GMACS: a Wide Field, Multi-Object, Moderate-Resolution, Optical Spectrograph for the Giant Magellan Telescope

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ABSTRACT

We present a conceptual design for a moderate resolution optical spectrograph for the Giant Magellan Telescope (GMT). The spectrograph is designed to make use of the large field-of-view of the GMT and be suitable for observations of very faint objects across a wide range of optical wavelengths. We show some details of the optical and mechanical design of the instrument.

Keywords: Extremely Large Telescopes, spectrographs

1. INTRODUCTION

Wide field, multi-object spectroscopy is a key capability for the Giant Magellan Telescope (GMT). Indeed, the original GMT Science Requirements document[1] states: "A spectrometer operating in the visible spectrum (0.32 µm to 1µm) with the capability to observe multiple targets simultaneously is critical to our goals in the areas of star formation, stellar populations and most extragalactic science." The ability to obtain moderate resolution spectra of astronomical targets at optical wavelengths has been a fundamental scientific capability for more than a century; the scientific information content of such measurements remains high and this capability is unlikely to become obsolete over the expected lifetime of the GMT.

We present an update to the design of the Wide Field, Multi-Object, Moderate-Resolution, Optical Spectrograph (called GMACS) for the GMT in this paper. Ultimately, the goal is to build and use an instrument capable of observing the faintest possible targets, those that are substantially fainter than the sky. High throughput, simultaneous wide wavelength coverage, accurate and precise sky subtraction, moderate resolution, and wide field (for an extremely large telescope) are the crucial design drivers for the instrument. We expect that GMACS will form one of the most basic scientific capabilities of the GMT.

A conceptual design of the GMACS instrument was described in the original GMT Conceptual Design Document in 2006. We have advanced and refined this original concept substantially during the past two years. The essential description of the instrument has not changed: a set of four fold mirrors at the GMT focal plane redirect a 9 arcminute × 18 arcminute field to four individual "arms" that each comprise a "two-channel" spectrograph (that is, each arm sees a 4.5 arcminute × 9 arcminute off-axis field and feeds a double spectrograph). There have, however, been considerable changes in the layout, structure, optical design, mechanism approach and design, and other specific characteristics of the spectrograph.

The individual channels are optimized for either the red or the blue, but have very similar design characteristics (plate scales, resolutions, common shutters, etc.). We have included in the design selectable and rotatable grating mechanisms,

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to increase observing flexibility and rapid instrument reconfigurations. Currently the design contains four separate VPH gratings (2 red; 2 blue) that give resolutions of ~2000 and ~4000 in each channel.

2. SCIENCE CASE AND TECHNICAL OBJECTIVES

We have developed science themes that define the purpose of GMACS. Specific observing projects have been developed that allow us to set the technical requirements for the instrument. The broad themes are similar to the GMT science justification and include a wide range of topics: from KBO surface composition studies to characterization of star formation in z=6 galaxies. The interplay between GMACS and the Dark Energy Survey (DES) and Large Synoptic Survey Telescope (LSST) imaging projects is likely to be extensive, since we anticipate that GMACS will be the most efficient spectroscopic follow-up instrument for both of these large imaging surveys. GMACS will be an enormously popular instrument for the GMT and will ultimately be used for an extremely broad range of science projects.

Although we have identified specific science projects GMACS can execute, it is worthwhile pointing out explicitly that these specific cases are merely representative of the science that GMACS can and will produce. Indeed, we expect that a list of the major science accomplishments and important results arising from the instrument after years of use will include many topics not presented here, if history is any guide. For example, according to Richard Ellis (2011, at the "Feeding the Giants: ELTs in the era of surveys" conference) the four most interesting results from the Keck telescopes between 1992 and 2007 were the identification and characterization of z=3 galaxies, observations that reveal the redshifts and nature of gamma-ray burst (GRB) sources, redshifts and identification of type Ia supernovae, and the discovery of extra-solar-system planets; none of these important and defining topics were mentioned in the 1985 Keck science case. Further, all were done with optical spectroscopy (of various resolutions). As further noted by Ellis, "optimism, versatility, and creativity are the key attributes for success." We enthusiastically agree and strive throughout this project to merge the particular objectives associated with the specific cases with more general considerations that our experience suggests will make GMACS versatile and allow for creative use.

We have developed a set of technical objectives for the instrument that are drawn from the science themes. These objectives include:

- Sensitivity: High throughput: >50% at peak and no worse than 30% at any wavelength
- Sensitivity: Detectors with low readout noise (<5% addition to background noise)
- Excellent image quality: <0.2 arcsec rms over the entire detector plane
- Accurate and precise sky subtraction: use direct slits
- Multi-object capability: focal plane masks
- Wide field: large focal plane masks
- Broad wavelength coverage: at least 400-950nm (goal is 350-1100nm)
- Moderate resolution: R~1000-5000
- Seeing limited operation: plan around use of a 0.7 arcsec slit (although the image quality could make use of GLAO in the far red)
- Spectral accuracy over long exposures of <0.1 resolution element; flexure compensation

These objectives guide our design decisions and are pragmatic choices for the instrument. We believe that meeting these objectives will result in an instrument that will produce a vast range of science at the GMT and satisfy most community needs for optical spectroscopic observations of faint objects.

