The Keck I Deployable Tertiary Mirror (K1DM3) Preliminary Design Report

The Keck I Deployable Tertiary Mirror (K1DM3) Preliminary Design Report

Authors: K1DM3 Team

1. EXECUTIVE SUMMARY

2. INTRODUCTION

2.1. K1DM3 Team

Name	Role	Institution
J. Xavier Prochaska	Principal Investigator	UC Santa Cruz
Jerry Nelson	Co-Principal Investigator	UCO (retired)
Hilton Lewis	Co-Principal Investigator	WMKO
Michael Bolte	Co-Investigator	UC Santa Cruz
David Cowley	UCO Project Manager	UCO
Sean Adkins	WMKO Project Manager	WMKO
Gerry Cabak	Mechanical Engineer	UCO
Chris Ratliff	Mechanical Engineer	UCO
Drew Phillips	Optical Engineer	UCO
Dale Sanford	Electrical Engineer	UCO
Michael Peck	Electrical Engineer	UCO (retired)
Will Deich	Software Engineer	UCO
Mike Dahler	Telescope Mechanical Engineer	WMKO
Mike Pollard	Senior Mechanical Engineer	WMKO
Bill Randolph	Design Technician	WMKO
Truman Wold	Mechanical Engineer	WMKO
Maerian Morris	Financial Analyst	UCO

2.2. Revision History

Version 1.0 – JXP, 25 August 2014 [Draft of Sections 2 and 3]
Version 1.1 – JXP, 02 September 2014 [Draft of Section 5.1]
Version 1.2 – JXP, 04 September 2014 [Draft of Sections 5.2.1, 5.2.2]
Version 1.3 – JXP, 07 September 2014 [Drafts of Sections 4.2, 5.2.3, 5.2.4, 5.3]
Version 1.4 – JXP, 11 September 2014 [Draft of Section 6]
Version 1.5 – JXP, 15 September 2014 [Edits on Sections 5.2.1, 5.2.2]
Version 1.6 – JXP, 16 September 2014 [Draft of Section 5.4]
Version 1.7 – MB, 21 September 2014 [Edits throughout]
Version 1.8 – JXP, 23 September 2014 [Draft of Section 4.1, 5.1.3; Edits in 5.2.2, 5.2.3]
Version 1.9 – SMA, 24 September 2014 [Used track changes to show edits]
Version 2.0 – JXP, 30 September 2014 [Full Draft. Many edits. Used track changes]

Version 2.1 – MB, 03 October 2014 [Polishing]
Version 2.2 – JXP, 06 October 2014 [Edits]
Version 2.3 – DS, 06 October 2014 [Section 5.3]
Version 3.0 – JXP, 08 October 2014 [Nearly Final draft]
Version 3.1 – JXP, 08 October 2014 [Final draft]
Version 3.2 – SA, 09 October 2014 [Section 3, 4.5, misc. cleanup]

2.3. References

[1] Slocum, A. Precision Machine Design. Society of Manufacturing Engineers. Dearborn, MI 1992.
[2] Adkins, S. Requirements for K1DM3: The Keck 1 Deployable Tertiary Mirror, Version 3.0. October 4, 2013.
[3] Adkins, S. Interface Control Document for K1DM3. Version 1.0. October 2014.
[4] Prochaska, J. X., et al. K1DM3 Design Note: Mirror Specifications for the K1DM3 Project. Version 1.3. September 2014.
[5] Prochaska, J. X., et al. K1DM3 Design Note: Positioning of M3 for the K1DM3 Project. Version 2.4. August 2014.
[6] Prochaska, J. X., et al. K1DM3 Design Note: Coordinate Systems for the K1DM3 Project. Version 1.4.1. August 2014
[7] Nelson, J. K1DM3 Design Note: Tertiary Kinematic Mounts. Version 1.0. September 2014.
[8] Phillips, A., et al. K1DM3 Design Note: Alignment Plan. Version 1.0. October 2014.

2.4. Overview

The K1DM3 project was inspired by the prominent role played by time domain astronomy (TDA) within and beyond the Keck community. In particular, projects dedicated to repeatedly image the night sky are generating a stream if not deluge of sources whose flux and/or position vary on human time-scales. The phenomena range from high-energy transients (e.g. gamma-ray bursts, tidally disrupted flares), to transiting planets, to the motions of stars orbiting our Galactic Center. The science questions being addressed range from the census and characterization of near Earth objects (NEOs) to the discovery and analysis of the universe's most distant phenomena. From planet formation to HI reionization, TDA science is at the forefront of modern astronomy. Advances in computing, data science techniques, and reduced detector costs have ushered in an era where astronomers are nearly taking movies of the sky.

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.

Broadly speaking, there are two principal modes of TDA observation:

1. Target of Opportunity (ToO) -- These are primarily transient events which are known to occur but whose timing cannot be predicted in advance. Examples include gamma-ray bursts (GRBs), supernovae, microlensing events, stellar flares, gravitational wave (GW) events, and other explosions and outbursts. With a ToO observation, one aims to characterize the event during or shortly after the outburst, usually on time-scales of minutes to hours as the source fades.
2. Cadence observations -- Contrary to our general perception of a static night sky, there are many sources that vary in flux or position that one wishes to measure through repeated observations on time scales of days to months. These include the stars orbiting our Galactic Center, planets orbiting their parent stars, and various types of binary stellar systems. An example of this type of observation would be to use a specific instrument and setup for an hour once per week spread of one or more semesters.

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. Figure 2-1 shows the optical configuration of the Keck telescope. The location of the tertiary mirror is noted by the red oval. This drawing does not show the details of the tertiary module or the tertiary tower. A photo of the tertiary mirror as it is stored when not in the telescope is shown in Figure 2-2. The desired instrument 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.

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.

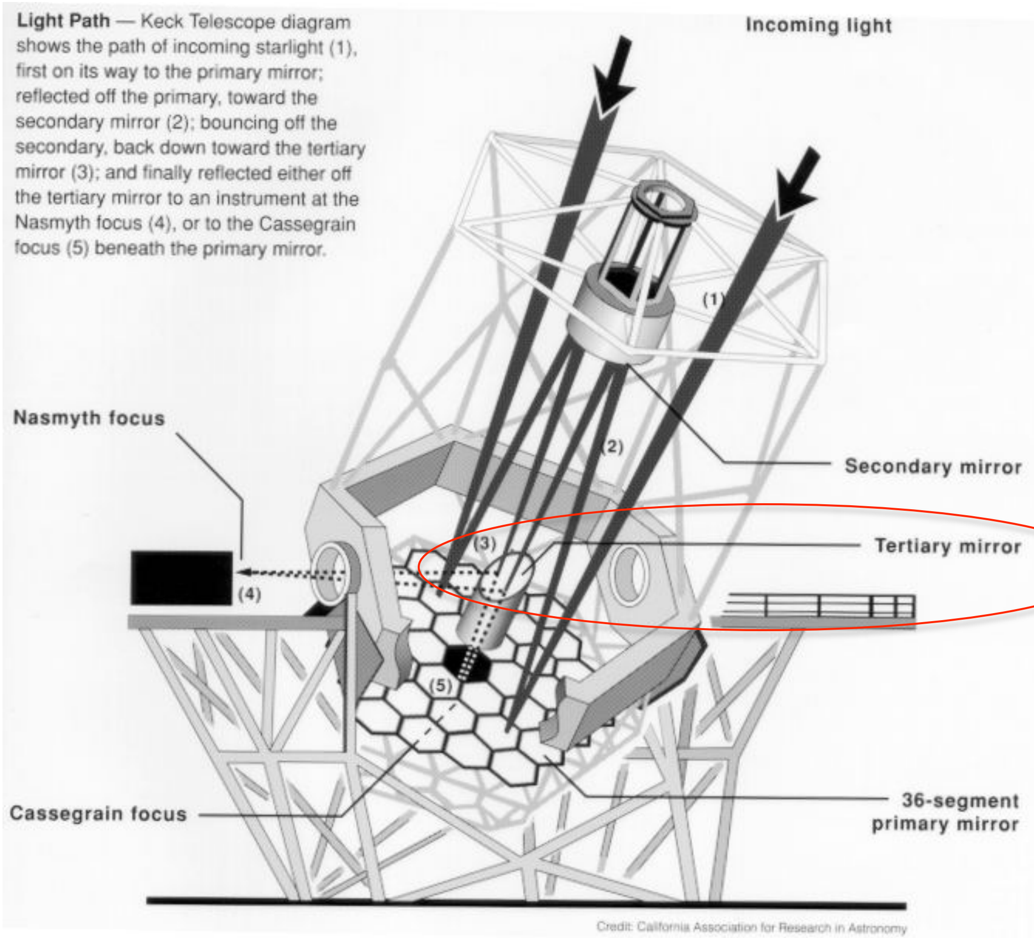


Figure 2-1: Keck I Telescope optical path

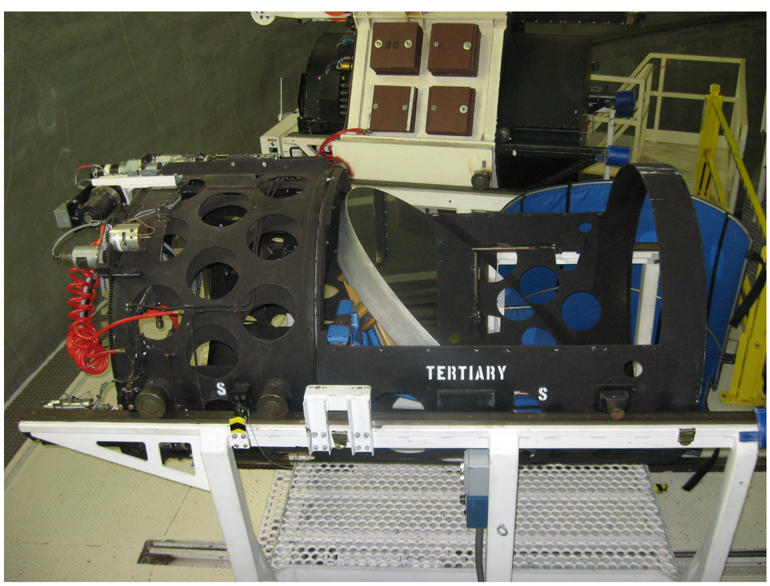


Figure 2-2: The existing Keck I tertiary module as stored on the Nasmyth deck. The tertiary mirror (M3) is clearly visible.

Figure 2-3 shows the overall configuration of the K1DM3 module and Figure 2-4 shows the module installed in the tertiary tower. Both figures show the tertiary mirror in the deployed (in beam) position.

Referring to Figure 2-3, 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 (two motors are used in a lead/lag drive to control backlash). 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 has a center post that connects the mirror and support structure to a swing arm. 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 and retracted position by a locking-latch mechanism. No power is required to maintain the mirror in either the deployed or retracted positions. In order to minimize power requirements (and accompanying heat production) the deploy and retract process will normally be performed at a selected elevation angle, e.g. 60°.

Rotation of the module drum is possible with the mirror deployed or 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 and retracted by a pneumatic cylinder.

The 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.

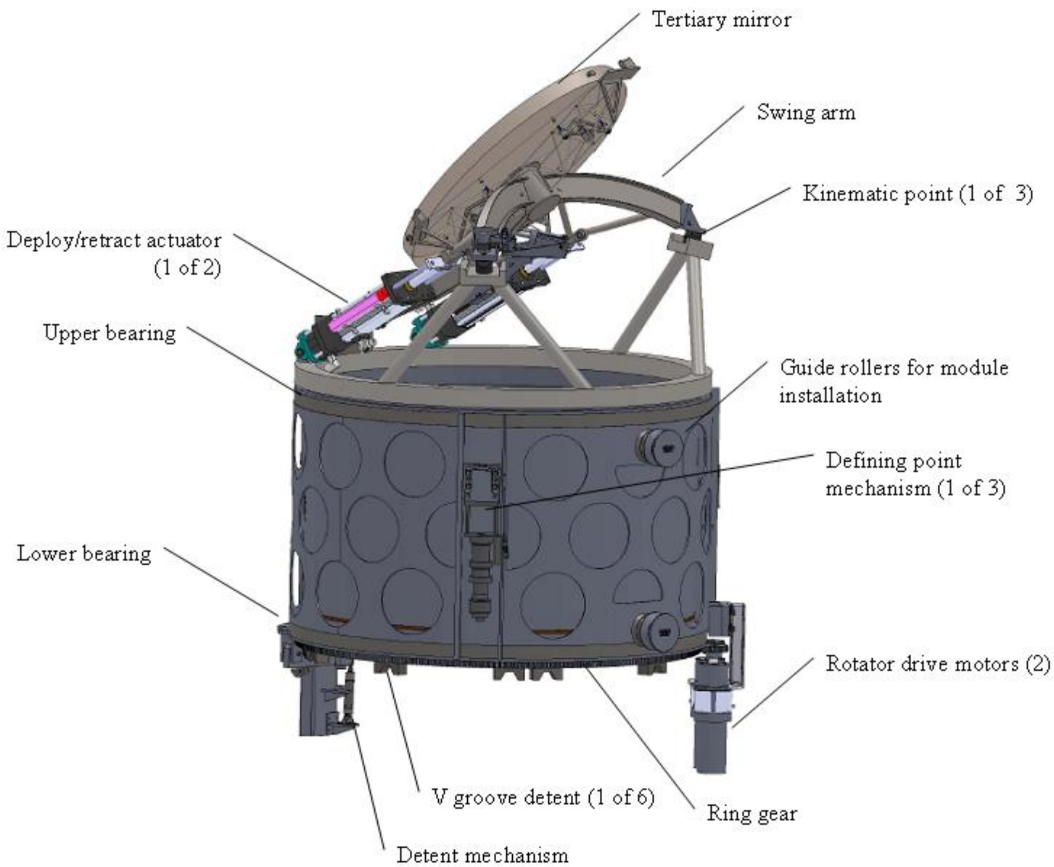


Figure 2-3: Schematic of the K1DM3 system.

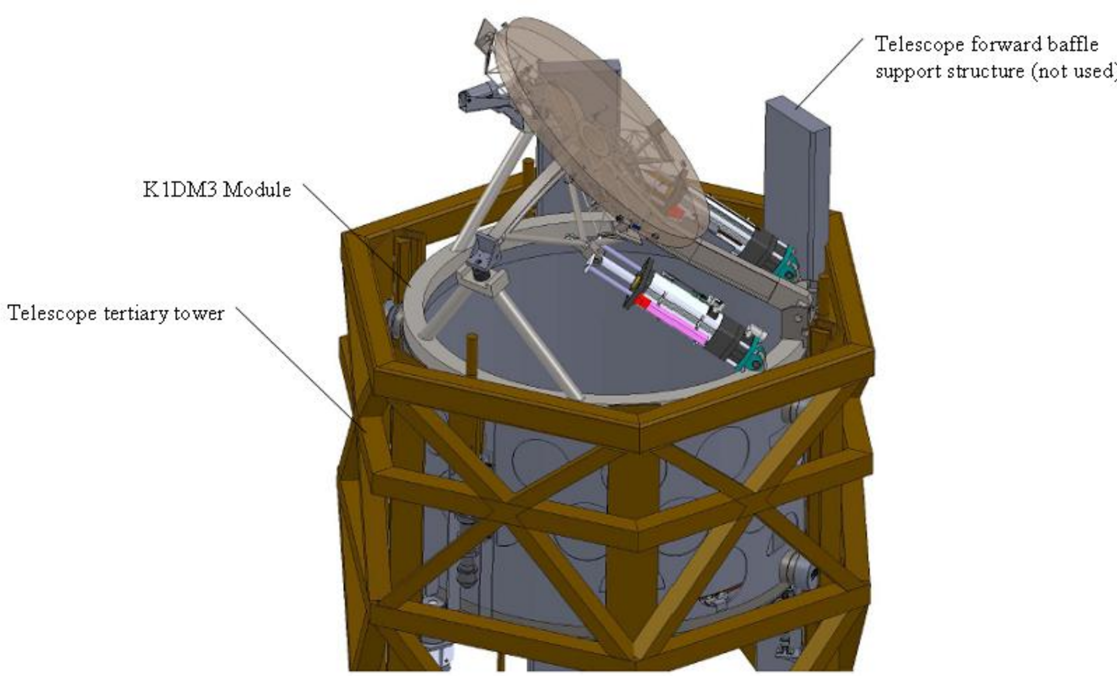


Figure 2-4: K1DM3 module installed in the Keck I tertiary tower

2.5. Operations Concepts and Observing Scenarios

2.5.1. Current Tertiary Module Operations

Nights on K1 are scheduled classically with the PI of an eligible institution awarded a fixed interval of a night for observation. These intervals are primarily full nights but half-nights or even smaller intervals are scheduled. Because of the limitations of the current tertiary module and other considerations, it is rare that more than one of K1's instruments is used on a given night.

2.5.2. Operations with K1DM3

The operations model described above has served WMKO and its community well over the past two decades. It is cost-effective, has demonstrated high on-sky efficiency, and serves well the scientific needs of the majority of the Keck community. However, as discussed in the Introduction, there is a growing demand for operation modes that would better enable TDA observing. The commissioning of K1DM3 is only one aspect of a probable evolution in the operation model of K1. Presently, the WMKO leadership and Keck Scientific Steering Committee (SSC) have sanctioned an *ad hoc* committee to explore new operation models, partly inspired by the K1DM3 project. We expect their findings and the resultant SSC recommendations to crystalize in the following year. For now, we proceed under the expectation that the full functionality of K1DM3 will be exercised day and night to permit calibrations (daytime) and observations (nighttime) with any of the mounted instruments on K1. Any fundamental change to the configuration of K1DM3 (i.e. rotation) should be able to be performed by software in response to selection of the desired instrument by the WMKO telescope operator (Observing Assistant; OA) or the Support Astronomer (SA).

To help motivate the design requirements for K1DM3 and help in understanding how K1DM3 will be used, we offer a few (brief) observing scenarios that would take advantage of K1DM3:

1. <u>A ToO observation</u> -- At 10:36 UT on September 3, 2017, the Swift satellite transmits an SMS message that a GRB has been localized to several arcseconds of the position RA=32.225°, DEC=+22.3234° (J2000) which is within range of the telescope. Prof. Kulkarni of Caltech has a TAC-approved program to obtain spectroscopy of GRB afterglows. He requests a ToO event through a WMKO web-interface (not provided by the K1DM3 project) and the OA is informed electronically. He informs the PI of the night, who is observing stars in Andromeda with the MOSFIRE spectrometer that they must slew to a ToO target after the current exposure. Based on the estimated flux of the GRB afterglow (15.5^m at *V*-band), Dr. Kulkarni has requested a HIRES observation.

   Upon completion of the MOSFIRE exposure, the OA selects HIRES from a drop-down menu. The telescope slews to an elevation angle of 60° and K1DM3 rotates to a defined angle for deployment/retraction. When the telescope and K1DM3 are ready (15 seconds), the M3 mirror is automatically deployed and locked into its kinematic mounts. The module then rotates to the nominal angle for HIRES and locks into a detent. The OA slews the telescope to the desired RA/DEC and acquires the new source on the HIRES slit guider. In the five minutes between the GRB alert and the start of the first exposure, the GRB afterglow has faded by 0.7^m but is still sufficiently bright for a high-signal-to-noise echelle spectrum. Upon completion of the ToO program (1 hour), the OA executes an instrument change back to MOSFIRE, which retracts the K1DM3 mirror, and then slews back to Andromeda. In the morning, the PhD student of Dr. Kulkarni requests an instrument change to HIRES to acquire calibration frames to complement their science exposures.

2. <u>Cadence observations of S0-2</u> -- In 2018, the brightest star (S0-2) known to orbit the black hole at our Galactic Center (GC) will reach pericenter. This will enable tests of gravity in a unique parameter regime. On April 23, 2018, Prof. Ghez of UCLA has been approved by the TAC to observe the GC with OSIRIS for the 35 minutes that its elevation exceeds 25°. The remainder of the night is scheduled for radial velocity spectroscopy with HIRES.

   At UT 14:15, the OA executes the instrument change while a support astronomer (SA) at WMKO headquarters completes initializing the laser guide star (LGS) AO system. The telescope slews toward a calibration star near the GC while the deployed K1DM3 rotates between the Nasmyth positions. Dr. Ghez performs her first OSIRIS observations at UT 14:22 once the telescope has completed slewing to the calibration star. At the end of her scheduled time, the OA selects HIRES and K1DM3 rotates back to that position and locks into place while the telescope slews to the next target for a radial velocity measurement. Dr. Ghez previously obtained all of the calibration files for her observations in the afternoon, in coordination with the HIRES observer.

3. <u>Flexible observing</u> -- On October 13, 2017, Prof. Max of UCSC is scheduled to observe the nucleus of NGC4231 with the LGS-AO system and the OSIRIS instrument. After twilight, however, the sky is covered by thick cirrus with variable and significant extinction ($>0.5^m$) and the seeing exceeds 1.5" FWHM. Dr. Max declares that she cannot obtain scientifically useful data in these conditions. Given the forecast, WMKO had already alerted Prof. Howard of Hawaii that his program to observe bright stars with HIRES in poor conditions may be executed. When Dr. Max declares the night unusable, the SA phones Dr. Howard who travels quickly to his remote observing room. The OA executes the instrument change from OSIRIS to HIRES and the K1DM3 module rotates accordingly. If conditions improved markedly, they may choose to change back to OSIRIS.

3. REQUIREMENTS

3.1. OVERVIEW

At the start of the PD phase for K1DM3, the team generated a Requirements Document (v2.0) to guide the design work. In this section, we summarize the requirements which have had greatest influence on the preliminary design. The reader is also encouraged to review the full K1DM3 Requirements Document, available on the K1DM3 Twiki. This document has been updated to reflect changes and additions to the requirements made during the PD phase and agreed to with WMKO. In the summaries that follow the section references e.g. §7.2.1.1 refer to sections in the K1DM3 Requirements Document.

3.1.1. OPTICAL REQUIREMENTS

1. The K1DM3 tertiary mirror will be sized to provide an unvignetted 5 arc minute diameter field of view at the Nasmyth foci. [§7.2.1.1, Table 8]

2. The K1DM3 module will not vignette the LRIS or MOSFIRE FOVs when the mirror is fully retracted. [§7.2.1.1, Table 8]

3. The K1DM3 system will not vignette M1 or M2 when the mirror is deployed. [§7.2.1.1, Table 8]

4. The K1DM3 system will not vignette M1/M2 when the mirror is retracted. [§7.2.1.1, Table 8]

5. The surface of the K1DM3 mirror will give an 80% enclosed energy EE80 in a 0.054" diameter aperture. This corresponds to a surface flatness specification of $9.7e^{-7}$ (rms) slope error and a 26 nm (rms) surface error over any 44 mm sub-aperture on the tertiary mirror. Reference [4].

6. The tertiary mirror shall be made of Ohara Clearceram-Z or equivalent. [§7.3.2.1]

7. The mirror shall be supplied uncoated and shall be coated with bare aluminum by WMKO. [§7.3.2.2]

Requirements related to the positioning of the K1DM3 tertiary mirror when deployed, which may affect image quality and performance, are summarized in the next section.

