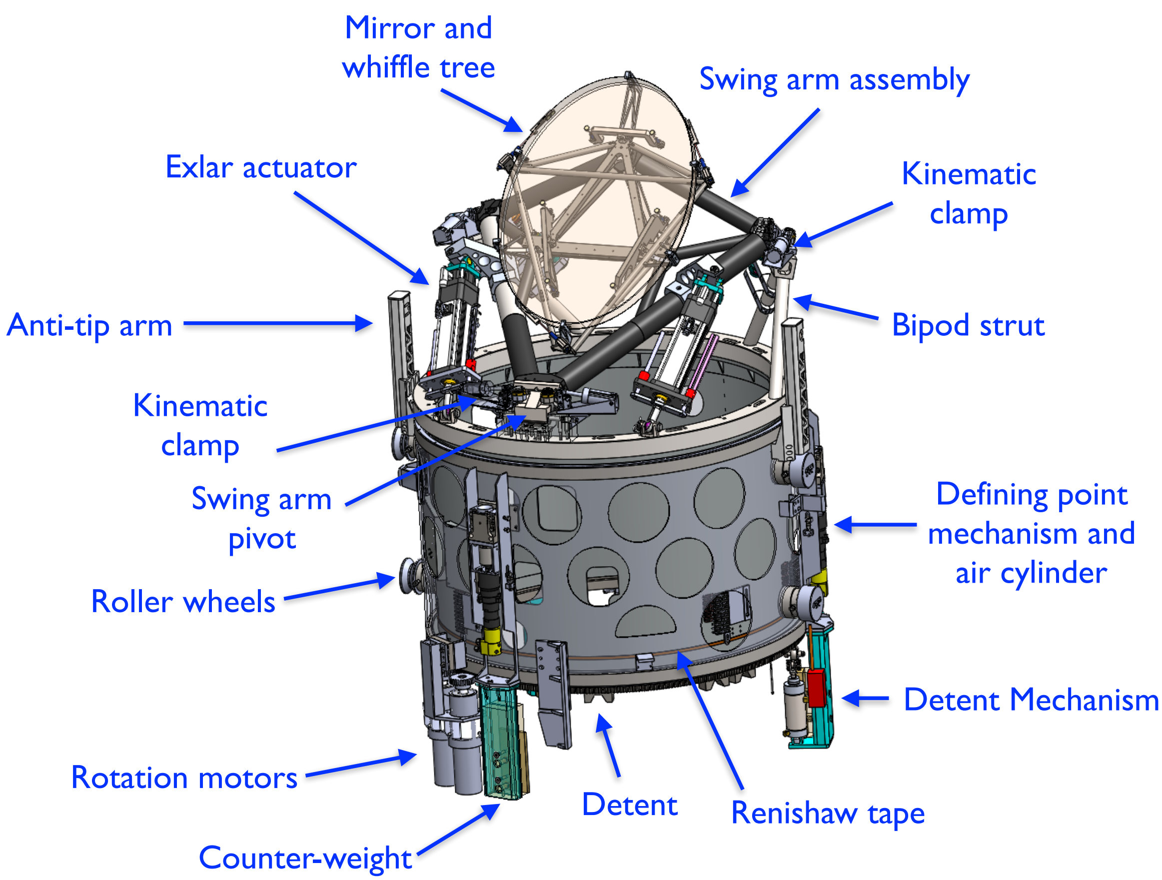
THE KECK I DEPLOYABLE TERTIARY MIRROR (K1DM3)
DETAILED DESIGN REPORT (V1.10)

K1DM3 Team

February 25, 2016



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1 EXECUTIVE SUMMARY

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

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

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

Presently, K1 cannot switch rapidly between instruments at Nasmyth or auxiliary bent Cassegrain foci and a swap between Nasmyth and Cassegrain focal stations requires the installation (or removal) of the tertiary mirror module. Thus, in practice, this limits any TDA investigation to a single instrument on a given night. Furthermore, it is essentially impossible to design an observing campaign to study a set of objects at high cadence (e.g., relatively short observations every night). The proposed K1 deployable tertiary (K1DM3) will directly address these shortcomings, enabling WMKO to fully and vigorously participate in TDA science with its unique set of K1 instruments. As the driving paradigm in observational astronomy shifts from a passive, static sky to one that displays dramatic changes on a nightly basis, it is critical to enhance our technical capabilities in this arena.

