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Detailed Design of a Deployable Tertiary Mirror for the Keck I Telescope

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ABSTRACT

Motivated by the ever increasing pursuit of science with the transient sky (dubbed Time Domain Astronomy or TDA), we are fabricating and will commission a new deployable tertiary mirror for the Keck I telescope (K1DM3) at the W.M. Keck Observatory. This paper presents the detailed design of K1DM3 with emphasis on the opto-mechanics. This project has presented several design challenges. Foremost are the competing requirements to avoid vignetting the light path when retracted against a sufficiently rigid system for high-precision and repeatable pointing. The design utilizes an actuated swing arm to retract the mirror or deploy it into a kinematic coupling. The K1DM3 project has also required the design and development of custom connections to provide power, communications, and compressed air to the system. This NSF-MRI funded project is planned to be commissioned in Spring 2017.

Keywords: Keck Telescope, tertiary mirror, time domain astronomy, telescope automation, passive whiffle tree

1. INTRODUCTION

A major thrust of astronomy in the 21st century is to study, observationally and with theoretical inquiry, time-variable phenomena in the night sky. This area is broadly referred to as time domain astronomy (TDA) and its high scientific priority was established by the Astro2010 report (National Research Council, 2010). Their highest recommendation for large telescope ground-based observing, for example, was to build the Large Synoptic Survey Telescope (LSST). In advance of that ambitious project, several projects are using wide-field cameras to image large areas of the sky at high cadence. This includes the partially NSF-sponsored Palomar Transient Factory (PTF) and its NSF/MSIP funded follow-on (ZTF), and the Pan-STARRS surveys which repeatedly image the full northern sky, finding hundreds of new transient phenomena on every clear night. These surveys are discovering thousands of supernovae, immense samples of asteroids and near-Earth objects, variable stars of diverse nature, flaring phenomena, and other exotic sources. These advances in TDA observing at optical wavelengths follow decades of TDA science performed at higher energies from space. Indeed, the first astronomical sources detected with γ-rays were themselves transient phenomena: the so-called γ-ray bursts (GRBs). Satellites like NASA's Swift and Fermi monitor $\approx \pi$ steradians of the sky, scanning for transient and variable high-energy events.

The focus of most previous and on-going TDA projects has been wide-field imaging of the sky in search of rare and new classes of events. To fully explore and exploit the astrophysics of newly discovered sources, however, one must establish the redshift and/or the type of object responsible. Optical and infrared wavelengths remain the most powerful and efficient passbands to perform the required spectroscopy. This is the primary role of large, ground-based observatories in TDA science. Recognizing their value, several 8 m-class observatories have established very effective observing strategies (generally at great expense) to perform such science. Both the Gemini and European Southern Observatories (ESO) designed their largest telescopes with systems that could rapidly feed any of the available foci. Furthermore, they designed queue operations to enable rapid responses to targets-of-opportunity (ToOs) and programs that repeatedly observe a source for short intervals at high cadence. Successes of this model include time-resolved spectroscopy of varying absorption lines from a GRB afterglow on minute time-scales and high-cadence monitoring of the Galactic center to recover high fidelity orbital parameters.

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The W.M. Keck Observatory (WMKO) boasts twin 10 m telescopes, currently the largest aperture, fully-operational optical/IR telescopes. Over the course of the past 20 years, we have successfully instrumented each telescope with high-throughput imagers and spectrometers spanning wavelengths from the atmospheric cutoff to several microns. The Keck I (K1) telescope hosts the Nasmyth-mounted HIRES spectrograph, one of the primary tools for obtaining high-resolution visible wavelength spectra from TDA observations. K1 also hosts the Nasmyth-mounted Keck I adaptive optics (AO) system with a high-performance laser guide star (LGS) system, and now hosts the near-IR integral field spectrograph OSIRIS, a key tool for synoptic observations of the Galactic center. Two K1 instruments are used at Cassegrain: the LRIS multi-object visible wavelength spectrograph and the near-IR multi-object spectrograph and imager MOSFIRE. This is a unique instrument suite, especially within the U.S. community: the HIRES spectrometer is the only echelle spectrometer on a large aperture telescope in the northern hemisphere; LRIS provides extremely sensitive spectroscopy especially at blue (< 4000Å) and red (> 8000Å) wavelengths, and MOSFIRE represents a unique capability for multi-slit, near-IR spectroscopy in the northern hemisphere.

By its nature, TDA science demands a more nimble and flexible approach to observations than the traditionally, classically-scheduled observing which has been the standard at WMKO. Most TDA programs require observations made with a specific instrument at specific times, while classical scheduling on a telescope with multiple instrument configurations may mean that the desired instrument will not be available for the TDA program. In the current configuration of the Keck telescopes a removable module, called the tertiary module, which contains the telescope tertiary mirror (M3), is used to support observations with Nasmyth and bent Cassegrain mounted instruments. The desired instrument along the elevation axis ring is selected by rotating the tertiary mirror around the telescope optical axis. To install and use a Cassegrain mounted instrument, the tertiary module must be removed from the telescope which is a process typically requires daycrew.

The K1 deployable tertiary (K1DM3) will directly address these shortcomings, enabling WMKO to fully and vigorously participate in TDA science with its unique set of K1 instruments. As the driving paradigm in observational astronomy shifts from a passive, static sky to one that displays dramatic changes on a nightly basis, it is critical to enhance our technical capabilities in this arena. The K1DM3 will increase the flexibility for ToO and Cadence observations with the Nasmyth, bent Cassegrain, and whichever Cassegrain instrument is installed in the telescope, without requiring any configuration change other than rotating the tertiary mirror to the appropriate focal station or retracting the mirror from the telescope beam. The K1DM3 will also reduce the time required for telescope reconfigurations by eliminating the need to remove or install the tertiary mirror module.

We proposed successfully to the National Science Foundation (NSF) Major Research Instrumentation (MRI) Program in 2013 for funding of the K1DM3 project. We received the full award requested and the total project budget ($2.1M USD) includes a 30% cost-share from WMKO, the UC Observatories, and the University of California Santa Cruz. The project entered its Detailed Design phase in October 2015 and this paper presents the Detailed Design. The K1DM3 device will enable astronomers to swap between any of the foci on Keck 1 in under 2 minutes, both to monitor varying sources (e.g. stars orbiting the Galactic center) and rapidly fading sources (e.g. supernovae, flares, gamma-ray bursts). The design consists of a passive wiffle tree axial support system and a flexure-rod lateral support system with a 4.7 arcminute field-of-view mirror. The mirror assembly is inserted into the light path with an actuation system and it relies on kinematic couplings for achieving repeatable, precise positioning. The actuation system may rotate (partially when retracted or fully when deployed) on two bearings mechanized with a pair of drive motors. It is our goal to commission K1DM3 at WMKO by March 2017.

Figure 1 shows the overall configuration of the K1DM3 module and the module installed in the tertiary tower. The K1DM3 module consists of a light-weighted fixed outer drum and a moveable inner drum. The inner drum is supported at each end by 4-point contact ball bearings. The lower bearing has a ring gear that is driven with a pinion gear by a servo motor system. An absolute position encoder is used to measure the position of the rotating drum. The tertiary mirror is supported by axial and lateral supports attached to a whiffle tree structure. This whiffle tree connects the mirror and support structure to a swing arm system. In turn, this swing arm moves the mirror between the deployed and retracted positions, driven by two linear actuators. The top of the drum supports the swing arm in the deployed position through a bipod structure with two defining points (at the right side of the figure) and a third defining point at the hinge point of the swing arm (the third defining point is not visible in the figure). The swing arm is locked in the deployed position by a set of 4 clamping mechanisms. No power is required to maintain the mirror in either the deployed or retracted positions. In order to set the swing arm into the kinematics, the deployment process will be performed at the elevation angle where the kinematics are oriented normal to gravity (64 degrees). We will retract the mirror at specific rotation angles, one of two positions where power and ethernet is supplied to the swing arm.

Full rotation of the module drum is possible with the mirror deployed. Interference with items at the top of the tertiary tower limit the rotation when K1DM3 is retracted. When the mirror is deployed, there are six positions used to direct the light to one of the two Nasmyth focal stations or one of the four bent Cassegrain positions. Each of these deployed positions is held by a detent mechanism engaging a v-groove. The detent mechanism is engaged by a pneumatic cylinder and retracted by a spring.

The K1DM3 module is inserted into the tertiary tower from the telescope's Cassegrain platform and moved through the tertiary tower to its operating position on a pair of rails. Guide rollers mounted on the outer drum support the module on the tracks. When the module is installed in the tower it is held in position using three defining point mechanisms equipped with kinematic mounting points that are engaged and disengaged by three air motors. The kinematic mounting points ensure repeatable positioning. K1DM3 is designed to be coated with Al at WMKO.

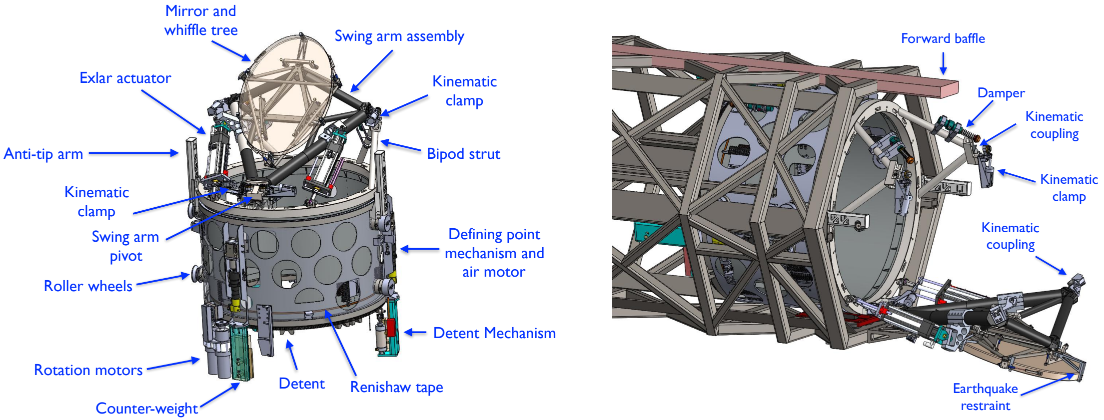


Figure 1. (left) Schematic of the K1DM3 system. (right) K1DM3 module installed in the Keck I tertiary tower.