3. DESCRIPTION OF INSTRUMENT CONCEPT

The concept provides complete, simultaneous spectral coverage over the wavelength range from ~0.38 to 1.0µm, for hundreds of objects in a 9 ×18 arcmin field of view. The default resolution with a 0.7 arcsec slit is ~1400 in the blue (at ~520nm) and ~2200 in the red (at 740nm) in the low-resolution mode; the resolution with the same slit in the high-resolution mode is ~2600 in the blue (at ~520nm) and ~4000 in the red (at 740nm).

The instrument concept splits the GMT focal plane into four segments, each of which is fed to a double spectrograph. The four arms were selected for two reasons. First, there is a legacy for the instrument that adopts this approach. Second, however, is that four arms represent a good balance of cost versus complexity. Fewer arms require larger optics and faster camera speeds (for a particular final focal plane scale), which is likely to increase cost and risks in obtaining appropriate optics blanks, gratings, etc. The four-arm design can be made from components that require no new technology development. A larger number of arms increases alignment and packaging complexity and does not substantially reduce cost. An eight-arm design, for example, could be made of somewhat smaller components than those described below, but (of course) twice as many would be required to cover the same field. Potentially this approach could allow lower costs, but our preliminary estimates suggest that the additional personnel cost for increased design, fabrication, assembly, test, and deployment would approximately equal the reduced component cost. For both these reasons, we decided to proceed with a 4-arm approach.

The GMACS concept is highly modular, as described below, and will likely be deployed in stages that progressively add capabilities as scientific priorities, user-community interest, and funding allows.

The GMACS concept is designed around a multi-slit approach to provide the best possible sky subtraction and instrumental throughput. The current optical design makes extensive use of refractive elements and has a baseline beam diameter of ~300 mm. Typical optical element sizes are ~400 mm. To create the maximum possible field, the optical design assumes the presence of a telecentric corrector and multiple collimators and spectrographs that would be deployed across the telescope focal plane in a "fly's-eye" approach.

4. OPTICAL DESIGN

The optical design is complete for the entire instrument and discussions with potential vendors have demonstrated that the optics can be fabricated with minimal risk. Estimated performance of the design meets image quality objectives: <0.2 arcsec rms polychromatic spots over the entire focal plane. Materials for the lenses are available and the surfaces (including aspherics) pose no significant challenge to figure or test. Lens and dichroic coatings that should guarantee exceptional throughput are available via lens fabrication vendors; estimated performance should meet the throughput objectives. Gratings with excellent performance are also available. More details of the optical design and performance can be found in elsewhere in these proceedings[3].

The design consists of a broad wavelength coverage collimator for each arm. The collimator feeds two cameras: a red camera optimized for 650nm to 1020nm coverage, and a blue camera optimized for 370nm to 670nm coverage. The blue camera works well to at least 350nm. The general layout of the optics is shown in Figure 1. Figure 2 shows more detail on the optical configuration of a single channel.

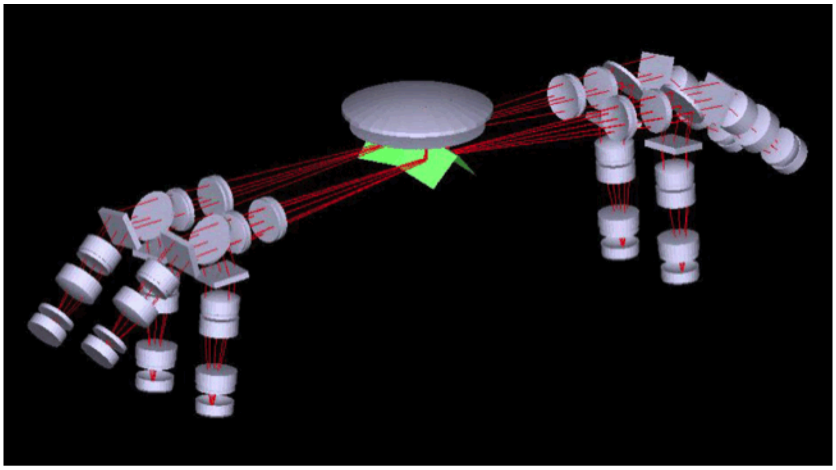


Figure 1: General optical layout of the GMACS design. The large lens in the middle is the last element of the GMT wide field corrector. The green "tent" looking reflections are the four mirrors that direct the quadrants into the individual spectrograph arms. Each arm consists of a two-channel spectrograph.

The collimator design is based on the IMACS collimator[2]. An initially on-axis design is rotated to an off-axis fly's-eye position with no reoptimization for that position. Multiple fly's-eye collimators would physically interfere, which requires that the tent mirrors fold (separate) the collimator axes. The collimators produce 300 mm diameter collimated beams with sufficient pupil relief to fit the dichroic and locate the gratings at the pupil.