3.1.2. 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. [§8.2.1, Table 9]
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. [§8.2.2.1]
3. The mirror will be able to rotate to any position about the telescope optical axis when retracted. [§8.2.2.1]
4. The mirror will be able to rotate about the telescope optical axis at a speed of at least 6° per second. [§8.2.1, Table 9]
5. The K1DM3 module shall not radiate more than 5 watts of heat into the telescope dome ambient environment during an observation. This includes

power dissipated when the K1DM3 is rotating to track the rotation of a Cassegrain instrument's field de-rotator, if this proves necessary to satisfy the requirement for no vignetting of the optical path to the Cassegrain focus. [§8.2.1.2]

6. If additional power dissipation must be allowed for deployment and retraction of the mirror the time for return of the affected parts of the K1DM3 module to return to ambient temperature shall not exceed 5 minutes. [Proposed]
7. The K1DM3 electronics shall be located remotely from the K1DM3 module in a location where either air conditioning or a liquid cooled heat exchanger system can carry away the heat generated by the electronics. The K1DM3 electronics shall not dissipate more than 1800 watts. [§8.2.1.3]
8. If required the rotator shall also provide for continuous rotation to maintain the retracted tertiary mirror in a position that does not vignette the science and guider FOVs of the Cassegrain instruments LRIS and MOSFIRE. [§8.2.1, Table 9]
9. The K1DM3 module must not weigh more than 1000 kg. [§8.2.1, Table 9]
10. The structure of the K1DM3 module shall meet the zone 4 earthquake survival requirements of Telcordia Standard GR-63-CORE, "NEBSTM Requirements". [§8.3.3.1]

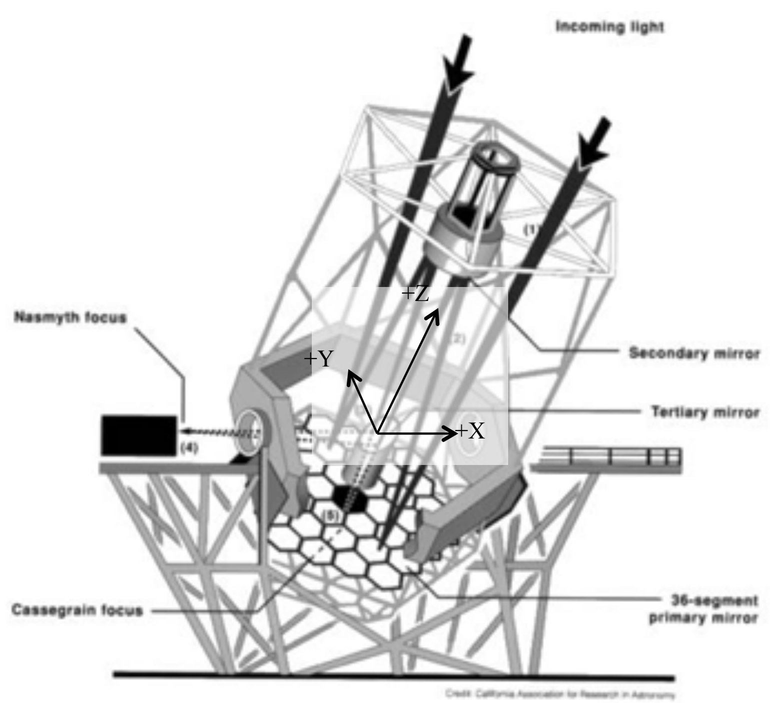


Figure 3-1: Telescope Coordinate System

In-beam Positioning Requirements

As built, the elevation axis of the K1 telescope lies in a plane 4.00 m above the primary, normal to the optical axis (Figure 3-1). For an ideal telescope with a desired circular FOV at the Nasmyth foci, an elliptical tertiary mirror should be inserted at a 45° angle with respect to the optical axis (telescope Z axis) and slightly off-center along the mirror's major axis. The reader may consult reference [5] for further details.

It is possible that the current M3 is at least slightly 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. 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. More details on this activity are provided in §4.1.3 where we discuss the alignment plan for K1DM3.

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. We discuss briefly the impacts of misalignment (see K1DM3_Design_Note_Positioning for further details) which motivate the requirements on accuracy, repeatability, and stability for the positioning of the K1DM3 mirror. These are some of the most demanding aspects for the K1DM3 design.

Translation or rotation of the mirror in its plane has a negligible effect on the performance for small motions and we ignore them in the following. The misalignments that significantly affect performance are errors in positioning of the mirror along the telescope X or Z axes (δ_X, δ_Z) and rotations about the minor axis of the mirror (tilt or $\delta\theta_{\mathrm{tilt}}$) or the telescope Z axis (tip or $\delta\varphi_{\mathrm{tip}}$). Because the tertiary is tilted by 45° in the beam, a tilt of the mirror causes a greater displacement of the image in the focal plane compared to a tip. Quantitatively, with the plate scale at the telescope focus of 0.7252 mm/1" and the focal plane located 6.5 m from the tertiary, displacements and rotations of the mirror lead to angular offsets in the focal plane of:

$$\delta\alpha = \frac{\delta_z}{0.7252\ \mathrm{mm}}(\mathrm{or}\ \delta_x)\ arcseconds$$

$$= \left(\frac{\delta\theta_{\mathrm{tilt}}}{11.5''}\right) arcseconds$$

$$= \left(\frac{\delta\phi_{\mathrm{tip}}}{16.5''}\right) arcseconds$$

Regarding accuracy and repeatability, we have derived requirements based on the existing AO system and the HIRES instrument and have also given consideration to future AO technology. For an AO system, there are two considerations: (i) maintaining alignment of the matched pupil mask and (ii) repositioning the pupil to a small fraction of the sampling subaperture. Regarding pupil alignment, the maximum allowed shift of the primary mirror image with respect to a matched pupil mask projected into primary mirror space is 66 mm. This corresponds to 4.4 mm at the tertiary or a tilt of 70". This should be easily achieved and does not drive the positioning requirements. Regarding repositioning, the current Keck AO system samples the pupil 20 times across its diameter. Future AO systems might sample more densely, perhaps 100 times across the diameter. If we allow 10% alignment variations of a subaperture then we want the pupil location to repeat to 0.001 of the pupil diameter. This requires that the tertiary tilt be repeatable to 11.5" and tip to 23" (rms). Similarly, this implies repeatability to 725 microns along the telescope X and Z axes (rms). Explicitly, it is important that the exit pupil be stable for HIRES, OSIRIS and future AO systems, i.e. a requirement that the pupil move no more than 1cm/10m over an observation. This implies the tertiary should tilt no more than about 11" during an observation.

Using the Zemax model for HIRES (without the image rotator), we have examined the effects of misalignments of the tertiary. We find that misalignments that would correspond to 1" offsets of a source at the focal plane lead to very small additional vignetting in HIRES (≈ 0.1%) and small increases in the rms of the spot sizes (0.5 to 1 microns). We have further consulted with HIRES PI S. Vogt who agrees that these effects may be considered negligible. Therefore, HIRES does not impose stricter requirements than those for the AO system. We believe the same to be true for any future optical spectrometer. If one were to develop a new IR instrument for K1, the primary concern would be pupil alignment.

We have also examined the consequences of misaligning M3 on guider performance and object acquisition and consider these to be minor for offsets of a few arcseconds in the focal plane [K1DM3_Design_Note_Positioning].

For reference, the existing tertiary allows repeatable positioning at the various focal stations with an error of < 5"

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" 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" and 0.46" (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. [§8.2.1, Table 9]
2. The K1DM3 mirror will position to the nominal rotations of tip and tilt to 11.5" and 23" (rms) respectively. We adopt the same requirement for repeatability. Reference [5]
3. The K1DM3 mirror will be held stable to displacements in the telescope X and Z axes to 29 microns (rms). [§8.2.1, Table 9]

4. The K1DM3 mirror will not move in tip and tilt due to external influences (vibration) by more than 0.65" and 0.46" (rms) respectively. [§8.2.1, Table 9]

3.1.3. 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. [§8.3.1.1]
2. The K1DM3 module shall be compatible with the existing module insertion and removal rails provided in the Keck I tertiary tower. [§8.3.1.1]
3. The K1DM3 module handler shall be based on the design of the existing K1DM3 tertiary mirror module handler and shall be as identical to that existing handler as possible. [§8.3.1.4]
4. 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. [§8.3.1.2, §8.4.4.3]

3.1.4. ELECTRIC/ELECTRICAL REQUIREMENTS

1. The K1DM3 system shall be powered from 120 Vac, 60 Hz. power at a maximum of 15 A. [§9.2.1.1]
2. The K1DM3 shall provide an emergency stop input that stops all motion when the Observatory emergency stop signal is activated. [§9.3.1.1]
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. [§9.3.2.1]
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. [§9.4.1.3.2]

3.1.5. SOFTWARE REQUIREMENTS

1. 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. [§11.4.1.1]
2. The K1DM3 software shall be written to run under a WMKO approved operating system. [§11.4.2]
3. The K1DM3 software shall conform to WMKO software standards. [§11.4.3]

4. The K1DM3 software shall be implemented as client-server architecture with communications over TCP/IP. [§11.5.1.1, 11.5.1.2]
5. The K1DM3 software shall support legacy (current Keck telescope DCS) and new (TCSU) use cases. [§11.5.2]

3.2. COMPLIANCE MATRIX FOR REQUIREMENTS

See §7.3.

4. PRELIMINARY DESIGN

4.1. OPTICAL DESIGN

4.1.1. MIRROR DESIGN

Design Description: The K1DM3 system will provide a new tertiary mirror for the Nasmyth and bent-Cassegrain foci of the Keck I telescope. This flat mirror will be made of Clearceram-Z glass from Ohara (or equivalent) and be shaped as an ellipse with major axis 2a = 881.1 mm and minor axis 2b = 623.0 mm, and a thickness of 50 mm (Figure 4-1). It will have an approximate mass of 52.7 kg.

The mirror will be polished by a vendor to less than 2 nm (rms) surface roughness 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 will be polished with a surface flatness of $8e^{-7}$ (rms) slope error across any 44 mm diameter. It will have a surface error of 26 nm (rms) across the same diameter or better.

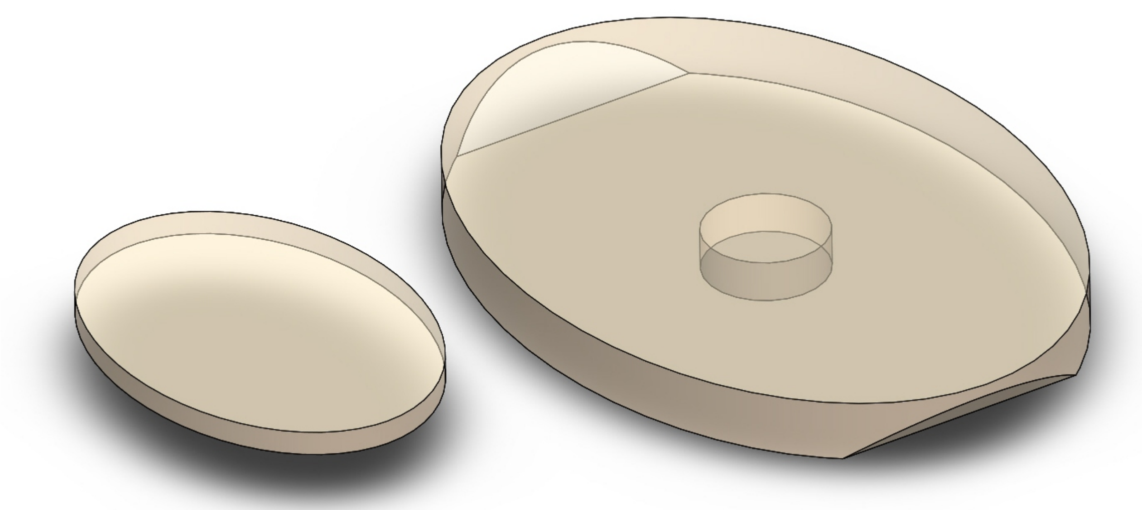


Figure 4-1: Planned K1DM3 mirror (left) and the current K1 M3 (right). The K1DM3 mirror provides a 5' FOV and is an ellipsoid having with major axis = 881 mm and minor axis = 623 mm. The current K1 tertiary provides for a 20' FOV.

The mirror will be delivered uncoated and later coated with bare Aluminum using the coating chamber at WMKO.

Design Analysis: To redirect the converging beam from M2 to along the elevation axis, one inserts a plane mirror at 45°. The intersection of a 45° plane with a cone yields an ellipse, with center slightly offset from the optical axis (along its major axis). For the required 5' FOV at the Nasmyth foci, the ellipse has the dimensions listed above (see reference [5] for a derivation) and is offset by 13.7 microns along the major axis away from the primary mirror. We may slightly oversize the mirror to allow for small misalignments, a reduction in effective size by the mount, etc.

To derive the tolerances on polishing M3, we considered performance in both seeing-limited and AO-assisted scenarios (see reference [4]). For seeing-limited observations, the requirement to achieve 80% enclosed energy in a 0.054" diameter translates to a $9.7e^{-7}$ slope error (rms) across any 44 mm aperture on M3. For AO-assisted observations, a Strehl of 0.9 at 1 micron requires a less than 26 nm (rms) surface error across a 44 mm diameter. The sources of error that will contribute include polishing, thermal and gravity deflections. Because we are estimating the latter two effects to be small (see §4.2.1), we impose a polishing specification of $8e^{-7}$ rms slope error. It is our experience that vendors can relatively easily achieve this specification on a flat mirror at our size.

Performance: The mirror design satisfies the optical requirements listed in §3.1.

Risks and Mitigations: We identify no significant risks with this aspect of the design. We only note in passing that care must be taken to clearly communicate to the polishing vendor the specifications on surface slope error.

4.1.2. VIGNETTING OF THE CASSEGRAIN INSTRUMENTS WHEN RETRACTED

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 reference [5] for further details.

Figure-XX illustrates the challenges we face when retracting M3 to avoid vignetting the rays from M1 to M2 and, at the same time, avoid vignetting the rays from M2 to the Cassegrain instruments. 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. 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 275.8642 mm above the elevation axis and radially offset by 690 mm from the optical axis, and at an angle α=99.5° (where α=45° is the deployed position and α=90deg is parallel to the optical axis). This results in no vignetting of the converging rays from M1 to M2 a full 20' FOV.

Another source of vignetting is the profile of the K1DM3 system relative to the converging beam from M2 to the Cassegrain focus. Presently, there are two Cassegrain instruments commissioned on Keck I (with none additional planned): LRIS with a 6' x 8'

FOV located 7' off-axis and MOSFIRE with an on-axis FOV of 6.14' x 6.14'. 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 (Figure 4-2). 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).

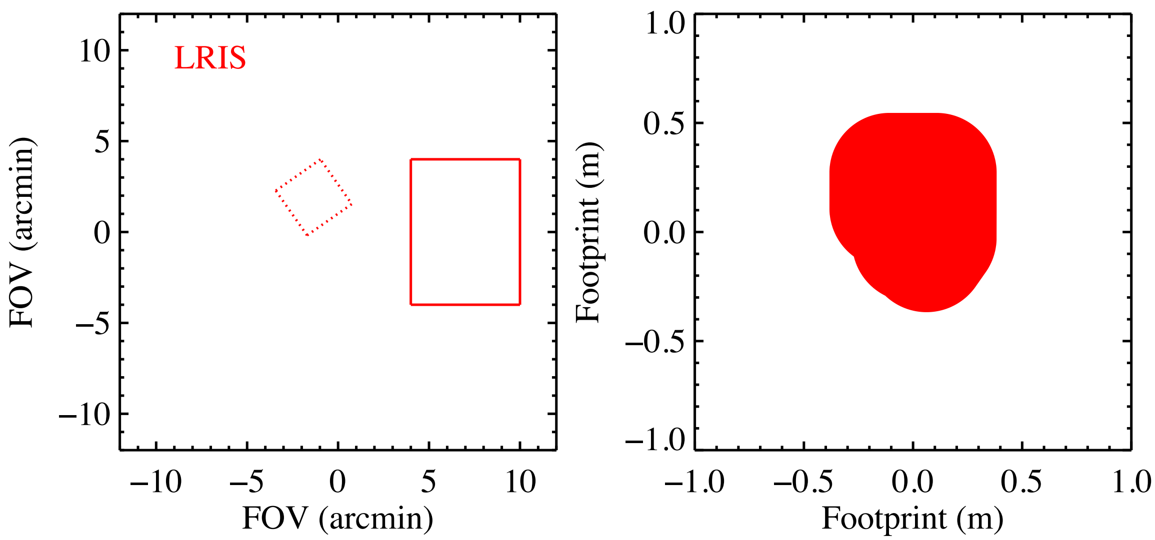


Figure 4-2: LRIS field of view for the science and guider cameras in the focal plane (left) and the footprint mapped at Z1 = 5 m above the primary mirror (elevation axis is 4 m above the primary). The latter was imported into SolidWorks to check whether K1DM3 vignettes LRIS when retracted.

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 (KeckI_PRIMARY.UDA), 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. We find that the mirror does not vignette the M1/M2 system for angles less than approximately 105°. For any smaller angles, the secondary structure 'shadows' the K1DM3 system.

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 then verified that these footprints vignette 100% of the rays traveling to the MOSFIRE or LRIS focal planes.

Performance: The mirror design satisfies the optical requirements listed in §3.1.

Risks and Mitigations: The sizing constraints imposed on the K1DM3 system by vignetting are challenging, but we are confident that the requirements are met by our design.

4.1.3. ALIGNMENT OF K1DM3

Design Description: As a key optical element in the telescope system feeding light to the Nasmyth or bent-Cass foci, the tertiary mirror of K1DM3 must be precisely positioned. As discussed in Section 3.1.1, misalignments of M3 lead to displacements of the image in the focal plane, misalignment of the pupil on the designed masks, etc. These considerations place tight requirements on the positioning of M3. Similarly, the commissioning of K1DM3 must include a detailed plan to insure proper alignment within the telescope. The following summarizes the K1DM3 Alignment Plan which is described in greater detail in reference [8].

If we were constructing the K1 telescope anew, we might attempt to align the M1-M2-M3 system in the ideal positions set by the optical design. One would then align the instrument on each Nasmyth platform to the telescope. In practice, however, we are introducing K1DM3 into a functioning system with instruments aligned to the existing telescope including the current M3. To avoid the realignment of the Nasmyth instruments (if possible), the goal of our alignment plan is to position K1DM3 to replicate the performance of the current M3 (as closely as possible).

Recognizing that modifications to the module mounts will be difficult when K1DM3 is installed within the tertiary tower, we have developed a two-stage Alignment Plan:

1. Internal Alignment at UCO, which establishes the rotation axis of K1DM3 and aligns and centers the mirror at a 45° angle to this axis.
2. Final Alignment at WMKO, where the matching of alignment to the existing tertiary (M3) is done.

We discuss each of these in turn. For each stage, we will mount K1DM3 within an Alignment Fixture (AF) described below.

Alignment Rig: For alignment and transportation of K1DM3, we will fabricate an Alignment Fixture (AF). The primary components and requirements are:

i. Kinematic Fixtures that match, as closely possible, the Tower Fixtures on K1 (TF1).
ii. A steel frame that supports these fixtures and holds K1DM3 in place when mounted.
iii. A design that facilitates packaging and shipping of K1DM3.
iv. A design that holds the existing tertiary module in a position where its mirror may be removed.

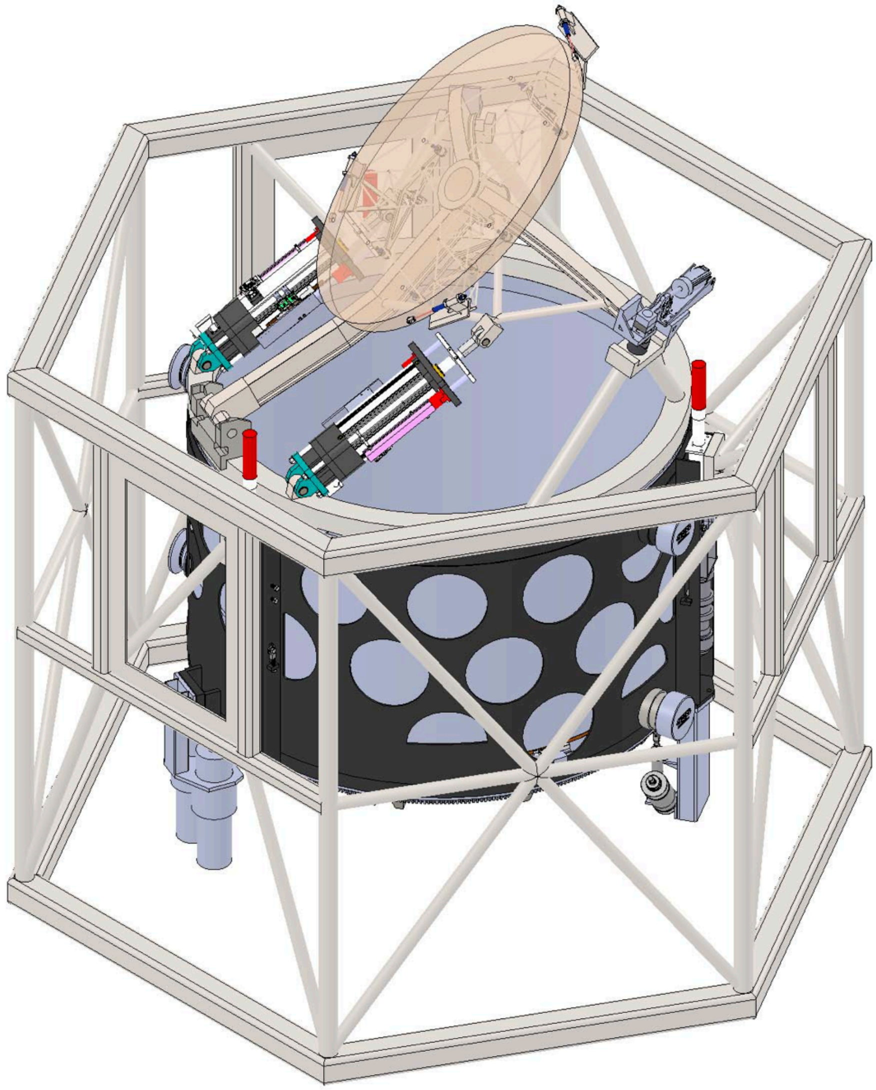


Figure 4-3: Conceptual design of the Alignment Rig.

<u>Internal Alignment:</u> The goals of this stage of the alignment, performed at UCO, are to:

1. Align the deployable mirror to the rotation axis.
2. Determine the range of travel remaining in adjustments; improve if necessary.
3. Measure the amount of flexure in the alignment rig with the module installed; stiffen as needed.

To achieve these goals, we will perform the following steps:

1. Install K1DM3 into the alignment fixture. The preferred orientation is vertical, i.e. with the rotation axis of the module parallel to gravity.
2. Retract K1DM3.
3. Install a cross-hair jig (XHJ) for defining the center of rotation of the K1DM3 bearings.
4. Rotate the module, and adjust XHJs to be on the rotation axis (ie, don't move under rotation).

5. Install a collimating/aligning telescope (CT1) along the rotation axis. This cannot be moved once aligned.
6. Deploy K1DM3 (remove XHJ before deployment if needed).
7. Use CT1 to put a (temporary?) mark on mirror at rotation axis.
8. Attach a precision 90-45-45 prism to mirror surface, aligned mechanically with the mirror axes.
9. Adjust the Deployable Kinematics (DKs) so that beam of alignment telescope returns on itself.
10. Retract K1MD3 (and re-install XHJ) and verify that CT1 is still aligned and on rotation axis.

At this point, the mirror should be aligned 45° with respect to the rotation axis. We may also perform a few additional tests:

a) Tilt to horizontal to measure amount of flexure.
b) Use mark on mirror to verify height matches design; adjust MKs to adjust height.
c) Determine the remaining range in adjustments; correct as needed. (NB: If MKs need adjustment to range, all steps must be repeated; if DKs need range adjustment, step 9 needs repeating.)

Final Alignment: The goals of this stage of the alignment, performed on the floor of the K1 dome at WMKO, are to:

1. Align axis of rotation to the existing M3 axis of rotation.
2. Align piston of mirror to the existing M3 piston.
3. Align normal of mirror to match the existing M3.
4. Align detents to match the existing M3.

