of the detector surface and its tip and tilt. The G-10 posts provide thermal isolation from the base of the detector housing (a.k.a. the CCD head), which is at ambient temperature.

The CCD package has two ribbon cables that hang on opposing sides and attach to an STA printed circuit board (PCB) amplifier that mounts on small G-10 posts below the CCD platten. A polished radiation shield is mounted between the platten and PCB to minimize radiative heating of the detector package by the electronics. Another ribbon cable leads from the amplifier PCB to a hermetic connector in a plate in the side of the CCD head. This cable carries power and signals between the board and the Archon controller.

A second hermetic connector on the same side plate carries signal and power for a heating resistor that is attached to a plate directly on the back of the CCD package, used to regulate temperature, and also temperature sensors both next to the heater and also on the cold plate of the dewar.

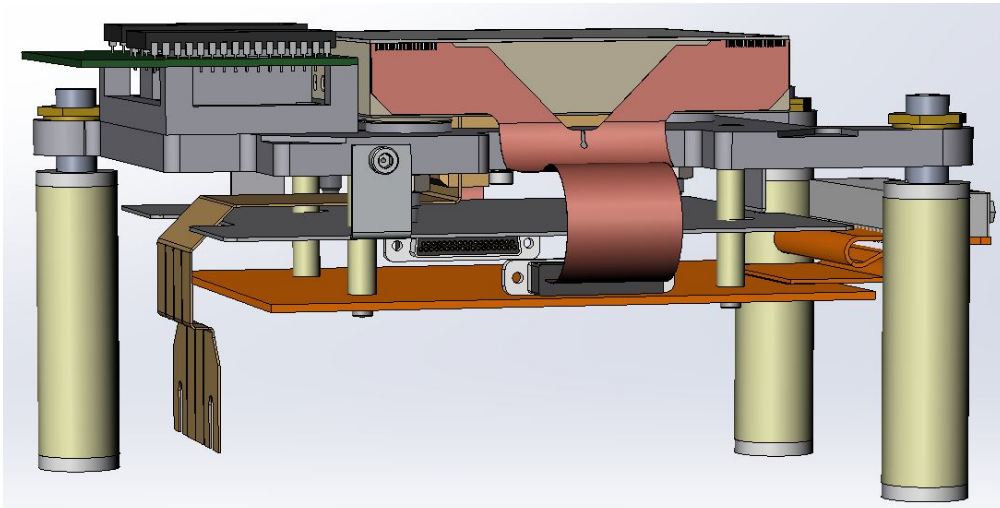

Figure 12. CCD mount assembly containing a CCD231-C6, offset guide and focus detectors, amplifier PCB, and thermal control components.

6.1 Thermal Management

A customized ND-8 dewar from Infrared Labs is attached to the back of the CCD head. Getters on the dewar cold plate activate when cold and take the vacuum level from ~10^{-4} at the initial pump down to ~10^{-6} to 10^{-7} Torr. An ion pump attached to the dewar will extend the lifetime of the vacuum level, maximizing the time between periodically scheduled warm-ups and re-pumpings. A vacuum gauge also attached to the dewar will allow for constant monitoring of the pressure level.