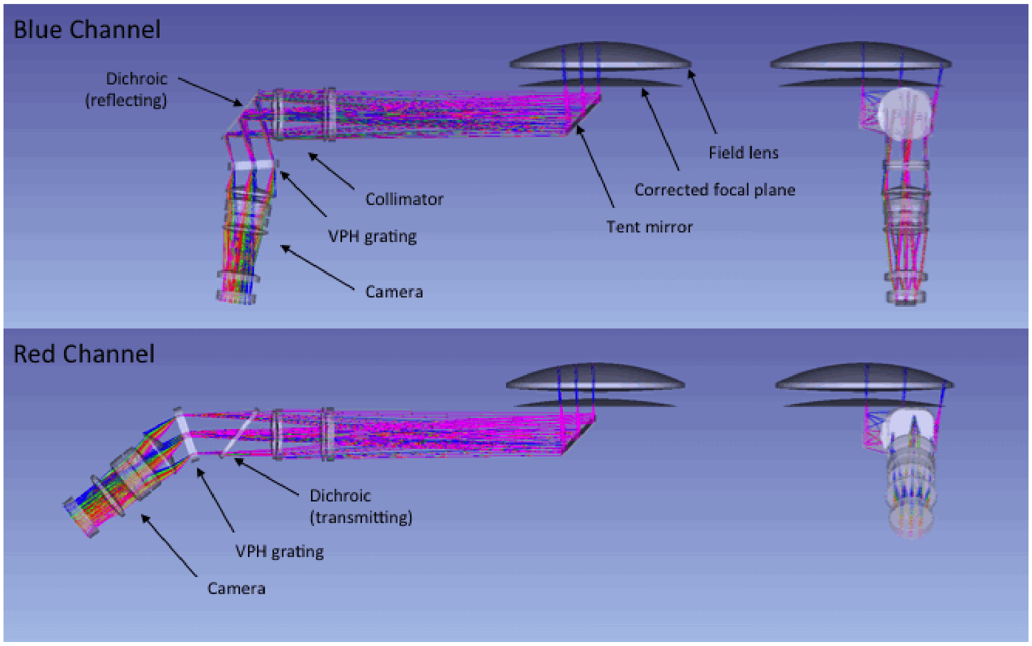


Figure 2: Additional details on the layout of each individual channel of GMACS shown from two orthogonal orientations. For scale, note that the large initial lens is the final element of the GMT wide field corrector, which is ~1.5m in diameter.

The cameras are *f*/2.25, 675mm focal length refractive designs optimized for the red and the blue (materials, coatings, etc.). The blue camera has 7 elements, including 3 aspheric surfaces. The materials are CaF2, Fused Silica, BSM51Y, and BSL7Y. The red camera also has 7 elements, again with 3 aspheric surfaces. The materials are CaF2, Fused Silica, PBL6Y, PBL35Y, and BSM51Y. All materials are available in appropriate blank sizes and there are multiple qualified vendors available to produce the required figures and polishing. The cameras produce a scale at the GMACS detector plane of 3.72 arcsec/mm. For 15 μm pixels, this corresponds to 0.056 arcsec/pixel. A 0.7 arcsec slit would be 12.6 pixels across (assuming no anamorphic factor). Table 1 and Table 2 summarize the end-to-end optical performance of the designs.

Table 1: Summary of rms spot diameters for the end-to-end performance of the blue channel. The scale is 0.053 arcsec/pixel, so the RMS spot diameters are everywhere less than ~4 pixels.

Wavelength	Blue Arm RMS Spot Diameter (arcsec)		
	Average	Minimum	Maximum
3700	0.11	0.05	0.21
4200	0.15	0.12	0.21
4800	0.07	0.05	0.09
5500	0.08	0.07	0.10
6700	0.13	0.10	0.14

Table 2: Summary of rms spot diameters for the end-to-end performance of the red channel. The scale is 0.053 arcsec/pixel, so the RMS spot diameters are everywhere less than ~3 pixels.

Wavelength	Red Arm RMS Spot Diameter (arcsec)		
	Average	Minimum	Maximum
6500	0.10	0.06	0.15
7700	0.08	0.07	0.08
8900	0.10	0.08	0.11
10200	0.12	0.09	0.16

Gratings

Four VPH gratings are needed for each arm: two blue and two red. We have adopted as a baseline blue gratings with 728 l/mm and 1300 l/mm, and red gratings with 783 l/mm and 1300 l/mm. These give two different resolutions across the detector plane. The low-resolution mode covers the entire wavelength range of a given channel at a resolution (λ / Δ λ) of ~2000; the high-resolution mode gives roughly half the wavelength coverage, but at resolution of ~4000 (all resolutions are using a 0.7 arcsec slit width). The high-resolution gratings will be capable of rotation to select a desired wavelength range.

Table *3* and Table 4 give more precise description of the resolutions at various wavelengths in each channel using the default gratings. The gratings are available commercially and have excellent throughput.

Table 3: More precise indication of resolutions with the adopted default blue gratings at wavelengths across the blue channel.

Blue Channel		
Wavelength (nm)	R (Low Res)	R (High Res)
370	993	1817
425	1140	2087
522	1400	2563/2662
595	1596	3035
670	1798	3418

Table 4: More precise indication of resolutions with the adopted default red gratings at wavelengths across the red channel.

