Conceptual Design of the MOBIE Imaging Spectrograph for TMT

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ABSTRACT

The Multi-Object Broadband Imaging Echellette (MOBIE) is the seeing-limited, visible-wavelength imaging multi-object spectrograph (MOS) planned for first-light use on the Thirty Meter Telescope (TMT). The MOBIE project to date has been a collaboration lead by UC Observatories (CA), and including the UH Institute for Astronomy (HI), and the NAOJ (Tokyo, Japan). The current MOBIE optical design provides two color channels, spanning the 310–550nm and 550-1000nm passbands, and a combination of reflection gratings, prisms, and mirrors to enable direct imaging and three spectroscopic modes with resolutions (λ/Δλ) of roughly 1000, 3000, and 8000 in both color channels, across a field of view that ranges from roughly 8x3 arcmin to 3x3 arcmin, depending on resolution mode. The conceptual design phase for the MOBIE instrument has been underway since 2008 and is expected to end in 2015. We report here on developments since 2010, including assembly of the current project team, instrument and camera optical designs, instrument control systems, atmospheric dispersion corrector, slit-mask exchange systems, collimator, dichroic and fold optics, dispersing and cross-dispersing optics, refracting cameras, shutters, filter exchange systems, science detector systems, and instrument structures.

Keywords: TMT, MOBIE, WFOS, MOS, spectrograph, (up to 8 keywords allowed)

1. INTRODUCTION

The Multi-Object Broadband Imaging Echellette (MOBIE) is the fourth design concept developed to meet the proposed science requirements for a wide-field optical spectrograph (WFOS) for TMT. Due to the nature of seeing-limited instruments for extremely large telescopes (i.e. large and expensive), and TMT project funding profiles, the conceptual design of the MOBIE instrument has progressed incrementally through a series of design and value engineering stages. In general, this staged approach has allowed the MOBIE instrument project to maintain a consistent level of coordination with the rest of the TMT project. The MOBIE project started in 2008 with a six-month feasibility study, and completed the second of three anticipated conceptual design stages in October 2013. The conceptual design phase is now expected to complete in late 2015. The initial (feasibility) optical design for MOBIE was documented previously[1], as was the first stage of the conceptual design phase[2]. An initial stray light analysis for MOBIE on the TMT was also documented previously[3]. We report here on the results of the second stage of the conceptual design phase, which has included assembly of the current project design team, which includes UCO, UH-IfA, and NAOJ. We report on development of the end-to-end optical designs and design of the instrument subsystems, including instrument control systems, the atmospheric dispersion corrector (ADC), the slit-mask exchange system, the active collimator mirror, dichroic, folding, and corrector optics, grating/prism exchange systems, blue and red channel cameras, mosaic detector systems, and instrument structures.

2. DESIGN REQUIREMENTS

The MOBIE concept is the fourth is a series of designs that have been proposed for the TMT science requirements (see Table 1) for a wide field optical spectrograph (WFOS), following previous concepts proposed by Caltech (MILES), UCSC (ELVIS), and HIA (HIA-WFOS).

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In the MOBIE design, we have attempted to provide flexibility in terms of resolution and multiplexing, and complete wavelength coverage at all resolutions, while simultaneously minimizing mechanical complexity. To accomplish those goals, the MOBIE instrument concept makes use of designs that were successfully pioneered on the most recent generation of instruments for the 6.5-10m class telescopes. For example, the baseline collimator design for MOBIE, which uses an off-axis conic reflector addressing a rectangular off-axis field, was first developed for the Keck LRIS imaging spectrograph, and subsequently used on the Keck DEIMOS and ESI instruments as well. The multi-object echellette (MOE[4]) spectroscopic mode was first demonstrated on the IMACS imaging spectrograph for the Magellan I telescope. The high efficiency gained by the concept of splitting the instrument optical path into red and blue color channels has been used by many other existing spectrographs, including LRIS on Keck, UVES on the VLT, MIKE on Magellan, MODS on the LBT, and many others. Thus, while MOBIE is a new and unique instrument design, not only for TMT, but in the world of optical spectrographs, it is also a system composed of many familiar and proven building blocks.

Description:	TMT Requirement:	MOBIE Concept Design:
Wavelength range:	0.31 – 1.0μm	0.30 – 1.0μm
Image quality: Imaging	≤ 0.2 arcsec FWHM in each band	< 0.2 arcsec FWHM
Image quality: Spectroscopy	≤ 0.2 arcsec FWHM at any wavelength	< 0.2 arcsec FWHM
Field of View:	40.5 sq. arcmin. Multiple fields okay.	8.33' x 3' = 25 sq. arcmin, single field, direct imaging and low resolution modes. Medium and high res. modes use smaller field sizes.
Slit Length:	≥ 500 arcseconds total	500 arcseconds
Spatial Sampling:	< 0.15" per pixel, goal < 0.1"	0.05" per pixel with 15 micron pixels
Spectral Resolution:	R = 500-5000 w/ 0.75" slit, R = 150-7500 (goal)	R = ~1000, ~4000, ~7000 (red) R = ~1000, ~5000, ~9000 (blue)
Throughput:	≥ 30% from 0.31 – 1.0μm, or "similar to best current spectrometers"	Will depend on cost and availability of gratings and optical coatings.
Sensitivity:	Shot noise limited for > 60s exposure. Background subtraction errors < shot noise for 100,000s. Nod and shuffle desirable.	Will depend on best available science detectors, N&S capable
Wavelength Stability:	Flexure < 0.15 arcsec at detector	Closed-loop control of focal planes.

Table 1 – A compliance matrix showing the TMT science requirements and the MOBIE conceptual design.

The MOBIE project team has developed several key systems engineering documents to guide the design process. The MOBIE Design Requirements Document (DRD), Operational Concepts Definition Document (OCDD), and an Interface Control Document (ICD) between the MOBIE instrument and the TMT telescope are all publicly available on the TMT website (www.tmt.org/documents), so will not be discussed in detail here. Table 1 lists the key TMT science requirements and the capabilities provided by the latest MOBIE design. The following sections describe the optical design of MOBIE and the subsystems which are required to provide the full range of capabilities and functionality enabled by that design.

3. OPTICAL DESIGNS

3.1 Optical Design Overview

The TMT produces an f/15 focal ratio at the Nasmyth focal stations, with a focal surface radius of ~3m, and plate scale of 2.18 mm/arcsec. The design and performance considerations motivating the MOBIE optical design were described previously[1]. The key features of the current MOBIE optical design can be summarized as follows. The design includes a single 8.33 x 3 arcmin field of view (de-scoped from the original 9.6' x 4.2'), centered 4.8 arcmin off-axis, a large (~1m x ~1.7m) reflecting collimator, a dichroic which splits the beam into two colors channels at 550nm, multiple spectroscopic and direct imaging modes on both the blue and red sides, and two f/1.9 refracting cameras. Although currently undersized for some operating modes, the blue and red camera designs both produce flat focal surfaces, roughly 180mm x 240mm, with plate scales of 276 microns/arcsec and covering 310-550nm and 550-1100 nm passbands, respectively. There have been substantial improvements to the optical designs in the second stage of the conceptual design phase; these are described below.

3.2 Collimator and Corrector Lenses

As was discussed previously, a reflecting collimator is the most natural choice for a wide field of view on a Ritchey-Chretien telescope. The parameters of the collimator mirror are strongly constrained by the telescope and the desired pupil diameter. Specifically, the focal length of the collimating mirror is selected to provide the desired beam diameter, and the conic constant and curvature are then fully specified by the F/# of the beam and the curvature of the telescope focal surface. The best performance for the collimator (without correctors) is obtained with a 9.00 m radius of curvature and a -1.17 conic constant. However, with this prescription, the space is quite limited for the dichroic; either the dichroic will have to be pushed down the beam, leaving insufficient space to fold the red arm and also fit in the prisms and gratings before the pupil forms. To provide a little extra space, it is useful to offset the vertex of the collimator mirror away from the MOBIE field of view (see Figure 1).

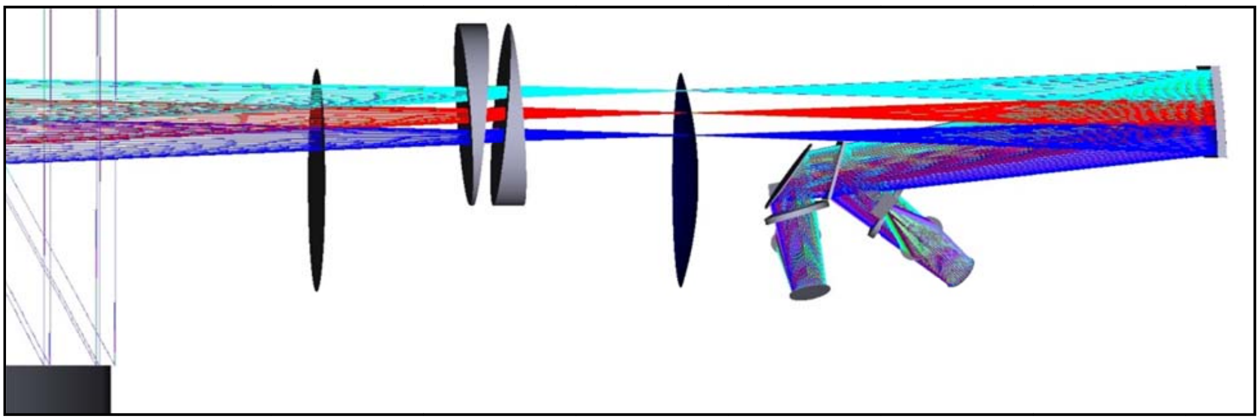


Figure 1 - The optical path and optical elements of MOBIE in position on the telescope (TMT primary at left). All optics are shown as designed, except the cameras which are shown here by paraxial approximations. For scale, the ADC prisms are ~1.4m in diameter.