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

2 Introduction

2.1 K1DM3 Team

Table 2.1: K1DM3 Team Members

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
Jerry Cabak	Mechanical Engineer	UCO
Will Deich	Software Engineer	UCO
Chris Ratliff	Mechanical Engineer	UCO
Michael Peck	Electrical Engineer	UCO
Drew Phillips	Optical Designer	UCO
Dale Sanford	Electrical Engineer	UCO
Jim Ward	Technician	UCO
Mike Dahler	Telescope Mechanical Engineer	WMKO
Sam Park	Mechanical Engineer	WMKO
Mike Pollard	Senior Mechanical Engineer	WMKO
Bill Randolph	Design Technician	WMKO
Truman Wold	Mechanical Engineer	WMKO
Lisa Ellis	Financial Analyst	UCO
Alex Tripsas	Undergraduate Researcher	UCO

2.2 Revision History

Version 1.0 – JXP on February 2, 2016
Version 1.1 – JXP on February 13, 2016
Version 1.2 – JXP on February 15, 2016 (draft of Commissioning Plan)
Version 1.3 – JXP on February 21, 2016 (many edits)
Version 1.4 – JXP on February 22, 2016 (alignment plan, risk table)
Version 1.5 – JXP on February 22, 2016 (edits)
Version 1.6 – JXP on February 23, 2016 (budget edits)
Version 1.7 – JXP on February 23, 2016 (edits from the co-authors)
Version 1.8 – JXP on February 24, 2016 (edits from the co-authors)
Version 1.9 – JXP on February 25, 2016 (continuing edits)
Version 1.10 – JXP on February 25, 2016 (continuing edits)

2.3 References

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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 at all passbands.

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), fast radio bursts (FRBs) 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 over 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 along the elevation axis ring is selected by rotating the tertiary mirror around the telescope optical axis. To install and use a Cassegrain mounted instrument, the tertiary module must be removed from the telescope.

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 2.3 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 connects the mirror and support structure to a swing arm system. In turn, this swing arm moves the mirror between the deployed and retracted positions, driven by two linear actuators. The top of the drum supports the swing arm in the deployed position through a bipod structure with two defining points (at the right side of the figure) and a third defining point at the hinge point of the swing arm (the third defining point is not visible in the figure). The swing arm is locked in the deployed position by a pair of clamping mechanisms. No power is required to maintain the mirror in either the deployed or retracted positions. In order to set the swing arm into the kinematics, the deployment process will be performed at the elevation angle where the kinematics are oriented normal to gravity (68 degrees). We will retract the mirror at specific rotation angles, one of two positions where power and ethernet is supplied to the swing arm.