To achieve these goals, we will perform the following steps:

1. Install the existing tertiary module in the Alignment Rig.
2. Remove M3 from the module.
3. Rotating module, mark center of rotation with cross-hairs at each end of module. (required error?).
4. Align collimating telescope (CT1) to lie on this axis. CT1 now defines the rotation axis.
5. Install M3.
6. Mark on the mirror the rotation axis intercept with the mirror (removable ink).
7. Rotate to AO detent position.
8. Align second collimating telescope (CT2) on normal of mirror.
9. Put reference mark on wall at some distance.
10. Rotate to HIRES position; place reference mark on wall.
11. Rotate to bent Cass position and place reference mark on wall.
12. Remove the existing tertiary module and insert K1DM3; place in retracted position. NB: fixture cannot move during this operation or all is lost!
13. Place XHJs on K1DM3 (confirm still on rotation axis).
14. Adjust MKs to place rotation axis aligned to collimating telescope (CT1). When finished, rotation axes are aligned.

15. Remove XHJs, deploy mirror and confirm that ink mark is still on axis of rotation.
16. Adjust piston on MKs to place ink mark on center of CT2 (focused on mirror). IMPT! Only piston must be adjusted (we should probably retract the mirror and verify rotation axis is still aligned; iterate until satisfied).
17. Place rotation at AO reference location*.
18. Using CT2 reflection (ie focused on telescope) adjust DMs to align normal of mirror (tip/tilt only, no piston adjustment – can monitor piston as needed).
19. At this point, we should be completely aligned. We should check against the reference marks on walls, etc., to confirm. Adjust angular detents as needed (except AO reference – this cannot be modified w/o returning to adjusting the DMs for the same mirror normal, step 18)

(*) may need to adjust detent for AO to make proper sense.

4.2. MECHANICAL DESIGN

4.2.1. MIRROR ASSEMBLY DESIGN

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 mechanism; (iii) insure 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 and 60 mm long, 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 4-4. The positions for the rods were determined from finite element analysis (FEA) to minimize the deflections of the mirror normal to its surface.

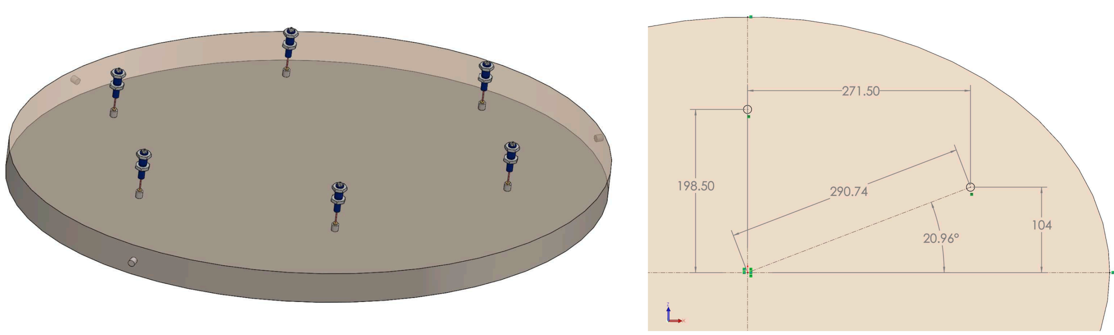


Figure 4-4 Left CAD image shows the six axial support rods attached to the back of the K1DM3 mirror. Diagram on right shows the placement of two of the rods indicated by open circles. The measurements are referenced from the major and minor semi-axes of the mirror.

Lateral support is provided by three rods glued to pucks on 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 4-5). These rods are 150 mm long and 3.5 mm in diameter, and are steel. These use the same pucks and glue as for the axial supports.

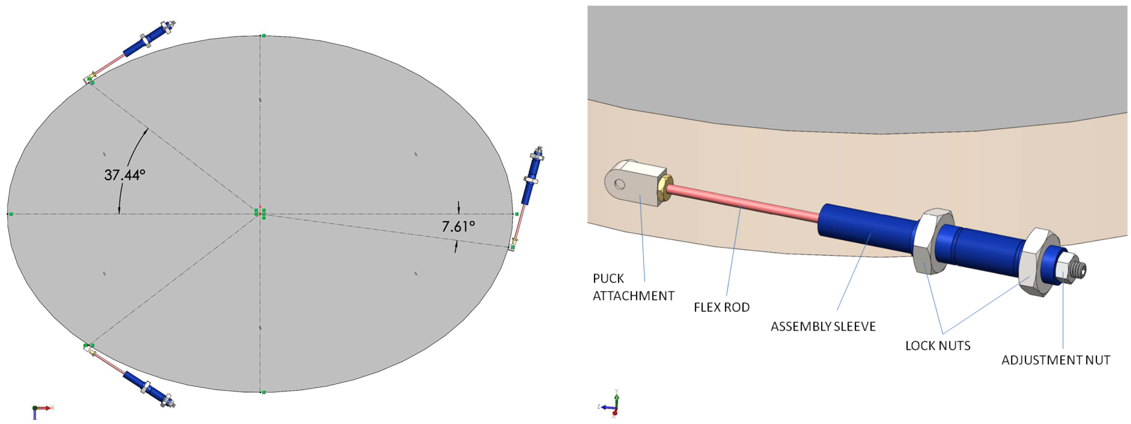


Figure 4-5 Left diagram shows the placement of the three lateral supports along the outside edge of the mirror. Right image is a close-up view of one of the lateral supports screwed to a puck that is glued to the edge of the mirror.

The axial and lateral rods are integrated within a whiffle-tree support system, shown in Figure 4-6. The whiffle tree uses 4 mm diameter struts 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 is estimated to be 54 kg.

The center post will be designed as a rigid and kinematic connection between the mirror assembly and the swing arm structure. It will provide the interface for removal of the mirror assembly for coating and for a repeatable re-attachment. The interface will consist of mating plates bolted together and having two alignment pins to prevent deflections in the plane of the interface.

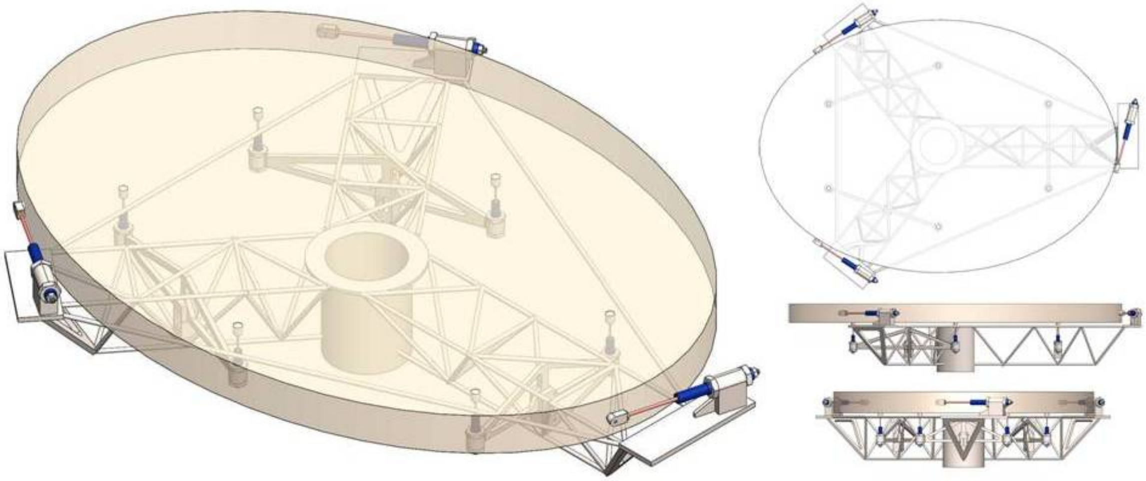


Figure 4-6: Various views of the whiffle-tree support structure for K1DM3.

<u>Design Analysis</u>

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. At the Internal PDR in April 2014, we were 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.

The positioning of the axial rods was optimized iteratively in a series of FEA models performed 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 more dense 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.). When possible, we constructed ¼ and ½ symmetry models to accelerate the calculations. 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.

Figure 4-7 shows the mesh geometry for an ANSYS model of the current design. The models assume Zerodur glass (this analysis was done before the decision was made to change to Ohara Clearceram Z) with a thickness of 50 mm, a major diameter of 881.2

mm, a minor diameter of 622.4 mm, and a mirror weight of 55 kg. The mirror is shown in Figure 4-8 with a beam footprint corresponding to an on-axis star. The pucks are glued to the glass with epoxy adhesive. The axial pucks (on rear surface) have a uniform glue thickness of 0.4 mm. The pucks on the edge for the lateral supports currently have 0.4 mm minimum thickness on the curved edge. Most likely the mirror blank will be fabricated with flat edge-faces at the lateral puck locations. This will allow a uniform 0.4 mm glue thickness.

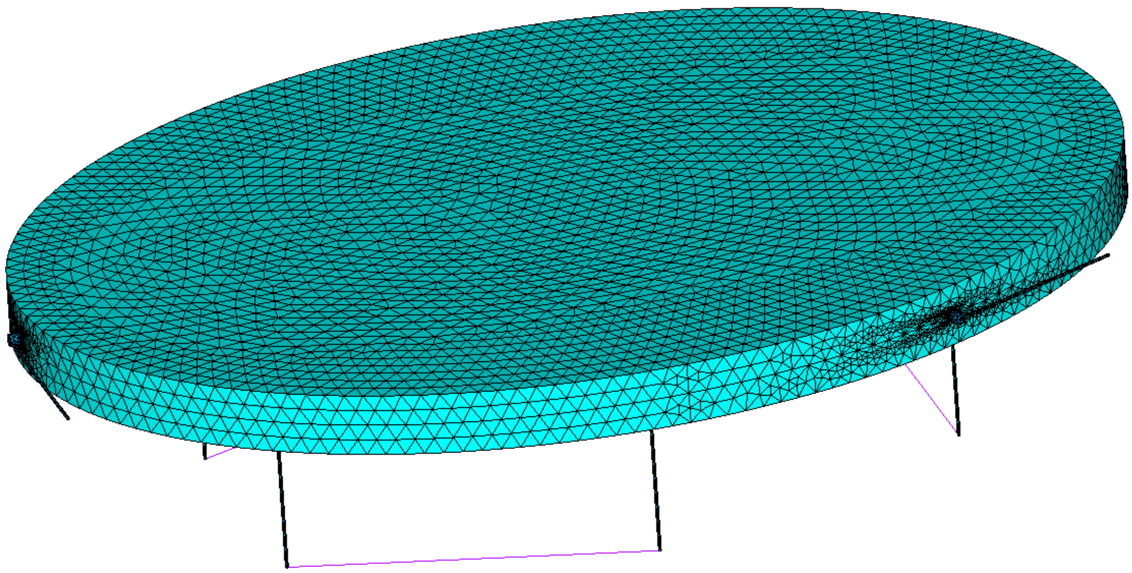


Figure 4-7: One of the many FEA models used to analyze the K1DM3 mirror and its support system.

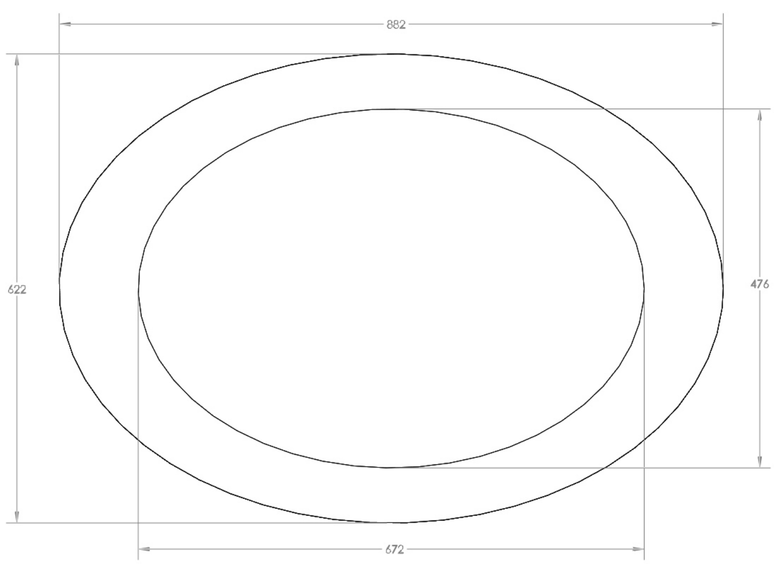


Figure 4-8: Plan view of mirror showing the outline of an on-axis star footprint. The mirror is 882 mm x 662 mm, the footprint is 672 mm x 467 mm.

Figure 4-9 is a deflection contour map of displacement (m) 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 97 nm.

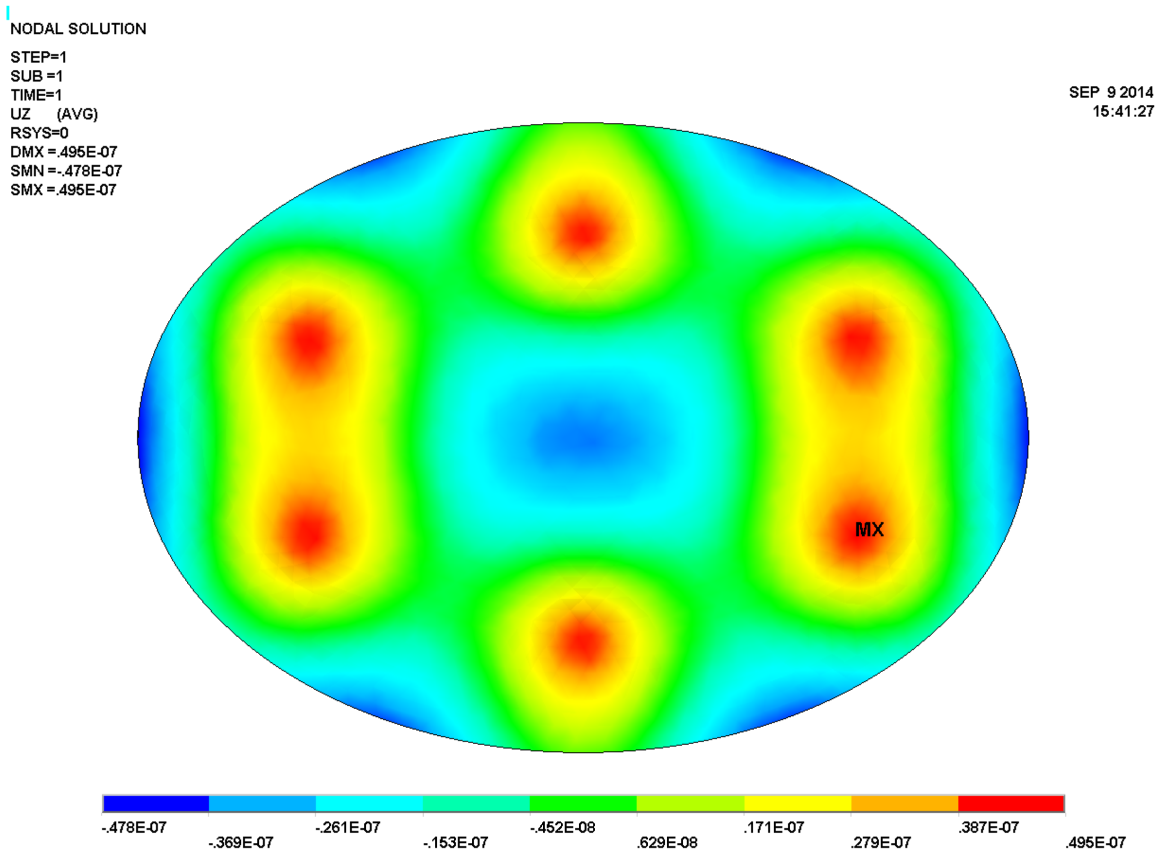


Figure 4-9: Surface deformation map for the six point support system due to gravity normal to the mirror. Deflections are in meters. The contour map is for the entire mirror surface. The peak-to-valley range is 97 nm. rms deflection of the entire surface is 22 nm. Model 21 is a uniform grid mesh.

A pseudo spot diagram shown in Figure 4-10 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 4-9) 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.

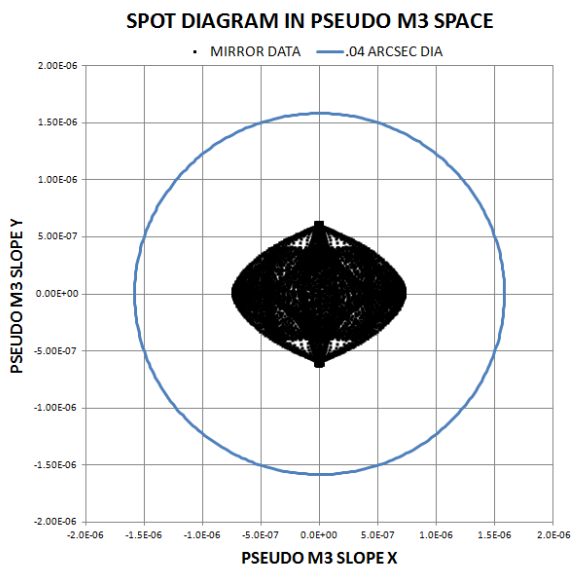


Figure 4-10: Spot diagram of based on results shown in Figure 4-9. This diagram represents where light reflected by the mirror would strike the focal plane. The image is a family of points which are calculated based on the slope error throughout the mirror. If the mirror were un-deformed (perfectly flat) the image would be single point at the center. Deflection slopes of the deformed mirror are used to predict the spot image spread. The blue circle for reference is 0.04" in diameter. The image spread for this case is well within 0.01".

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".

Table 4-1 summarizes the quantitative effects of gravity and changes in temperature.

LOAD CASE	**DEFORMATIONS (nm)**		**rms SLOPE DEVIATION (")**
	Peak-to-Valley	**rms**	
GRAVITY (major axis)	34	1.9	.003
GRAVITY (minor axis)	43	2.1	.005
GRAVITY (normal)	97	22.1	.05
CTE (ΔT = 30 °C)	2.4	0.6	.0011

Table 4-1 Mirror surface deformation response to various loads

The error budget for the mirror is shown in Table 4-2. 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:

$$Maximum\ permissible\ rotation = \sqrt{{\theta_x}^2 + 2 * {\theta_y}^2} = 1.68\text{E-}6\ radians$$

Table 4-2 lists the rms slope error for various conditions and allowances. The support design error is based on the static response due to gravity normal to the mirror surface, which is the worst case gravity vector.

CTE Axial refers to differentials in thermal expansion or contraction which would influence the mirror thru adhesive and the Invar pucks attached on the mirror's rear surface. CTE Lateral is the same effect caused by the three attached pucks on the outer edge of the mirror.

Fab errors axial refers to a 1N load inplane load caused by the attachment of the axial support system. Fab errors lateral is a similar assessment for the lateral support system. The moment fab errors are based on a 0.2 N-m moment error in the respective support systems.

Item	**Combined Error (radians)**	**Comments**
Polishing	9.7E-7	Unknown, best guess
Support design	4.76E-7	Largest gravity normal to mirror
CTE Axial	2.08E-8	Glue & pucks
CTE Lateral	9.95E-9	Glue & pucks
Fab errors axial	7.95E-9	1N force error allowed in plane of mirror
Axial pivot error	3.0E-8	1 mm error in pivot location
Fab error axial moments	1.012E-7	0.2 N-m moment allowed
Fab errors lateral	6.05E-8	1 N force error allowed
Fab error lateral moments	7.94E-8	0.2 N-m moment allowed
SUBTOTAL	1.09E-6	
CUSHION	1.28E-6	
TOTAL	1.68E-6	Maximum allowed

Table 4-2 Error Budget

The axial pivot error 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.

One portion of the preliminary design has not yet been analyzed. This is the whiffle tree support system. The compliance of this assembly only contributes rigid body motion to the mirror. The pivots are supported by the trusses and ensure kinematic support of the mirror. This truss system, however, needs to be analyzed and optimized to reduce the rigid movement and pointing error of the mirror.

Modeling, simulations, and prototyping

A three point axial support system for the mirror is also under consideration. A three point support has great advantages since a whiffle tree system is not required. This dramatically simplifies the mirror support design. However, mirror deformations for such a configuration are not optimal. A solution to this problem would require polishing the mirror flat while being supported at these three locations. This would eliminate the print thru under the most severe gravity load, which is normal to the mirror.

The challenge is finding a supplier who is willing to polish the mirror in this arrangement and estimating the added cost for this complexity. We have found two suppliers who are interested but have not had the opportunity to sufficiently discuss details to get viable quotes to study and evaluate this option.

Risks and Mitigations

1. Earthquake – Dynamic analysis will be vigorously pursued in the next phase. The system needs to be designed and optimized for dynamic response according to the project requirements. Keck's earthquake analysis study has been made available as a reference. It will be thoroughly reviewed and used as a guide and input to this work effort. Part of the mirror assembly design will include provisions to capture and protect the mirror during seismic events.
2. Adhesive strength/longevity – There is much history and experience with adhesives at Keck and UCO. This expertise will be leveraged for the applications needed on this project. K1DM3 is unique due to the range of dynamic motion to which the system will be subjected. This will place new demands on the adhesive bonds. We have several epoxy candidates for consideration. Current analysis is using mechanical properties for the adhesive that TMT plans to use. We also have great success with the material used for the optics in the Automated Planetary Finder (APF). Although the gravity vector does not change for the APF instrument, it is constantly subjected to dynamic loads as the telescope slews in azimuth. Most notable is the adhesive study Keck has performed in response to micro-fractures developing in the primary segments. Extensive research and testing were conducted on a variety of materials. A report has been published and it will be used for reference and guidance in our selection of the appropriate material.
3. Coating of pads/glue – The lateral support restraints on the mirror attach to the outer edge. They may have to be protected and covered during recoating. K1DM3 is much smaller than the existing M3 so there should be no space constraint for this protection. It is possible that the coating process may degrade

or otherwise affect the glue bonds. To properly eliminate this risk, a test program should be performed. It will probably be easier to design in protection to these components. The project will weigh these options and decide a course of action.

4.2.2. Mirror Deployment Design

Design Description: 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 kinematic couplings. Those are discussed in the Section 4.2.3.

The Mirror Assembly described in the previous section will fasten to a tripod swing arm fabricated with ASTM-A36 steel. Figure 4-11 illustrates the shape and overall dimensions of this part. It is a weldment of steel members. At the end points of the main arms are the kinematic couplings (canoe spheres) that enable repeatable, precise positioning of the system. This swing arm is attached to a pivot on the top bearing ring of the K1DM3 module. This pivot is compliant to allow the kinematic coupling to determine the deployed position of the mirror. The pivot mechanism consists of two rolling element bearings suspended by O-ring cells, which has been shown to not negatively affect repeatability.

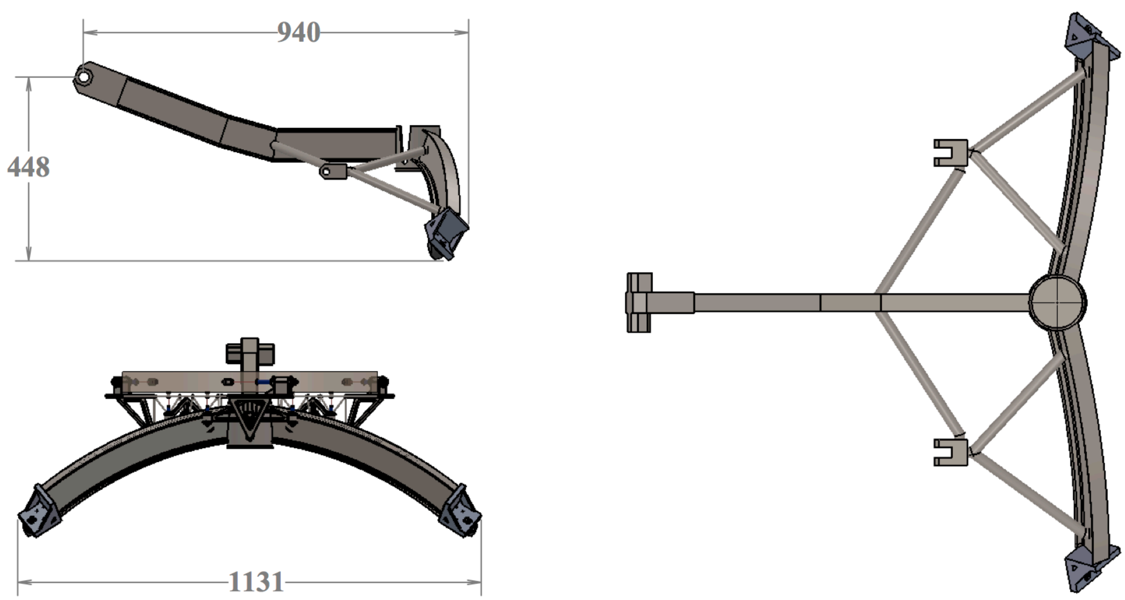


Figure 4-11: Swing arm. All dimensions in mm.