This is sufficient to provide enough room to fold the red beam and increases the clearance at the dichroic by more than 50mm. Without corrector lenses, the RMS spot radius over all field positions in the MOBIE field of view varies between 0.1 and 0.2 arcsec, including the telescope, ADC, and collimator mirror. RMS spot size grows with field radius and at large zenith angles. These images are too large to guarantee that the final image performance requirements, including cameras, can be met (0.2 arcsec FWHM). It is possible to improve the image quality by adding a single corrector lens to each color channel, after the fold mirror on the red side and after the dichroic. By optimizing the collimator mirror and correctors together, it is also possible to adjust the conic constant on the mirror to exactly -1.0, which should simplify the fabrication and testing of the mirror, and may reduce fabrication time and risk. On the red side, a fused silica corrector lens provides good correction over the full wavelength range. On the blue side, better correction can be obtained with S-FSL5Y or CaF_2, both of which have lower dispersion than fused silica, and therefore produce less chromatic aberration. S-FSL5Y has been base-lined as the blue side corrector material. Both the red and blue corrector lenses have spherical surfaces.

3.3 Cross Dispersing Prisms

After the collimator and corrector designs were revised, the layout of the dispersion elements was changed to use the prisms in double-pass (see Figure 2). This dramatically reduced the total length of beam that was needed for the dispersion elements between the dichroic and the red and blue pupils. It may now be possible to move the correctors closer to the pupils, which would reduce their required diameter and total cost. It would then be worthwhile to re-optimize the corrector lenses in a location as close to the pupils as possible without colliding with the cameras. It is also tempting to think that the recovered beam length could be used to move the dichroic farther away from the collimator, but that is probably not a good idea because it would push the red fold mirror closer to the focal plane of the telescope.

The area around the focal plane will be crowded already with wavefront sensor and guider cameras and the support structure of the instrument, so it is probably a good idea to keep the red fold mirror out of that volume.

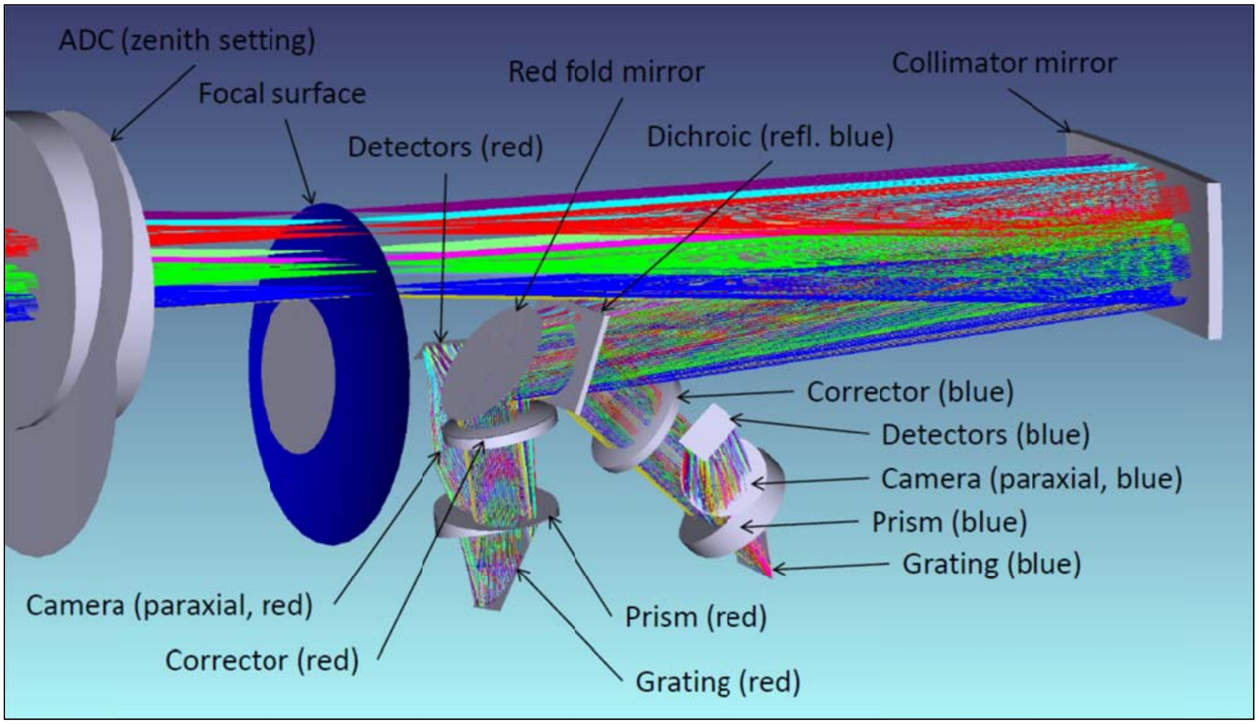


Figure 2. The MOBIE optical layout for the R~8000 mode in two color channels.

3.4 Finalizing the MOBIE Optical Designs

The cameras in the current MOBIE design are aggressive in terms of pupil extraction, angular field of view, and image quality, but their diameters are quite modest compared to the overall scale of MOBIE, its field of view, and its resolution. The largest optical diameter at the mouth of the cameras has been tightly constrained to be less than 450mm, to match the availability of calcium fluoride at the outset of the MOBIE conceptual design phase, and to contain the total cost of the cameras. Since that time, the optical layout of the area around the gratings and prisms has evolved to solve problems associated with the total beam length available between the collimator mirror and the pupil, and a double-pass configuration has been adopted for the prisms. As a result, the most pressing issue to address in the finalizing the MOBIE optical design is vignetting of the beams into the cameras in the high resolution modes. The primary factors that come into play are the pupil diameter and the pupil-camera spacing (pupil extraction), which is constrained by the prism configurations and the grating quasi-Littrow angle. Reducing the pupil diameter will increase the pupil magnification, so it will likely be necessary to reduce the resolution by the same fraction that the pupil is reduced, in order to achieve the desired goal of reducing the beam diameter at the camera mouth. The camera size could also be increased if desired, as it is now possible to obtain quotations for generated calcium fluoride lens blanks up to 650mm in diameter and 200mm thick.

4. INSTRUMENT CONTROL SYSTEMS

4.1 Instrument Operating Modes

The state of the instrument (e.g. the optical modes) is defined by a particular hardware configuration. Selecting a particular instrument configuration requires a command to be sent to the instrument controller (a generic observatory component). The controller will then send commands to the various assemblies, which will in turn send commands to the hardware control daemon (HCD), which finally send commands to the subsystem controllers (see Figure 3, left side).

4.2 Observation Planning and Slit Mask Management

Observation planning is an essential part of the MOBIE instrument concept. Slit mask designs must be prepared in advance. The software suite includes a planning tool that will allow the user to select a collection of targets, to simulate the target image or spectra, and to optimize one or multiple masks for observations. The planning tool will also allow the user to select guide stars and other reference objects, in order to cut the slits and holes for reference objects (for guiding, wavefront sensing, and flexure sensing). The planning tool will be connected to an observatory database, which will be used for mask creation and mask inventory management. The database will be used at the time of observation, to assist in setup, mask positioning, and data processing.

4.3 User Interfaces

User interfaces are not discussed in great detail in the conceptual design phase. It is planned that the observatory will provide a standard toolkit, look and feel, and interface guidelines at a later stage of development. Instead of providing a user interface description, the instrument will be provided with a set of properties that can be configured to select an operating mode, and a set of published data that can be monitored to determine the current state of the instrument.