2. KEY REQUIREMENTS

The K1DM3 team generated a requirements document to help guide the design of our module.[1] Below is a short list of key requirements that have the most impact to our design. This paper will focus on the opto-mechanical design; a brief summary of electronics and software is given in the Appendix.

2.0.1 Optical Requirements

1. The K1DM3 tertiary mirror will be sized to provide an unvignetted 4.7 arcminute diameter field of view at the Nasmyth foci.
2. The K1DM3 module will not vignette the LRIS or MOSFIRE FOVs when the mirror is fully retracted. The K1DM3 system will not vignette M1 or M2 when the mirror is deployed or retracted.
3. The surface of the K1DM3 mirror will give an 80% enclosed energy EE80 in a 0.054 arcsecond diameter aperture. This corresponds to a surface flatness specification of 9.7E-7 (rms) slope error.[2]
4. The mirror shall be supplied uncoated and shall be coated with bare aluminum by WMKO.

2.0.2 Mechanical Requirements

The following requirements primarily concern the motion of the K1DM3 system when installed.

1. The mirror will deploy or retract in less than 120 seconds.
2. The K1DM3 module shall be provided with a rotator mechanism that serves to point the deployed tertiary mirror at the desired Keck I Nasmyth or bent Cassegrain focal position by rotating the mirror about the telescope optical axis. When the mirror is positioned at one of the six focal station positions it shall be locked in place by a detent or other means. When deployed, the mirror will be able to rotate about the telescope optical axis at a speed of at least 6 degrees. per second.
3. The K1DM3 module shall not radiate more than 5 watts of heat into the telescope dome ambient environment during an observation.
4. The K1DM3 module must not weigh more than 1000 kg.
5. The structure of the K1DM3 module shall meet the zone 4 earthquake survival requirements of Telcordia Standard GR-63-CORE, "NEBSTM Requirements".

2.0.3 In-beam Positioning Requirements

The current M3 is offset from this ideal position, because of the as-built locations of M1 and M2, the as-built tertiary tower, and/or errors in the original alignment procedure.[3] Because the Nasmyth instruments on K1 (HIRES, OSIRIS) have been aligned to the existing M1-M2-M3 telescope, we endeavor to replicate (to a specified tolerance) the position of the current M3. The following requirements describe performance of the system when deployed relative to the desired location for the K1DM3 mirror. Again, this "desired location" may or may not be the optimal position for a perfect telescope system (see[4] for further details).

Regarding the stability of K1DM3 positioning during an observation (e.g. to vibrations), established convention is to allow uncorrelated effects on image quality at the level of 10% of the seeing disk. Based on this convention, for 0.4 arcseconds seeing, translation of the mirror along the telescope X or Z axes should be no more than 29 microns. We adopt this as an rms constraint. Confining the motion to ±29 microns (rms) places a stability requirement on tip and tilt of the tertiary of 0.65 arcseconds and 0.46 arcseconds (rms).

Synthesizing the above discussion, we derive the following requirements regarding the positioning of the K1DM3 mirror when deployed:

1. The K1DM3 mirror will position to an accuracy of 725 microns along the telescope X and Z axes (rms). We adopt the same requirement for repeatability.
2. The K1DM3 mirror will position to the nominal rotations of tilt and tip to 11.5 arcsecond and 16.5 arcsecond (rms) respectively. We adopt the same requirement for repeatability.[4]
3. The K1DM3 mirror will be held stable to displacements in the telescope X and Z axes to 29 microns (rms).
4. The K1DM3 mirror will not move in tip and tilt due to external influences (vibration) by more than 0.65 arcseconds and 0.46 arcseconds (rms) respectively.

2.0.4 Interface Requirements

The following list of requirements relate to the interface between the K1DM3 system and the K1 telescope.

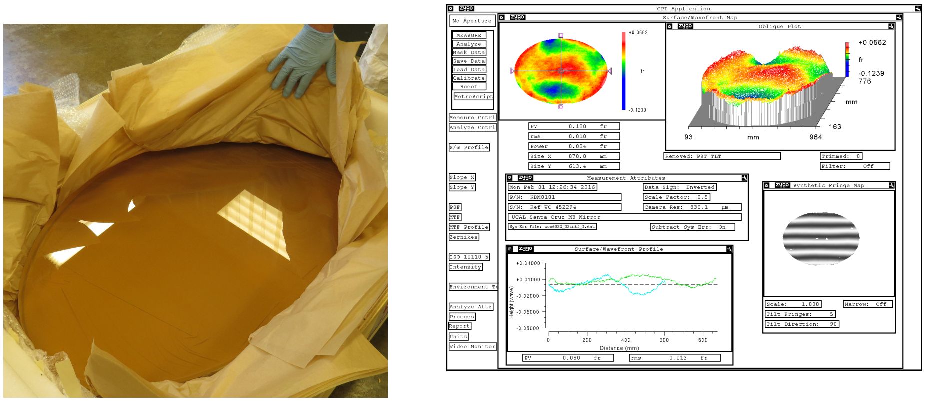
1. The K1DM3 module shall be designed for installation in the Keck I tertiary tower using the same defining points provided for the existing Keck I tertiary mirror module. All adjustments to align the K1DM3 module in the telescope shall be made by adjusting the defining point halves located on the K1DM3 module.
2. The K1DM3 module shall be compatible with the existing module insertion and removal rails provided in the Keck I tertiary tower.
3. The K1DM3 tertiary mirror shall be removable for recoating and shall be provided with an adapter as required to permit the use of the existing Keck I tertiary mirror handling fixture when the mirror is removed for recoating.

3. OPTICAL DESIGN

3.1 Mirror Design

The K1DM3 system will provide a new tertiary mirror for the Nasmyth and bent-Cassegrain foci of the Keck I telescope. The flat mirror is made of Zerodur glass and is shaped as an ellipse with major axis 2a = 901.1 mm and minor axis 2b = 643.0 mm, and a thickness of 44.5 mm. It has an approximate mass of 51.74 kg. The K1DM3 project obtained the mirror blank from the TMT project, on permanent loan, and a second blank as a spare.

The mirror was fabricated by Zygo and has been delivered to UCO (Figure 2). The figured mirror has an edge exclusion of approximately 15 mm width around the outer circumference that has poorer image quality. This reduces the clear aperture FOV to approximately 4.7 arcminute (see[5] for further details). Within the clear aperture, the mirror was polished by Zygo to 0.2 nm (rms) surface roughness (Figure 2) and to meet a (60-40) scratch/dig surface quality per MIL-PRF-13830B. The non-optical surface finish is R2 ground flat, 400 grit finish or better. The reflective surface was polished to a P-V of 57 nm and a surface error of 6 nm. The mirror will be delivered uncoated and later coated with bare Aluminum using the coating chamber at WMKO. Multi-layered-protected silver coatings were considered by the project but deemed too expensive given the associated risks with transport and handling.



PV 0.180 fr
rms 0.018 fr
Power 0.004 fr
Size X 870.8 mm
Size Y 613.4 mm
Removed: PST TLT
Trimmed: 0
Filter: Off
Mon Feb 01 12:26:34 2016
P/N: KDM0101
S/N: Ref WO 452294
UCAL Santa Cruz M3 Mirror
Sys Err File: zos6022_32intf_I.dat
Data Sign: Inverted
Scale Factor: 0.5
Camera Res: 830.1 µm
Subtract Sys Err: On
Scale: 1.000
Narrow: Off
Tilt Fringes: 5
Tilt Direction: 90
PV 0.050 fr
rms 0.013 fr

Figure 2. (left) Image of the as-built K1DM3 mirror, cut and polished by Zygo and now delivered to UCO. (right) Surface quality measurements on the clear aperture of the as-built mirror for K1DM3.

3.2 Vignetting of the Cassegrain Instruments when Retracted

3.2.1 Design Description

A key aspect of the K1DM3 system is to enable observations with the mounted Cassegrain instrument by retracting the tertiary mirror out of the beam on demand. This is a unique functionality in comparison to the existing tertiary module. We have designed K1DM3 accordingly and have also considered carefully the dimensions and positions of the module and retracted mirror to avoid vignetting the light arriving at the Cassegrain focus. We summarize the main issues that have been addressed and refer to[4] for further details.