Also attached to the bearing ring is a pair of bipod struts made of 1020 tubular steel. Each bipod holds a V-groove kinematic coupling for positioning the mirror when deployed. The struts are approximately 409 mm long and are positioned at 120° from the swing arm pivot (see Figure 4-12). These are tilted at an angle 15.4° away from the optical axis. The third sphere/v-groove interface is adjacent to the compliant point.

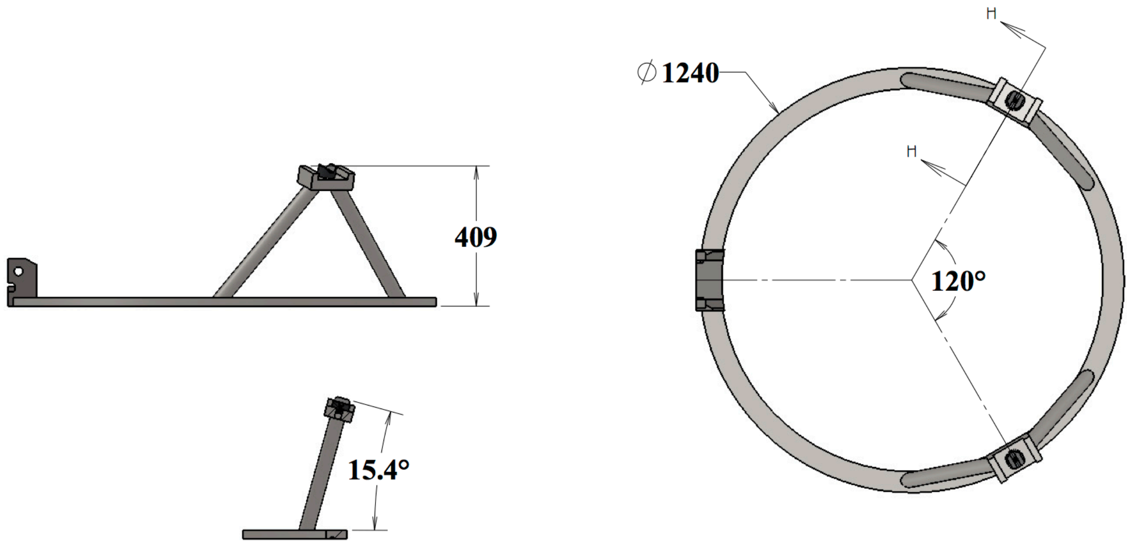


Figure 4-12: Bipod struts. All dimensions shown are in mm or degrees. Refer back to Figure 2-3 for the location of these struts.

The swing arm is pushed into place (or pulled from the deploy position) by a pair of linear actuators (Exlar model GSX40-0601), each providing up to 850 N-m of torque. Each actuator is attached to the bearing ring by a pin and bushing joint. The opposite end is attached to the swing arm with a spherical bearing joint.

Figure 4-13 shows the K1DM3 system in the deployed configuration. For reference, a portion of the tertiary tower is shown including estimated positions for the fixed part of the tower kinematic fixtures for defining the existing tertiary module (or K1DM3) and the forward baffle tracks. In the deployed position, the mirror center is offset by 13.7 microns along its major axis.

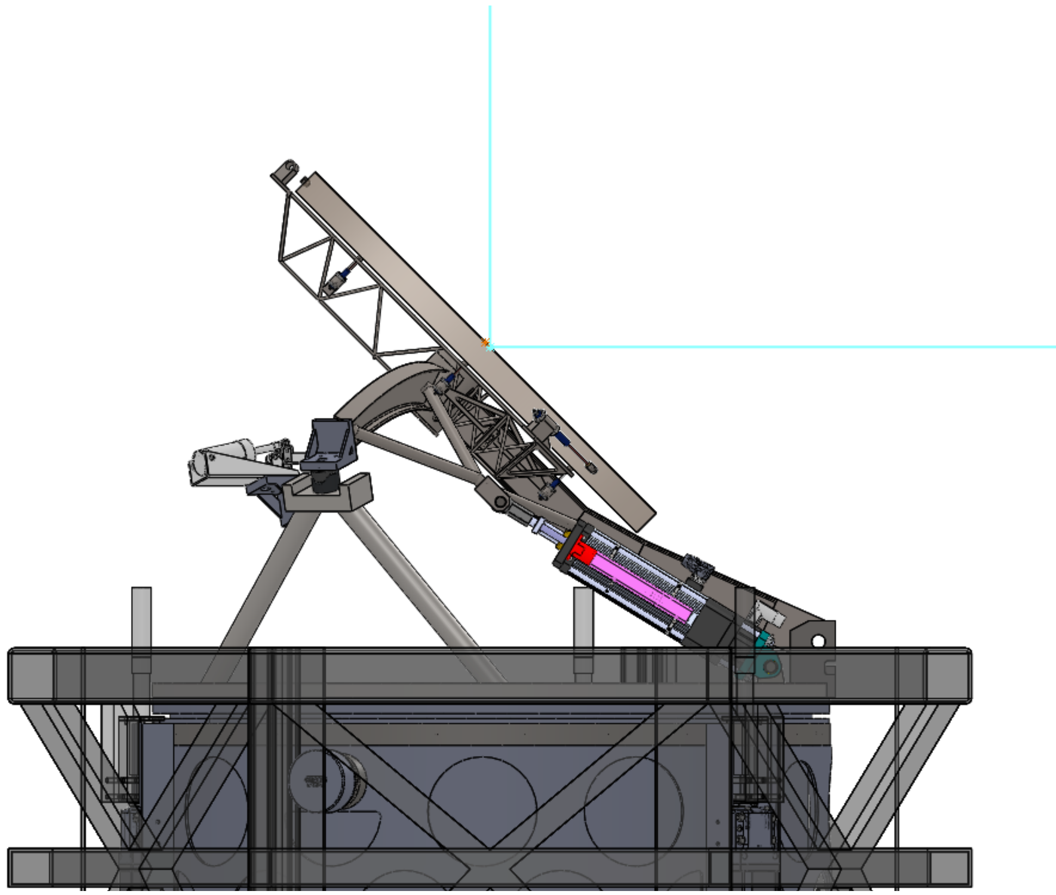


Figure 4-13: View of K1DM3 with the mirror deployed.

Figure 4-14 shows views of the K1DM3 system with its mirror retracted. The center of the mirror is positioned at 9.7 mm above the elevation axis and 500-600 mm from the optical axis. The mirror surface is outwards facing at an angle α=99.5°, where α=45° is the deployed position and α=90° is parallel to the optical axis. Vignetting in this configuration is discussed in §4.1.2.

The total mass of the Actuation Assembly is approximately 46 kg without the Mirror Assembly. Together they weigh approximately 100 kg.

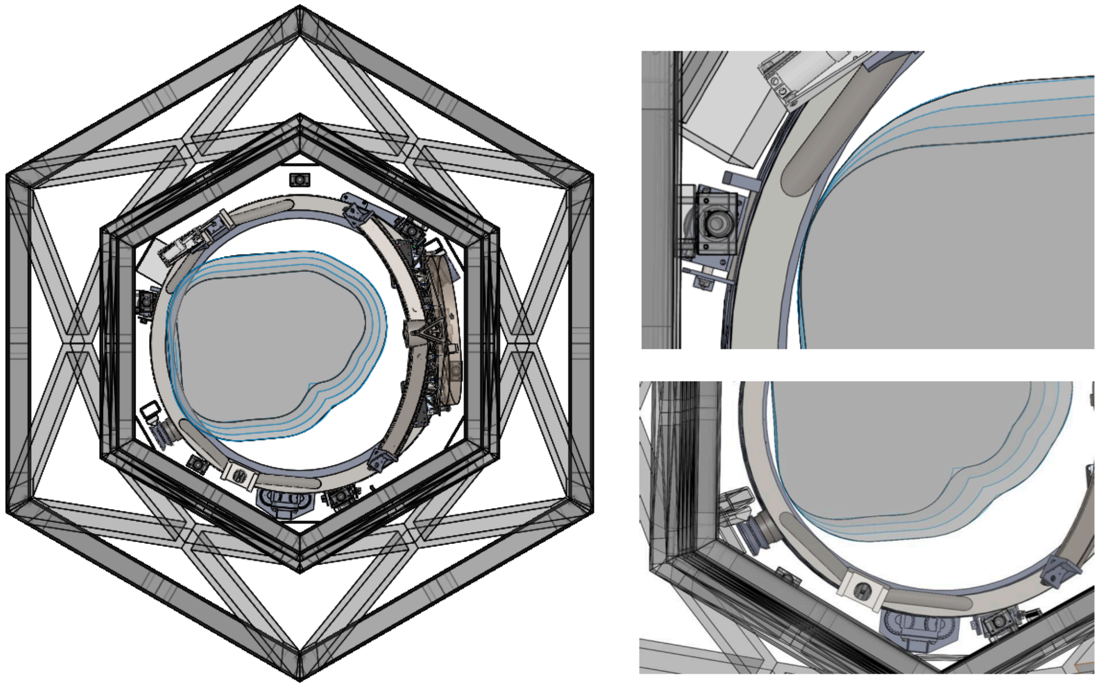


Figure 4-14 Top views of K1DM3 with the mirror retracted.

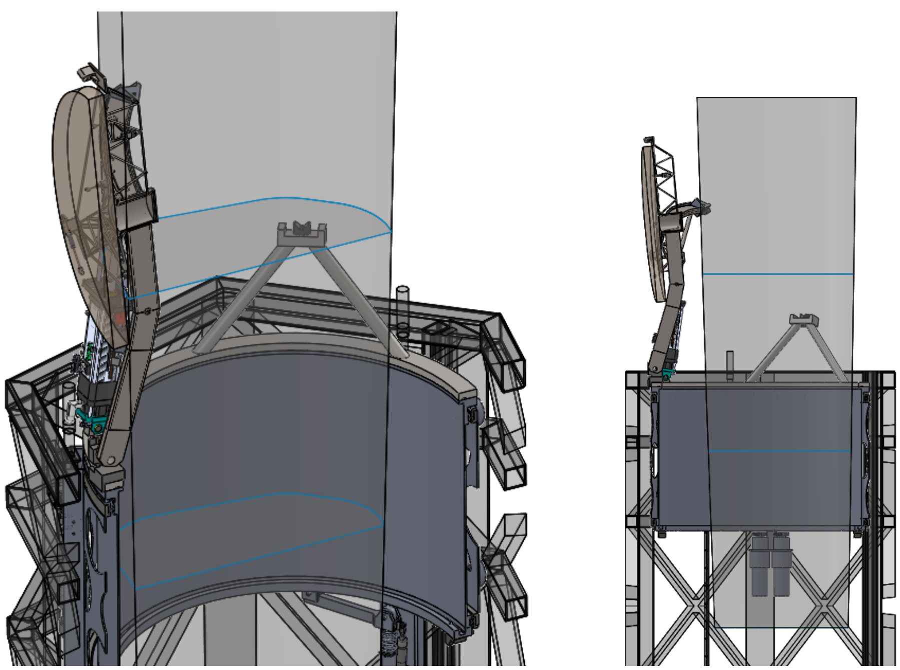


Figure 4-15 Side views of K1DM3 with the mirror retracted.

<u>Design Analysis</u>: There are multiple issues to address in this aspect of the design.

Motor Torque: The two linear actuators need sufficient torque to deploy and retract the Actuation assembly and Mirror assembly under gravity. Although we intend to minimize the required torque by specifying that K1DM3 be nominally deployed/retracted with the telescope at an elevation angle of 60° (90° is at Zenith) and at a drum rotation angle[1] of 90°, 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 two bipod struts. 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 (e.g. air cylinders, forward baffle mounts). The current design satisfies all of these constraints.

FEA of Swing Arm and Bipod structure: Preliminary first order FEA models were made of the mirror assembly attached to the swing arm and connected to the bipods. The models were crude and approximate, finally yielding rotations of about 20" when optimized. The first mode of vibration for these earlier models varied from 16 to 60 Hz.

As a result of these first attempts a new design approach was considered and a more accurate structural model was implemented. This resulting model is shown in Figure 5-17. The truss system supporting the pivot beams has been eliminated. The pivots are now directly supported by the swing arm structure.

This model more accurately represents the mirror with its support by the axial and lateral flex rods. The swing arm structure was modeled as beams which can easily represent any desired beam cross section. The proper kinematic restraints at the v-groove are employed in the model. The bases of the bipods, which connect to the drum ring, are fixed to ground.

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.

Three gravity load cases were applied in the following orthogonal directions:

- Gx – Perpendicular to the optical axis and the minor axis of the mirror, in the plane of the mirror's major axis. This condition would exist when the telescope is pointing at horizon and the mirror is facing either downward or skyward.
- Gy – This represents the gravity condition at zenith. Gravity is parallel to the optical/tower axis.
- Gz – Telescope again at horizon. Mirror pointing along the elevation axis, as to an instrument on the Nasmyth Platform. Gravity is pointing in the direction from one bipod to the other.

---

[1] Where 0° orients K1DM3 towards the AO system.

Results of the static gravity cases are shown in Table 4-3. 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.

The first five modes of vibration for this structure are shown in Table 4-5. These results show that a sufficiently rigid and stiff structure is possible. Additional work is needed to further optimize the structure, primarily for the purposes of avoiding vignetting.

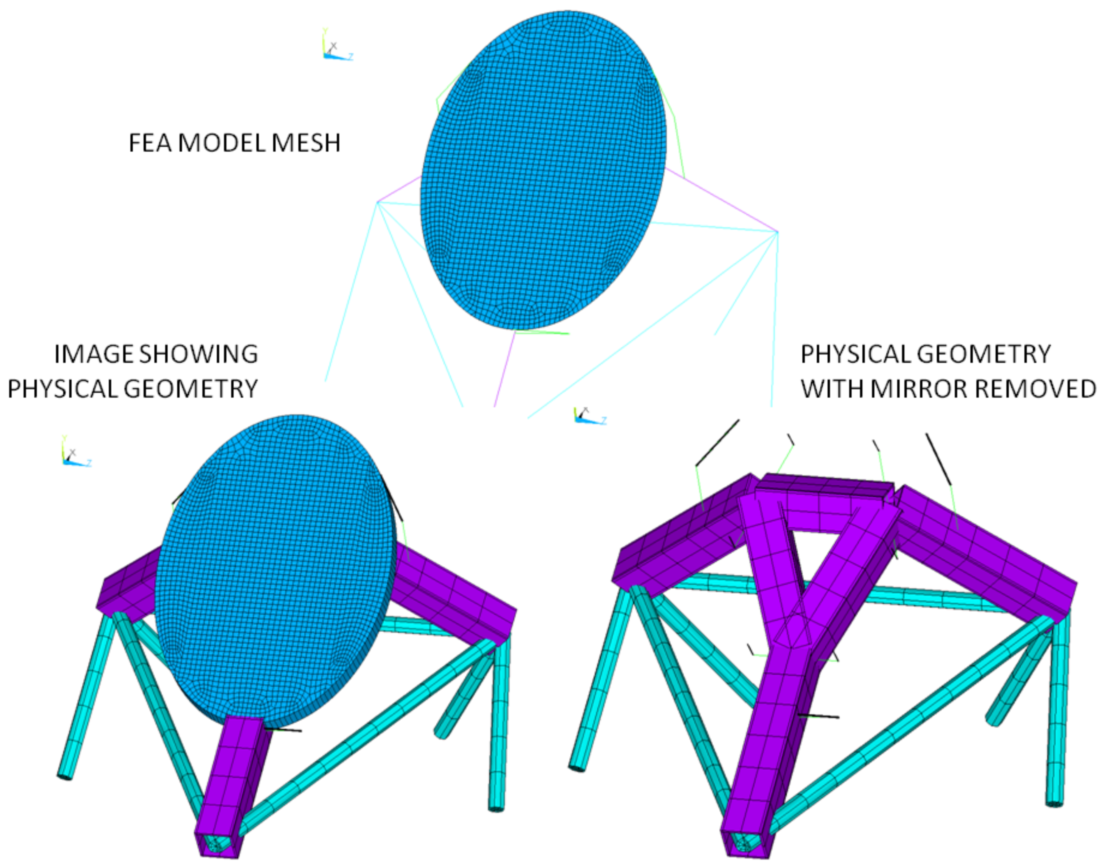


Figure 4-16: FEA models of swing arm and bipod structure

Gravity Case	Piston (µm)	Tilt (")	Tip (")
Gx	15.1	0	1.15
Gy	13.7	0	3.74
Gz	0	1.62	0

Table 4-3: Out of plane displacement and rotations to due gravity. Tilt is rotation about the mirror minor axis. Tip is rotation about the major axis.

Mode	Description
79	Mirror translation in plane along major axis
85	Mirror translation in plane along minor axis
108	Mirror rotation about minor axis
112	Mirror rotation about major axis
121	Mirror piston and rotation about minor axis

Table 4-4: First five natural frequencies (Hz) for the mirror mounted on the swing arm and bipod structure.

Vignetting: §4.1.2 provides a full discussion of vignetting of the beam by K1DM3. Figure 4-18 (top-view) shows that neither the struts nor the retracted mirror vignettes the LRIS or MOSFIRE footprints. We may be required, however, to rotate the K1DM3 module during LRIS observations and have specified this in our design.

CTE: The temperature of the entire telescope will change by as much as 25 °C (summit temperatures vary from 14 °C to -11 °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/deg C. This material and material with very similar CTEs have been selected for the K1DM3 design (see Table 4-5). We estimate that there will be a 12 mm change in the height of the struts, but all three will move together maintaining the geometry.

Material	Use	CTE (ppm/ °C)
ASTM-A36 Steel	Tertiary tower structure	11.7
52100 Steel	Rolling element bearings	12.5
A500 Steel		12.1
440C Steel	Kinematic interfaces	10.1
1020 Steel		11.7-13.9
AISI 4340 Steel	Inner drum; v-grooves	10.4

Table 4-5

Time to Deploy/Retract: With the dual actuator design, the rod must extend 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.

Tower clearance: To meet the requirements, we must be able to rotate the K1DM3 module to any angle, both when deployed and retracted. We have modeled in SolidWorks the top of the tertiary tower using the WMKO drawings. We have also modeled two additional components: (i) the three mechanisms for the telescope half of the tertiary module/K1DM3 defining points that are located 659.5 mm from the optical axis have 35 mm diameter and extend 100 mm above the tower; (ii) three forward baffle tracks that extend 400 mm above the tower. We then confirmed using SolidWorks that the Actuator assembly of the K1DM3 design clears all of these obstructions when rotated, both in deployed and retracted configuration.

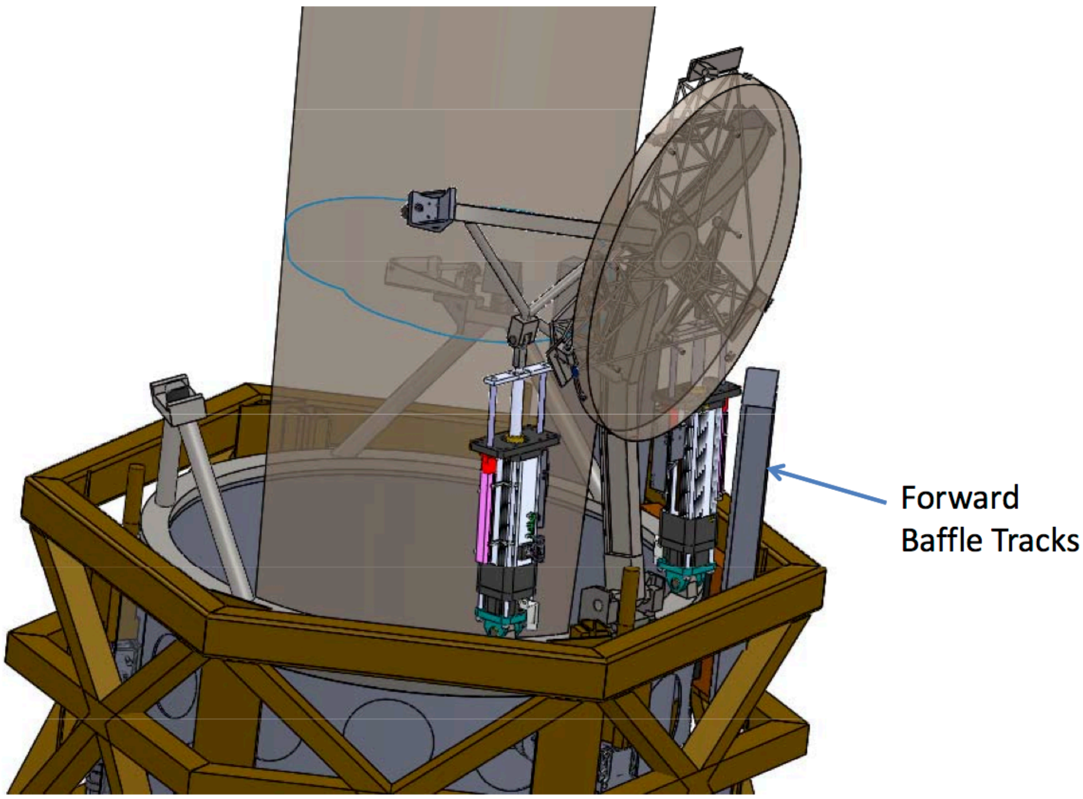


Figure 4-17: Top end, side-view with baffles.

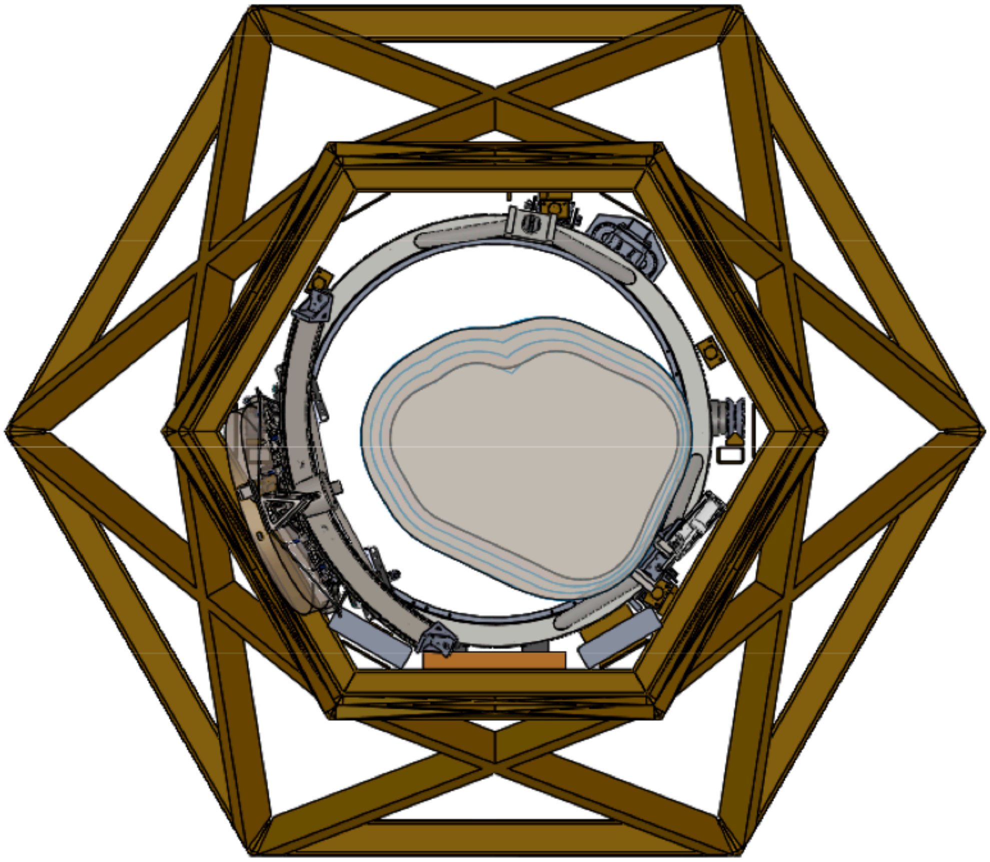


Figure 4-18 Top-view with baffles.