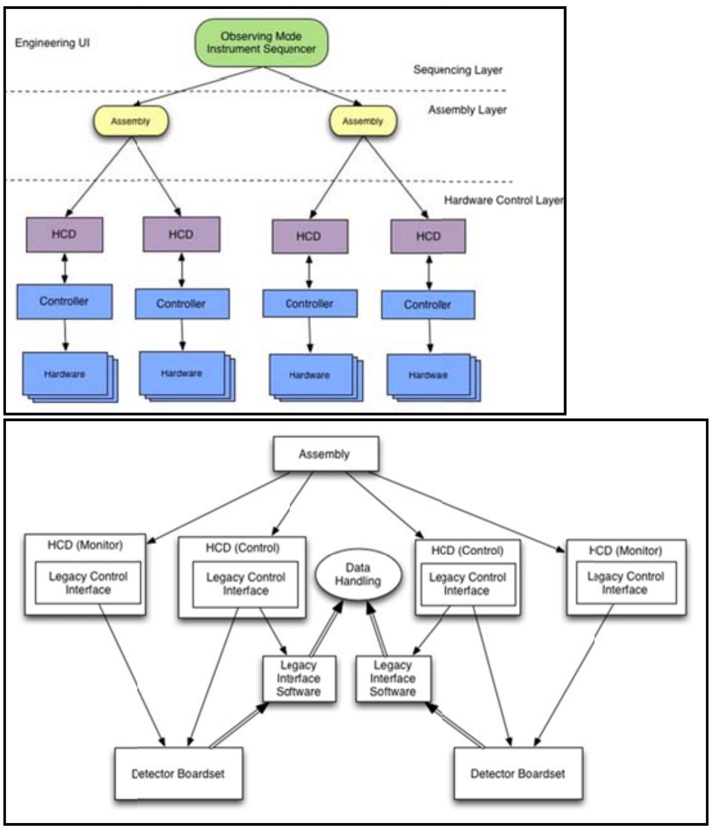


Figure 3 - MOBIE instrument software architecture (left) and detector system architecture (right).

4.4 Motion Control Systems

The MOBIE motion-control model is based on the TMT software architecture, which is shared by all observatory components. The instrument as a whole is broken into software subsystems, all of which is controlled by observatory software. Each subsystem is controlled by an "assembly," which is a software object that controls interacting hardware components. Each hardware component is controlled by an HCD that provides a standard interface to mechanism-specific commands. Most mechanisms are controlled by variants of a single HCD, which controls motion controllers and other similar components over a TCP interface. The motion control HCD forms the basis for specific MOBIE motion controllers (e.g., a linear stage).

The MOBIE motion control functions present only a couple of challenges for implementation. There are linear and rotary servomotor stages, air power stages, hexapods, and a slit-mask exchanging robot. From a software perspective, the servomotor and air power stages are quite simple, so a standard HCD can be adapted for each stage. For the conceptual design phase, it's assumed that a MOBIE HCD will command the focal plane hexapods through a vendor-supplied application programming interface (API). Similarly, it's assumed that the slit-mask exchanger robot will again be controlled by a MOBIE HCD through a vendor-supplied API. The shutters are tightly coupled with the camera systems, and are operated directly by the detector controllers.

All other mechanisms fall into one of three classes: limited linear motion, limited rotary motion, and dual-position. From a software standpoint, all three of these controllers are easy to implement, and require nearly identical code. None of the software requires high-speed communications or high data rates, so a simple interface to an off-the-shelf motion controller is sufficient. The HCDs will simply convert positioning commands into the corresponding motion controller commands.

4.5 Detector Control Systems

The detector controllers are the most complicated software elements in the system. The detector controllers accept text commands over a TCP/IP interface. The detector system HCDs will accept commands from a higher-level assembly, convert them into the appropriate low-level controller commands, and send them to the detector controllers (see Figure 3, right side). Unlike a motion controller, a single operation will require a sequence of low-level commands to be sent, and a separate process will be required to collect and store the data.

4.6 Flexure Control

The control of image motion at the blue and red camera focal planes, due to gravitational and/or thermal effects within the instrument, will be enabled by multiple MOBIE hardware and software subsystems. As the first line of attack, the MOBIE optical and structural designs seek to balance mass around the instrument rotational axis, and to carry subsystem loads in tension/compression elements, such that the primary contribution of gravity-induced flexural image motions will be elastic and repeatable (a simple function of instrument rotation angle). In this case, blue and red channel look-up tables based on instrument rotation angle should be able to reduce any flexural image motions by a factor of ~10. This level of flexure control has already been demonstrated in multiple instruments.[5,6,7] An active flexure control system then only has to correct the residual (non-repeatable) motions, which can be done slowly (over minutes) and should not require rapid readout of flexure-sensing detectors.

To provide the closed-loop control of residual image motions, the motion must be first sensed, then one or more corrections calculated, and then corrective actions commanded to the relevant systems. In the imaging modes, pre-selected targets will form images on the two flexure control CCDs located adjacent to the science detectors (which are read out independently). In the spectroscopic modes, fixed targets in the telescope focal plane will be created with optical fibers and a copper-argon light source. These targets will form images on the flexure control detectors in the camera focal planes. In the cross-dispersed modes, filters will block the flexure-sensing light to avoid contamination of the spectra. This approach has been used successfully in the Keck DEIMOS instrument[6]. With regular read-out of the flexure-sensing detectors, motion of image centroids will be calculated, and corrective signals sent to the active elements (tip/tilt/piston control of the collimator, and 6 degrees of freedom motions of the science focal planes via the hexapods). Active tip/tilt/piston of the collimator mirror can only correct image motions that are identical direction and magnitude in both color channels. If these common-path image motions are later shown to be negligible, actuation of the collimator will still be useful for thermally-induced collimator defocus, and will greatly reduce the initial alignment requirements on the collimator. Since most thermal and flexural image motions are generally expected to be different in each color channel, corrections made with the collimator will primarily stabilize the image motion arising at the slit mask, at the collimator itself, and in the intervening support structures. Non-common path image motions (both translations and rotations of the focal plane images) downstream from the collimator will be corrected by motions of the blue and red focal mosaic hexapods. Active flexure control via tip/tilt/piston of collimator mirrors[5] and by actuation of focal plane mosaics[6,7] have been previously demonstrated, and pose no fundamental conceptual challenges for the MOBIE instrument hardware, software, or control systems.

5. ATMOSPHERIC DISPERSION CORRECTOR

5.1 Overview

The MOBIE ADC concept consists of a pair of 1.4m diameter prism which will translate linearly to compensate for atmospheric dispersion for zenith angles between 0 (at zenith) and 65 degrees (from vertical). This style of "linear" ADC has been demonstrated previously on the Keck I telescope[8]. However, the Keck ADC, which is attached to the primary mirror structure, only sees varying gravity loads in one direction, due to rotation of the telescope structure about the elevation axis. The MOBIE ADC, which must be carried by the instrument, sees the gravity rotate about the ADC optical axis. For this reason, the MOBIE ADC also includes a rotation drive, to compensate for the differing rates of rotation of the telescope field and the direction of atmospheric dispersion. The ADC prism separation mechanisms move the two prisms symmetrically about a common point, so that the ADC center of gravity remains fixed with respect to the instrument structure (to avoid flexure in the instrument structure as a function of prism separation). Each prism represents approximately 440 kg in mass. The front ADC prism (the prism closest to the telescope) and its cell will be sealed with the ADC structure to keep dirt from entering the instrument. This will require a sliding seal, a bellows, or a "bello-fram" (rolling diaphragm) that can operate over the full 1200mm stroke of the prism.

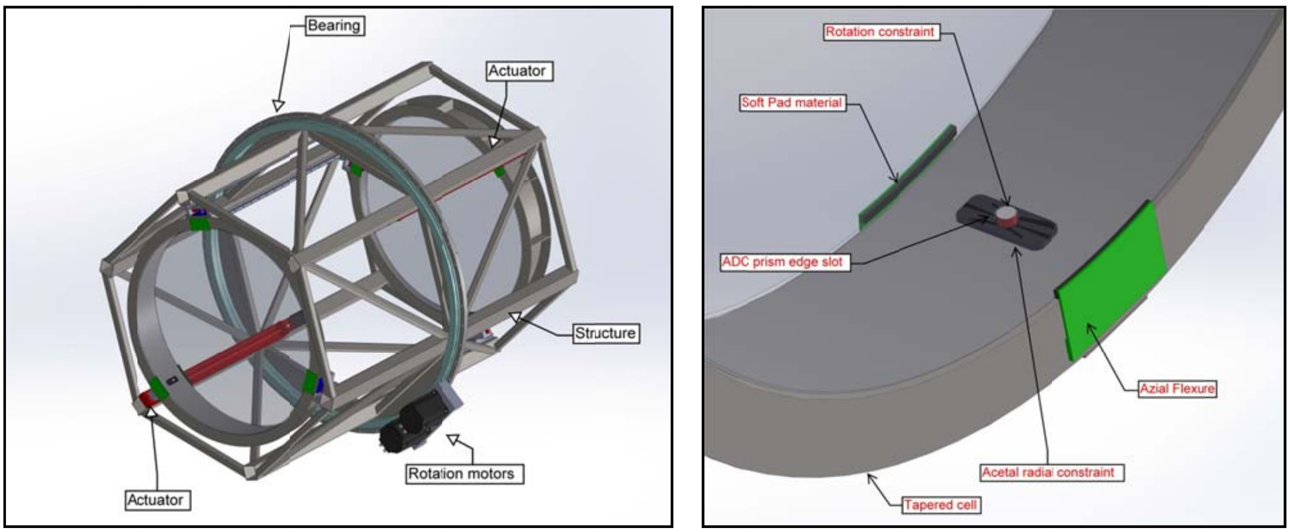


Figure 4 – The ADC conceptual design layout with 1.4m diameter prisms (left) and details of the opto-mechanical interface to the ADC prisms (right).