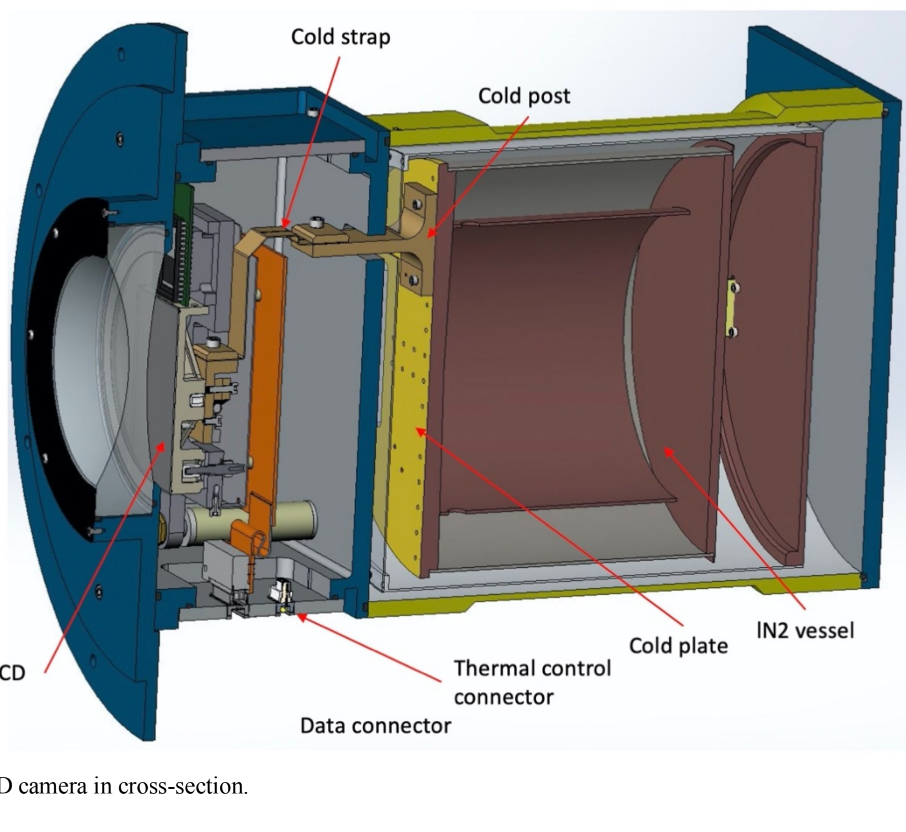

Figure 13. CCD camera in cross-section.

The CCD is cooled via heat conduction through a thermal path made entirely of gold-plated copper. A post is bolted to the cold plate in the dewar and extends through the back face of the CCD head. Accessible through a second side plate in the CCD head, a clamping plate attaches a formed copper ribbon to the post that weaves around the amplifier PCB, radiation shield and platten to clamp in place on a block attached to the back of the CCD package. The ribbon may be adjusted so that the CCD package settles passively at a temperature within 10°C below the desired operational temperature so that minimal application of heat will maintain thermal stability.

6.2 Flexure and Focus Monitoring

The GMT guiding and wavefront sensing system promises to deliver outstanding pointing and tracking just a short distance in front of ComCam. However, there may be flexure between that position and the ComCam focal surface that effectively results in guiding errors. There may be focus offsets as well, both due to flexure and to variation as a function of temperature. ComCam is expected to provide feedback to the GMT for guiding and focus, the former to be countered by pointing adjustment, and the latter to be adjusted by repositioning the telescope's secondary mirror. This will be accomplished by monitoring guide stars outside of the main field of view.

This function was not fully considered when the optical design was originally done. Since a goal of the optical design was to be frugal with the size and complexity of the optical system while still meeting or somewhat exceeding the requirements, the unvignetted field of view outside of the science CCD's footprint is small and ultimately inadequate for guiding; the likelihood of a suitable guide star falling in that region is too low. The FOV could be enlarged to allow keeping the science CCD on-axis and increasing the capture size of an offset guide field, but doing so would drive the cost of the optics in a dissatisfying way. Furthermore, it would require increasing the diameter of the field lens, which is the primary source of vignetting outside of the designed FOV, and the glass chosen for that lens is already at the maximum size available. Increasing the FOV would require changing the lens material, but an attempt at re-optimization with fused Silica led to unsatisfactory results.

A compromise is to offset the science CCD laterally in order to make available within the existing clear aperture a suitable field for guide and focus monitoring. This is shown in Figure 14. The required field of view on the main detector is still more than achieved, although the exposed field has an unusual shape, and of course it is somewhat dissatisfying to under-utilize the large CCD. To potentially mitigate this, the entrance window has been offset relative to the guide field and science CCD so that if flexure and focus adjustments can be repeatably set via a look-up table after some experience using the instrument, the CCD camera can be rotated 180° relative to the face plate and window, and the science CCD can therefore be maximally illuminated while allowing the guide fields to be completely vignetted.