Red Channel		
Wavelength (nm)	R (Low Res)	R (High Res)
650	1948	3499
740	2218	3984
840	2518	4522/4975
875	2623	5182
1020	3058	6040

5. MECHANICAL DESIGN

The conceptual mechanical design of GMACS has two basic sub-systems: a focal plane unit that translates into the active space in the GMT instrument rotator (GIR) and is lifted to the telescope focal plane via an elevator mechanism, and a set of optics modules that contain the individual arms and channels. The focal plane unit is stored in the lower half of one GIR bay; the optics modules are permanently fixed to the "ceiling" of the GIR and occupy the top half of two bays (separated by 180 degrees). Each is described in additional detail below. Figure 4 and Figure 5 show the locations of these sub-systems in the GIR. The design of GMACS is very modular. We believe that this will ease deployment by allowing "staging" of the modules. The modularity will also allow future upgrades and reconfigurations of the instrument capabilities, which helps to ensure that the instrument is capable of meeting future science goals. Additional information about the mechanical design of the instrument can be found elsewhere in these proceedings[4]

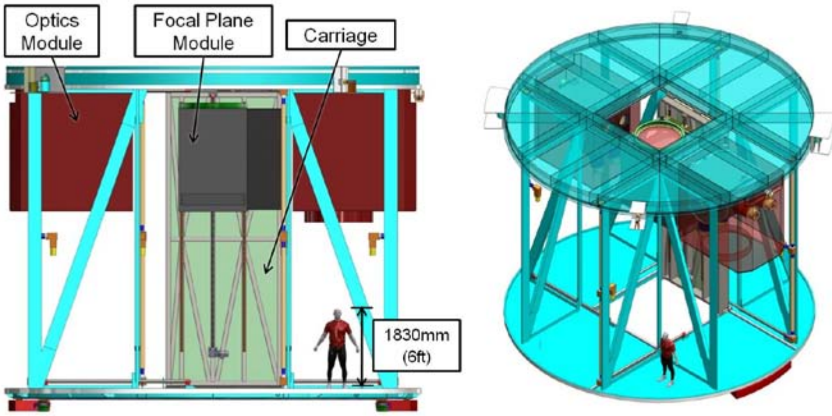


Figure 3: Side view of the GIR showing the various sub-systems in the aligned and ready-to-observe position. A person is given for scale.

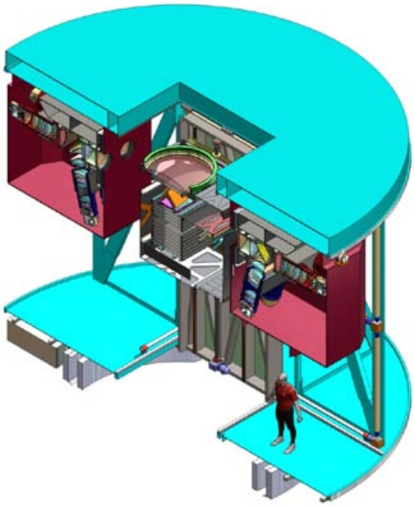


Figure 4: Section view of the GIR with GMACS installed.

Figure 6 shows the focal plane unit with associated sub-assemblies. The focal plane unit holds and positions the final element of the GMT wide-field corrector lens, slit mask, and tent mirrors in optical alignment relative to the telescope and optics modules. The focal plane unit also contains a magazine of slit masks that will be used during the night. Up to 12 slit masks can be held ready for observing. The unit also holds the electronics to control and use the accompanying mechanisms.

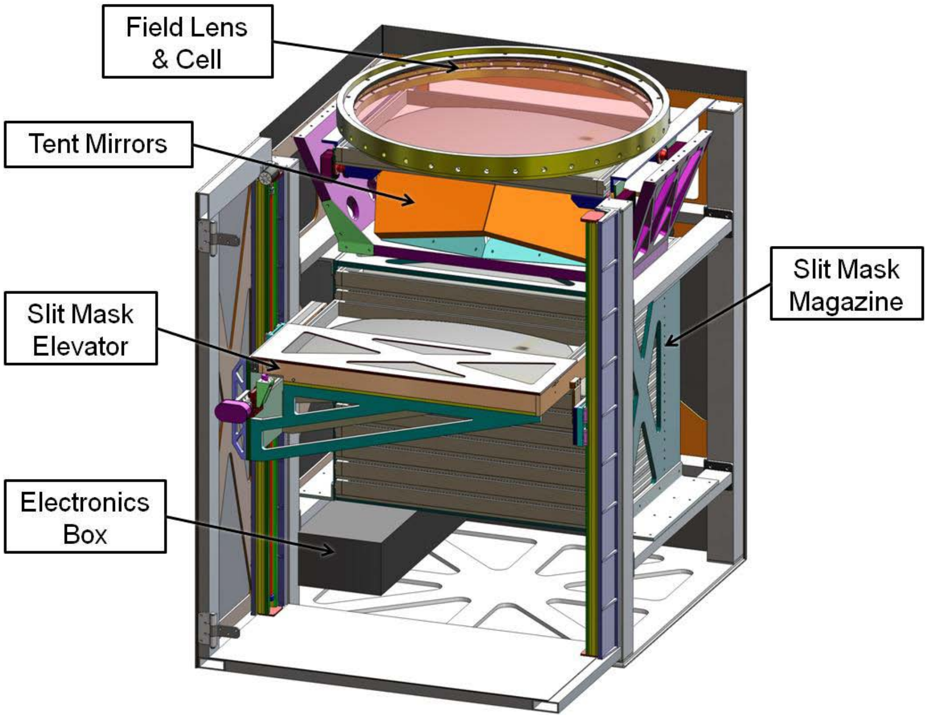


Figure 5: Focal plane unit and labeled sub-assemblies. This unit moves laterally into the active space for observing in the GIR and then is lifted into final position on an internal elevator. Note that guide/acquisition cameras will also be mounted near the focal plane.