5.2 ADC Prisms and Opto-Mechanics

The prisms will be held in steel cells with quasi-kinematic constraints. Axial and radial restraints will be located around the perimeter of the prism, spaced by ~120 degrees. The cell concept uses a tapered weldment whose primary purpose is to hold the radial and axial prism locating pads and to transfer the prism loads to the actuators and guides. The cells must be tapered to meet minimum required prism separation of 20mm, which occurs when the telescope is pointed at the zenith. The actuator attachment points align with the radial and axial restraints to ensure a direct load path through the cell and into the structure, thereby minimizing the stress in the ADC cell and hence reducing the required stiffness and mass of the cell. The conceptual design is currently 93 kg. The cell to optic mass ratio is 457/93 or 4.9:1 which represents an efficient use of material.

The three radial restraints are arranged with one at the base of the prism and the other two located +/-120 degrees away. For some ADC rotation angles, a single radial pad will support the full 440 kg mass of the prism, so each pad area is selected to carry the full mass of the prism and meet a 500 PSI stress requirement (to limit stress birefringence in the prisms). To athermalize the radial supports, a material with a high coefficient of thermal expansion will be used and the pad length selected to minimize thermal stresses. Axial restraints will be provided by opposing pairs of fixed and flexure pads with soft faces acting on opposite faces of the prism (see Figure 4). In normal operation, the axial restraints can operate at low preloads because the prisms operate in a vertical position, rotating only around a horizontal axis. To assure that the prisms can be held safely in their cells in any orientation for shipping or storage, the flexures will have hard points (not shown) at the end of their range to limit their total travel. The last unconstrained degree of freedom is rotation about the optical axis. This motion will be prevented with a polymer pin keyed into a machined slot in the edge of the prism. The axial preload will provide sufficient axial force to restrain prism rotation during normal operation. These constraints will be reviewed in later design phases to assure safety of the prisms under seismic loadings.

5.3 ADC Structure and Motion Stages

The MOBIE ADC structure is envisioned as a hexagonal weldment (see Figure 4) made from structural steel tubing. This shape matches the position and arrangement of the two THK actuators and the four LM guides required to support the prisms. Because the apexes of the prisms are 180 degrees out of phase, the actuator and slides will also be located 180 degrees out of phase**.** The flat facets of the hexagonal weldment will be covered with panels that are designed to be light-tight and air-tight. The covering panels will be mounted with quick-release fasteners to allow convenient access to the prism stages for service. The inner surfaces of the ADC structure will be coated to minimize scattered light. The ADC will mount to the instrument structure on a bearing with an integrated spur gear to drive the de-rotation of the ADC as the MOBIE field rotates differentially with respect to the atmospheric dispersion angle. A pre-loaded, double-row, angular-contact bearing with an inner diameter of 2000mm will be used (similar to the rotator bearing chosen for the Keck MOSFIRE spectrograph[9]).

This bearing design is significantly more robust design than the instrument rotator bearings used for ESI, which has been in use for over 15 years. The current ADC mass as designed is approximately 50% lighter than MOSFIRE, and will therefore have an additional load safety factor of 2 if the same bearing is used.

The axial location of each prism within the ADC will be controlled by a THK SSR-65 linear actuator, which is composed of a ball screw driving a preloaded crossed-roller slide. These actuators have been used previously in the collimator of the ESI[5] instrument with excellent results. The actuators will attach to the base of the prism cells to minimize the moment arm between the actuation axis and the CG of the prism and cell. Each SSR actuator constrains 6 degrees of freedom of one prism and will be rigidly connected to the cell at the base. These actuators can be supplied with 2 blocks (one driven by the screw and the second free) to double the moment-carrying capacity of the actuator if required. The remaining two radial pad locations will couple to LM slides with a spring connection to ensure that only a force constraint occurs at this interface (to prevent over-constraint of the prism cells). Each actuator will be driven by a DC servomotor and gearbox. The positioning requirements for the prisms do not require closed-loop feedback to provide acceptable accuracy, however the design will include a secondary load encoder to make the ADC motion stages consistent with MOBIE motion stage standards. Operating the ADC in a dual closed-loop configuration (with the second load encoder) would also allow more complete diagnostic and error recovery capability.

6. SLIT MASK SYSTEMS

6.1 Mask Exchange Systems

Conceptual designs for the MOBIE mask exchange systems were described previously[2]. Use of a commercial robot for optical element exchange has already been successfully demonstrated[10]. The key concept for the MOBIE mask exchange system is the location of the robot; either on the fixed or rotating part of the instrument structure (see Figure 5). The two alternatives have differing impacts on operations, driven by the need (or not) to rotate the instrument to a fixed position each time a mask exchange is required, with the corresponding loss (or not) of observing time. Similarly, the two approaches have differing risks in terms of the challenges of operating the robot in a standard configuration, mounted to the floor, or a more unusual configuration, where the robot rotates with the instrument and must operate in a variety of attitudes with respect to gravity. In either case, the robot will load a slit mask into a mounting fixture located at the telescope focal surface, and will hold the mask in the correct position and shape during use. A detailed trade-study in the next design phase will be needed to identify the best risk/cost/performance configuration for the mask exchange system.

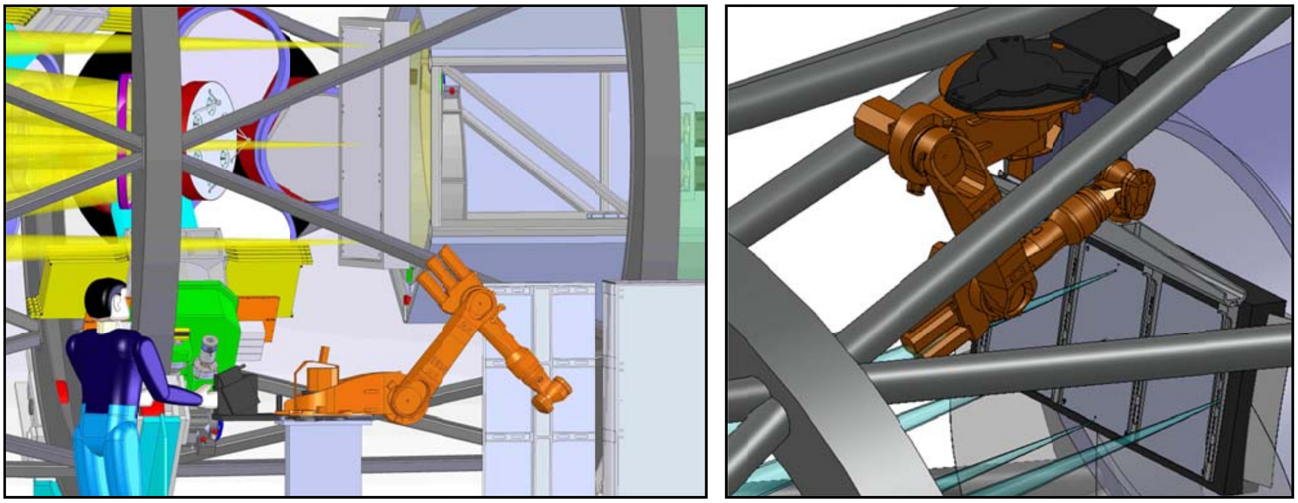
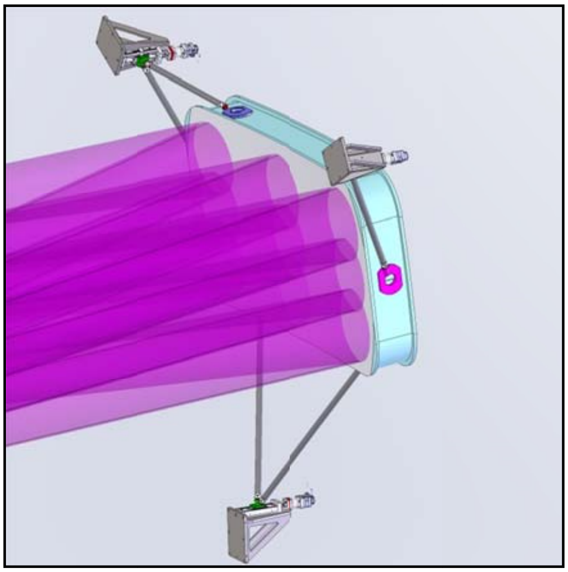


Figure 5 - Two alternatives for mounting of the slit mask exchange robot (in orange), on the floor (left) and on-board the instrument (right). A focal plane fixture holds the mask in the active position on the instrument.