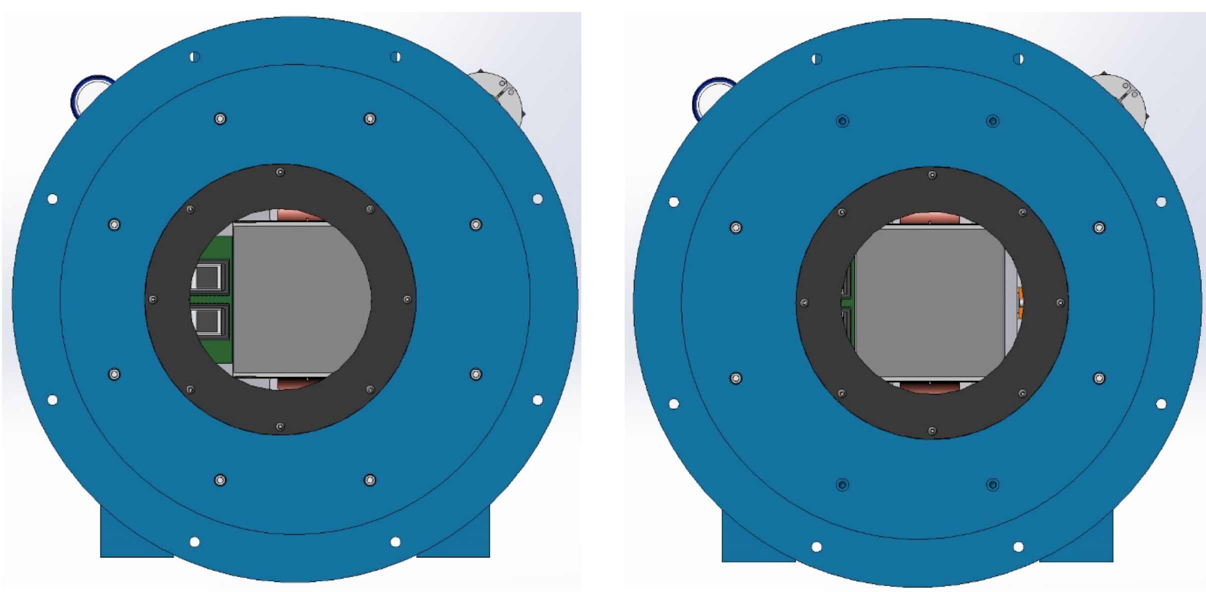

Figure 14. CCD camera face plate in two orientations, one centered on the science CCD (right) and one that accommodates the flexure/focus CCDs (left).

It is ideal to minimize any potential offsets between the guide star signal and the main CCD. The best possible location for guide CCDs is adjacent to the science CCD on the same mounting platten. An alternative option would be to introduce a set of transfer optics that would collect light from an offset field and send it outside of the cryostat to a completely separate detector package. This may be worth further consideration, but instead an arrangement was modeled where two frame transfer CCDs (e2v CCD47-20[‡]) are mounted adjacent to the large CCD with one in front and one behind focus. Guiding can then be monitored by centroiding a single star on either detector, and focus can be monitored by observing the focus differences of stars on both CCDs.

The feasibility of this arrangement, including the precision of axial placement, thermal management, header PCB design, and cable routing will be explored further during the preliminary design phase.

The requirement to have two focus/flexure monitor stars, one on each offset CCD, is potentially a disadvantage. To assess the likelihood of meeting this condition, calculations were made to predict guide star availability and concluded that *if* the field rotation can be set arbitrarily so that the offset CCDs can patrol an annular region around the field center, and especially if the absolute pointing can be offset by a modest amount, guide star availability is very high even at the Galactic pole where the area density of stars is most limited.

7. CONTROLS AND SOFTWARE

GMT standards define a software and controls paradigm based on the use of an EtherCAT fieldbus system that treats the entire facility, including instruments, as integrated. High level control software is centrally defined by a set of standards and an observatory-specific software development kit (SDK).