We face significant challenges when M3 is retracted to avoid vignetting the rays from M1 to M2 and, at the same time, avoid vignetting the rays from M2 to the Cassegrain instruments. An additional concern is vignetting related to the LRIS ADC (see[6] for further details). When M3 is retracted, it will be held above the module and the tertiary tower with the reflective surface facing away from the optical axis as shown on the left side of Figure 3). In this position, we must avoid the rays travelling to M1 and (more importantly) the converging rays from M1 to M2. We will retract the center of M3 to this position: a height of 267.16 mm above the elevation axis and radially offset by 759 mm from the optical axis, and at an angle $\alpha = 104.5$ degrees (where $\alpha = 45$ degrees

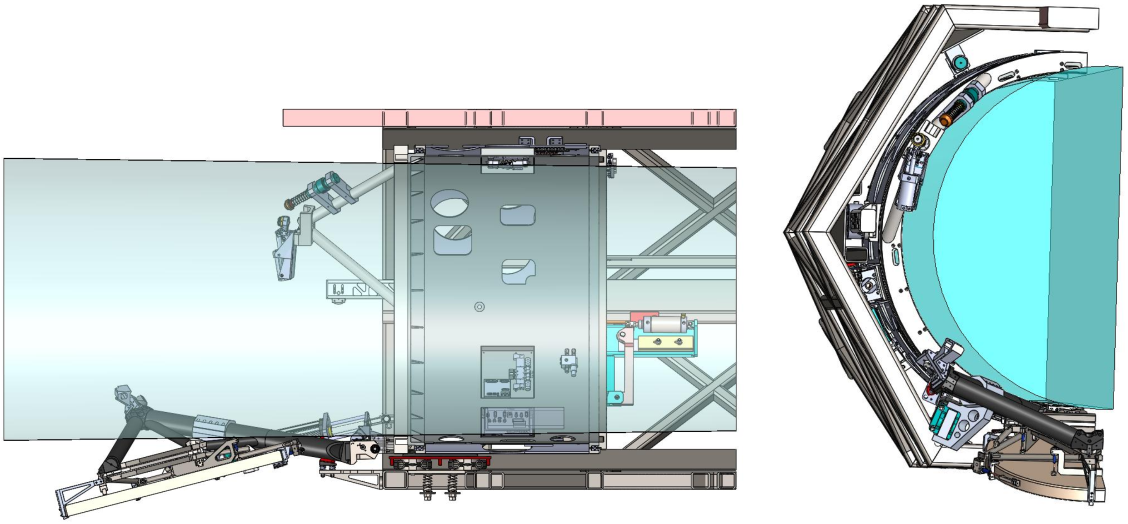


Figure 3. Two views of K1DM3 in the retracted position showing proximity of the M2 to Cassegrain beam footprint (colored shroud).

is the deployed position and $\alpha = 90$ degrees is parallel to the optical axis). The result is no vignetting of the converging rays from M1 to M2 over the full 20 arcminute Cassegrain FOV.

Presently, there are two Cassegrain instruments commissioned on Keck I (with none additional currently planned): LRIS with a 6 arcminute x 8 arcminute FOV located 7 arcminute off-axis and MOSFIRE with an on-axis FOV of 6.14 arcminute x 6.14 arcminute. Each instrument has an off-axis guide camera. The rectangular fields of view of the science and guide cameras for LRIS and MOSFIRE generate rounded "footprints" normal to the optical axis that one must avoid to prevent vignetting. The dimensions and shape of these footprints decrease as the beam converges from M2 to the Cassegrain focus (i.e. as a function of elevation along the optical axis).

3.2.2 Design Analysis

Analysis of vignetting of the retracted K1DM3 mirror on rays traveling from M1 to M2 was performed with the Zemax software package. We implemented the user-defined aperture (UDA) for the Keck primary mirror, a circular M2 mirror with radius of 700 mm, and the apertures needed to represent the M2 spider. In addition, we modeled obscuration by the tertiary tower as a hexagon with sides of 880.4 mm placed at a height of 3451.6 mm above the primary. We also modeled the obscuration by the secondary structure as a hexagon with sides of 1.32 m. Lastly, we calculated the vignetting of rays by the retracted M3 as an elliptical aperture held at the position defined above. The secondary mounting structure casts a sizable shadow on the surface of M1. The retracted K1DM3 fits entirely within this shadow. The rays converging from M1 to M2 present a tighter constraint, but we find that K1DM3 does not vignette any of these rays if the angle of the retracted mirror is less than approximately 105 degrees. The footprints described above were generated with an IDL code using simple geometrical arguments and the known dimensions of the K1 telescope. We then generated UDAs at several heights above the primary and imported these within the as- built Zemax models for the LRIS and MOSFIRE designs. We verified with Zemax that these footprints are correctly sized.

4. MECHANICAL DESIGN

4.1 Mirror Assembly

4.1.1 Design Description

The mirror for K1DM3 requires a support structure that will (i) maintain the mirror's figure under varying gravity vectors and temperature changes; (ii) interface the mirror with the deployment (swing arm) mechanism;

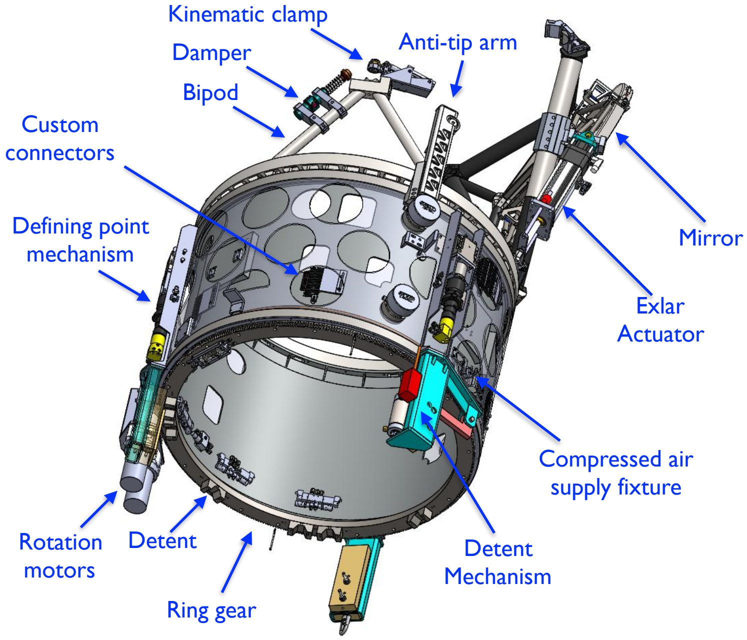


Figure 4. K1DM3 module as viewed from below, with callouts. See Figure 1 for a view from above.

(iii) ensure the safety of the system during an earthquake; and (iv) provide a means to coat the mirror within the WMKO coating chamber.

For axial support, the K1DM3 design uses six rods inserted into pucks glued to the back (i.e. non-reflective) side of the mirror. These rods are 1.7 mm in diameter, have 60 mm free length, and will be made of AISI M2 steel. The pucks are Invar and will be glued with an epoxy adhesive. The axial rods are screwed into the pucks. The layout of these six axial support rods is shown in Figure 5. The positions for the rods were determined from finite element analysis (FEA) to minimize the deflections of the mirror normal to its surface. These were updated to reflect the final dimensions of the mirror.

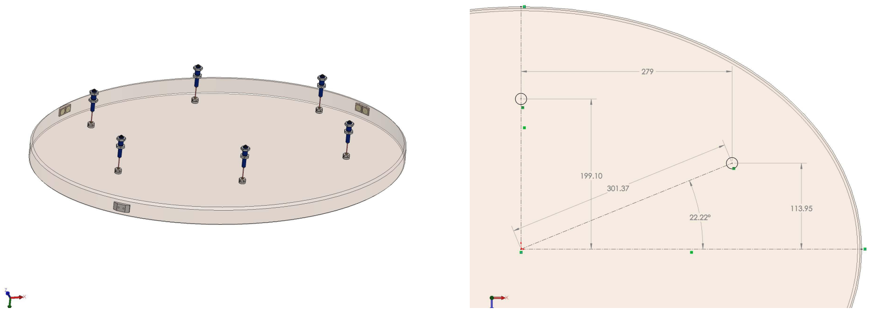


Figure 5. The left CAD image shows the six axial support rods attached to the back of the K1DM3 mirror. The diagram on right shows the placement of two of the rods indicated by open circles. The measurements are referenced from the major and minor semi-axes of the mirror.

Lateral support is provided by three flexure rods fastened to pucks glued to the mirror's edge, similar to the axial flexure rods. These are at approximately the major axis of one side and two other positions opposite (Figure 6). These rods are 125 mm free-length and 3.0 mm in diameter, and are AISI M2 steel. The pucks were designed to ensure a less than 15 micron difference in the glue thickness across the surface. For expected temperature changes, the design results in 130 PSI (static) and 655 PSI (dynamic) of stress in the bonds and glass. These stresses are significantly smaller than the estimated 3000 PSI of stress that the bonds can endure and are also significantly smaller than the limits that we wish to maintain for Zerodur.

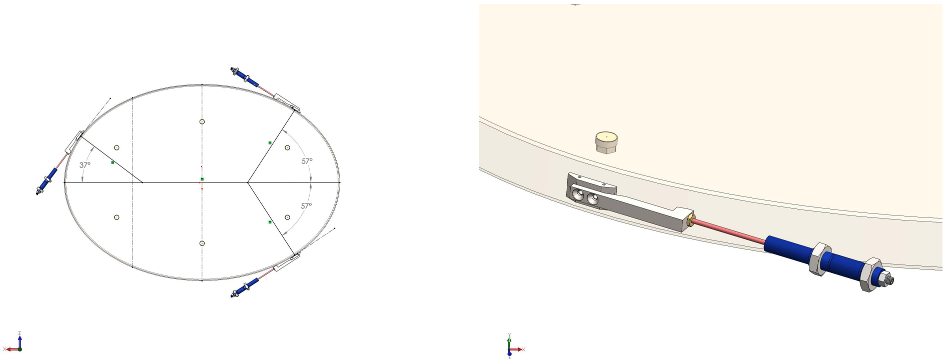


Figure 6. Left diagram shows the placement of the three lateral supports along the outside edge of the mirror. Right image is a close-up view of one of the lateral supports screwed to a puck that is glued to the edge of the mirror.

The axial and lateral rods are integrated within a whiffle-tree support system, shown in Figure 7. The whiffle tree uses 0.75 inch diameter struts (5/32 inches thick) in a determinate truss pattern. It allows the Mirror Assembly to be bolted to the Deployment System and then removed for re-coating. The total mass of the Mirror Assembly including the mirror is estimated to be 70 kg.