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

The 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

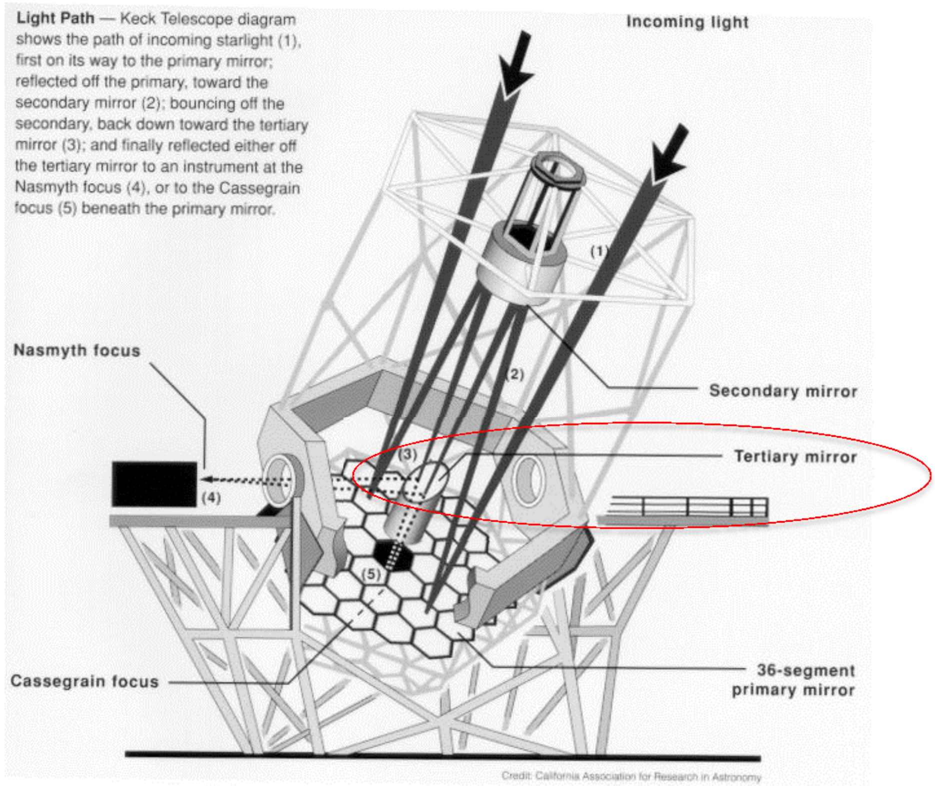

Figure 2.1: Keck I Telescope optical path

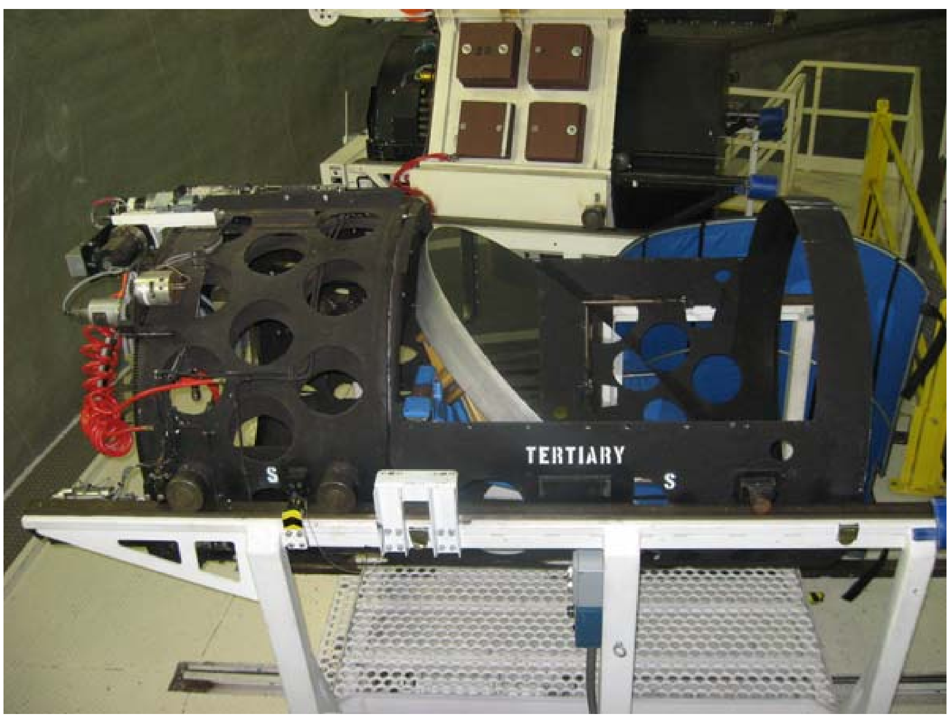

Figure 2.2: Keck I M3 module on the Nasmyth deck. The tertiary mirror lies at the center of the photo.

kinematic mounting points ensure repeatable positioning. K1DM3 is designed to be coated with Ag at WMKO. The design includes all necessary fixtures and handling carts.

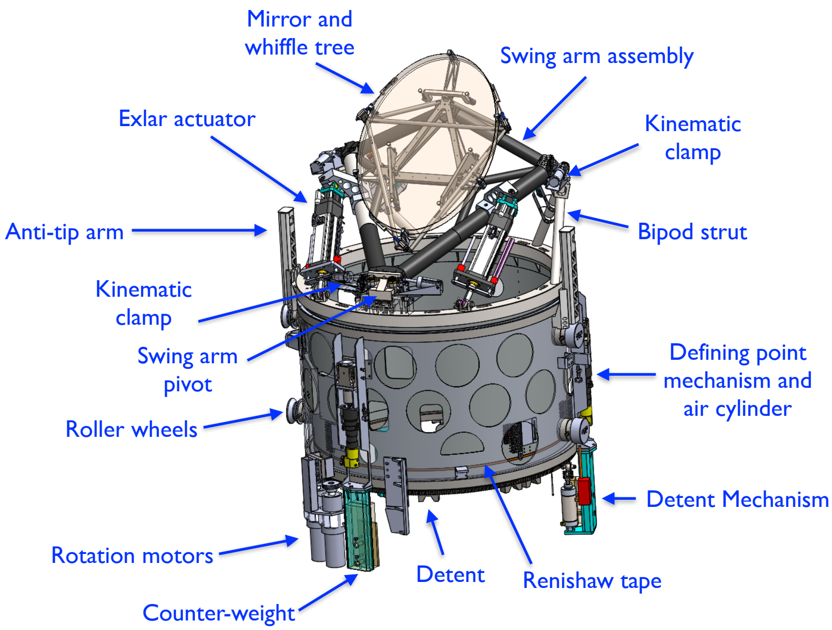

Figure 2.3: Schematic of the K1DM3 system.