7.1 Controls

A conceptual plan as well as a relatively detailed hardware and signals inventory has been developed for implementing EtherCAT control of ComCam electronics as well as Safety over EtherCAT according to GMT standards. A conceptual diagram of data communication paths is shown in Figure 15.

In general, absolute encoders will be used in most ComCam mechanisms, closing control loops in software. Proximity sensors will be used for discrete position detection on some mechanisms.

The EtherCAT master Device Control Computer (DCC) will be Linux-based, with EtherCAT slaves all being Beckhoff modules. Both master and slaves will be part of the GMT EtherCAT fieldbus ring. The control logic will be implemented in the DCC, effectively embedded as a result of applying the GMT-provided SDK to ComCam-specific configuration files. The DCC will receive status data from the local Interlock and Safety System (ISS) using an "Open Platform Communications - Unified Architecture" (OPC-UA) interface.

Safety over EtherCAT will be implemented also according to GMT requirements and integrated into the GMT's dedicated safety fieldbus ring. The system will have one Emergency Stop (E-Stop) local pushbutton and provide a Safe Torque Off (STO) signal to each motor controller to ensure a safe, unpowered state upon a local or remote E-Stop signal activation. More safety features may be added according to the results of a forthcoming hazard analysis.

[‡] A different offset CCD model will likely be chosen during the preliminary design phase.

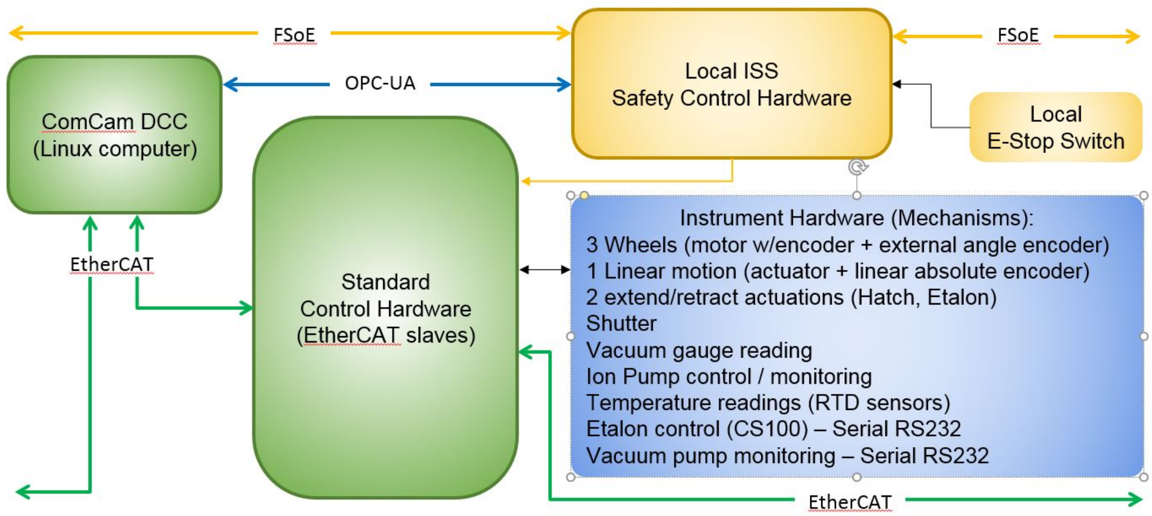

Figure 15. Controls communication flow diagram. Abbreviations: Device Control Computer (DCC), Interlock and Safety System (ISS), Safety over EtherCAT (FSoE), Open Platform Communications - Unified Architecture (OPC-UA)

7.2 Software

The high level ComCam software architecture has been blocked out at the conceptual level, including a set of necessary packages (see Figure 16) to be developed.

The ComCam Device Control System (DCS) follows standards defined by the GMT, is responsible for controlling and monitoring all instrument actuators and sensors, and for ensuring that the instrument can be integrated and operated efficiently at the observatory in all of the different phases of operation from proposal preparation to final data reduction and quality assessment. The ComCam DCS is part of the GMT Instrument DCS package in the Observatory Control System[6] (OCS) structure and will be developed using the framework defined in the GMT SDK. All such DCS designs follow a common, required architecture defined as a standard by the GMTO.