Prototyping: We considered several other configurations for the Actuator assembly. We looked at a rotary actuator that was larger and heavier. We considered a single linear actuator that was presented at the IPDR.

Performance Predictions:

- Thermal too

Risks and Mitigations:

- Proper CTE?
- Uncertainties related to top of tertiary tower

4.2.3. MIRROR KINEMATIC COUPLING DESIGN

Design Description: There are two sets of kinematic couplings associated with the K1DM3 design:

1. 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.

2. Within the K1DM3 module is a complete set of kinematic mounts designed to position the mirror when deployed. We refer to these as the Deployable Kinematics (DKs).

We discuss the design of each in turn.

Defining Point Mechanism: The DPM fixtures on K1DM3 will replicate the fit and function of the fixtures on the current tertiary module. The existing design for these will be re-used to the maximum extent possible. There are three fixtures located with 120° separations around the module, approximately 146 mm below the top bearing with three different contact points to form a kinematic mount:

- Flat on flat
- Sphere in cone
- 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 4-19 through Figure 4-21 show the three MK fixtures. Each of these are made of AISI 4130, Hardness Rockwell C 50 minimum, chrome plated to QQ-C-320, Type 1, class 2 material. Each of these will allow 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.

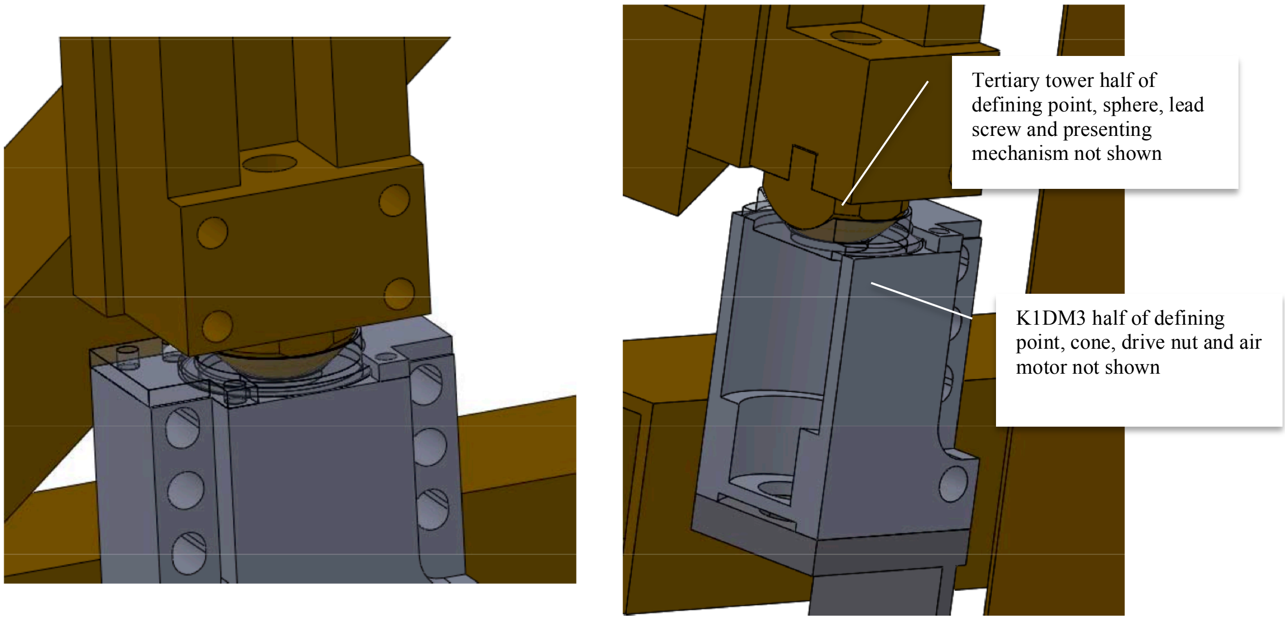


Figure 4-19 Defining point; sphere in cone

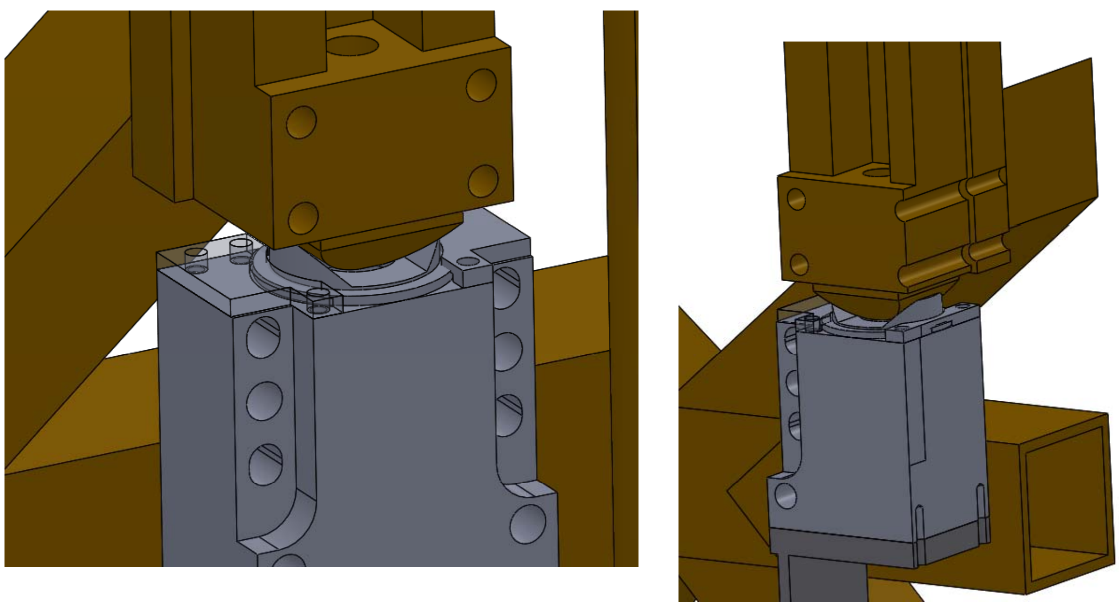


Figure 4-20 Defining point; V-groove

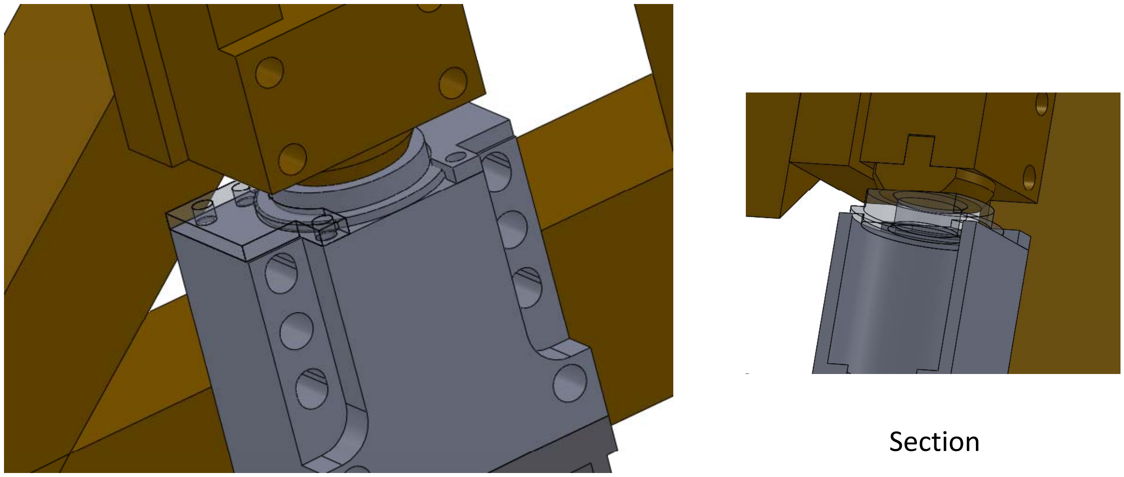


Figure 4-21 **Defining point; Flat on flat**

Deployable Kinematics: We will employ 3 sets of canoe-sphere/v-groove fixtures (Figure 4-22) in the kinematic coupling used for positioning the K1DM3 mirror when deployed. The canoe spheres will have a radius of 500mm. 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 40 mm from the pivot point.

The v-grooves will be 12.7 mm wide and 49 mm long (see Figure 4-22). Two of these will be held at the ends of the bipod struts (Figure 4-12) in a common plane. The third v-groove is mounted to the end of the pivot mechanism for the swing arm (Figure??). Its axis lies in a plane parallel to that defined by the struts but offset by 655 mm.

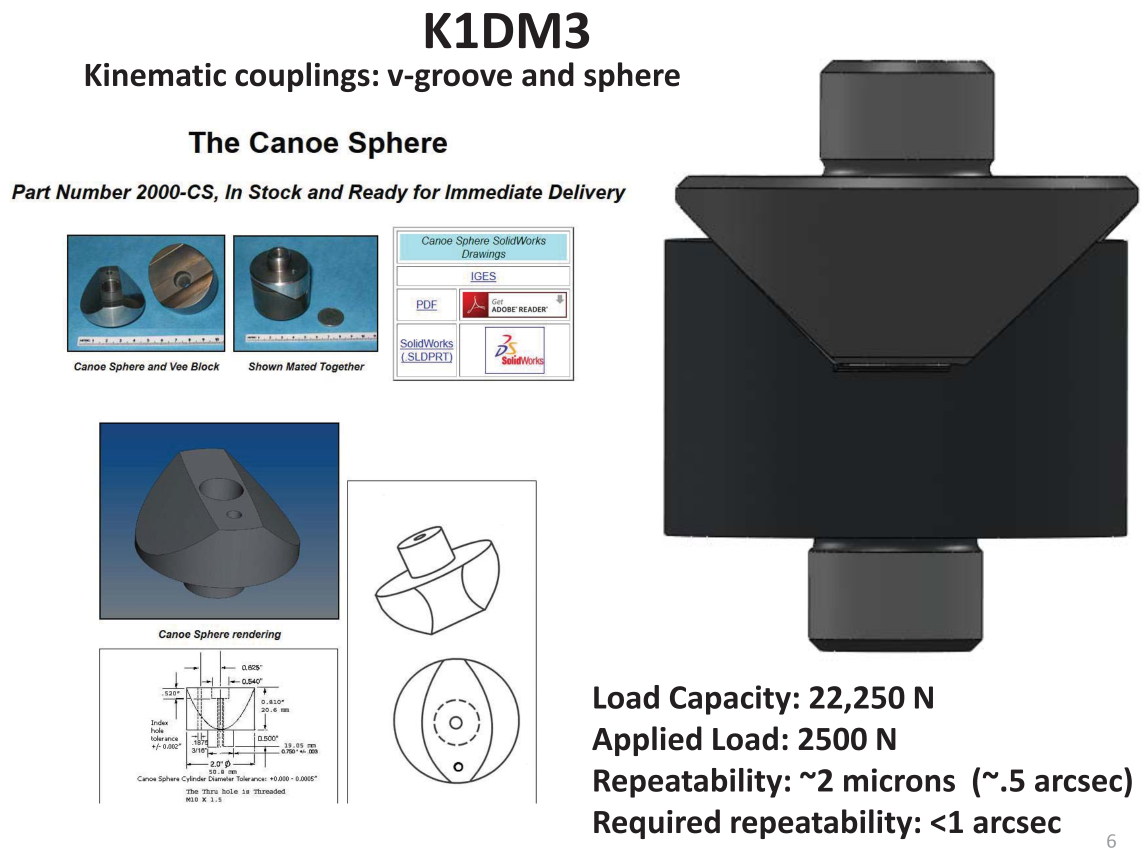


Figure 4-22 **Deployable kinematic coupling.**

All of the DK fixtures will be made with 440 stainless steel, polished to 0.2 micrometer rms roughness, and plated with TiN to prevent rusting.

When engaged the DKs will be clamped with a clamping mechanism that maintains 3000 N of sustained forced (Figure 4-23). This mechanism holds the coupling in place even with a loss of electric power. 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.

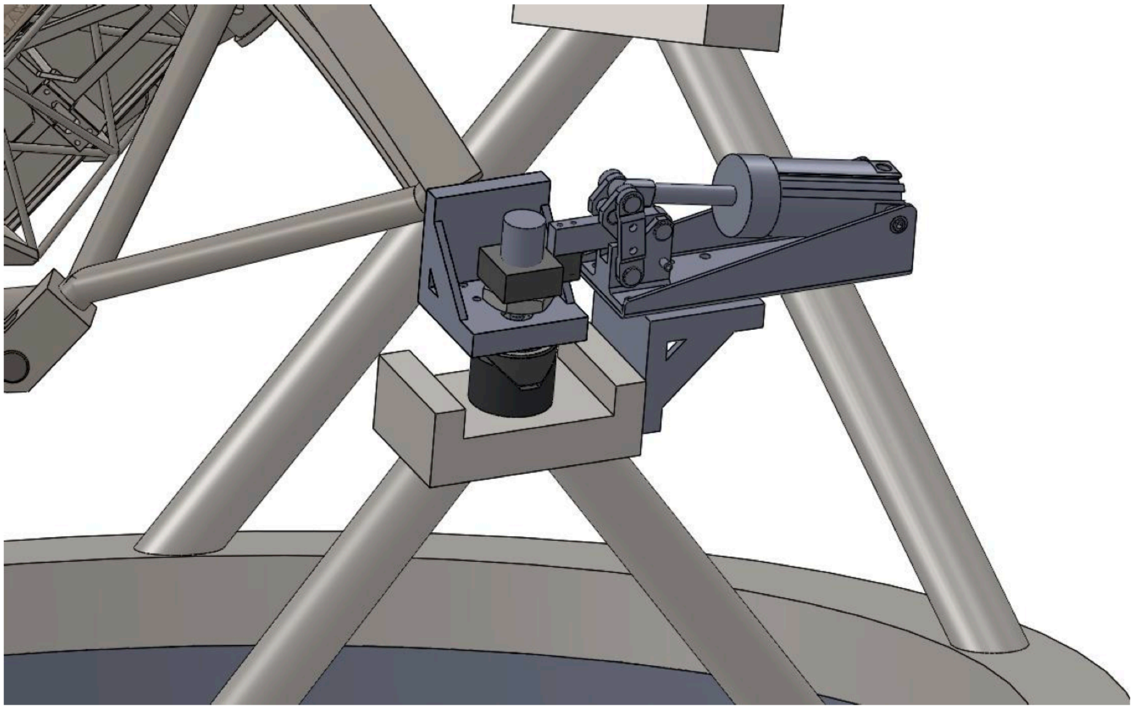


Figure 4-23: Clamp

The v-groove fixtures will have adjustability in X,Y, and Z and rotation about the axis of the mounting screw to allow fine adjustments during Alignment. These will have approximately 10 mm of end-to-end adjustment and are required to place the mirror at 45° with respect to the module rotation axis. See Section 4.1.3 for additional details on Alignment.

Design Analysis: The positioning requirements of K1DM3 impose strict tolerances for repeatability and stability. Again, we discuss the DPM and DK couplings in turn.

Defining Point Mechanism: 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 5 microns. During Detailed Design, we will fabricate these fixtures and the outer drum. We will then deliver them to WMKO to test clearance and perform initial alignment of these fixtures (e.g. test that they couple to the tower fixtures).

The end-to-end positioning for the DPM fixtures well exceeds our estimate for the uncertainty in positions of the tower fixtures (after Detailed Design; see Section XX).

Deployable Kinematics (DKs): After studying the standard reference on kinematic couplings (Slocum, 1992), we decided on a canoe-sphere/v-groove coupling system for the DKs. These have the advantages over the more traditional cone-flat-groove couplings. We then researched vendors that manufacture these fixtures and have selected Baltec. We have analytically estimated the precision for repeatabile positioning as follows. [Insert JN numbers]

Because the DKs are critical to the success of K1DM3, we decided to purchase a complete set of fixtures during PD and manufacture test beds to construct a kinematic coupling. We could then test the positional performance empirically with three LVDTs. Thus far, we have successfully achieved sub-micron repeatability under specific conditions (see §7.1 in the appendix).

For positional stability, the DKs will be clamped with a sustained force of 3000 N by a clamping mechanism (Figure 4-23). We estimate less than 1.0 microns of motion with any change of gravity. This satisfies the requirements on stability.

Prototyping: As described in Section 4.1, we have purchased a set of canoe-sphere/v-groove fixtures from Balltec and have tested their performance in a pair of test beds.

Performance Predictions:

- Preliminary test results show we will likely achieve repeatability of less than 1 micron (see §7.1 in the appendix for the details of this testing).

Risks and Mitigations:

- The coupling of the K1DM3 module to the tower will be tested during Detailed Design by shipping the fabricated drum with fixtures to WMKO. By installing this within the tower, we will test the MK coupling, making adjustments to the FTK positions as necessary.
- During our lab tests of the DKs, the fixtures experienced significant condensation and rapidly developed a thin layer of rust. To prevent rusting in our delivered DKs, we will plate the fixtures with TiN. We have already identified a vendor (Champion Bearing in Palm Springs) and are awaiting a quote.
- The DKs will operate in the open dome and will be subject to dust and dirt from the interior and exterior environments, especially when K1DM3 is retracted. We may design covers to protect the fixtures when K1DM3 is retracted or utilize compressed-air cleaning mechanisms.

4.2.4. DRUM ASSEMBLY DESIGN

Design Description: The backbone of the K1DM3 system will be a ASTM A36 steel drum, rolled and then precision machined to have an outer diameter of 1240 mm and a thickness of 5 mm. The drum will have holes to reduce its mass without compromising its stiffness (Figure 4-24). The drum is approximately 815 mm long.

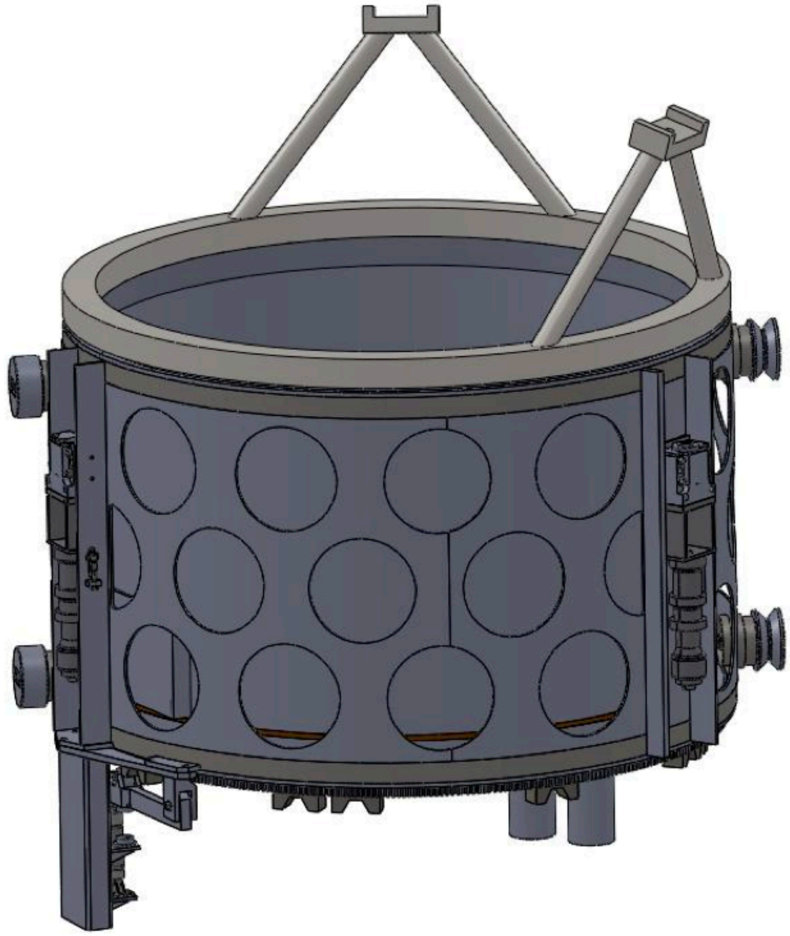


Figure 4-24 Drum side view.

Attached to the top and bottom of the drum are two ring bearings with inner diameter of approximately 1160 mm and an outer diameter of 1218 mm. These enable the inner drum assembly to rotate about the optical axis. The top bearing will be located 702 mm below the elevation axis. The bottom portion of the drum will also include a slip ring mechanism to provide connectivity for network and power under rotation. At 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. The ring gear will be made of ANSI 4130 material, have an inner diameter of 1060 mm, and 378 teeth around the full circumference. It will be driven by two DC servo motors using a Harmonic Drive gear head. One of the two servo motors will oppose the torque of the main drive servo to eliminate backlash.

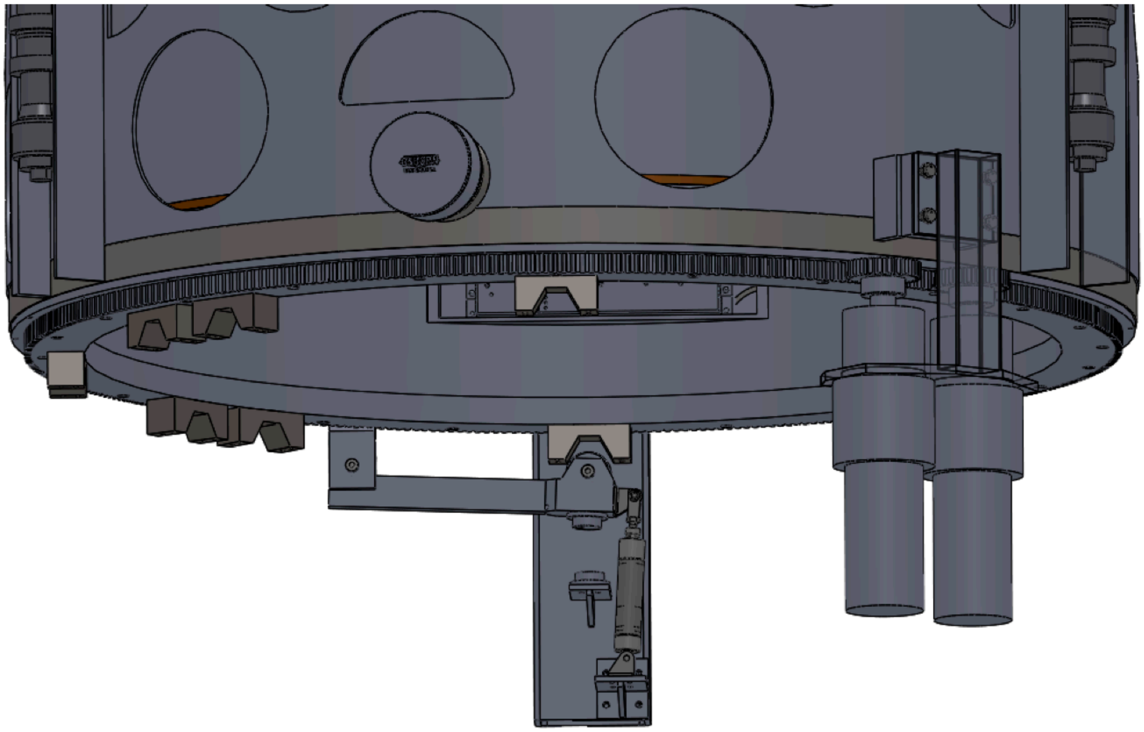


Figure 4-25: Detents, ring gear

The six detents will be 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 bolted to the ring gear during alignment at WMKO (§4.1.3). This coupling will be engaged by an air-pressure driven detent mechanism mounted below the module (see Figure 4-26).