7. COLLIMATOR SYSTEM

7.1 Collimator Mirror and Opto-Mechanics

The MOBIE articulated collimator design draws on heritage from existing Keck telescope instruments, including the ESI[5] active collimator and the HIRES[11] Schmidt camera mirrors. As in HIRES, the concept for the large optic is made from borosilicate glass using the Hextek[12] gas-fusion process. Mechanical connections to glass bulkheads within the Hextek mirror substrate use polymer contact points and mechanical fasteners to attach the clamping halves to the mirror. These mounting flanges are in turn attached to struts with crossed flexures at each end. The far ends of the mounting struts attach to the moving block on the three THK LM actuators (see Figure 6). A key difference between the ESI and MOBIE collimator systems is that as a Cassegrain-mounted instrument, ESI sees a variable gravity vector as the telescope points in altitude and azimuth (and rotates about the optical axis to de-rotate field rotation). MOBIE, as a Nasmyth-mounted instrument, rotates about a single (horizontal) axis to unwind field rotation. While the MOBIE collimator is slightly tilted with respect to the Nasmyth axis, in general, most of the loads will be carried radially (in the central plane of the mirror), with only a small varying gravity component in the axial direction (normal to the mirror surface). For this reason, the opto-mechanical mounting for the MOBIE collimator should be biased for the predominant loading directions in the plane of the mirror. It can be seen in the left side of Figure 6 that the six mounting struts carry the mirror loads primarily in the radial direction, with only small tilt angle away from the central plane of the mirror (to provide some stiffness in the axial direction).



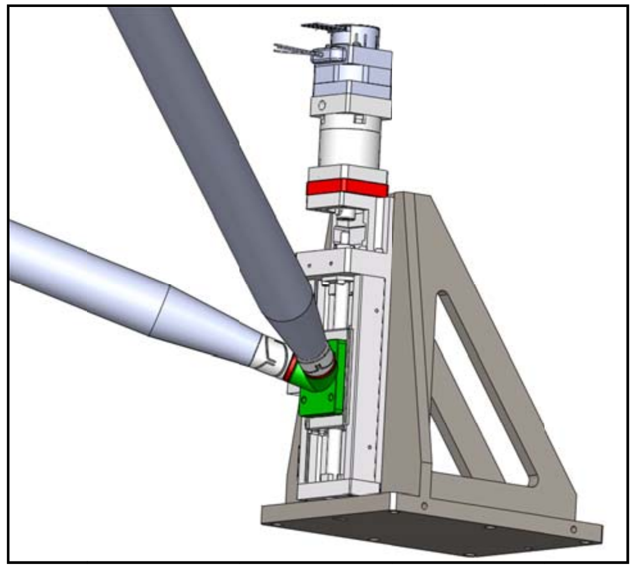


Figure 6 - Two images of the MOBIE collimator mirror system, showing the mirror with its support struts (left) and positioning actuators (right).

7.2 Collimator Flexure Control

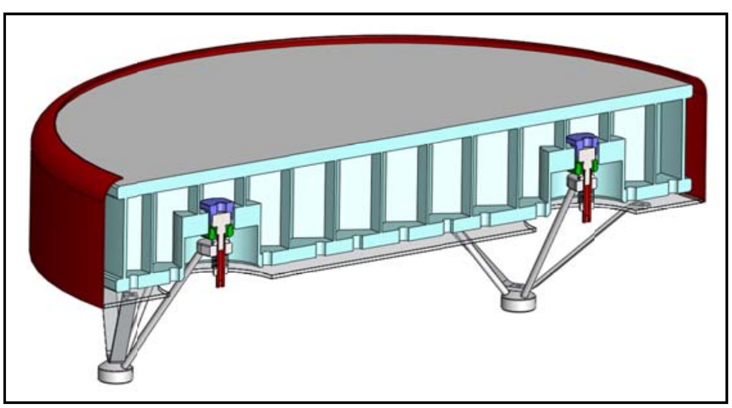
In the conceptual design phase, we assume that flexure and focus control of the collimator mirror will be required primarily to compensate for gravity-induced flexure and thermal-optical defocus of the collimator mirror itself. The collimator can't be used to correct flexure in the rest of the instrument, as flexure compensation motions for the two color channels will differ. However, experience with the active collimator in ESI suggests that the design can achieve very low hysteresis, so compensating motions can be mapped and applied with a look-up table (as described previously).

8. PUPIL OPTICS AND FIELD CORRECTORS

The region of the optical design containing the dichroic, red channel fold mirror, and blue and red field lenses provides a variety of challenges for the MOBIE opto-mechanical conceptual design. The dichroic separates the blue and red color channels, and operates at a low incidence angle to reduce polarization and ghosting. Separate field lenses in each color channel improve telescope field-dependent image quality errors, and provide sharper images of the telescope pupil at the diffracting optics, and better images at the camera focal planes.

8.1 Red Fold Mirror and Mount

The red fold mirror concept uses a ~700mm diameter Hextek light-weight borosilicate mirror. The mounting concept is kinematic, and uses three bipods to attach the mirror to the instrument structure (or folding optics structure if used).



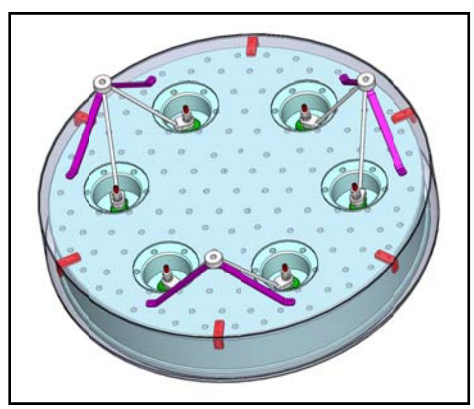


Figure 7 - Section view through red fold mirror assembly, showing kinematic mountings for the support bipods, and a back-side view showing the locations of the mounting bipods.

The attachments to the mirror are similar in concept to the HIRES camera corrector supports. A pre-loaded ball-socket joint is carried by two halves of a polymer clamping pair (see Figure 7). The clamps are held together by Belleville springs. Tip, tilt, and piston alignment is accomplished with precision thickness shims (or gage blocks) between the bipod feet and the instrument structure. The mirror can be removed from the assembly for re-coating. Small in-plane displacement errors associated with the attachments between the bipods and the instrument structure are negligible, as the red fold mirror is slightly oversized for the optical beam, and small in-plane translations of the (flat) mirror do not result in image size or motion errors. The mirror assembly includes a cover and aperture mask (shown in red in the figure above).

8.2 Dichroic and Mount

The MOBIE dichroic is approximately 710mm x 520mm x 30mm. Substrates in the required material (fused silica) and size are available from multiple sources. A similar mounting concept will be used for the dichroic and corrector lenses; kinematic mounting with six defining contact points, and pre-load forces opposite each support point. Kinematic mountings are designed to avoid distorting the optics under varying gravity vectors, and will allow the optics to be removed easily from their cells for re-coating. The cells have two main components; a cell body, and a retaining ring attached to the cell. The cell components will carry the kinematic defining point assemblies and the spring preload assemblies. The cell body is relieved on one side (see Figure 8) to provide clearance for the rays passing the dichroic on their way to the collimator mirror.

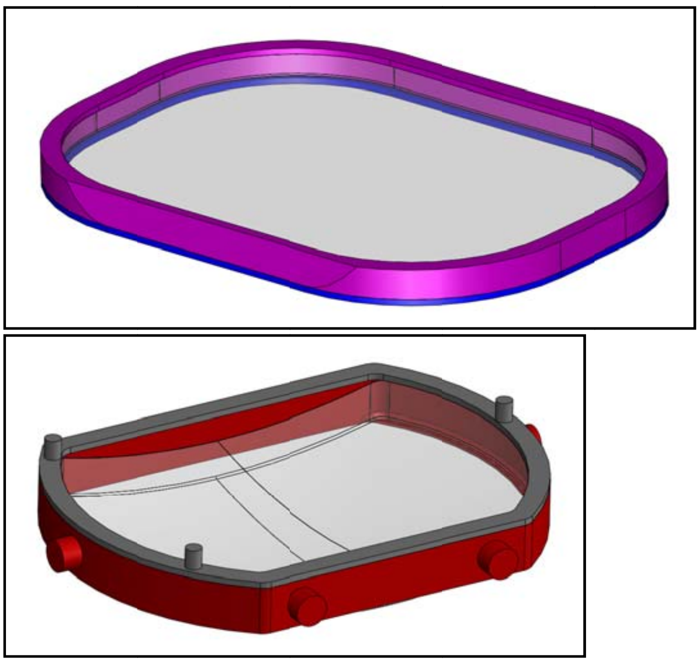


Figure 8 – (Left) The dichroic mounting concept. Defining points and spring preloads are omitted in this image. (Right) The red field corrector mounting concept. Radial and axial support points are shown schematically by the red and grey cylinders.

8.3 Field Corrector Lenses and Mounts

The lenses will be mounted in cells, using the approach described for the dichroic. The lenses are supported at six points, with matching preload forces applied opposite each defining point (see Figure 8). Distortions of the cell mounting, or the cell itself, are not transmitted into the optics. Tip, tilt, and piston adjustments of the optic in the cell are accomplished with threaded features in the defining point assemblies. Like most MOBIE optical subsystems, the cell will locate kinematically in the mounting structure with indexing features (diamond pins and drill bushings) to allow repeatable removal and installation without requirement re-alignment of the instrument optical system.