The ComCam DCS will have interfaces with other observatory control system applications, such as Core Services (logs, telemetry, configuration, alarms, and user interfaces), the Telescope Control System (TCS), Data Systems (pipelines and archive), Observing Tools (Phase 1 and Phase 2), the observing sequencer, and the Global Interlock and Safety System.

Characteristics of the software and instrument development life cycle make the definition of a complete list of formal requirements for both users and hardware difficult to define during a conceptual design phase. However, to provide formal goals for the software scope and functionality, qualitative software features have been defined and will be further developed during the next design phase.

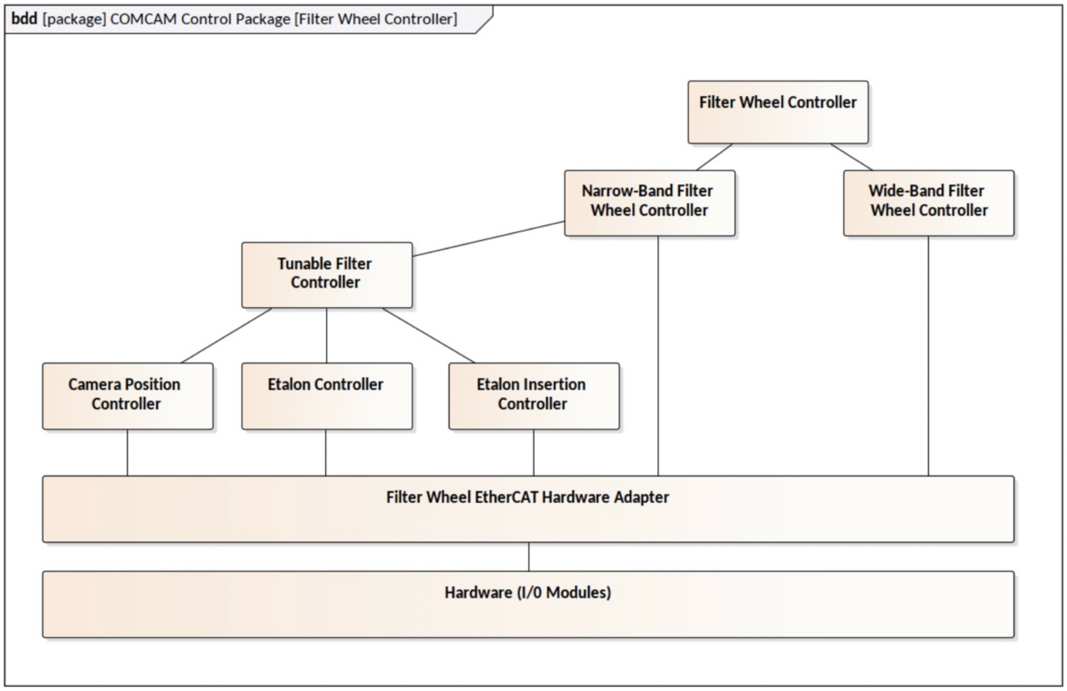

Figure 16. Example software component package block diagram: filter controller.

8. MANAGEMENT AND SCHEDULE

The ComCam project takes advantage of a tradition of soft management based on the flexibility afforded by a modest team of engineers and scientists working in collaboration with industry vendors and research labs. Common tracking tools are used for the purpose of status reporting to the GMT and its partners.

Systems engineering activities include the management of requirements, risk, operations concepts, interface control, and assembly, integration and test planning, as well as supporting certain formal project management activities. Within the GMT system, a basic set of systems engineering tools enables an observatory-level understanding of the instrumental contributions to the success of the facility.

ComCam development will soon enter the preliminary design phase. The lifetime of the project will be metered according to the GMT's anticipated commissioning schedule, with delivery of the instrument well in advance of on-sky needs at the telescope. The project will use a multi-phase approach with design reviews gating progression from one phase to the next.

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