The carriage will conform to the GIR standard for translation stages. This will provide for lateral motion from the storage position into the observing position. An additional motion upwards to put the focal plane unit at the main focus of the telescope will also be required.

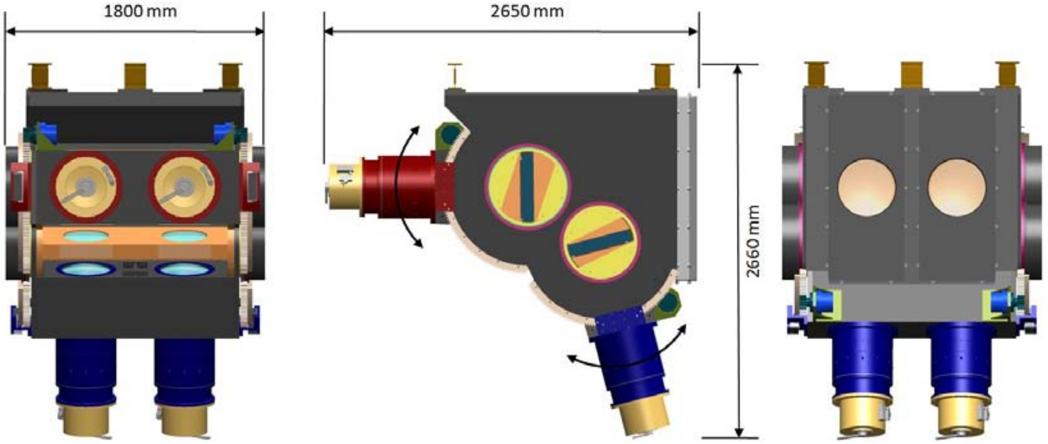
The focal plane unit will contain a cell for the last element of the corrector. The cell will be made from aluminum and will have radial, spring-loaded supports to account for CTE differences between the glass and aluminum housing. The lens is expected to be 1393mm in diameter and weigh roughly 426 kg, so the cell will need careful design and analysis to guarantee optical alignment is maintained for all telescope pointing angles and temperature extremes.

The tent mirrors quarters the field and directs the resulting portions to the appropriate collimators. Instrument focus will be provided by a set of three actuators on the back of each mirror; these could also be used for flexure compensation. The assembly includes four, identical, Zerodur mirrors. Each mirror fits within a 605 x 370 x 60mm envelope and has a mass of 29kg. The entire assembly is affixed to the field lens bench and has a mass of 286kg.

Individual slit masks ride on rails and are inserted into the observing position with a linear actuator. The slit masks are captured kinematically and will be held in place with a stability of ~10 microns, which corresponds to ~0.01 arcsec. The slit masks are a minimum of 527mm x 1145mm in extent; we currently anticipated that each mask will have a cartridge that will be 1286mm x 860mm x 80mm; the masks will be curved to follow the best focal surface of the telescope. The masks will ride on rails as inserted into the storage and observing locations. The top sets of rollers that guide the cartridges into location will have eccentric shafts to set distance between sets of rollers & guide wheels. Rollers are used on the right to keep the slit mask from being over-constrained. While translating, the tracks will remain in contact with at least 2 pairs of guide wheels at any time. The slit mask magazine holds as many as 12 slit masks and the slit mask elevator moves the slit masks from the magazine to the observing position. The elevator uses two linear motions and a rotating motion to move the mask from the magazine to the focal plane. The rotating motion engages a detent on the mask cartridge. A horizontal linear motion extracts the mask from the magazine, and vertical linear motion raises the mask to the height of the focal plane where the mask is inserted beneath the field lens (i.e., the last element of the corrector).

The optics modules contain the spectrograph collimators, dichroics, gratings, and cameras and are attached via flexures to the "ceiling" of the GIR. Two optics modules collimate, disperse, and reimage the slit field. There are four arms total, two per module. The light is split in each arm into a red and blue channel.

Both red cameras, as well as the two blue cameras, articulate as a pair to achieve different spectroscopic modes. The technical specifications require the instrument to have two resolutions per channel. For reference we have adopted a low resolution (R ~ 2000) and a high resolution (R ~ 4000) capability for the fiducial design. This requires articulated cameras and a grating exchange mechanism. To simplify articulation and to do it in a way that is mechanically stiff, both red cameras and both blue cameras are articulated in pairs. Gratings from the two channels are also articulated as an ensemble. The "open" design does expose many optical surfaces to dust and debris, as well as stray light. We will need an environmental enclosure that surrounds the optics module. Aluminum is used throughout in order to minimize mass, maximize stiffness, and avoid CTE mismatches at critical interfaces. Figures 7-9 show various views and renderings of the optics modules and give additional design details.