9. SPECTROGRAPH OPTICS

9.1 Overview

The MOBIE grating exchange systems (GEX) concepts use rotary motion stages to enable selection of the different operating modes in both color channels, ruled (reflection) diffraction gratings for primary dispersion, double-pass prisms for cross-dispersion (in the medium and high resolution modes), and mirrors for the direct imaging modes. By virtue of the use of gratings in the Littrow configuration, each MOBIE spectroscopic mode provides complete wavelength coverage at the specified resolution without variable tilt of the gratings. The elimination of grating tilt control substantially reduces cost, reduces flexural image motions, and increases reliability of the instrument. The low resolution spectroscopic modes (blue and red channels) create single-order spectra (without cross-dispersion or CD prisms). The medium and high resolution modes are cross-disperse and create multi-order spectra. Direct imaging in both color channels is provided by exchanging a flat mirror in place of a spectroscopic optical assembly.

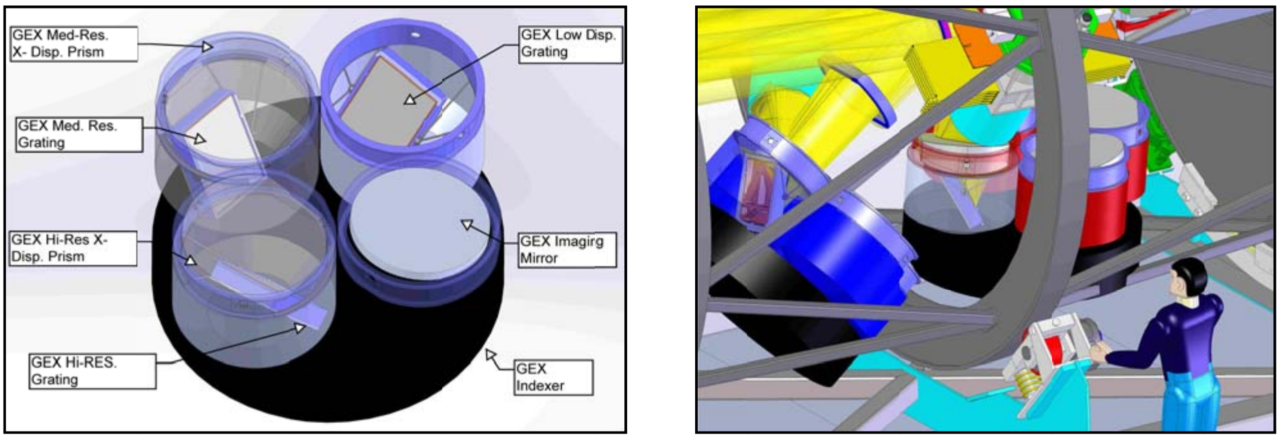


Figure 9 – Spectrograph and direct-imaging optics are mounted in kinematic cells (left) and are carried in rotary exchange stages (right) in both color channels (shown in blue and red).

9.2 Gratings, Prisms, Mounts, and Stages

The prisms are mounted kinematically in cells through three connection points on each prism. The gratings connect to the prism cells via determinate strut assemblies to ensure that no moment loads are transmitted to the optics as the instrument rotates and flexes. The prism use fused silica and are ~600mm in diameter. The grating substrates for the low and medium resolution modes use standard Newport grating sizes (~300mm x ~400mm). The high resolution modes require grading substrates that are ~300mm x ~500mm long. We currently do not have a source for this grating size as it exceeds the capacity of Newport’s ruling engine. However, we are optimistic that the Changchun Institute of Optics, Fine Mechanics and Physics will successfully produce a 300 x 500 mm echelle by the end of 2014. If a single grating of the required size does not become available, we will develop options including double ruling replication on a single substrate and mechanical mosaics. The GEX motion stage concepts are based on the use commercial rotary motion components, including turntable bearings, gearboxes, and motors. The GEX systems will require very high accuracy and stiffness for a system which occupies a large volume but has relatively low mass. Most commercial-off-the-shelf (COTS) indexers of suitable size tend to be designed for much larger masses and are therefore significantly larger than MOBIE can accommodate. If a suitable COTS stage is not found, the GEX indexer will to be designed in-house.

10. CAMERA SYSTEMS

Figure 10 shows the conceptual design of the MOBIE spectrograph camera systems. The camera system main body mounts lens cells, a filter exchanger system, a shutter and a detector unit. The main body has an interface flange to the MOBIE main structure. The blue and the red cameras will have slightly different structures as required by their optical layouts. However in the conceptual design phase, we did not fully detail both cameras as the optical layout will be updated in the next design phase.

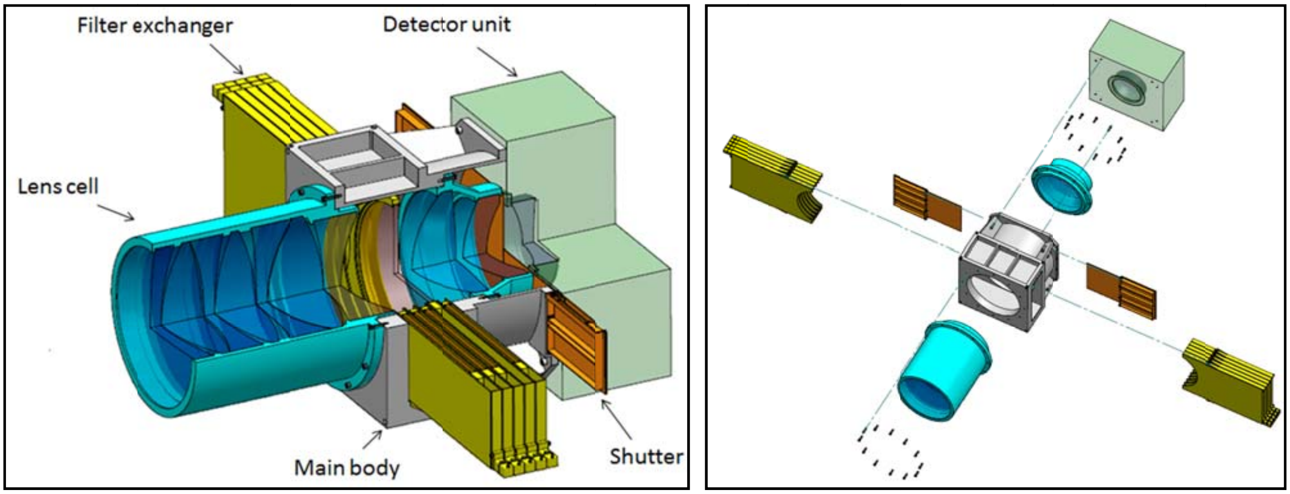


Figure 10 - Conceptual structure of the spectrograph camera systems. A detector system unit is not included in the camera systems and only their rough dimensions are shown.

10.1 Camera Systems

For high-throughput over the wavelength range of 310 – 600 nm, only silica and calcium fluoride (CaF_2) will be used in the blue camera. CaF_2 lenses will be used for the red camera to minimize lens count. Hence the MOBIE camera systems require large (~500mm diameter) CaF_2 lenses. Although large CaF_2 crystals are a key technical issue, Hellma Materials has produced large CaF_2 crystals (up to 440mm in diameter), with even larger capability. The refractive index homogeneity and stress birefringence at these sizes has been measured to be < 3.5×10^{-6} and < 3.4 nm/cm, respectively[13]. Supporting mechanisms for large lenses are one of the technical issues for such large instruments, and have been investigated[14]. CaF_2 is well known as fragile material, and has large coefficient of thermal expansion (CTE). Therefore special care is needed for their supporting mechanism. In the blue camera, CaF_2 lenses are coupled with silica lenses which have small CTE compared to CaF_2. Assuming a temperature range of ~30 C and the diameter of about 400mm, the thermal expansion difference between CaF_2 and silica lenses becomes about 0.2mm. Lens cells must compensate such large expansion difference in order to avoid large mechanical stress on the lenses. Individual lens cell designs will be developed further in the next phase. Optical testing of the integrated systems is another key technical issue. Optical refractive indexes of CaF_2 and silica have large temperature dependence and their signs are opposite. Hence lens systems consisting mainly of those materials are expected to have large temperature dependence in their optical performance. Because of this temperature dependence, final optical testing will be carried out at the same temperature expected for normal operation (~0 C). A large temperature-controlled lab will be used for this testing.

10.2 Filter Exchange Systems

In the filter exchanger concept (see Figure 11, left), the filter exchanger system (FEX) consists of a stack of identical units which each hold one filter. The filter capacity in each camera will be finalized later. In the FEX concept, a filter is inserted and extracted by a motorized mechanism with a ball screw and two linear guides. To replace a filter, the unit is detached from the main body, and, after exchanging the filter, it is re-attached to the main body. Each unit will have a mass of ~10 kg including a filter, which allows easy maintenance.

10.3 Exposure Control Shutters

Two identical shutter units are attached to the main camera bodies and each unit has a thin blade made of carbon fiber reinforced plastic. The blade is inserted and retracted by using motorized mechanism with a ball screw and two liner guides (see Figure 11 - right). A hardware controller such as a programmable logic controller (PLC) will be used in order to achieve the exposure time accuracy of 0.01 sec. Exposure time uniformity is expected to be less than 1% because the motor can precisely follow signal from the controller in the case of sufficiently light load and because pitch error of the ball screw has negligible effect on the uniformity.