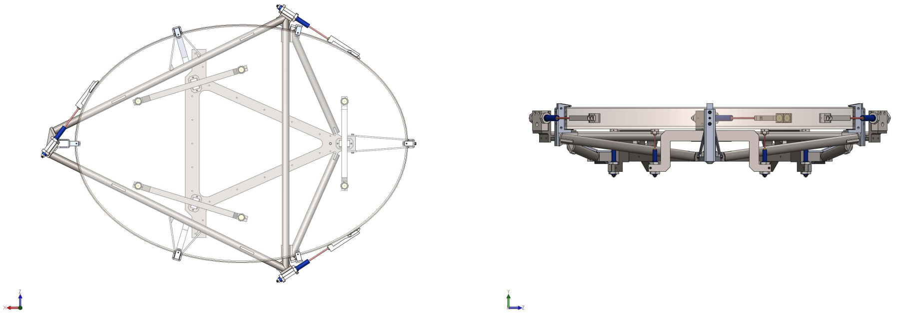


Figure 7. Top and side views of the whiffle-tree support structure for K1DM3.

The mirror assembly includes three kinematic fixtures (0.5 meter radius spheres in v-grooves) that interface it with the swing arm assembly. This allows one to remove the mirror assembly from the K1DM3 system for coating. It then enables one to repeatably and precisely reattach the mirror assembly to the swing arm assembly. The design also allows for fine adjustment of the kinematics during the alignment phase.

We have designed an earthquake restraint system consisting of 6 clips affixed to the mirror and the whiffle tree truss system. These are spaced approximately evenly around the circumference (Figure 7). They are made of Aluminum with Teflon pads positioned in normal operations with a gap (i.e. not touching the mirror). These are designed to take the static load of the mirror assembly in the event that the glue bonds fail during an earthquake.

4.1.2 Design Analysis

The guiding philosophy for the Mirror Assembly design is to provide adequate support while minimizing complexity. We started from the current M3 support-structure which utilizes 24 axial rods glued into holes that were drilled into the back surface of the glass. There is one lateral support assembly with pads along a ring that were glued to a hole drilled deep into the glass.

Our first efforts reduced the previous M3 support structure design to six axial rods and lateral support assembly similar to that of the current M3. We believe this satisfied all requirements related to mirror stability. We were then encouraged to consider a design without holes drilled into the glass. With additional investigation, we determined that a six axial rod and 3 lateral rod design provides adequate support. The rod assemblies will be attached to pucks glued to the glass.

FEA Modeling: The positioning of the axial rods was optimized iteratively in a series of FEA models processed with ANSYS. The modeling and static deflection analysis was performed with traditional 3D, 20-node brick elements which yield displacements (3 degrees of freedom) at the nodal locations. To obtain slopes (rotations) and reasonable statistics, the surface deformations of the top surface were mapped to a denser and uniform shell model. Results of this second model provided the surface slopes (and deflections) over a uniformly distributed surface. These results were exported to Excel for easy processing to obtain statistical values (max, min, rms, etc.). Our primary metric in evaluating a given model was the peak-to-valley (PV) deflections over the surface. We examined these with three orthogonal gravity vectors: one normal to the mirror surface and the other two along the directions of the major and minor axes. We implemented a mesh geometry for an ANSYS model of the current design. The model assumes the mirror properties described in § 3.1.

Figure 8 is a deflection contour map of displacement (nm) normal to the surface. The load is gravity normal to the mirror surface. This is the most severe loading condition encountered by the mirror during normal operating conditions. The peak-to-valley displacement is approximately 124 nm with an rms of 29 nm. A pseudo spot diagram shown in Figure 8 is an assessment of the worst-case deformations reported above. The basis for this diagram is the deformation response of the mirror due to normal gravity. Surface deflections of the model (Figure 8) are mapped to a uniform shell mesh. The plot is an aggregate of all the points on the uniform mesh. Each dot on the graph represents the two out of plane rotations of the point. X Slope is about the mirror major axis; Y Slope is about the minor axis. For a perfectly flat mirror all points would be at the center. This shows that the rotations are small and the overall image blur is negligible.

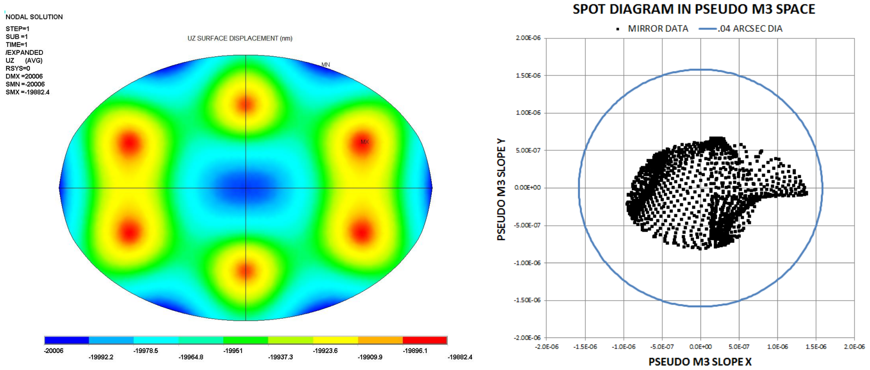


Figure 8. (left) Surface deformation map for the six point support system due to gravity normal to the mirror. The peak to valley range is 124 nm. Rms deflection of the entire surface is 39 nm. (right) Spot diagram representing where light reflected by the mirror would strike the focal plane. The image is a family of points which are calculated based on the slope error throughout the mirror. The blue circle for reference is 0.04 arcseconds in diameter.

CTE: Within the K1 dome one may experience changes in temperature ranging from −10° C to 20° C. Thermal expansion of the glass and the mirror support structure will lead to deformations in the mirror surface and its position. The design minimizes the effects of CTE (for a temperature change of 30° C) to about 2.4 nm peak-to-valley, 0.6 nm rms, and a maximum slope error of 0.0011 arcseconds.

Deformation Summary: The error budget for the mirror considered a range of conditions, as detailed below. We allow a total rms blur (due to slopes) in the focal plane of 7.3E-8, θ_y (slope error about major axis) must be less than 8.42E-7 at tertiary and θ_x (slope error about minor axis) must be less than 1.19E-6.

Rotations refer to the slope in the mirror surface due to deformation. The formula becomes:

$$Maximum\, permissible\, rotation \;=\; \sqrt{\theta_x^2 + 2 * \theta_y^2} = 1.68 \times 10^{-6} \text{ radians} \tag{1}$$

We studied the the rms slope error for various conditions and allowances: (i) the support design error, based on the static response due to gravity normal to the mirror surface, which is the worst case gravity vector; (ii) CTE axial error, which refers to differentials in thermal expansion or contraction which would influence the mirror through adhesive and the Invar pucks attached on the mirror's rear surface. (iii) CTE Lateral error, which is the same effect caused by the three attached pucks on the outer edge of the mirror. (iv) fab errors axial, which refer to a 1N load in plane load caused by the attachment of the axial support system. (v) fab errors lateral which is a similar assessment for the lateral support system. (vi) moment fab errors which are based on a 0.2 N-m moment error in the respective support systems. and (vii) axial pivot error, which considered a pivot alignment, or location, error of 1 mm. Such an imbalance would result in improper reactions at the six support locations, thereby increasing surface deformations. This is based on worst case gravity acting normal to the mirror surface.

The quadrature sum of these error terms is 7.14×10^{-7} and is well below the maximum allowed value.

Kinematic Fixtures: We will use 3 sphere-in-groove kinematics (0.5 m radius spheres) to repeatedly and precisely attach the mirror assembly to the swing arm assembly. These have a purported repeatability in position of less than 1 micron and should contribute negligibly to misalignment. These couplings also have fine adjustments which will be set during alignment tests at UCO (i.e. prior to delivery to WMKO).

Gluing: A critical aspect of the mirror assembly is the gluing of the lateral and axial support pucks to the glass. The project has chosen to rely on the extensive expertise of WMKO for this process. Their staff has performed extensive research[7–13] into adhesive selection, application, and strength performance testing which resulted in their choice of the preferred gluing agent (Hysol Loctite E-120HP), finding that it performed well in strength tests and is substantially easier to mix and apply. It will be necessary to etch the glass with a solution produced by Schott prior to gluing, which follows a rigorous cleaning and surface preparation regimen.

WMKO has invested heavily and developed equipment, material, and procedures for bonding Invar to Zerodur in preparation for their segment repair program. With their guidance and consultation we will build proof test samples to validate the design to the anticipated loads, including all fixturing, tooling, and part fabrication for the final gluing assembly.

Earthquake restraints: We designed the earthquake restraint system to bear the full weight of the mirror in the event that an earthquake tears the glue bonds on the axial and lateral rods. We designed for 25 pounds of axial load (equivalent to the load on an axial rod) and the full load of the mirror laterally for each restraint. This system has a small safety factor; the restraints may bend/deform during an earthquake and would need to be replaced afterwards.

4.2 Mirror Deployment (Swing arm)

4.2.1 Design

The K1DM3 system is designed to deploy and retract its mirror upon software command. In the following, we describe the parts critical to the actuation of K1DM3 with the exception of details on the bipods and kinematic couplings that position the assembly during deployment. Those are discussed in § 4.3.

The Mirror Assembly described in the previous section will fasten to a tripod swing arm fabricated with ASTM-A36 steel. Figure 9 illustrates the shape and overall dimensions of this part. It is a weldment of several steel members with varying diameter designed to maintain rigidity while minimizing profile. At the end points of the main arms are the kinematic couplings (canoe spheres made by Baltec, division of Micro Surface Engineering, Inc.) that enable repeatable, precise positioning of the system. This swing arm is attached to a pivot on the top ring of the K1DM3 module. This pivot is compliant (≈ 1 mm) to allow the kinematic coupling to determine the deployed position of the mirror. The pivot mechanism consists of a shoulder screw that is supported by two spherical-rolling element bearings, each supported by O-rings. (see Figure 10).