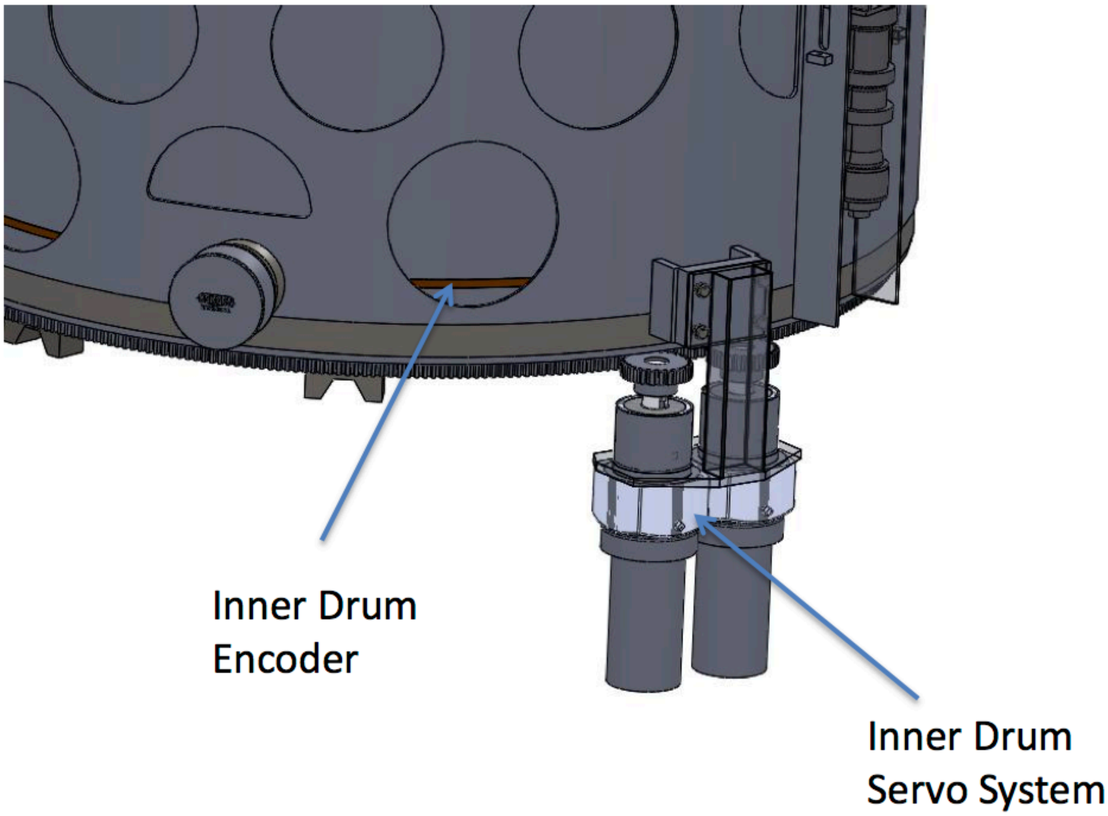


Figure 4-26: Detent mechanism

The rotation angle of the K1DM3 module will be monitored by reading a magnetic tape attached to the drum, XX mm above the bottom edge. We will use a single head with an absolute encoder for precise and continuous reads even as the module rotates through the tape "gap'".

We estimate a total mass for the K1DM3 drum and attached components of ~600 kg.

Design Analysis: There are numerous considerations to the design of the K1DM3 drum:

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 XXX. [Fill in] [Contact bearing manufacturers; max deflection = 1.7"]

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. Section 4.1.2 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 tower and existing tertiary module.

Rotation analysis: We may estimate the rotation speed of the K1DM3 module as follows. The peak capable speed will be 18°/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°/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. With the slip ring, the K1DM3 module may be retracted to any angle with the Actuation Assembly deployed or retracted.

Rotational 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 six 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 (see Section 4.1.3). The detent mechanism provides sufficient force (~1200 N) to insure the module is locked into place. This pneumatic mechanism also reliably releases the detent. [Comment on what happens with loss of air pressure] [Discuss magnetic tape]

Prototyping:

- May want to build into mockup

Performance Predictions:

- 1 micron linear
- 35" angular

Risks and Mitigations:

1. Positioning precision – Will test on mock-up.

4.2.5. SUMMARY

- Total error budget (see CR Table)
- Total weight = approximately 600 kg

4.3. ELECTRIC/ELECTRONIC DESIGN

4.3.1. DESIGN DESCRIPTION

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.

4.3.1.1. DEPLOYMENT STAGE

The deployment stage electronics are located on the rotating drum portion of K1DM3. These electronics are responsible for mirror deployment, mirror retraction, and the kinematic clamping of the mirror when deployed. Power and communication to the deployment stage will be provided through contacts on a large diameter slip ring. All of the deployment stage electronics will be powered except when the mirror is being deployed or retracted. An overview of the deployment stage electronics is shown in Figure 4-27.

Deployment of the mirror is handled by two linear actuators. The linear actuators are powered by brushless DC motors. These actuators have absolute position feedback and feedback switches at the stowed and deployed positions. Temperature sensors will be installed on the actuators for additional monitoring of operations.

Kinematic clamping will be done with three DC motors driving over center clamps. Feedback switches will verify when the clamps are locked and unlocked. Each motor will have a temperature sensor. The motors will be powered off once the clamps are locked or unlocked.

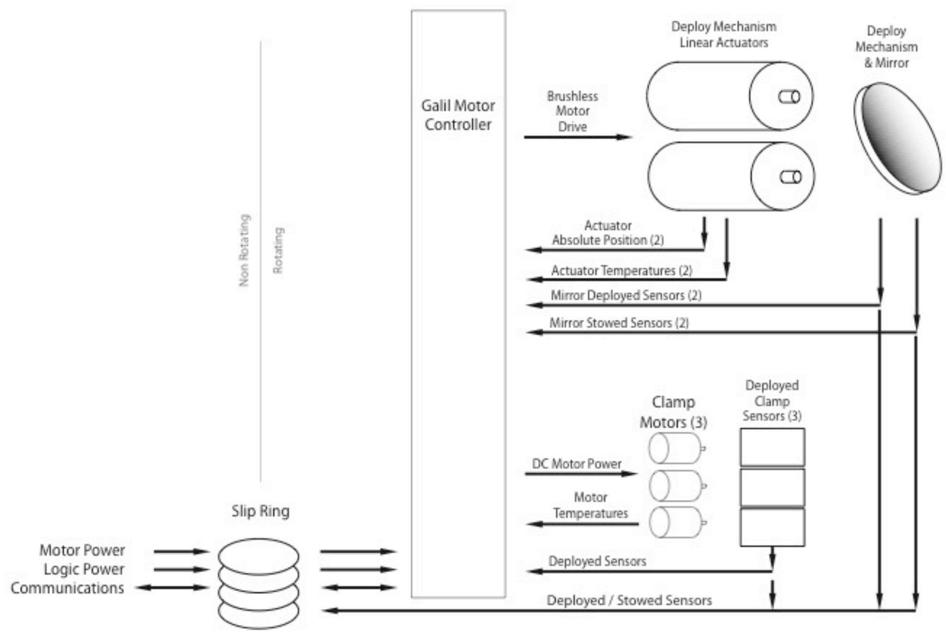


Figure 4-27: **Deployment stage electronics**

A Galil controller will be used to operate the clamps and deployment actuators. All positional and temperature feedback will be fed into the Galil. An Ethernet connection to the Galil will be provided through the slip ring via modems.

Separate power for the motors and control logic will be provided through the slip ring. 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 slip ring. These signals will allow mirror position to be verified without powering up the deployment electronics.

4.3.1.2. SLIP RING

The slip ring provides electrical power and signals to the moving drum of K1DM3. The slip ring will provide the following connections:

48 VDC @ 15A (motors)
12 VDC @ 1A (controller & logic)
two contacts for mirror deployed / stowed feedback
two contacts for communications to Galil controller

4.3.1.3. ROTATION STAGE

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 4-28.

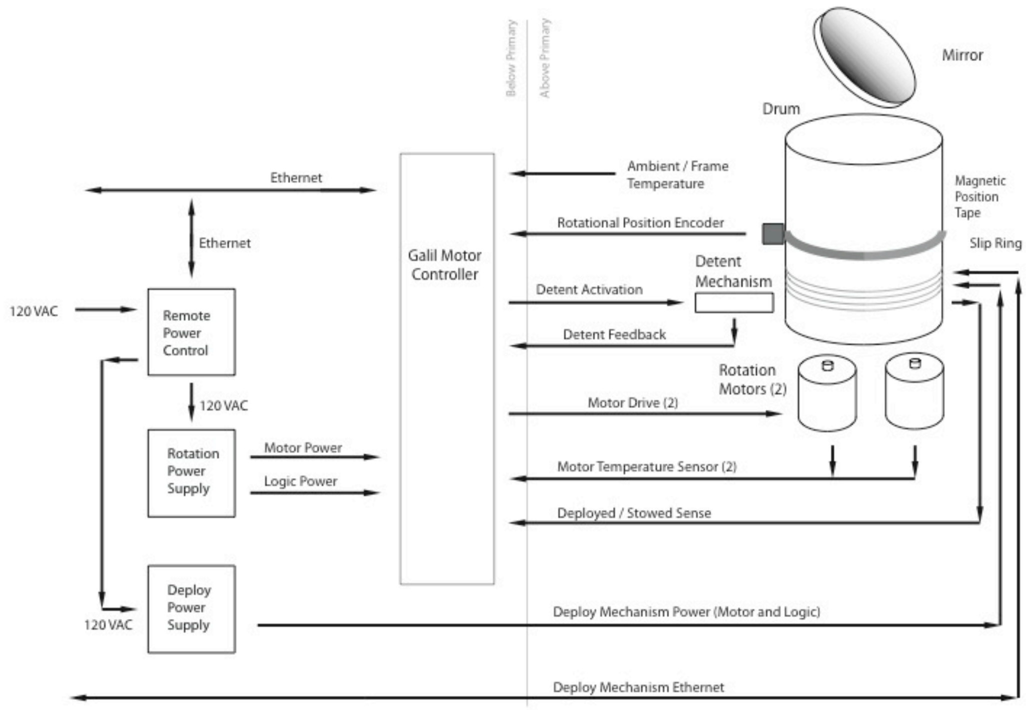


Figure 4-28: K1DM3 rotation electronics

Two DC motors will be used to drive the rotation. Rotational encoders will provide motor feedback. An absolute position encoder 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 Galil controller and power supplies will be located beneath the primary mirror where the heat can be extracted.

4.3.1.4. MISCELANEOUS ELECTRONICS

A remotely controllable power switch will be provided to enable a hard reset of the electronics. This power switch will also be used to power down the deployment stage electronics except during when deploying or stowing the mirror. This switch will be located beneath the primary mirror.

A pair of modems will be used to provide a low bandwidth TCP/IP connection to the Galil controller on the rotation stage. The modems will provide a more robust communication link that only requires two wires. One modem will be located on the rotation stage and the other modem will be beneath the primary.

4.3.2. 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.

4.3.3. RISKS AND MITIGATIONS

The following programmatic risks have been identified with the electronics:

Slip ring communications: Commercial slip ring vendors have been asked to provide quotes for the necessary communication and power. We are still waiting on pricing and confirmation of the communication contact bandwidth. Mitigations: we have multiple fallback options. We are relatively confident that with proper optics we can make a direct fiber Ethernet connection with the drum in a fixed position. A cable wrap would be another option.

Power dissipation: Drum rotation and mirror deploy/retract use a significant amount of power. Mitigations: Limit frequency of rotations and deploy/retract. Add heat extraction to rotation motors.

Loss of motor control: Failure of wiring, slip ring, or motor controllers would prevent operation of deploy / retract, clamps, and drum rotation. This could possibly leave telescope in an inoperable state. Possible mitigations: Spare controllers and wiring harnesses. A hand paddle or portable controller could be provided to allow manual operation of K1DM3.

4.4. SOFTWARE DESIGN

5.4.2 Software Architecture

The K1DM3 software, like all WMKO instrument software is based on three software layers, a low-level server layer, the 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 consists of a server module called *galildisp*. This server implements communications with the motion control systems and provides a keyword server interface via the KTL layer.

The KTL layer is a standard WMKO software component that is used in every instrument at the Observatory. This layer is implemented as a set of library routines to provide keyword control of the servers. Instrument specific keywords are defined in a keyword list. Common practices and standards exist for the development of keyword lists, and the keyword lists for K1DM3 are based on existing keyword lists used with the current tertiary module.

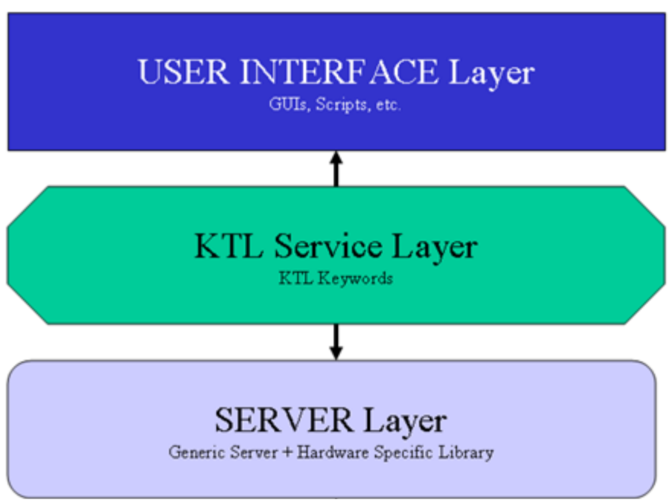


Figure 4-29: K1DM3 Software Layers

4.4.1. CONTROL AND CLIENT SOFTWARE

The software to control the K1DM3 mechanisms is the latest generation of the same *galildisp* application that controls the K1 ADC and the LRIS red-side focus mechanism.

K1DM3 will supply an engineering interface, written in Python, with full capabilities for controlling and monitoring the system.

K1DM3 will also be delivered with two applications that are not required for operation, but are invaluable tools for troubleshooting, long-term trend analysis, and detecting/reporting problem conditions:

- A keyword history system that uses an instance of the *keygrabber* application, configured to capture all K1DM3 keywords, and store their timestamped values in a Postgres database that will be running on the K1DM3 instrument computer. This permanent keyword history can be interrogated at any time using either the *gshow* application, or by making direct SQL queries.
- A keyword monitor application that uses an instance of the *emir* application to watch arbitrary expressions involving keywords, and generate alarms when problems are detected. It also comes with a self-configuring GUI that presents a hierarchical view of all monitored conditions.

4.4.2. Server and Clients: Computer and Environment

The K1DM3 control software will run on a host computer that is running a Keck-specified version of Red Hat Linux. The software may be run on a virtual host, if desired. Currently, development is being done on computers running both CentOS 6 and CentOS 7.

Client software can run on any host with capable of running the *dtune* KTL client library code, which is written in standard C and depends only on the core KTL libraries (including KTL/MUSIC) and the *libxml2* external library.

4.4.3. *Galildisp* Galil Controller and KTL Service

The *Galildisp* application, written in Tcl, presents a standard KTL service interface to all control and status elements of the system. It has built-in code for handling a wide variety of stage types, plus analog and digital I/O. In addition to its use in two small Keck subsystems, it is also at the heart of five major instruments at Lick Observatory.

Galildisp is a single-threaded, event-driven application that can handle simultaneous operations for any axes and I/O operations in parallel. It establishes two TCP connections to the Galil: one is primarily used for sending commands and receiving acknowledgements, while the second one is reserved strictly for asynchronous status updates of all axes. The Galil has a poor ability to generate rapid asynchronous updates on a TCP channel, so *galildisp* receives these at only 250 ms intervals. (A future version may try using UDP updates for better performance.) The event streams that are the main drivers for *galildisp* are the two TCP connections to the Galil and its KTL keyword service interface. Scheduled events, such as periodic broadcasts of status, are another source of events for the application.

4.4.4. Control Capabilities vs Requirements

We note that among *galildisp*'s capabilities, the following are listed explicitly because they directly address requirements specified in section 11 of the K1DM3 Requirements document:

- Startup time <= 10 seconds on recent-generation computers.
- Status requests processed in < 10 ms.
- Motion commands initiated in < 10 ms.
- Configurable to handle arbitrary sets of E-stop hardware signals and similar software (keyword) signals.
- Any number of axes can be simultaneously controlled.

- Positioning can be done by using named or enumerated positions, angle of rotation or actuator extension, millimeters of motion, or direct encoder values.
- Complex motions, such as are required for deploying or retracting the mirror, are directly supported by built-in abilities for combining and sequencing a set of motions by different axes, or by off-loading the complex logic to co-processes.
- Support for either DCS-style keywords (STBY/INIT/HALT) or TCSU-style keywords will be done using a co-process to monitor the keywords, do any necessary adaptation to *galildisp* keywords, and handle the response.

The following capabilities of *galildisp* will need enhancement to meet requirements:

- Time to respond to an E-stop digital signal is currently up to 250 ms. This will be reduced to <10ms by moving the handling from high-level application code to onboard Galil code.
- *Galildisp* is designed to automatically handle recovery from loss of network connections and resets of the Galil controller. In practice, *galildisp* is observed to sometimes fail to recover on its own, and instead logs a continuous stream of retry attempts.

4.4.5. System Assumptions

The system's detailed design remains an area of active development, and so the software design remains in flux. The following assumptions represent the system that our current software design is expecting to see; if they are all implemented, the control software will be able to present a full picture of the system to clients.

The electronics are generally assumed to be as described in §4.3.

4.4.5.1. Module Insertion

- There is a digital signal that is active if and only if the module is fully inserted. Under normal conditions, *galildisp* will not issue commands to the module if the signal is not active. For engineering purposes, it will be possible to bypass this signal.

4.4.5.2. Rotation Control

1. The Galil DMC-40x0 will remain powered under all normal operating conditions.
2. The instrument positions are accurately located via a detent mechanism controlled with digital signals.
3. There will be feedback to indicate that the detent mechanism activates successfully.
4. An absolute encoder tape will provide precise rotation positions.
5. There will be a coarse home reference and precise index marks.
6. (TBD) Rotation will be controlled via two servo motors.
7. A velocity encoder on each servo motor shaft.
8. The rotation drive is capable of at least 9°/s.
9. The rotation drive probably will not be back-driven by the mirror assembly. If that proves to be a problem, one rotation drive motor will have a brake.

10. The drive motor(s) will be unpowered when not actively moving between positions.

The two motors can be controlled through "electronic gearing" of two motion control axes.

4.4.5.3. Deployment Control

1. Almost all electronics associated with the deploy/retract subsystem will be powered off except when deploying or retracting. The sole exceptions are digital sensors for detecting whether the mirror is in its fully-deployed or fully-retracted state.
2. Deployment is controlled via a separate Galil DMC-40x0 that will be powered off except when deploying or retracting the mirror.
3. There will be two deployment actuators, driven by brushless motors. Each actuator will have an absolute position actuator encoder with effective resolution XXX mm. The absolute encoder is expected to have sufficient precision that a supplementary high-precision incremental encoder is not required. However, if a load encoder is supplied, it can be used for enhanced performance.
4. The two actuators must operate in parallel to within XXX mm.
5. Each actuator may have a signal to indicate that it's at the fully-deployed point.
6. Each actuator may have a signal to indicate that it's at the fully-retracted point.
7. Each actuator will have a motor temperature sensor.
8. The Deployment clamping system will have
    a. Clamping motor or digital drive (3)
    b. Clamp active signal (3)
    c. Clamp withdrawn signal? (3)
9. The actuators can deploy within 30 seconds, not including final "cleanup" motions.
10. Deploy/retract is only done with swing arm moving in a vertical plane.
11. Deployment is at telescope elevation = 60°; retraction is at any elevation.
12. Brakes on motors hold position when retracted.

4.4.6. Motion Algorithms and Timing Estimates

The following sections describe the algorithms that will be used for motion control.

4.4.6.1. Deployment

Deployment of the mirror, from an arbitrary retracted orientation, is done as follows:

1. Move to deploy position, by doing the following steps in parallel:
    a. Rotate the drum to the deploy position. Time <= 20 s.
    b. Slew the telescope elevation to 60°. Time <= 30 s from any elevation >= 30°.
    c. Power up the deployment Galil. Time <= 30 s.
2. Initialize the brushless actuator motors. Do this sequentially so that one brake is active at all times. Time <= 10 s.
3. Adjust actuators to correct for any position cocking. Time < 2 s.

4. Use Galil's "electronic gearing" commands to move the actuators in parallel to the maximum extended position. Time < 30 s.
5. Retract actuators slightly to remove force on mirror. Time < 2 s.
6. Apply 3 clamps. Time < 5 s.
7. Move to target position (dcs keyword CURRINST); these steps occur in parallel:
    a. Slew telescope to target elevation. Time <= 30 s from any elevation >= 30°.
    b. Rotate the drum to the correct detent, and activate detent. Time <= 25 s.
    c. Shut off power to deployment Galil and motors. Time <= 1 s.

Total deployment time: <= 115 s.

4.4.6.2. Retraction

1. Move to retract position; these steps occur in parallel:
    a. Rotate the drum to the deploy position. Time <= 20 s.
    b. Power up the deployment Galil. Time <= 30 s.
2. Initialize the brushless actuator motors. Do this sequentially so that one brake is active at all times. Time <= 10 s.
3. Adjust actuators to correct for any position cocking. Time < 2 s.
4. Use Galil's "electronic gearing" commands to move the actuators in parallel to the retracted position. Time < 30 s.
5. Move to target position (based on dcs keyword CURRINST and, for Cassegrain instruments, the current rotator value); these steps occur in parallel:
    a. Rotate the drum to the correct detent, and activate detent. Time <= 25 s.
    b. Shut off power to deployment Galil and motors. Time <= 1s.

Total retraction time: <= 98 s.

4.4.6.3. Moving Between Deployed Instrument Positions

1. Retract rotation detent. Time <= 5 s.
2. Rotate to other position. Time <= 20 s.
3. Activate detent. Time <= 5 s.

Total motion time: <= 30 s.

4.4.6.4. Retracted Position Tracking

- Per the requirements, the K1DM3 rotation module will implement the command and status interface specified in Keck Software Document 46 (that is, the STBY/INIT/HALT model), and (eventually) the new TCSU model.
- When operating, the rotation module will track the ROTPOSN keyword of the current Cassegrain instrument.
- The module will rotate only when required, to minimize the amount of time that the motors are on and generating heat.
- Optional: if motion of the module causes vibration that affects science observations, then the *galildisp* can publish a keyword when it's time to move,

and require an explicit ack that the move is OK. This would allow the astronomer an opportunity to pause an exposure or simply forbid motion while an exposure completes.

4.5. INTERFACES WITH K1 TELESCOPE

The interfaces between the K1DM3 and the Keck I or "K1" telescope (which includes all of the facilities needed to support the K1DM3 including computer networking, power, and so on) are documented in the interface control document (ICD, reference [3]). The document is organized in major sections by discipline (optical, mechanical, electronic/electrical, and software) and within each section the instrument and telescope portions of each interface are described. The ICD is intended to ensure that compatible interfaces are defined, and to identify needed features, including design and implementation details that the instrument and telescope must provide for each interface.

The instrument portions of the interfaces are specified in the K1DM3 requirements document (reference [2]). When the telescope portion of the interface requires modifications or additions to the telescope a formal engineering change request (ECR) process will be initiated. This process includes the development of requirements, designs and documentation as required to specify and implement the needed changes. The ECR process is overseen by the Observatory's Telescope Change Control Board (TCCB). The ECR process is initiated once the requirements for the change are established. The project requesting the changes submits documentation on the required changes to the TCCB and requests approval to implement the changes. Depending on the complexity and scope of the changes needed the TCCB may request additional information and may also review the design documentation for change prior to implementation. In addition, for more complex changes the project will usually make a presentation describing the ECR at one of the monthly TCCB meetings.