Optics module mass:
3267 kg as shown
3506 kg including the enclosure

Figure7: Optics modules; there are two of these in the full GMACS implementation, separated by 180 degrees.

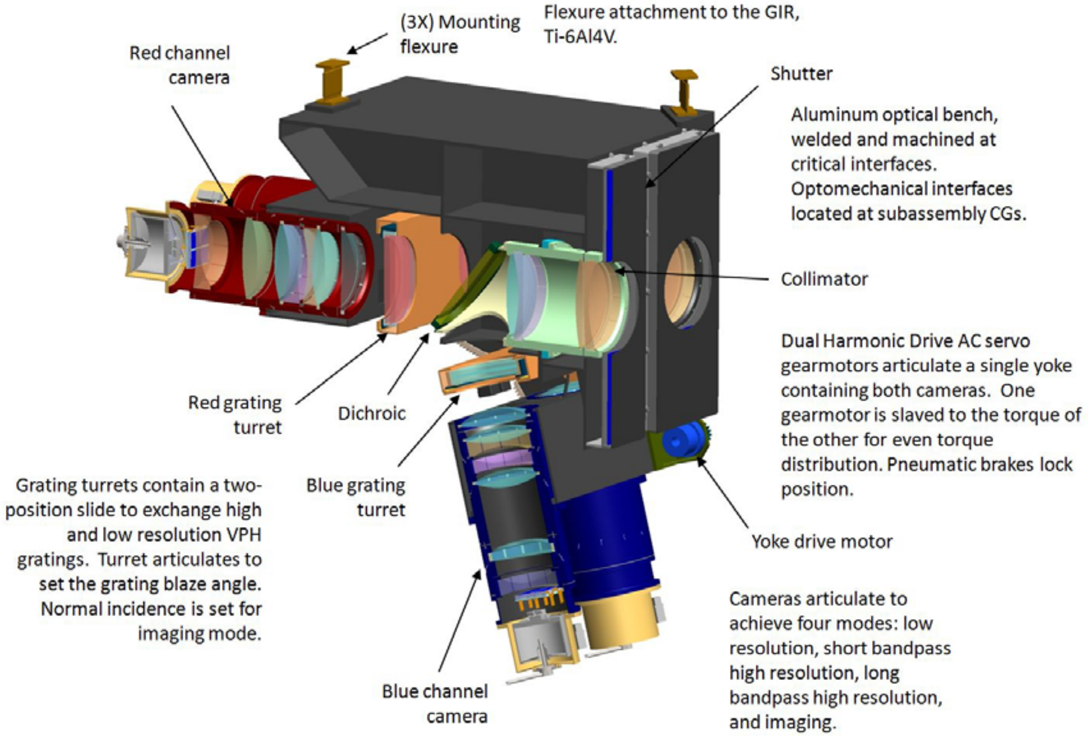


Figure 8: Cut-away of optics module with various additional detail.

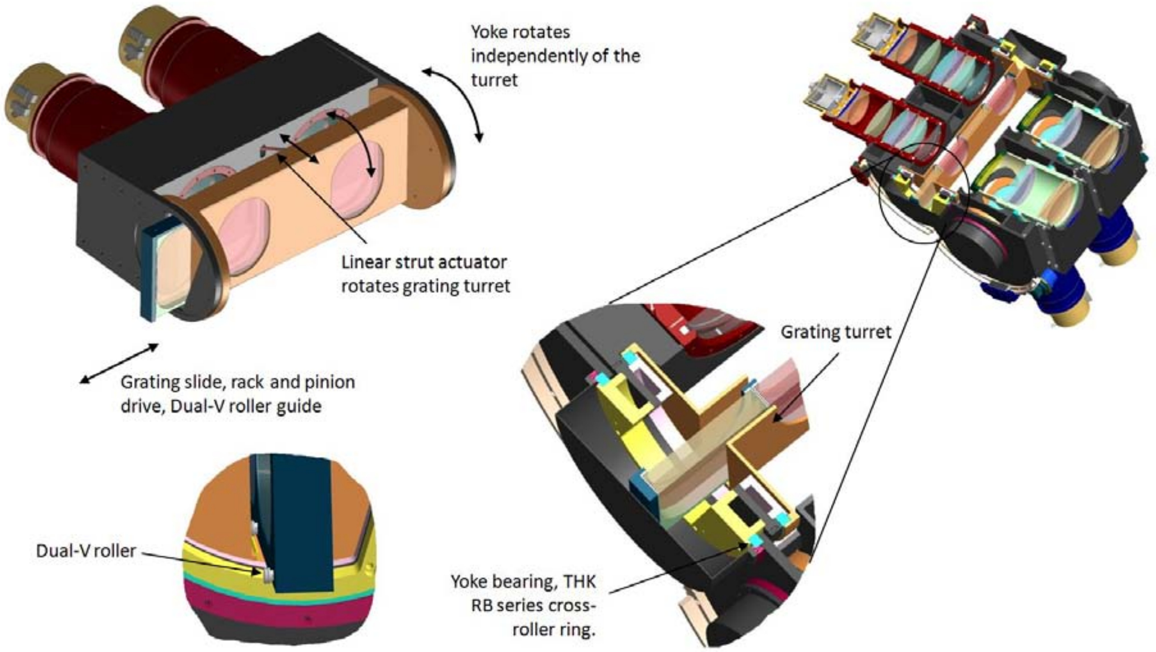


Figure 9: Additional detail on the optics modules.