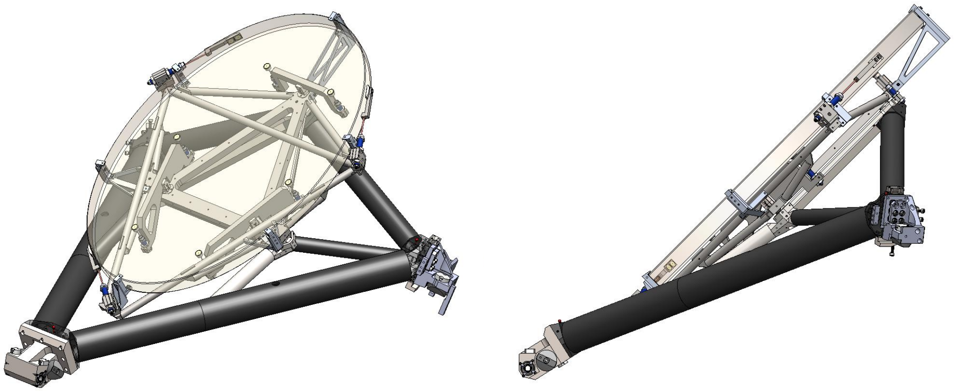


Figure 9. Perspective and side views of the mirror support swing arm.

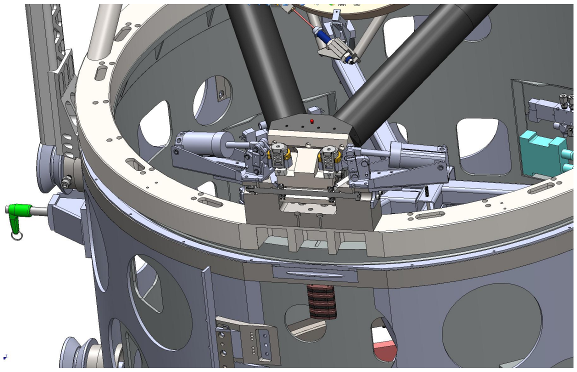


Figure 10. View of the swing arm pivot.

The swing arm is pushed into place by a pair of linear actuators (Exlar model GSX40-0601). Each actuator is attached to the bearing ring by a pinned spherical joint. The opposite end is attached to the swing arm with a universal joint.

4.2.2 Design Analysis:

Motor torque: The two linear actuators need sufficient torque to deploy and retract the Actuation assembly and Mirror assembly under gravity. The required torque will be less at the elevation angle designed for deployment (64 degrees) and at the nominal drum rotation angle of 90 degrees (where 0 degrees faces K1DM3 towards the AO system), but we have calculated the torque required assuming a worst-case configuration. Specifically, this implies a force of 6860 N. Each of the linear actuators has a manufacturer reported force of 9450 N.

Bipod strut placement: When deployed, the K1DM3 mirror will be lowered onto three kinematic fixtures (grooves) held in a plane by weldment consisting of two bipod struts on a large ring. These were positioned (i) to avoid vignetting the converging beam from M2 to the Cassegrain focus; (ii) to orient the three grooves in a plane (or parallel planes); (iii) to mount on the bearing ring; and (iv) to avoid collisions with the known extensions of the tertiary tower at any rotation angle of the K1DM3 module (e.g. Acme screw presenters, forward baffle mounts). The current design satisfies all of these constraints.

FEA analysis: FEA models were made of the mirror assembly attached to the swing arm and connected to the bipods. This led to an iterative process for the design of the placement, size, and material of the swing arm struts. The model accurately represents the mirror with its support by the axial and lateral flex rods. The swing arm structure was modeled as a series of beams with full elastic properties reflecting the materials of construction. The kinematic restraints at the v-groove are modeled as pin connections. The bases of the bipods, which connect to the upper ring, are fixed to ground. The pivot was also included. Extensive analysis of the deformation of the mirror surface has been conducted by independent analysis covered earlier. The purpose of the model and analysis described here is to determine the performance of the supporting structure and rigid body displacement and rotation of the mirror.

We then measured the deflections in the mirror from nominal position (telescope pointed at Zenith) for the extreme case of observing at 72 degrees off Zenith. Results of the static gravity cases are shown in Table 1. Only the displacements causing out of plane motion of the mirror are reported. These are piston, tip (rotation about the minor axis), and tilt (rotation about major axis) of the mirror. These values are satisfy the requirements for positioning and repeatability of the mirror.

Table 1. Out of plane displacement and rotations to due gravity for the mirror when observing at 72 degrees off Zenith.

Focus	**Piston (μm)**	**Minor axis ($''$)**	**Major Axis ($''$)**
bent-Cass	114	2.4	3.6
AO	64	9.1	5.7

Vibrational analysis: Over the course of its lifetime, the K1DM3 module will experience a range of stresses as it is transported to WMKO, handled during installation and coating, and tipped about during observations. As such, it must be designed to survive these conditions and maintain sufficient stability during observations to not significantly degrade the image quality.

There are two particular requirements that the K1DM3 design must satisfy regarding vibrations and the stresses that result: (1) The stresses on the mirror must not compromise the structural integrity of the K1DM3 components. Our primary concern is the glass of the mirror which has a maximum tensile strength for Zerodur of 42 MPa (6000 PSI) with a vendor-recommended limit of 10 MPa. We have designed K1DM3 to limit stresses to be less than 1000 PSI. (2) Motions of the mirror must contribute less than 10% rms to the optimal seeing disk of 0.4 arcseconds. As described in,[4] this implies less than 29 microns (RMS) of translational motion and less than 0.65 arcseconds and 0.46 arcseconds (rms) for motions in tip and tilt respectively.

We examined the predicted performance of the current K1DM3 design in a range of environments. Specifically, the K1DM3 team was provided a set of forcing functions (Tables 4,5,6 of[1]) that are intended to describe the random motions as a function of frequency that the module would experience in three conditions: (1) during transportation; (2) during handling at WMKO (e.g. installation, removal for coating); (3) during normal operations when installed on the telescope.

The maximum stresses for the K1DM3 mirror when deployed are 444 PSI, 163 PSI, and 0.1 PSI for transportation, handling, and observing respectively. Not surprisingly, the stresses on the mirror during transportation would nearly exceed our 500 PSI limit. We will design the shipping crate and packing materials to reduce the stress to tolerable levels. Regarding normal operations when deployed, we estimate 0.3 arcseconds (rms) of tilt and tip motions and 1 micron of translation. The stress of 0.1 PSI is far within tolerance and we predict maximum accelerations of less than 0.05 g.

Vignetting: § 3.2 provides a discussion of vignetting of the beam by K1DM3. Figure 3 shows that neither the struts nor the retracted mirror vignettes the LRIS or MOSFIRE footprints. We are required, however, to rotate the mirror to face one corner of the hexagonal face of the tertiary tower to avoid the beam from M2 to M1 (when the secondary baffle is not installed). This is the nominal parking position for K1DM3 when retracted.

CTE: The temperature of the entire telescope will change by as much as 25 degrees C (summit temperatures vary from 14 deg C to −11 degrees C). Given this temperature variation, it is important to consider thermal expansion effects on the alignment of the tertiary mirror.

Our goal has been to limit the effects from thermal expansion to be the same or less than those experienced by the current M3 system. The key to reducing the sensitivity is to pick materials with coefficients of thermal expansion that match the rest of the telescope structure. The predominant material used in the telescope structure is ASTM-A36 steel which has a CTE of 11.7 ppm/ degrees C. This material and material with very similar CTEs have been selected for the K1DM3 design We estimate that there will be an approximately .12 mm change in the height of the struts for 25 degrees C, but all three will move together maintaining the geometry.

Time to Deploy/Retract: With the dual actuator design, the rod must retract approximately 100 mm to change from the retracted position to deployed. The manufacturer-listed peak speed is 21 mm per second. We will actuate slower than the peak speed and allow 30 seconds to provide a smooth velocity profile for both deploy and retract.

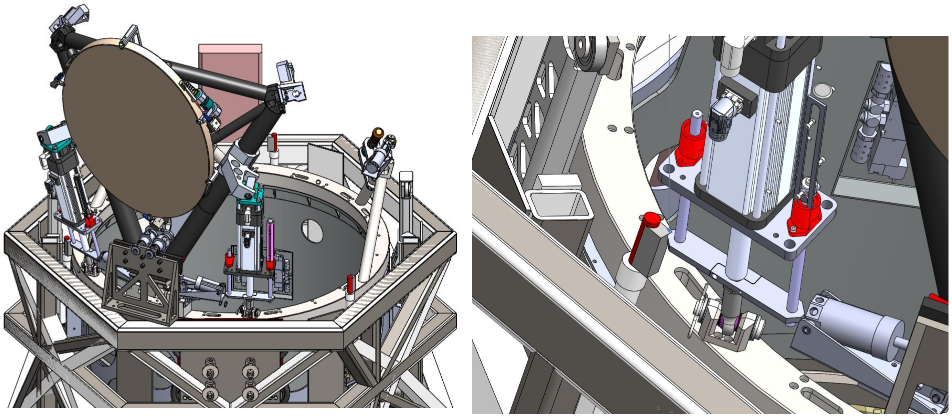


Figure 11. (left) Parking position of the K1DM3 mirror when retracted. In this position, no portion of the assemblies vignettes the light traveling to the Cassegrain instruments nor the light from M1 to M2. (right) Zoom in on potential interference between K1DM3 and the magnetic switch on one of the Acme screw presenters of the DMP system. We may need to rotate these switches to avoid interference.

Tower clearance: To avoid vignetting in certain configurations of the M2 baffles, we must rotate the K1DM3 mirror when retracted to the parking position indicated in Figure 11. During Detailed Design, WMKO approved and executed the removal of the forward baffle tracks on the K1 tertiary tower. This reduced the potential for interference between K1DM3 and the tower. The only remaining source of significant, potential interference are the Acme screw presenters associated with the tower defining points. We have modeled in SolidWorks the top of the tertiary tower using the WMKO drawings and measurements by our team during DD. We have also modeled the three mechanisms for the telescope half of the tertiary module/K1DM3 defining points that are located 659.5 mm from the optical axis, 35 mm diameter in diameter, and extend 100 mm above the tower.