The optical interfaces section of the ICD describes the features provided by the K1DM3 to direct light to the Nasmyth and bent Cassegrain foci of the telescope, and to allow direct passage of light from the telescope secondary to the Cassegrain focus. The mechanical interfaces section of the ICD describes the features needed to mount the K1DM3 in the telescope, align the K1DM3's mirror with the telescope optical path, and maintain that alignment during observations. The mechanical interfaces also describe the features needed to install the K1DM3 in the telescope, remove it, and store it when necessary. Features to support removal of the K1DM3 mirror for re-coating are also described. Finally, the mechanical section of the ICD covers the compressed air and liquid cooling needed by the K1DM3 and provided by the telescope, and the mounting of any computers or other accessories such as electronics and power supplies that are part of the K1DM3 system.

The electronic/electrical section of the ICD describes the electrical power and control connections of the K1DM3 and the interconnection of the K1DM3 with the telescope, including the Observatory's emergency stop system and the Observatory's computer network. The electronic/electrical section also describes the features for control of the K1DM3 defining process and the interconnection of any accessory electronics, power supplies or computers with the K1DM3 and the electrical power connections for these items.

The final section of the ICD describes the features provided by the K1DM3 to support software control of mirror deployment and rotation through the standard WMKO client/server control architecture using keywords. The software section of the ICD also describes the K1DM3 control computer network connection(s) between the K1DM3 and the Observatory's control network.

5. MANAGEMENT PLAN

5.1. PROJECT STRUCTURE AND ORGANIZATION

The K1DM3 project is being funded by a Major Research Instrumentation (MRI) grant from the National Science Foundation (NSF) to the University of California, Santa Cruz (UCSC). UCSC is the headquarters of the University of California Observatories (UCO), a Multi-campus Research Unit (MRU) funded by the UC Office of the President (UCOP).

As proposed, the project is the collaboration between UCSC, UCO and the W. M. Keck Observatory (WMKO). Funding to UCO came directly through UCSC to PI Prochaska from the NSF MRI award. Funding to WMKO is administered as a sub-award by UCSC on an annual basis. The three organizations – UCSC, UCO and WMKO – all contribute management, technical staff, and administrative staff to the project.

5.2. PROJECT MANAGEMENT

The K1DM3 project is led by three Principal Investigators (PIs): J. Xavier Prochaska and Jerry Nelson at UCO and Hilton Lewis at WMKO. In practice, PI Prochaska leads coordination of the project at UCO, PI Nelson is intimately involved in the design work, and PI Lewis has delegated authority as PI to Sean Adkins (WMKO Instrumentation Project Manager) who manages K1DM3 activities at WMKO.

An Organization Chart of the full team is presented in Figure 5-1. Dave Cowley serves as the Project Manager of UCO activities, managing a modest workforce of engineers and technical staff.

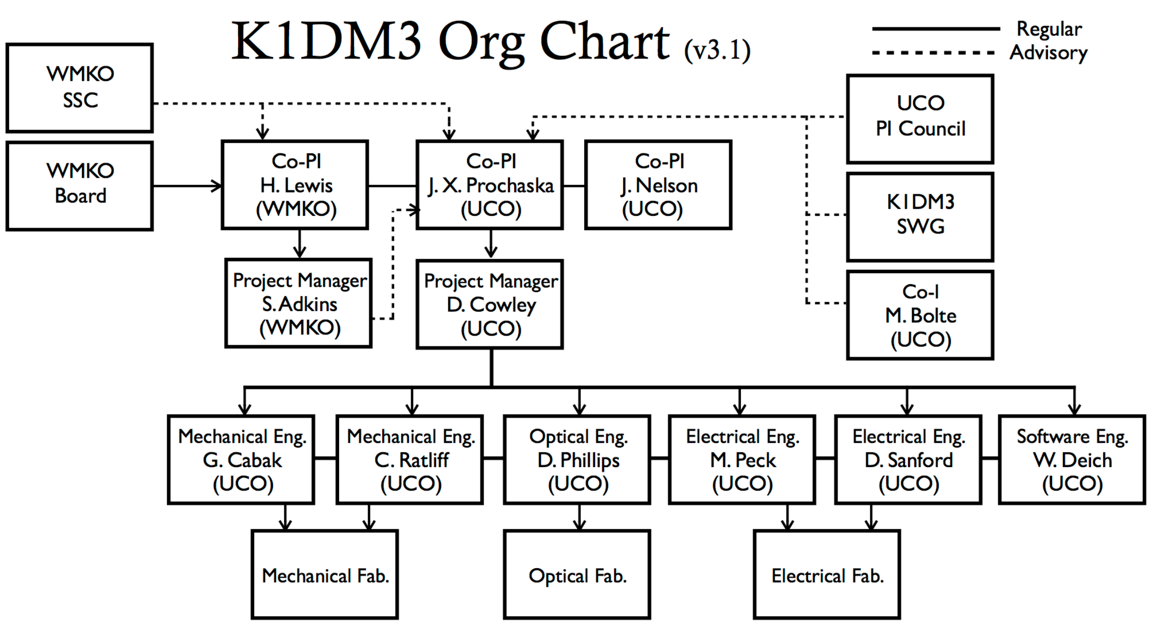


Figure 5-1: Org Chart for the K1DM3 project.

The UCO team members meet weekly to discuss progress and upcoming activities, reprioritizing as necessary. WMKO team members join these meetings once per month and meet as required on their own. The UCO team prepares a report monthly on the project status (work accomplished, budget, schedule; available on the K1DM3 TWiki), which is reviewed by WMKO leadership. During PD, the UCO team also held an Internal Review to gauge project progress and guide future efforts. The presentations and outcomes of that review are available on the K1DM3 TWiki.

At UCO, the project is further supported by administrative staff: Maerian Morris (financial), Betsy Lee (purchasing), Paula Towle (assistant to the UCO Director). At WMKO, the project is further supported by executive assistant Leslie Kissner, and WMKO finance and purchasing staff.

In addition to the K1DM3 team described above, there are several other bodies that intersect with the project:

- <u>K1DM3 Science Working Group</u>: A committee selected by PI Prochaska to provide input on specific aspects of the K1DM3 design that directly relates to science with K1DM3 or impacted by its replacing the current M3. In practice, the KSWG has been consulted only rarely.
- <u>Keck Science Steering Committee (SSC)</u>: This committee advises WMKO and the CARA Board on scientific priorities at the observatory. It is the main conduit between WMKO and its broader scientific community. The K1DM3 project regularly updates the Keck SSC on project status, budget, and schedule.
- <u>UCO PI Council</u>: A committee of UCO members that are leading major projects and/or in the upper administration at UCO. This group meets bi-weekly to discuss on-going and future projects at UCO, in part to coordinate staff time among the various projects. PI Prochaska and Project Manager Cowley are members of this committee.
- <u>National Science Foundation</u>: The NSF requires annual reports on the project status, budget, and schedule. The K1DM3 project submitted its first report in July 2014, which was approved by the program officer.

5.3. RISK ASSESSMENT AND RISK MANAGEMENT

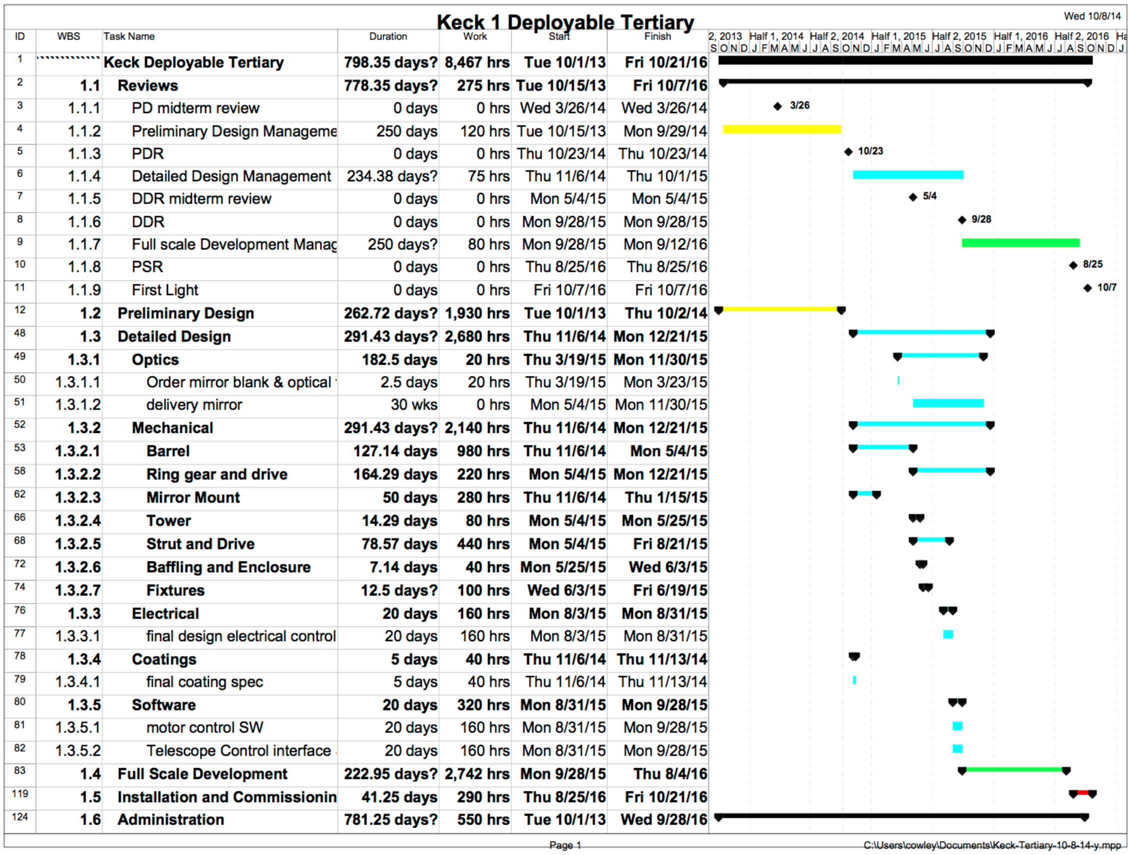
There is great emphasis on risk assessment and management within the K1DM3 project, especially on issues related to telescope safety and system reliability. These are discussed at the weekly meetings and described (when appropriate) in monthly reports. More formally, the team has generated a Failure Modes and Effects Analysis (FMEA) document (v3.0) to detail the many potential failure modes of the system. We have assessed the likelihood, impact, and mitigations for these failure modes. The full document is on the K1DM3 TWiki. Table 5-1 presents the top 10 risks identified by the project and their likelihood, impact, and mitigation.

Description	Likelihood	Effect	Severity	Mitigation
Piece breaks off K1DM3 and falls onto M1	Small	Damage to one or more segments	Critical	Safety wire on any piece that is attached with only one fastener. Lock tight all fasteners.
Deployable kinematics do not achieve required precision on pointing	Moderate	Poor image quality, mis-alignment of pupil	Moderate	Test kinematic coupling during PD and DD phases. Verify precision at UCO before delivery.
Interference between K1DM3 and tertiary tower when rotated	Moderate	K1DM3 will not rotate to any arbitrary angle	Critical	3D-scan tertiary tower to verify location and size of all items at the top of the tower.
K1DM3 vignettes a portion of the telescope beam	Small	Reduced observing efficiency	Moderate	Comprehensive Zemax modeling of the optical system.
CTE of structure	High	Poor positioning	Moderate	Construct with same materials as tertiary tower; consider new pointing model for K1.
One or more motors or controllers are unreliable	Moderate	Reduced performance of K1DM3; loss of observing	Severe	Extensive testing at UCO prior to delivery. Replace faulty items.
Misalignment of K1DM3	Moderate	Poor image quality, mis-alignment of pupil	Moderate	Development of a comprehensive Alignment Plan. Extensive testing at UCO prior to delivery. Verification of performance at WMKO prior to installation.
Vibration of K1DM3	Moderate	Poor image quality	Severe	??
Exceed MRI Budget	Moderate	Incompletion of project	Critical	Seek additional funds to complete.
??				

Table 5-1 Risk table

5.4. WORK BREAKDOWN STRUCTURE AND SCHEDULE

A detailed Work Breakdown Structure (WBS) to Level 5 detailing 121 activities including PD is provided in on the TWiki as a Microsoft Project Plan file. Effort levels for the work in the project plan were arrived at by expanding the top level WBS into underlying tasks, assigning appropriate personnel and estimating the required effort. Project personnel, including those budgeted in the subawards, were involved in developing the task lists and making the labor estimates. This file is updated approximately every other month to reflect changes in work progress and staff scheduling. Figure 5-2 shows the WBS to Level 2.



ID	WBS	Task Name	Duration	Work	Start	Finish
1		**Keck Deployable Tertiary**	**798.35 days?**	**8,467 hrs**	**Tue 10/1/13**	**Fri 10/21/16**
2	**1.1**	**Reviews**	**778.35 days?**	**275 hrs**	**Tue 10/15/13**	**Fri 10/7/16**
3	1.1.1	PD midterm review	0 days	0 hrs	Wed 3/26/14	Wed 3/26/14
4	1.1.2	Preliminary Design Manageme	250 days	120 hrs	Tue 10/15/13	Mon 9/29/14
5	1.1.3	PDR	0 days	0 hrs	Thu 10/23/14	Thu 10/23/14
6	1.1.4	Detailed Design Management	234.38 days?	75 hrs	Thu 11/6/14	Thu 10/1/15
7	1.1.5	DDR midterm review	0 days	0 hrs	Mon 5/4/15	Mon 5/4/15
8	1.1.6	DDR	0 days	0 hrs	Mon 9/28/15	Mon 9/28/15
9	1.1.7	Full scale Development Manag	250 days?	80 hrs	Mon 9/28/15	Mon 9/12/16
10	1.1.8	PSR	0 days	0 hrs	Thu 8/25/16	Thu 8/25/16
11	1.1.9	First Light	0 days	0 hrs	Fri 10/7/16	Fri 10/7/16
12	**1.2**	**Preliminary Design**	**262.72 days?**	**1,930 hrs**	**Tue 10/1/13**	**Thu 10/2/14**
48	**1.3**	**Detailed Design**	**291.43 days?**	**2,680 hrs**	**Thu 11/6/14**	**Mon 12/21/15**
49	**1.3.1**	**Optics**	**182.5 days**	**20 hrs**	**Thu 3/19/15**	**Mon 11/30/15**
50	1.3.1.1	Order mirror blank & optical	2.5 days	20 hrs	Thu 3/19/15	Mon 3/23/15
51	1.3.1.2	delivery mirror	30 wks	0 hrs	Mon 5/4/15	Mon 11/30/15
52	**1.3.2**	**Mechanical**	**291.43 days?**	**2,140 hrs**	**Thu 11/6/14**	**Mon 12/21/15**
53	**1.3.2.1**	**Barrel**	**127.14 days**	**980 hrs**	**Thu 11/6/14**	**Mon 5/4/15**
58	**1.3.2.2**	**Ring gear and drive**	**164.29 days**	**220 hrs**	**Mon 5/4/15**	**Mon 12/21/15**
62	**1.3.2.3**	**Mirror Mount**	**50 days**	**280 hrs**	**Thu 11/6/14**	**Thu 1/15/15**
66	**1.3.2.4**	**Tower**	**14.29 days**	**80 hrs**	**Mon 5/4/15**	**Mon 5/25/15**
68	**1.3.2.5**	**Strut and Drive**	**78.57 days**	**440 hrs**	**Mon 5/4/15**	**Fri 8/21/15**
72	**1.3.2.6**	**Baffling and Enclosure**	**7.14 days**	**40 hrs**	**Mon 5/25/15**	**Wed 6/3/15**
74	**1.3.2.7**	**Fixtures**	**12.5 days?**	**100 hrs**	**Wed 6/3/15**	**Fri 6/19/15**
76	**1.3.3**	**Electrical**	**20 days**	**160 hrs**	**Mon 8/3/15**	**Mon 8/31/15**
77	1.3.3.1	final design electrical control	20 days	160 hrs	Mon 8/3/15	Mon 8/31/15
78	**1.3.4**	**Coatings**	**5 days**	**40 hrs**	**Thu 11/6/14**	**Thu 11/13/14**
79	1.3.4.1	final coating spec	5 days	40 hrs	Thu 11/6/14	Thu 11/13/14
80	**1.3.5**	**Software**	**20 days**	**320 hrs**	**Mon 8/31/15**	**Mon 9/28/15**
81	1.3.5.1	motor control SW	20 days	160 hrs	Mon 8/31/15	Mon 9/28/15
82	1.3.5.2	Telescope Control interface	20 days	160 hrs	Mon 8/31/15	Mon 9/28/15
83	**1.4**	**Full Scale Development**	**222.95 days?**	**2,742 hrs**	**Mon 9/28/15**	**Thu 8/4/16**
119	**1.5**	**Installation and Commissionin**	**41.25 days**	**290 hrs**	**Thu 8/25/16**	**Fri 10/21/16**
124	**1.6**	**Administration**	**781.25 days?**	**550 hrs**	**Tue 10/1/13**	**Wed 9/28/16**

Figure 5-2: Project Plan with WBS

As we complete Preliminary Design, the project has slipped approximately 2 months from the projected completion date at the start of PD. This was driven primarily by the project's decision to perform analysis on a test-bed designed to emulate the deployable kinematic mounts for K1DM3. It was also due to the decision to explore design work on a mirror support system without holes in the back of the mirror, as recommended by the IPDR committee.

[Compare DD and the rest to original schedule]
We now project a commissioning date of October 2016.

5.5. DELIVERABLES

The following lists detail the key deliverables of the K1DM3 project to WMKO upon completion of the project.

- Hardware – All of the hardware will be owned by UCO/UCSC and loaned indefinitely to WMKO.
    - A fully assembled and tested K1DM3 system ready to mount on the K1 telescope

- A storage cart for handling K1DM3 when it is off the telescope
    - An alignment fixture for shipping and the alignment of K1DM3
    - A handling cart for re-coating the K1DM3 mirror in the WMKO coating chamber
    - Spares for critical and difficult to obtain parts that are expected to require repair or replacement during the useful life of the K1DM3
- Software
    - Low-level control software
    - A system to diagnose (and archive) the status of K1DM3
- Drawings and Documentation
    - As-built assembly and fabrication drawings
    - Copies of purchase orders and manuals for all purchased parts
- Preventative Maintenance (PM) plan
    - Spare parts and a recommended list
    - Maintenance documentation
    - A PM schedule
- Alignment/Commissioning plans
    - An extensive plan to align the K1DM3 mirror to the existing M3
    - A commissioning plan to fully exercise usage of the system

5.6. MILESTONES AND REVIEWS

The WBS shown in Figure 5-2 details the remaining major milestones and reviews for the K1DM3 project. As with PD, the reviews will be managed by WMKO and held at UCO.

5.7. BUDGET

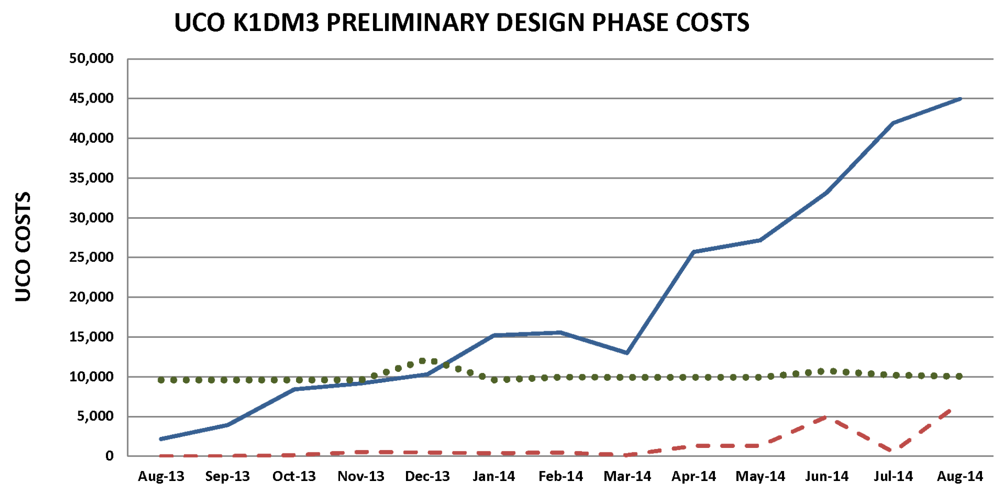
5.7.1. FUNDING SOURCES

The K1DM3 project is funded by the NSF MRI award to UCSC (PI Prochaska) and UCSC and WMKO cost sharing commitments. The NSF award provides funding of $1.479M over the duration of the project. UCSC administers this grant and provides sub-awards to WMKO on an annual basis. The MRI award requires a cost-share contribution equaling 30% of the total project cost which amounts to $634,064 and $2.113M respectively. WMKO, UCO, and UCSC have agreed to split the cost-share amongst the three institutions as follows:

- In-kind labor of PI Prochaska, PI Lewis, D. Phillips (UCO), Bolte (UCO), and various WMKO staff
- Five nights with K1 for commissioning contributed by WMKO
- $96k cash for fabrication from UCSC

5.7.2. EXPENDITURES DURING PRELIMINARY DESIGN

The PD phase of the K1DM3 project began on October 1, 2013. Since that time, UCO staff have billed hours to the project using K1DM3 activity codes to track the activities. An Excel spreadsheet of the monthly breakdown of UCO costs is provided on the TWiki. Figure 5-3 summarizes the expenditure profile during the project (including WMKO), split between labor, materials, and cost-share. Table 5-2 shows a breakdown of the costs integrated over the entire PD phase[2].



	Aug-13	Sep-13	Oct-13	Nov-13	Dec-13	Jan-14	Feb-14	Mar-14	Apr-14	May-14	Jun-14	Jul-14	Aug-14
K1DM3 PD Labor	2,150	3,920	8,400	9,145	10,295	15,200	15,560	12,970	25,690	27,170	33,180	41,920	44,958
K1DM3 PD Materials	0	0	140	520	460	380	460	140	1,300	1,300	4,960	520	6,660
K1DM3 PD Cost Share	9,589	9,589	9,589	9,589	12,185	9,589	9,953	9,911	9,911	9,911	10,734	10,182	10,042

Figure 5-3: Expenditure profile for UCO Costs during PD.

The total labor and materials costs of $324k exceeds the total budgeted amount as proposed to the NSF ($241,409). Part of the excess is due to the fact that a portion (approximately $30k) of the costs in PD include parts (e.g. one linear actuator) and work that we had expected to incur later in the project. We further note that we have not spent a significant portion of the cost-share monies provided by UCSC. Lastly, the NSF budget included $153k for reviews and administration which has not been costed separately at UCO. We estimate that the project has incurred a $25k overrun (10%) during PD.

[2] Note that the PD Review was budgeted separately and is not included here.

Table 5-2: PD Costs

K1DM3 Preliminary Design Costs (in Thousands)				
INITIAL AWARD--MRI NSF		ITD		PD
Description	Awarded	PD End Balance	PD Expenses	PD Proposed costs
FABRICATION LABOR	894	643	252	190
FABRICATION MATERIALS	154	125	29	
INSTALLATION TRAVEL	18	18	0	0
SUBAWARD WMKO	400	357	43	52
NSF SUBTOTAL	1466	1143	324	241
UCSC VCR				
UCSC VCR	96	90	6	32
TOTALS	1562	1233	329	273

Regarding cost-share, we have booked only 17% to the project to date (approximately half of the requirement). We note, however, that several large cost-share items are planned for late in the project (e.g. commissioning nights). It is also likely that the project will re-balance some of the in-kind work towards UCO (e.g. increase PI Prochaska's contribution to two months per year).