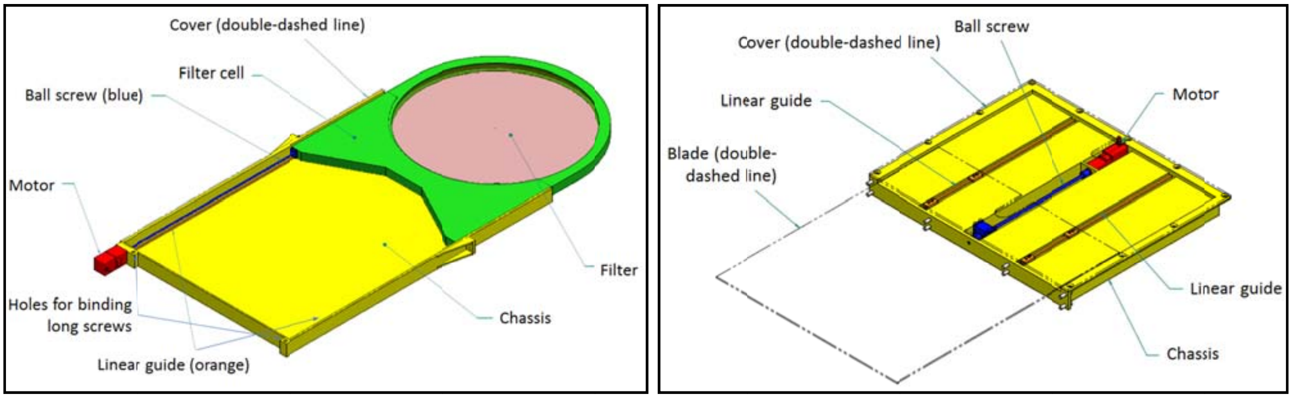


Figure 11 - Conceptual designs of a single filter exchanger unit (left) and a shutter (right).

11. SCIENCE DETECTOR SYSTEMS

11.1 Science Detectors and Focal Plane Mosaics

The detectors and focal plane mosaics in MOBIE must accommodate the full range of wavelengths and operating modes in each color channel. The imaging and spectroscopic modes provide differing focal plane footprints (see Figure 12 for an example), as well as differing rotation angles of the spectra with respect to the detector rows and columns of pixels. The design of the MOBIE detector systems, which includes six degrees of freedom articulation of the focal planes, seeks to provide an efficient mapping of image formats to focal plane arrays in each mode.

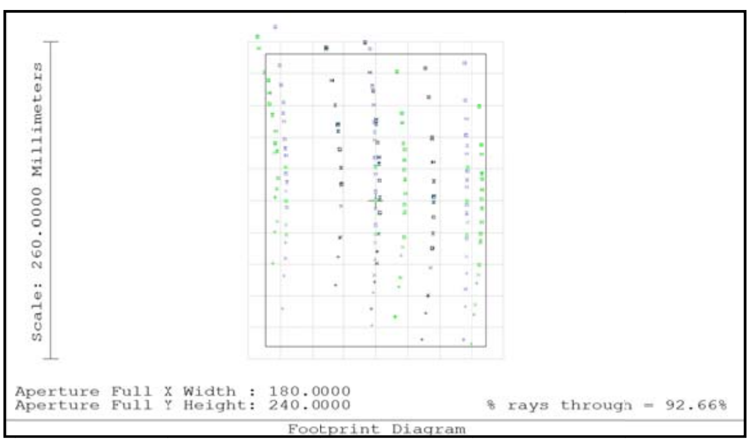


Figure 12 - This footprint diagram shows a simultaneous layout of all three spectroscopic modes at the focal plane of the red channel. Field positions are shown over the full field of view for all modes (including field corners and edges). Light green squares show the imaging mode. Light green X, O, and + marks show the low resolution mode. Black points show the high resolution mode. Spectra will extend beyond the CCD edges at extreme wavelength if objects are placed at the extreme corners of the field of view.

The choice of science detectors for the MOBIE focal planes involved tradeoffs between multiple performance parameters, form factors, and iterations with the optical design. As previously mentioned, base-line design choices enables proof of existence, describe a design that can be reviewed, allows flow down of requirements, generates input to the other technical disciplines, and provides a basis for a cost estimate. The baseline choices are not intended to be final and will be revisited in the following design phases as detector options and the optical designs evolve. For the blue and red channel detector systems, each focal plane assembly concept is composed of a mosaic of CCD detectors. Four different rectangular fields of view were under consideration. To complete the flow-down of requirements of detectors to CCD controllers, two possible alternatives were used:

1. For the largest focal plane options and the nominal field of view, the base-line design is a 3x4 mosaic of 4Kx4K, 15 micron pixel, e2v CCD231-84 CCDs (12K x 16K pixels, 180mm x 240mm). This configuration is shown in Figure 13 (left).
2. For the smaller focal plane options, the base-line is a 2x2 mosaic of 9K x 9K, 10 micron pixel, e2v CCD290-99 CCDs (18K x 18K pixels, 180mm x 180mm). This configuration is shown in Figure 13 (right).

The remaining features of the detector systems (vacuum vessels, hexapods, and cryo-coolers) are essentially unchanged in the second half of the MOBIE conceptual design phase, and were discussed previously[2].

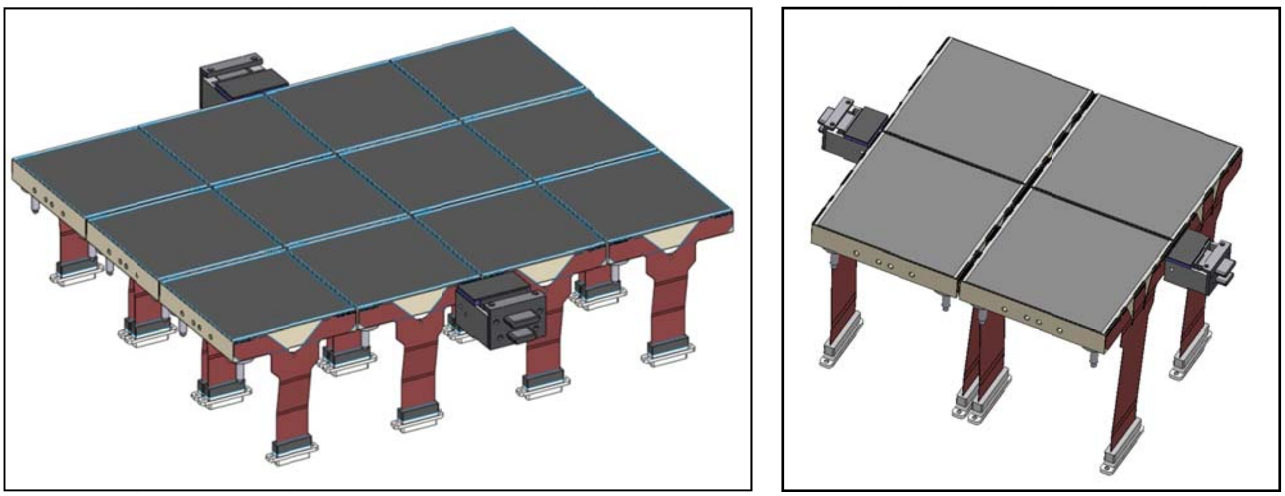


Figure 13 – A 3x4 mosaic of 4K x 4K x 15 micron devices (left) and a 2x2 mosaic of 9K x 9K x 10 micron devices (right). Flexure sensing CCDs are shown at the top and bottom of the science field as it falls on focal surface.

11.2 CCD Controllers

The detector system electronics follow the MOBIE architecture standard of distributed, networked, and independent subsystems. To implement this architecture, we will use individual controller units for detectors. Each set of controller electronics will have its own LAN (Local Area Network) interface. The UH-IfA STARGRASP[15] controller was chosen as the baseline design concept for MOBIE. Key features of the system include fiber gigabit Ethernet interfaces and Eurocard form factors. A light-weight, liquid-cooled, compact enclosure will be used to house both red and blue controller units. A commercial standard Air Transport Rack (ATR) enclosure is currently base-lined (see Figure 14).

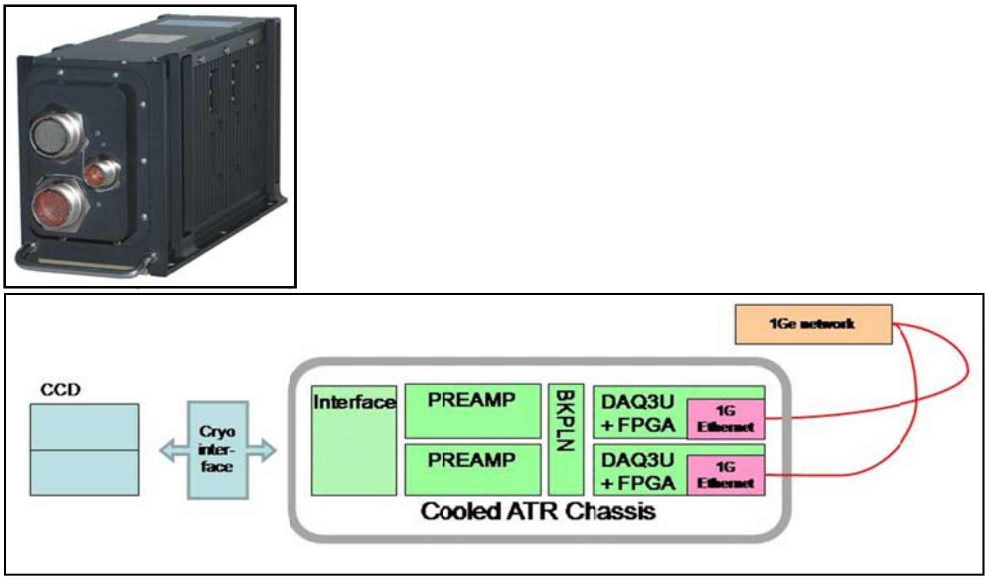


Figure 14 - ATR Chassis and STARGRASP Controller Block Diagram.