We then confirmed using SolidWorks that the swing arm assembly of the K1DM3 design clears all of these obstructions when rotating to the parking position. This required us to reduce the profile of the Exlar actuators and use a particular orientation for mounting these devices. There is a potential interference with the magnetic switches on the cylinders (Figure 11, right) which may require us to rotate these prior to installation of K1DM3.

4.3 Upper Assembly Design

4.3.1 Design Description

Upper ring: At the top of the two drums is an upper ring (structural steel) which supports the swing arm (described in § 4.4). This part has an inner diameter of 1104 mm, an outer diameter of 1240 mm, and is 56.4 mm wide. It is manufactured with a recess that centers it on the inner drum.

Bipod struts: Also attached to the bearing ring is a pair of bipod struts made of A500 tubular steel. Each bipod holds a v-groove kinematic coupling for positioning the mirror when deployed. The struts are approximately 457 mm long and are positioned at 120 degrees from the swing arm pivot. These are tilted at an angle 13.7 degrees away from the optical axis. The third sphere/v-groove interface is adjacent to the compliant point.

As a safety measure, we will attach an Enidine damper to each of the bipod struts to “catch” the swing arm assembly in the event of a major software or hardware failure. This will insure that the kinematics engage with the swing arm moving at a speed of less than 10 mm per second. Figure 12 shows the designed damper system.

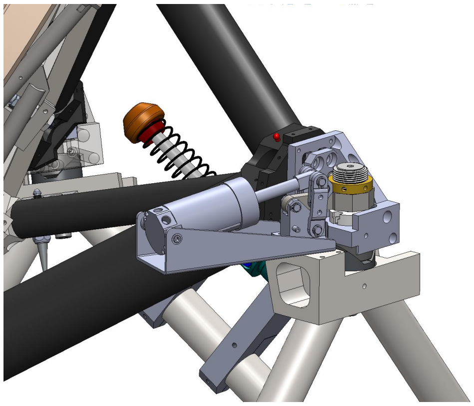


Figure 12. In the foreground, one views the damper attached to the bipod strut which will slow the K1DM3 swing arm in the event of a failure of the actuators. The clamp mechanism which holds tight the kinematic coupling at the top of the bipod struts is also shown.

Deploy kinematics (DKs): We will employ 3 sets of canoe-sphere/v-groove fixtures in the kinematic coupling used for positioning the K1DM3 mirror when deployed. The canoe spheres will have a radius of 500 mm. Two of these are mounted at the ends of the swing arm and the third is mounted on the under-side of the swing arm at approximately 44 mm from the pivot point.

The v-grooves will be 25.4 mm wide and 49 mm long. Two of these will be held at the ends of the bipod struts in a common plane. The third v-groove is mounted to the end of the pivot mechanism for the swing arm. Its axis lies in a plane parallel to that defined by the struts but offset by 655 mm. All of the DK fixtures will be made with 440 stainless steel, polished to 0.2 micrometer rms roughness, and plated with chromium nitride and tungsten di-sulfide (WS_2). The former is to prevent rust and the latter is to achieve a low coefficient of friction.

Clamps: When engaged the DKs will be clamped with a pneumatic clamping mechanism that maintains 1500 N of sustained forced on each canoe sphere/v-block interface (Figure 12). There is 1 clamp on each bipod strut and a pair at the pivot (Figure 10). These air actuated mechanisms will be controlled via a solenoid valve which holds the coupling in place even with a loss of air pressure. It will be important for the actuation assembly to bring the kinematic fixtures in close contact, but this pneumatic mechanism will be relied upon to fully engage the coupling. Feedback switches will be provided to verify that each clamp is open or closed.

4.3.2 Design Analysis:

Deploy Kinematics (DKs): After studying the standard reference on kinematic couplings,[14] we decided on a canoe-sphere/v-groove coupling system for the DKs. These have advantages over the more traditional cone-flat-groove couplings. We then researched vendors that manufactured these fixtures and selected Baltec. We have analytically estimated the precision for repeatable positioning as described in.[4]

Because the DKs are critical to the success of K1DM3, we purchased a complete set of fixtures during PD and manufacture test beds to construct a kinematic coupling. We then tested the positional performance empirically with three LVDTs. We will perform a series of new positioning and repeatability tests with the new set of kinematics at the start of full scale development.

Clamping: For positional stability, each DK will be clamped with a sustained force of 1500 N by a clamping mechanism (Figure 12). We estimate less than 1.0 microns of motion with any change of gravity. This satisfies the requirements on stability.

Damper system: We selected a set of Enidine damper devices (OEMXT 1.5Mx3) that have a damping force that will slow the K1DM3 swing arm assembly to less than 10 mm per second in the event of a complete loss of the actuators. This speed was estimated assuming the total weight of the swing arm assembly is borne by the dampers. These were also chosen because of their small profile, i.e. to avoid vignetting the light path.

4.3.3 Prototyping:

We have the as-built kinematic couplings at UCO and will test their performance with an upgraded swing arm during FSD. We have built one of the clamping mechanisms at UCO and have tested its performance. Provided it is driven with air pressure exceeding 90 PSI, we achieve 1500 N of force.

4.3.4 Fabrication:

The deployable kinematics were made by Baltec and then polished at UCO. These were then coated with CrN and WS_2. The clamping mechanisms have been purchased from DeStaCo and modified at UCO. We have two complete systems in operation. The bipod struts will be fabricated an external vendor.

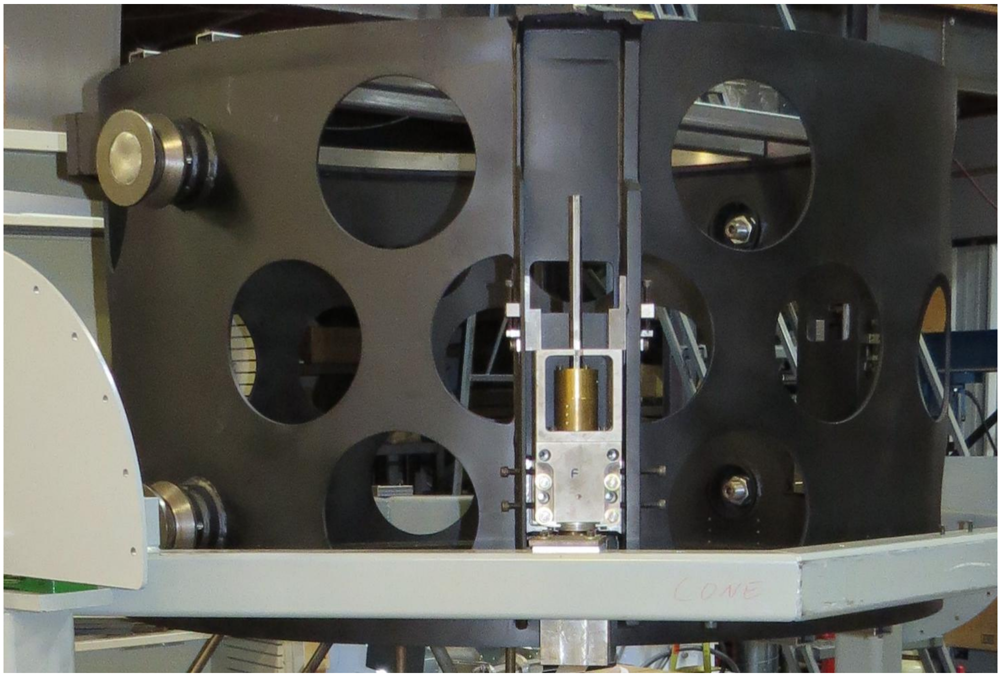


Figure 13. Photo of the fabricated outer drum for K1DM3 (at UCO).

4.4 Drum Assembly Design

4.4.1 Design Description:

Outer drum: The backbone of the K1DM3 system is an ASTM A36 steel drum, 1/4 inch rolled plated precision machined to have an outer diameter of 1240 mm. The drum has holes to reduce its mass without compromising its stiffness (Figure 13). The drum is approximately 737 mm long.

Wheels: For installation and removal of K1DM3 in the K1 tertiary tower, we have purchased (from Osborn) 4 steel wheels each with a diameter of 4.5 inch. These are now attached to the outer drum (Figure 13).

Anti-tip arms: As designed, the center of mass of the K1DM3 module when the mirror is deployed lies 63 mm behind the forward wheels (those closest to the mirror) toward the rear set of wheels. In principle, this implies the system is stable to tipping. To further mitigate against tipping during installation, we have designed bronze counter-weights attached to the lower end of the assembly and a pair of anti-tip arms which can bear the full weight of the system. These will be affixed to the outer drum as an additional safety measure.

Defining points: Fixtures attached to the exterior of the K1DM3 module to position it within the tertiary tower. These are referred to as the Defining Point Mechanism (DPM), and the complete kinematic coupling includes the tower fixtures. These provide the mechanical interface between K1DM3 and the telescope. The DPM fixtures on K1DM3 replicate the fit and function of the fixtures on the current tertiary module. We re-used the existing design to the maximum extent possible. There are three fixtures located with 120 degree separations around the module, approximately 141 mm below the top surface of the top bearing with three different contact points to form a kinematic mount: (i) Flat on flat; (ii) Sphere in cone; and (iii) Cylinder in groove.

Each defining point mechanism consists of two parts or halves. One half of each defining point mechanism is mounted on the tertiary tower and incorporates a rotationally fixed Acme thread lead screw that is extended through the fixed half of the kinematic point by an air cylinder when the defining sequence is initiated. This "presents" the lead screw to the instrument mounted half of the defining point which has a hole in the center of the mating half of the kinematic point. Behind this is an Acme thread nut which engages the fixed lead screw presented by the tertiary tower half of the defining point mechanism. The nut is rotated by a reversible air motor incorporated in the instrument half of the defining point mechanism. Once the two halves of the three defining points are all in initial contact, each defining point is mated in sequence, starting with the sphere, then the cylinder, and then the flat. The system is very tolerant of small misalignments, and each defining point can carry loads in excess of 2000 kg. Position sensors are incorporated in the system to ensure proper positioning before the defining sequence is started.