5.7.3. Budget to Completion

The project plan in Figure 5-2 projects to the cost-profile for UCO described in Table 5-3. The Table also lists the projected costs at WMKO for their work during the DD, FSD, and Installation/Commissioning phases of the project. These estimates differ from those proposed to the NSF in a few ways. First, we have now included costs associated with a prototype of K1DM3 to be delivered to and tested at WMKO during DD. This is an additional expense of approximately $100k. The new costs also reflect the fact that less work was performed at WMKO and more at UCO in the PD phase compared to the subaward proposed to the NSF. Lastly, they properly reflect the estimated materials costs which exceed those estimated for the NSF proposal. Altogether, we estimate the project will exceed the NSF budget and cost-share contributions by approximately $100k.

K1DM3 Projections (in Thousands)										
Description	**PD**	**PD Proposed**	**DD**	**DD Proposed**	**FS**	**FS Proposed**	**I & C**	**I & C Proposed**	**R & A**	**R & A Proposed**
FABRICATION LABOR	252	190	387	304	317	357	47	76	0	153
FABRICATION MATERIALS	29		132		102		21		0	
INSTALLATION TRAVEL	0	0	0	0	0	0	18	0	0	0
SUBAWARD WMKO	43	52	115	58	145	32	45	65	0	103
NSF SUBTOTAL	324	241	634	361	564	389	131	141	0	256
UCSC VCR										
UCSC VCR	6	32	0	32	0	32	0	0	0	0
TOTALS	329	273	634	393	564	421	131	131	0	256

Table 5-3: Projected cost at completion by phase

The materials cost estimates have been updated to reflect quotes received during PD. Table 5-4 lists the component parts or subassemblies with significant cost as of the Preliminary Design of K1DM3.

ITEM	QTY	EST	QUOTE	TOTAL	SUPPLIER
Rotation Bearing	2		18800	37600	Kaydon
Drum	1	20000		20000	
Whiffle tree assy	3	3300		9900	
Deployable kinematics	6		600	3600	Previously purchased
Rotation Galil	1	7000		7000	Galil
Deployment Galil	1	7000		7000	Galil
Slip ring	1	7000		7000	
Alignment Fixture	1	8500		8500	
Linear actuator		10994		21988	Exlar
Mirror	1		58900	58900	Zygo
Rotation motor	2		800	1600	Magmotor
Harmonic Drive	2		1600	3200	Harmonic Drive
Swing arm	1	10000			
Switches		1000			
Rio controller	1	1000			
Ring gear	1	10000			
Detent mechanism	1	2000			
Power supply	1	2000			
			Total	**212288**	

Table 5-4: Component cost estimate

We emphasize that the rules of our NSF award stipulate that the project cannot carry contingency.

6. Glossary

COTS	Commercial Off The Shelf
DCS	Drive and Control System
FOV	Field Of View
NEBS	Network Equipment Building System
MOSFIRE	Multi-Object Spectrometer for InfraRed Exploration
LRIS	Low Resolution Imaging Spectrograph
ICD	Interface Control Document
KSD	Keck Software Document
TBC	To Be Completed
TBD	To Be Determined
TCSU	Telescope Control System Upgrade
WMKO	W. M. Keck Observatory
UCSC	University of California, Santa Cruz

7. APPENDICES

7.1. KINEMATIC COUPLING TEST BED

To precisely position the tertiary mirror within the K1DM3 system when deployed, we will rely on a set of kinematic couplings (see 4.2.3). Although our theoretical expectation is that one can achieve sub-micron repeatability (K1DM3_Design_Note_Kinematics), we have performed a series of tests to measure the performance of various kinematic couplings. Specifically, we have attached two styles of kinematic couplings to two steel plates and have measured the position of these plates when coupled. Set 1 is a set of three canoe-spheres which employ a v-groove and a canoe-shaped v-block. These have a radius of curvature of 0.5 m. The second type of coupling is spheres contacting three different bases: a flat, a v-groove, and a cone.

To precisely measure the position of the test bed, we attached three LVDTs (Linear Variable Differential Transformers). These probes are specified to measure distances to 0.015 micron precision. We connected the LVDTs to three LVDT conditioners (Schaevitz PML1000, and Schaevitz LVD-2412) and then calibrated each device with an interferometer (Figure 7-1).

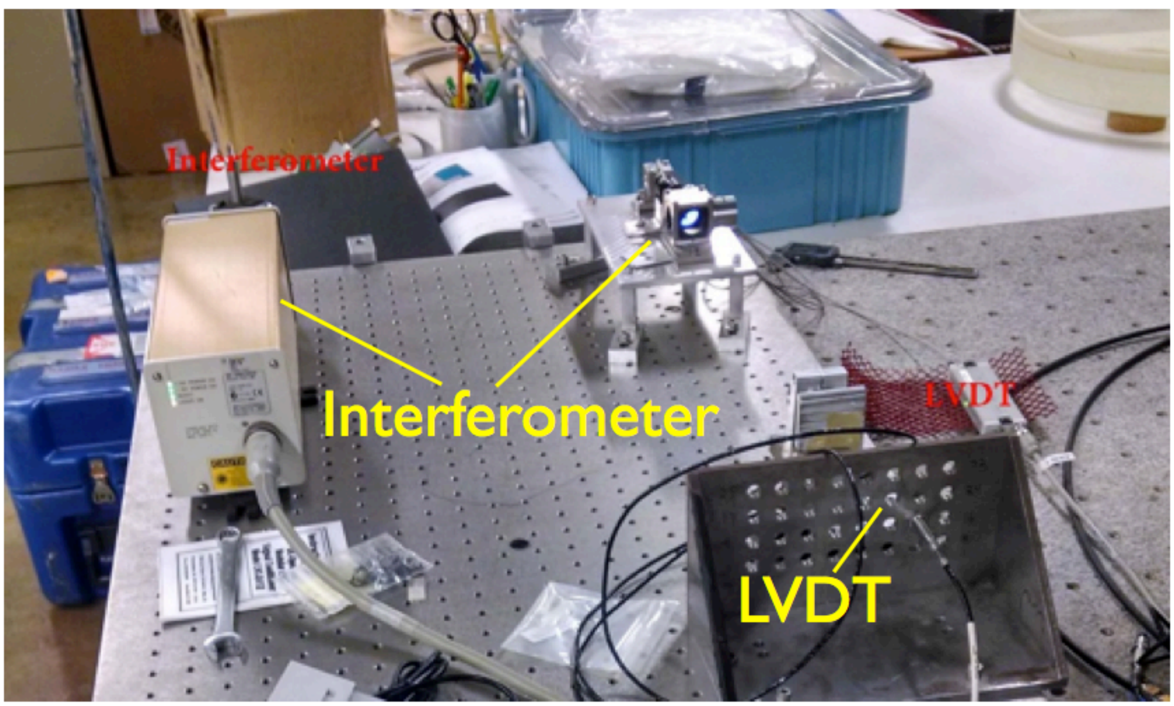


Figure 7-1: Interferometer and LVDT on a flat bed. The LVDT was connected to a metal plate whose position was measured by the LVDT and the Interferometer to calibrate the former.

After calibration, we tested the repeatability of the LVDT by attaching each a sphereometer and measuring the position against a smooth, polished surface (Figure 7-2). We lifted the spherometer off and on the surface and the LVDT recorded the same position to approximately 0.1 micron.

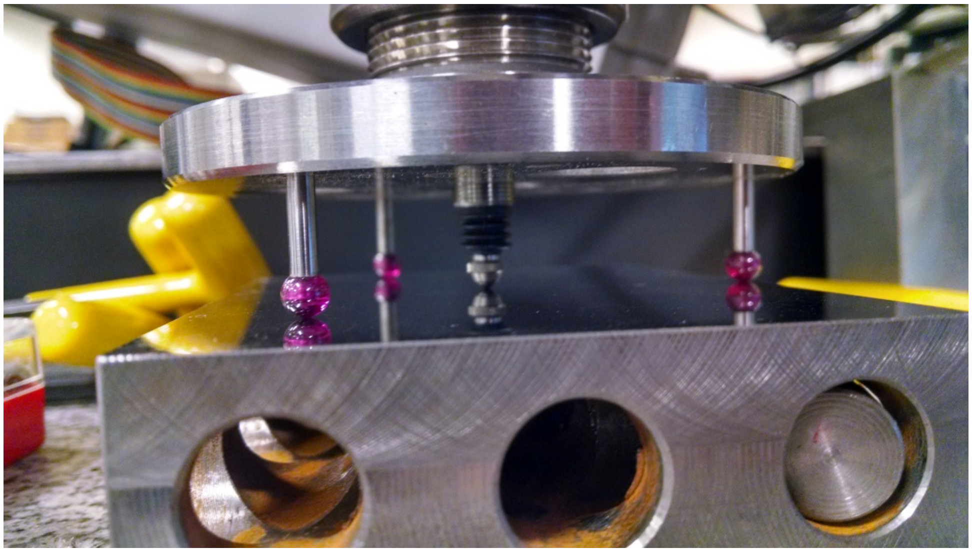


Figure 7-2: LVDT (center) placed within a spherometer. The position of the LVDT is measured when placed on the flat, smooth surface in the figure.

We tested each kinematic coupling by recording the LVDT measurements during a series of "lifts" where the upper plate was lifted off the other and then carefully replaced. The positioning of this plate was measured for a set of 3 LVDTs.

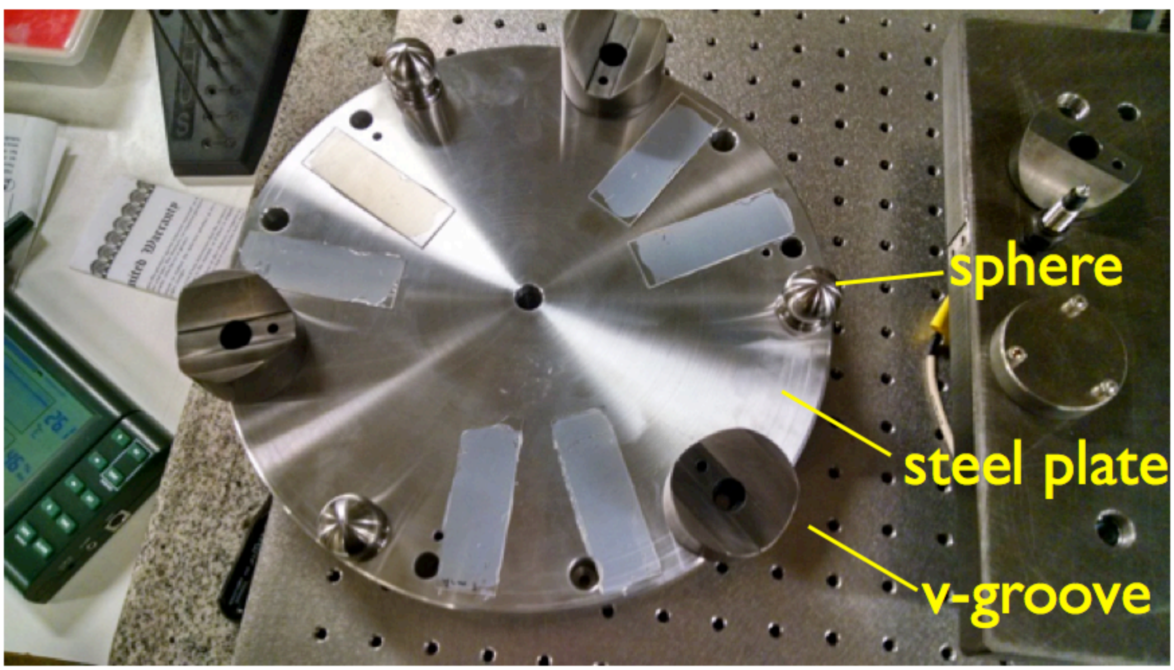


Figure 7-3: Lower half of the test bed. One views the v-grooves for the first set of kinematics and the three spheres for the other stye. The translucent rectangles are pieces of glass glued to the steel plate to provide a flat surface for the LVDT measurements.

We first tested the Sphere/V-groove/flat/Cone kinematics. The differences between each lift were within our requirements at approximately ±0.3 microns (Figure 7-5). We then tested the canoe-sphere kinematics. In this case, the difference in LVDT positions between each lift was smaller. The maximum offset was 0.17 microns and the device was generally repositioned to within 0.05 microns (Figure 7-4).

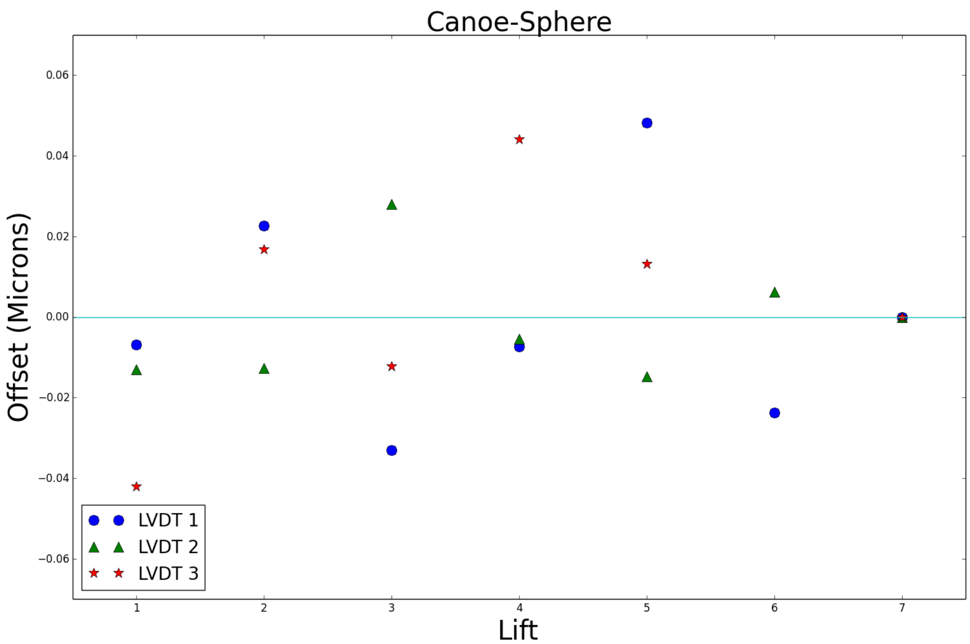


Figure 7-4: Canoe-sphere

After testing, the canoe-spheres were considered to be sufficient for our design. Canoe-spheres also have the advantage that each kinematic shares the load more evenly for different gravity vectors. They also maintain centering for thermal expansion and contraction.

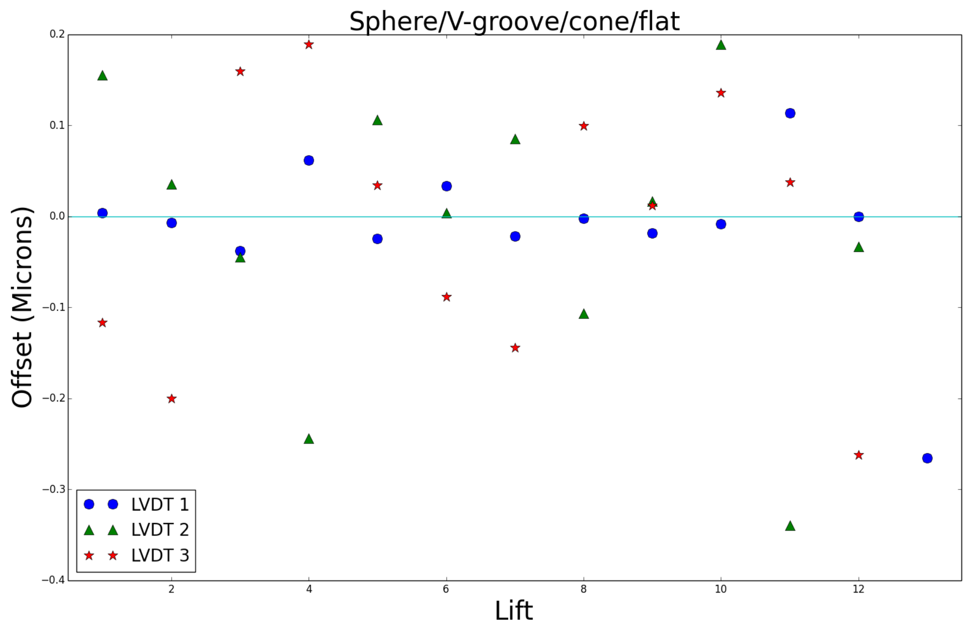


Figure 7-5: Sphere, v-groove, etc.

7.2. FIBER OPTIC COUPLING TESTS

To deploy/retract the mirror of K1DM3, one requires a communication link between the linear actuators and other mechanism and the control electronics located on the rotating portion of the module. Our initial design considered communicating through a disconnected set of fiber optics at a fixed rotation of the instrument. This would avoid potential mechanical issues with contacts and cable wraps. It would require, however, precise positioning of the drum to prevent substantial signal loss between the fibers.

To test the feasibility of this implementation, a test jig was constructed. The jig has five adjustments to position the fibers: X, Y, Z, tip, and tilt (Figure 7-6).

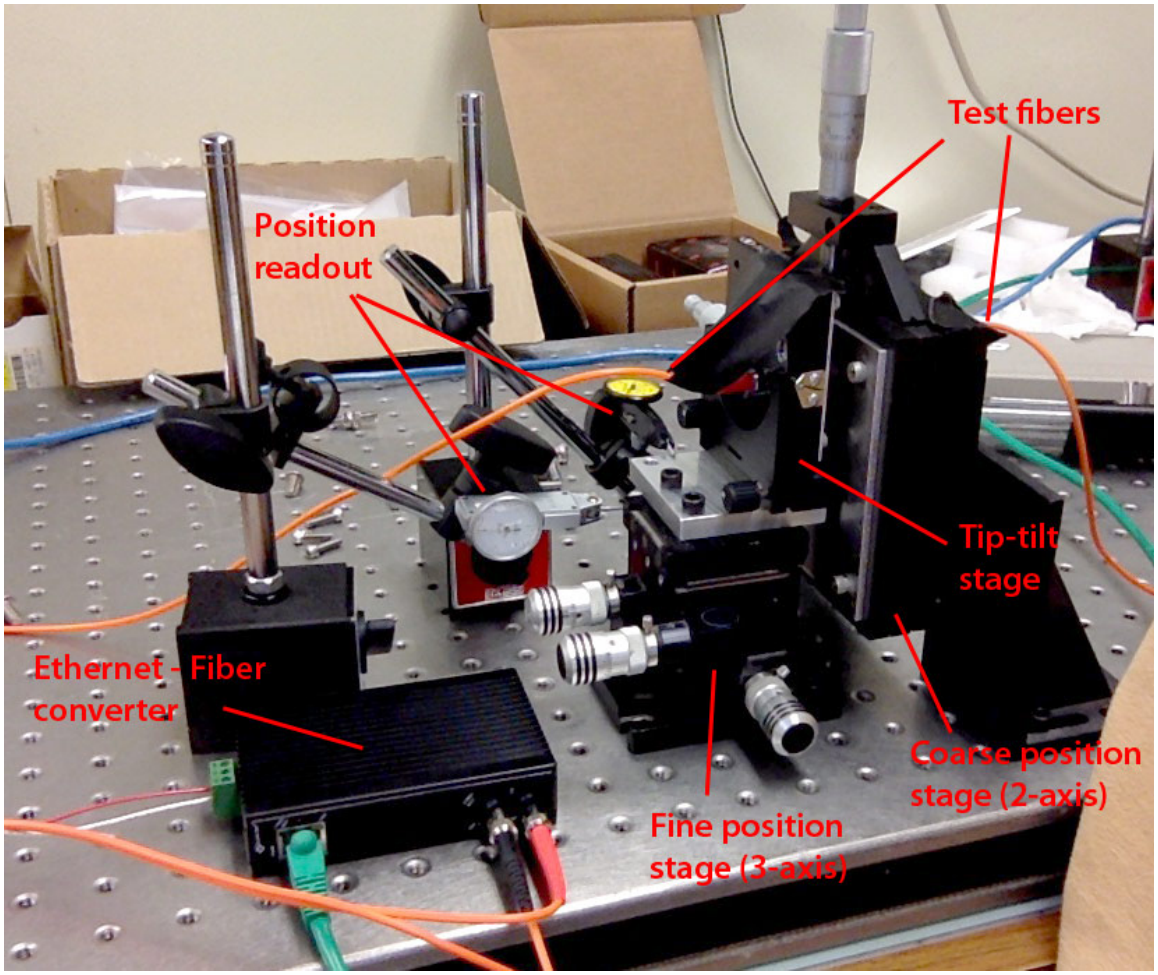


Figure 7-6: Test jig for testing signal loss due to mis-positioning in the fiber optics system

Signal loss of the fiber during testing was measured with standard 62.5 micron fibers using a light source and an optical power meter. Signal loss was measured relative to two fibers connected with a standard ST fiber coupler. Signal loss was measured with variations in tip/tilt, horizontal displacement, and vertical displacement. Signal drop off was relatively uniform in any direction from the optimal fiber position. A sample test result is shown in Figure 7-7.

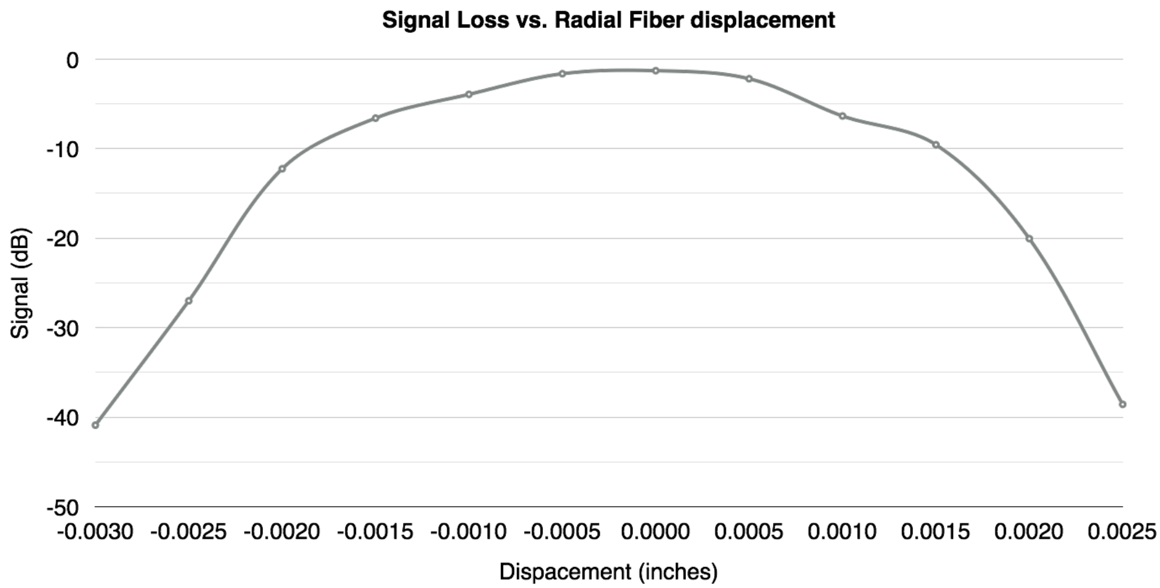


Figure 7-7: Signal loss through fiber system as a function of radial fiber displacement

The test jig fibers were also connected to two Black Box LMC270A-MM-ST Ethernet media adapters. Testing showed that the media adapters maintained a link reliably until the signal loss exceeded -15 dB. Up to loss of link there was zero packet loss and no errors. Once the link is lost there is a 100% loss of packets.

Restrcting to a less than -15 dB signal loss, we find that we can tolerate position errors on the fibers of up to ±0.002" (± 50 microns). While this is theoretically within the alignment tolerances of the rotating stage, there was concern about dirt and dust blocking the fibers. An attempt was made to increase the dirt and mechanical tolerance by using collimation optics.

Thus far tests with the collimation optics have been unsuccessful. While the optics result in a signal over a large area (±1 mm) the signal is not strong enough to maintain an Ethernet link. This is most likely due to the positional inaccuracy of the optics relative to the fiber. It is likely that this approach can be made reliable with some engineering effort. So far no off the shelf components have been found to make a working link.

Given that there are promising leads on large diameter commercial slip rings that can provide an Ethernet connection, further testing of the fiber link is on hold.

7.3. Compliance Matrix for Requirements