12. INSTRUMENT STRUCTURES

12.1 Design Overview

The MOBIE instrument structure (see Figure 15) is composed of a fixed portion which is attached to the telescope, the instrument carriage, and a rotating portion, the mainframe. The mainframe concept uses space-frames (truss elements) to connect three monocoque disks, which are kinematically supported and driven in rotation by the instrument carriage. The carriage has support rollers at the front and rear disks which allow for kinematic definition of the mainframe with respect to the carriage (and the telescope), and a DC servomotor drive system which acts on the circumference of the center disk. These structure concepts were developed and proven with the IMACS spectrograph structure[7]. The utility wrap, which consists of a rotating guide attached to the mainframe and a stationary housing attached to the carriage, is located at the end farthest from the telescope.

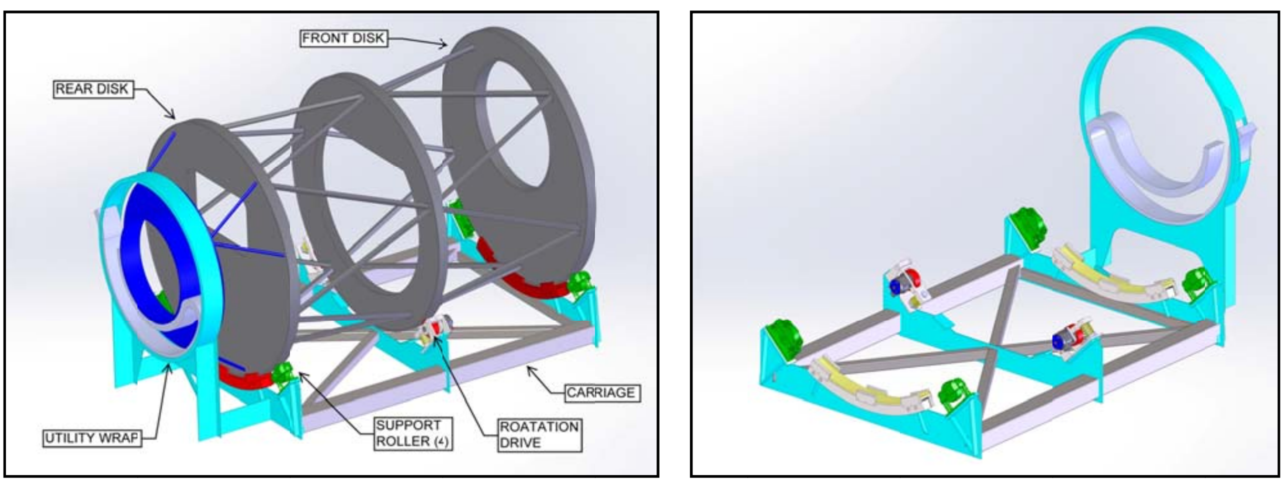


Figure 15 – The instrument structure (left) and the carriage (right) with IRS, seismic restraints, and utility wrap.

12.2 Seismic Restraints

A key design challenge for MOBIE is the TMT requirement to survive 200 and 1000 year return earthquakes with minimal damage. The rolling surfaces of the supported disks are seismically vulnerable due to the high working stress at these surfaces in normal operation. For this reason the support roller flexures are designed to fail in buckling if the vertical accelerations exceed safe limits for the disk bearing surfaces. The seismic restraint system is designed to prevent the mainframe from separating with the carriage under >1g seismic accelerations. The restraint structures will be lined with ultra high molecular weight polyethylene or equivalent material to protect the drive surface and to provide a high level of damping. These restraints will attach to the carriage with fasteners via an encapsulated rubber block, with mechanical properties that will be tuned to provide sufficient protection to the mainframe. For added safety the rubber block is encapsulated in a steel plate saddle structure to prevent catastrophic failure.

13. CONCLUSION

The MOBIE imaging spectrograph project for the Thirty Meter Telescope has made significant progress towards completing its conceptual design. For general efficiency and control of risk, the MOBIE conceptual design efforts have made use of subsystem designs from existing successful and operational instruments, and references to the heritage designs have been provided where appropriate. In October 2013, the MOBIE project principal investigator (Bernstein) and project manager (Bigelow) left the UC Observatories to take positions at the Giant Magellan Telescope project. The MOBIE project continues under the leadership of the lead engineer (Radovan) and the project scientist (C. Steidel), and on-going commitments from the UH-IfA (Onaka, Isani, and Yamada) and the NAOJ (Miyazaki and Ozaki). MOBIE will be built by an international consortium of partners including the United States, China, Japan and India. To this end, the project is currently engaged in an intensive effort to connect the interests and capabilities of these partners to relevant MOBIE instrument subsystems. The team that emerges from this process will carry the MOBIE design forward into the final stage of the conceptual design phase in 2015, followed by the start of the preliminary design phase in early 2016.

14. ACKNOWLEDGEMENTS

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REFERENCES

[1] Bernstein, R. A. and Bigelow, B. C., "An optical design for a wide-field optical spectrograph for TMT", Proc. SPIE 7014, (2008).

[2] Bigelow, B. C. and Bernstein, R. A., "Progress on the Conceptual Design for the MOBIE Imaging Spectrograph for the Thirty Meter Telescope", Proc. SPIE 7735, (2010).

[3] Ellis, K.S., Bernstein, R.A., and Bigelow, B. C., "Conceptual design phase stray light analysis of the MOBIE imaging spectrograph for TMT", Proc. SPIE, 7735, (2010).

[4] Sutin, B. M., and McWilliam, A., "Multi-object high-resolution echellette spectroscopy with IMACS", Proc. SPIE 4841, 2003

[5] M.V. Radovan, B.C. Bigelow, J.E. Nelson, A.I. Sheinis, "Design of a collimator support to provide flexure control on Cassegrain spectrographs" Proc. SPIE, Vol. 3355, March, 1998

[6] Faber, S., et. al., "The DEIMOS spectrograph for the Keck II telescope: integration and testing", Proc. SPIE 4841, 2003
[7] Dressler, A., Hare, T, Bigelow, B. C., and Osip, D. J., "IMACS: the wide-field imaging spectrograph on Magellan-Baade", Proc. SPIE 6269, 2006
[8] Phillips, A. C., et. al., "The Keck-I Cassegrain ADC", Proc. SPIE 7014, 2008
[9] McLean, I. S., Steidel, C. C., Epps, H., Matthews, K., Adkins, S., Konidaris, N., Weber, B., Aliado, T., Brims, G., Canfield, J., Cromer, J., Fucik, J., Kulas, K., Mace, G., Magnone, K., Rodriguez, H., Rudie, G., Trainor, R., Wang, E., and Weiss, J., "MOSFIRE: the multi-object spectrometer for infrared exploration at the Keck Observatory," Proc SPIE 8446, 2012
[10] Sako, S., Aoki, T., Doi, M., Ienaka, N., Kobayashi, N., Matsunaga, N., Mito, H., Miyata, T., Morokuma, T., Nakada, Y., Soyano, T., Tarusawa, K., Miyazaki, S., Nakata, F., Okada, N., Sarugaku, Y., Richmond, M. W., "KWFC: four square degrees camera for the Kiso Schmidt Telescope", Proc. SPIE 8446, 2012
[11] Vogt, S. S., Allen, S. L., Bigelow, B. C., et. al., "HIRES: the high-resolution echelle spectrometer on the Keck 10-m Telescope", Proc. SPIE 2198, 1994
[12] Hextek Corporation, Tucson, AZ 85733 (www.hextek.com)
[13] Hahn, D., v.d. Goenna, G., Bernstein, R. A., Bigelow, B.C., "Large Diameter High Quality Fluoride Crystals for ELT Spectrographs and Imagers", High resolution optical spectroscopy (2013)
[14] Fata, R. G. and Gabricant, D. G., "Mounting large lenses in wide-field instruments for the converted MMT", Proc. SPIE. 3355, 275-284 (1998).
[15] Onaka, P., Tonry, J. L., Isani, S., Lee, A., Uyeshiro, R., Rae, C., Robertson, G., Ching, G., "The Pan-STARRS Gigapixel Camera #1 and STARGRASP controller results and performance", Proc. SPIE 7014, 2008