Figure 13 shows the as-built sphere-in-cone DPMs mounted on the outer drum of K1DM3. Each of the DPMs are made of AISI 4130, Hardness Rockwell C 50 minimum, chrome plated to QQ-C-320, Type 1, class 2 material. Each allows for adjustment for 6 degrees of freedom (3 translational and 3 angles). These will have an end-to-end positioning range of about 12 mm.

Ring bearings: Attached to the top and bottom of the drum are two ring bearings with a nominal ID of 1180 mm and 1218 mm OD. They are essentially identical in form, fit, and function to the bearings on the existing modules. These enable the inner drum assembly to rotate about the optical axis. The top bearing will be located approximately 711 mm below the elevation axis. These were manufactured by Kaydon and have been delivered to UCO.

Inner drum: The inner drum will be rolled 1/4 inch plate, welded and turned ASTM A36 steel. It will have an inner diameter of 1150 mm, and be 768 mm long. The bearing surfaces will be concentric to 50 microns and the drum has an interference fit with the supporting bearings of 50 microns. This interference fit is to insure our rotation axis does not shift with respect to the bearings. We have also designed pockets for the Galil controller and a programmable logic controller (RIO) which acts as an interlock device for the Galil.

Compressed Air supply: To provide air pressure to the pneumatic clamps, we have designed a custom fixture that connects an air supply on the fixed, outer drum to plumbing on the inner drum. There will be a pair of these mechanisms at 0 and 180 degrees rotation angles. The latter is the orientation when the mirror is deployed/retracted and the former is for removing the mirror for coating. Figure 15 shows one device in the assembly and a photo of our prototype. The system will engage when oriented to within 1 degree of alignment.

Ring gear and detents:

As shown in Figure 16, the very bottom will be a ring gear and servo system to position the inner drum to within 10 microns. Six detents (v-grooves) are mounted to this ring to precisely set the rotation angle for the foci on the elevation ring. The ring gear will be made of ANSI 4130 steel. There are two additional detents for deployment and retraction. 4130 material, have an inner diameter of 1075 mm, and 378 teeth around the full circumference. Two pinions gears turned by two DC servo motors using harmonic drive gear heads will drive the ring gear. One of the two servo motors will lag the other slightly to eliminate backlash between the drive pinions and the ring gear.

There will be eight detent blocks made of steel hardened to 45 to 50 Rockwell Scale C and will be v-grooves that are 88 mm long and 40 mm wide. These will be pinned to the ring gear during alignment at WMKO. This coupling will be engaged by an air-pressure driven detent mechanism mounted below the module (see Figure 16).

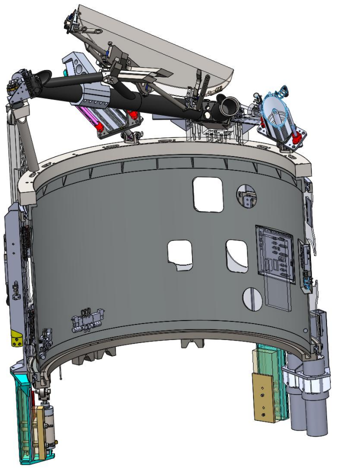


Figure 14. Cross-sectional view of the inner drum. One notes “pockets” for the Galil and RIO mechanisms and fixtures for air supply and electric connectivity.

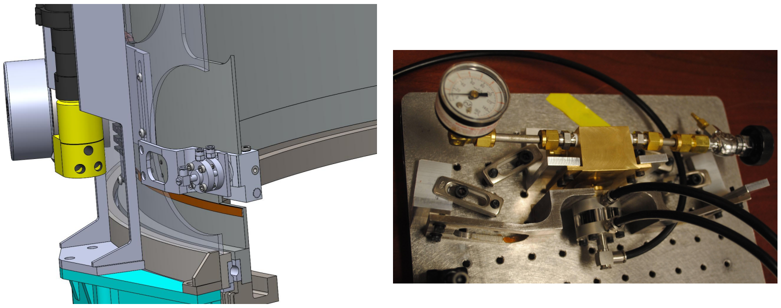


Figure 15. Figure showing the fixture supplying compressed air to the upper assembly (top) and a photo of the prototype of the fixture (bottom).

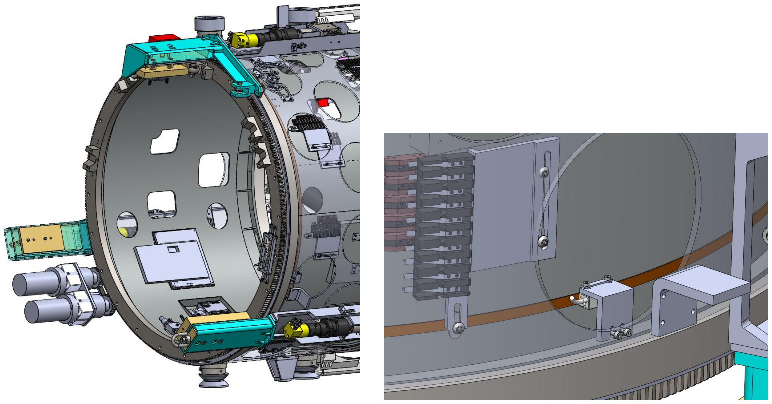


Figure 16. (left) Ring gear, detents (v-grooves) and detent mechanism (cyan, top). (right) Renishaw tape (brown) on the inner drum. The figure also shows the readhead in the assembly.

Encoder: The rotation angle of the K1DM3 module will be monitored by reading a Renishaw magnetic tape attached to the drum, approximately 78 mm above the bottom edge as noted in Figure 16. We will use a single read head with an incremental encoder with distance coded reference marks for precise and continuous reads.

We estimate a total mass for the K1DM3 drum and attached components of ∼595 kg.

4.4.2 Design Analysis:

Defining Point Mechanisms (DPMs): By replicating the existing design for the K1DM3 defining point mechanisms, it is our expectation that the system will position as precisely as the current module. We estimate the positioning repeatability to be within 3 microns (lateral) and that the normal of the mirror will rotate less than 0.5 arcseconds.

During Detailed Design, we fabricated these fixtures and the outer drum. We delivered them to WMKO to test clearance and perform initial alignment of these fixtures (e.g. test that they coupled to the tower fixtures). We successfully mounted the outer drum on the K1 tertiary tower defining points and measured that its center of rotation lay within several mm of the current tertiary module (see[15] for further details).

Our design will allow for 12 mm of positioning of the DPMs to facilitate the alignment of K1DM3.

Stiffness: As the underlying support for the K1DM3 system, the drum must be sufficiently stiff and strong to hold the Actuation Assembly in place under a varying gravity vector. We have estimated the flexure in the drum by performing an FEA within SolidWorks. We estimate that the deflection between vertical and horizontal orientations is 0.65 arcseconds and approximately 1.1 microns of translation. These are primarily due to flexure of the two bearings. Such deformations are within the requirements for positioning.

Vignetting: Unlike the drum of the current tertiary module, the Drum assembly of K1DM3 must be sized to avoid vignetting the converging beam from M2 to the Cassegrain focus. For example, the ring gear designed for the current existing tertiary module has too small of an inner diameter and we have re-designed it accordingly. § 3.2 describes our vignetting analysis in detail and we find that the Drum assembly does not vignette the beam at any rotation angle.

CTE: The drum will have the same CTE as the tower and existing tertiary module. This mitigates against the effects of thermal expansion.

Anti-tip: The center of mass of K1DM3 with the mirror deployed is estimated to lie 63 mm behind the forward set of wheels toward the back set of wheels. Each anti-tip arm was designed to hold the entire force of the K1DM3 module (3000 N) if it tipped and expressed the entire force onto only one rail (allowing for misalignment of the rails). We estimate a maximum stress of 12510 PSI which is a factor of 4 below the yield stress of each anti-tip arm.

Rotation analysis: We may estimate the rotation speed of the K1DM3 module as follows. The peak capable speed will be 18 degrees/s if we run the servo at 1079 RPM, given the gear reduction of 354:1. We will limit this speed to a lower number (e.g. 9 degrees/s) which would still allow K1DM3 to move from AO to HIRES in 20 seconds. The velocity profile will be a trapezoidal shape and utilize features such as S transitions to minimize vibration. The K1DM3 module may be rotated to any angle with the mirror deployed. Interference with components on the tertiary tower limits the rotation to approximately 30 degrees when retracted.

Rotation positioning: The previous section described the positioning of the K1DM3 module in the tertiary tower using the Module Kinematics. Regarding rotational position of the Drum, the K1DM3 module will have eight detents (v-grooves) bolted to the bottom ring bearing. These are to be positioned such that K1DM3 precisely folds the light from M2 into the Nasmyth and bent-Cass foci. The precise location of the v-grooves will be established during Alignment at WMKO. The detent mechanism provides sufficient force (1200 N) to insure the module is locked into place and also provides stable orientation for mirror removal and the mirror retract and parking positions. This pneumatic mechanism also reliably releases the detent.

4.4.3 Prototyping:

We had the outer drum fabricated during DD and delivered it to WMKO to test its integration.[15] This includes our coupling the K1DM3 defining points to the K1 tertiary tower defining points. For the DPMs, we have mounted the outer drum with the fabricated K1DM3 DPMs on the K1 tertiary tower in October 2015. We have fabricated at UCO the custom fixture for providing air to the clamping mechanisms. This has been tested under the environmental conditions (e.g. low temperature) relevant to WMKO.