The grating drive has similar design principles. For example, limit switches set range of motion and hard stops preclude over-travel. Two sets of dual-V roller bearings ride on parallel tracks to provide the requisite linear motion. We expect that the motive force will be a rack and pinion drive, although details are not yet complete.

Figures 10-12 show various details of the collimator housing and the red and blue camera structures. The lens cell concepts shown are borrowed directly from the cells used in the FourStar infrared camera and the SDSS spectrographs, which are known to work well. These are incorporated into the optics modules.

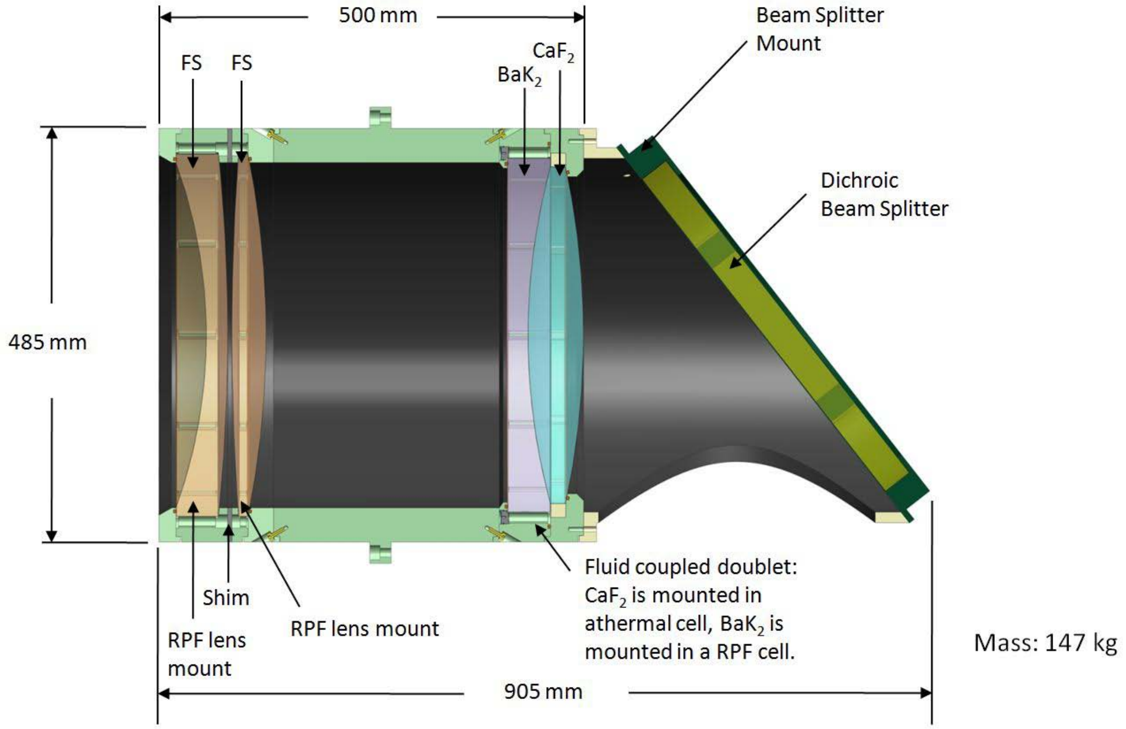


Figure 10: Collimator cell and structure.