4.4.4 Fabrication:

The outer drum was manufactured by Wilcox. The wheels were made by Osborne and the anti-tip mechanism was manufactured by UCO. The pair of rotation bearings were manufactured by Kaydon. The defining point mechanisms were manufactured at UCO and have been attached to the outer drum. The inner drum is being manufactured by Wilcox. We have manufactured the pneumatic coupling fixtures at UCO. One unit is complete. The ring gear will be fabricated by an external vendor. We have received quotes from Cage Gear and Machine and Wilcox. The detent mechanism and detents will be manufactured by UCO.

APPENDIX A. ELECTRONICS AND SOFTWARE

This Appendix provides a brief summary of the detailed design of K1DM3 as regards electronics and software.

A.1 Requirements

1. The K1DM3 system shall be powered from 120 Vac, 60 Hz. power at a maximum of 15 A.
2. The K1DM3 shall provide an emergency stop input that stops all motion when the Observatory emergency stop signal is activated.
3. The K1DM3 module shall not produce stray light from LED or lamp indicators, optical switches or optical shaft encoders over the wavelength range of 300 to 20000 nm.
4. Cables and wiring shall be routed so that they do not interfere with the optical path of the telescope. Cables and wiring shall be routed so that full travel of moving or adjustable parts is not affected and does not place a strain on the mounting or connections of any cables or wiring.
5. The K1DM3 software user interface software shall be implemented as a DCS control row or other Observatory user interface paradigm. The user interface shall control the K1DM3 via keywords.
6. The K1DM3 software shall be written to run under a WMKO approved operating system.
7. The K1DM3 software shall be implemented as client-server architecture with communications over TCP/IP.
8. The K1DM3 software shall support legacy (current Keck telescope DCS) and new (TCSU) use cases.

A.2 Electronics Design

The electronics for K1DM3 provides control and feedback for four actions: rotating the drum, locking the drum position, deploying and retracting the mirror, and locking the mirror kinematics.

A.2.1 Deployment Stage

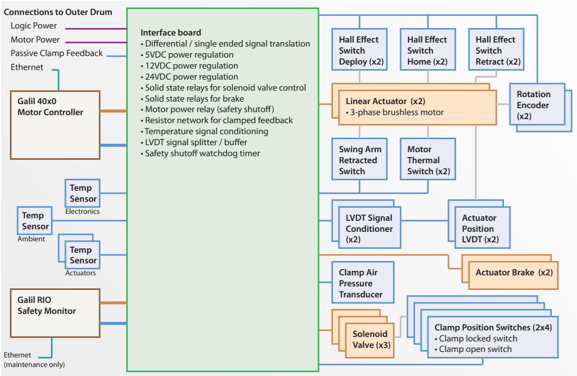


Figure 17. Block diagram of the deployment electronics.

The deployment stage electronics are located on the rotating drum portion of K1DM3. These electronics are responsible for mirror deployment and mirror retraction. Power and communication to the deployment stage will be provided through custom contacts, affixed at two rotational positions on the outer drum. All of the deployment stage electronics will be powered off except when the mirror is being deployed or retracted. An overview of the deployment stage electronics is shown in Figure 17.

Deployment of the mirror is handled by two Exlar linear actuators. The linear actuators are powered by brushless DC motors. Each actuator has the following feedback: a LVDT for absolute position feedback, motor rotation encoder, motor hall effect sensors, temperature sensor, a home location indicator, and switches at the stowed and deployed positions. Each actuator has a brake.

Kinematic clamping will be done with four pneumatic over-center clamps. Solenoid valves will control pneumatic cylinders for the clamps. Feedback switches will verify when the clamps are locked or unlocked. A pressure transducer will monitor the air supply line for adequate pressure.

Control of the motors, brakes, solenoid valves, and all feedback will be through a Galil 4040 series controller. Commands to the Galil will be sent over Ethernet. The Ethernet connection to the Galil will be provided through custom contacts on the drum.

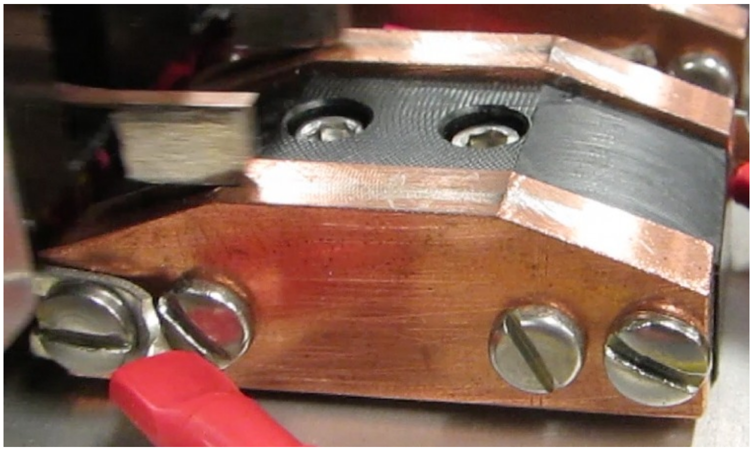


Figure 18. Image of a prototype of the custom contacts, brush on ramp. The final system will consist of a series of these contacts coated in Ag with a slightly modified brush design.

Separate power for the motors and control logic will be provided through the custom contacts. After careful consideration of a slip ring for communications, the team chose to develop a set of custom communications to minimize cost, minimize complexity and to enable easier servicing. Our design uses a set of spring contacts (or brushes) that are pulled across a set of contact ramps (Figure 18). The contacts are carbon impregnated with silver. The ramps will be made from copper and plated with silver. We will also likely coat the ramps and brushes with a product formerly called ProGold. Our tests show the contact resistance dropped from 100 mOhms to 3 mOhms when using this product and it is reported to inhibit oxidation.

Power supplies will be located beneath the primary mirror where the heat can be extracted. Two passive signals for stowed and deployed positions will be passed through the custom contacts. These signals will allow mirror position to be verified without powering up the deployment electronics.

An independent safety monitoring system will insure the safe operation of deploy and retract movements. The safety monitor system will be based on a Galil RIO PLC. The safety monitor system will monitor the position and speed of the deployment stage. If excessive speed is detected motor power will be cut and the brakes set. Maximum allowable speed is reduced when approaching stops at either the deployed or retracted position. The safety monitor also receives a local lockout input to defeat all motion during servicing, and receives the observatory E-stop input which stops all K1DM3 module motion (including the rotator) when the E-stop input is activated.

A.2.2 Rotation Stage

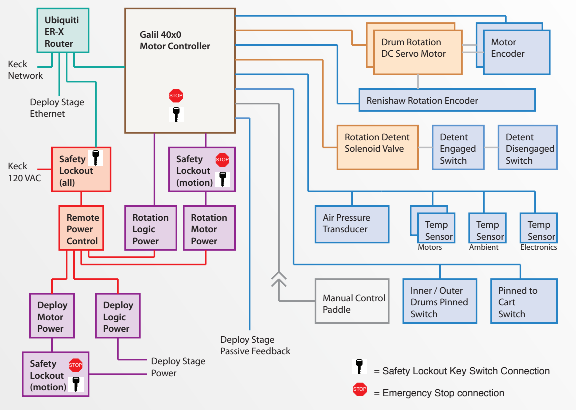


Figure 19. Block diagram of the rotation electronics.

The rotation stage electronics controls the angular position of the drum and the detent actuator. An overview of the rotation stage electronics is shown in Figure 19.

Two DC motors will be used to drive the rotation. Rotary encoders will provide motor feedback. An absolute position encoder (Renishaw) and a home switch will provide drum position feedback. Motor temperatures will be monitored for system health and safety. The motors will be powered down except during movement.

The air actuated kinematic detent mechanism will be controlled via a solenoid valve. Feedback switches will be provided to verify that the detent mechanism is fully engaged or fully retracted.

A Galil controller will be used to control and monitor the motor(s) and detent mechanism. Drum position, motor encoder, detent monitors, and motor temperatures will be fed into the Galil for monitoring and feedback. In addition the Galil will also monitor the mirror retracted/deployed signals from the deployment stage. Communications to the Galil will be via Ethernet. The rotation Galil will remain powered up and will continuously monitor drum position and other feedback sensors. The rotation stage Galil controller receives a local lockout input to defeat all motion during servicing, and receives the observatory E-stop input which stops all K1DM3 module motion (including the rotator) when the E-stop input is activated.

The Galil controller and power supplies will be located beneath the primary mirror where the heat can be extracted.

A.2.3 Safety

Two levels of hardware safety lockouts will be provided. One level will disable all actuators and motors while leaving all the feedback sensors available. The second level will remove all power from the system. These satisfy the observatory requirements.

A.3 Software

The K1DM3 software, like all WMKO instrument software is based on three software layers, a low-level server layer, the Keck Task Library (KTL) layer, and a user interface layer, which provides the graphical user interfaces (GUIs). The block diagram shown in illustrates these three layers.

The low level server layer implements communications and control over the instrument hardware, and provides a keyword server interface via the KTL layer. For K1DM3 the hardware motion controllers are two Galil DMC-4040's and a standalone Galil RIO. Each of the DMC-4040's is controlled by an instance of UCO's standard *galildisp* daemon, and they are both part of the single *k1dm3* KTL service.

The KTL layer is a standard WMKO software component that is used in every instrument at the Observatory, allowing client applications to communicate with any server daemon in a uniform, standardized way. All data in a server is represented in keyword/value pairs. Any client application accesses the KTL layer via KTL's standard library routines. The "upper half" of the KTL layer is a uniform application programming interface (API) used in the same way by any application, whereas the "lower half" of the KTL layer uses one of several different messaging methods for communicating with KTL servers. K1DM3 uses KTL/MUSIC, which uses MUSIC messaging as the transport layer.

The *k1dm3* service will support the existing TCS/DCS tertiary control keywords, and the new keywords defined by the TCSU. It also has an extensive set of keywords to provide detailed engineering support, and detailed feedback about the status of all controlled and monitored elements.

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