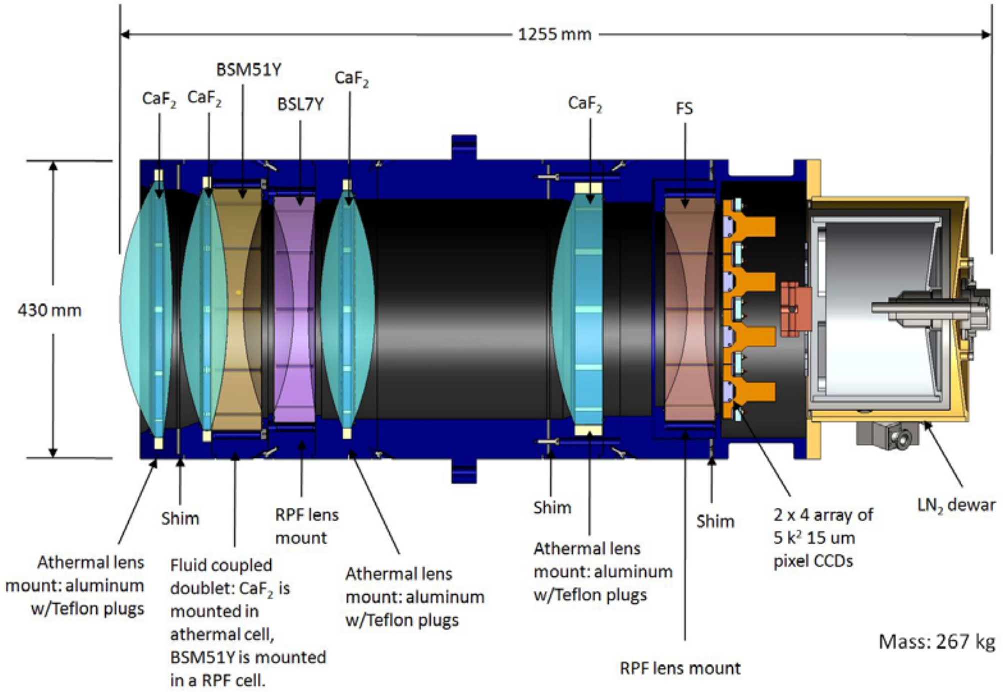


Figure 11: Blue camera showing lens arrangement, structure, and cryostat for detectors.

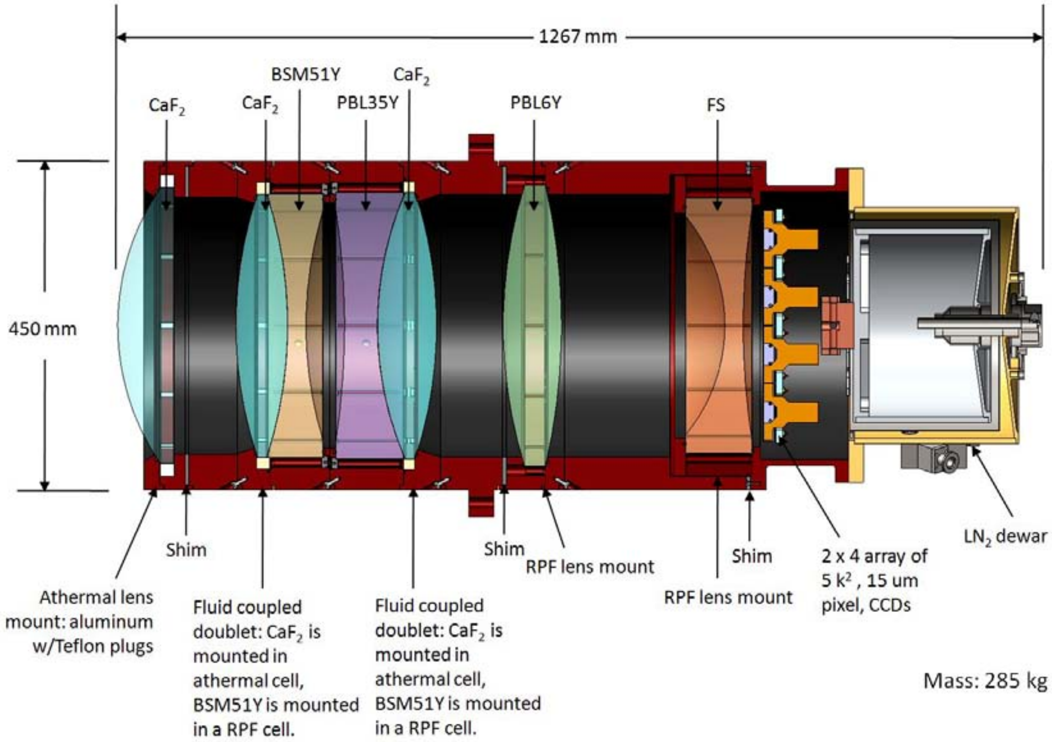


Figure 12: Red camera showing various layout, structure, and design details. Also shown is the cryostat for the detectors.

6. CONCLUSIONS

We have a solid conceptual design for a wide-field, multi-object, moderate resolution optical spectrograph for the GMT. The scientific potential of the instrument is substantial and we believe that the range of specific science cases we have developed demonstrate that GMACS will have impact across most of modern astrophysics. If historical precedent is a guide, then GMACS will be one of the most heavily used and popular instruments on the GMT.

The conceptual design of the instrument is now soundly established and we feel we have mitigated the most serious technical risks. The optical design performs well and all the individual elements can be fabricated. The mechanical design of the instrument fits within the allocated volume and is based on proven heritage. We have an excellent team and adequate facilities to design, fabricate, assemble, and test an instrument of this size and scale. The main remaining technical risk is the development of the flexure compensation system, but we feel we have good concepts for the mitigation scheme.

We have identified some obvious de-scope options for the instrument. Although these reduce the capabilities of the instrument, they do so in a way so as to allow for future upgrades. Essentially, we would design and build the entire instrument, but populate only part with optics and detectors. The savings could be substantial, but the cost will be in observing time for nearly all the identified science projects.

We have recently been advised that GMACS will form one of the "first-light" instruments for the GMT. We look forward with great anticipation to continuing the design process of the instrument, moving to fabrication and acquisition phases of the project, and then on to assembly, test, and deployment in conjunction with the GMT Project.

ACKNOWLEDGEMENTS

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