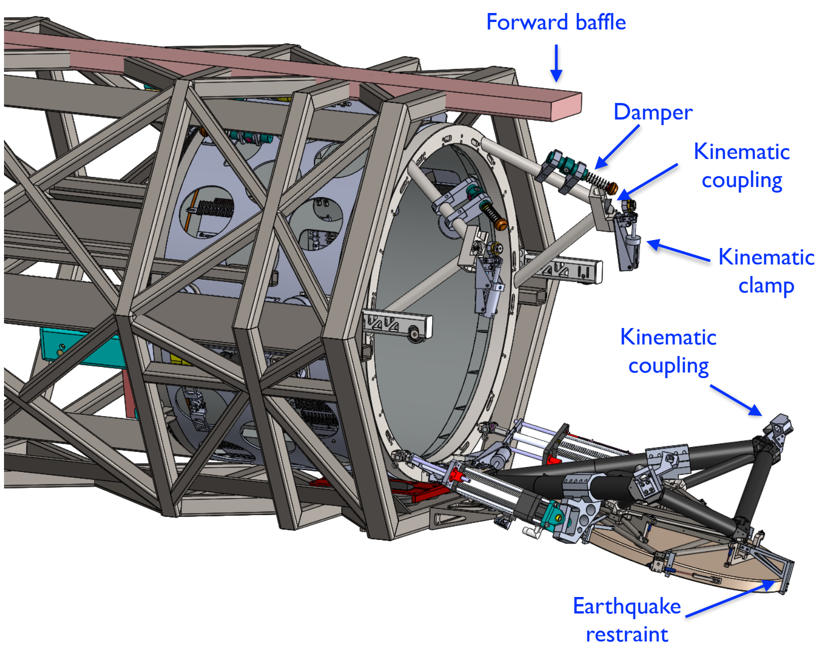

Figure 2.4: K1DM3 module installed in the Keck I tertiary tower.

2.5 Operational Concepts and Observing Scenarios

Current Tertiary Module Operation:

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. The current tertiary module requires approximately one hour of day crew time for installation/removal. The mirror is coated at WMKO using custom fixtures and handling carts and a set of tools and procedures for controlling and/or removing K1DM3 outside of computer control, as required.

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 a demonstrated high on-sky efficiency, and serves well the scientific needs of the majority of the Keck community. As discussed in § 2.4, however, there is a growing recognition and 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 Keck Scientific Steering Committee (SSC) are preparing a new Strategic Plan that will explore new operation models, partly inspired by the K1DM3 project. We expect their findings and the resultant SSC recommendations to crystallize 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 data collection with any of the mounted instruments on K1. Any fundamental change to the configuration of K1DM3 should be executable by software either acting in response to a reconfiguration (i.e. tertiary mirror rotation) of the active instrument or when an instrument change is requested by a WMKO staff member.

To help motivate the design requirements for K1DM3 and better guide this report, we offer a few (brief) observing scenarios that would exercise K1DM3:

- A ToO observation – 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 degrees, DEC=+22.3234 degrees (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 and the telescope operator (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 after the current exposure. Based on the estimated flux of the GRB afterglow (15.5 mag at V-band), Dr. Kulkarni has requested a HIRES observation

  Upon its completion, the OA selects HIRES from a drop-down menu. The telescope slews to an elevation angle of 68 degrees and K1DM3 rotates to the defined rotation angle for deployment/retraction. When the telescope and K1DM3 are ready (~15 s), the M3 mirror is automatically deployed and clamped into its kinematic mounts. The module then rotates to the nominal angle for HIRES and locks with a detent. The OA then slews the telescope to the desired RA/DEC and acquires the new source on the HIRES slit guider. In the 5 minutes between the GRB alert and the start of the first exposure, the GRB afterglow has faded by 0.7 mag but is still sufficiently bright for a high signal-to-noise echelle spectrum. Upon completion of the ToO program (1 hr), 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 compliment their science exposures.

- Cadence observations of S0-2 – 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 degrees. The remainder of the night is scheduled for radial velocity spectroscopy with HIRES.

  At local HST 02:15am, 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 02:22 am 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 and by using K1DM3. For that effort, the SA had executed the instrument changes from WMKO.

- Flexible observing – On October 13, 2017, Prof. Max of UCSC is scheduled to observe the nucleus of NGC 4231 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 mag) and the seeing exceeds 1.5″ FWHM. Dr. Max declares that she cannot obtain scientifcally 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

During the PD phase of K1DM3, the team generated a Requirements Document (v3.0) to guide the design work. This document was updated during Detailed Design and we provide the full and current document on the K1DM3 TWiki. In this section, we summarize the requirements which have had greatest influence on the detailed design. Items in boldface represent modifications in the requirements since PD.

3.1.1 Optical Requirements

1. The K1DM3 tertiary mirror will be sized to provide an unvignetted 4.7 arcminute diameter field of view at the Nasmyth foci. **[§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 or 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 arcsecond 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. [1]
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 rotate to a non-vignetting position when retracted. **[§8.2.2.1]**

4. When deployed, the mirror will be able to rotate about the telescope optical axis at a speed of at least 6 degrees 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. [§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. The K1DM3 module must not weigh more than 1000 kg. [§8.2.1, Table 9]
9. 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]

3.1.2.1 In-beam Positioning Requirements

As designed, the elevation axis of the K1 telescope lies in a plane 4.00 m above the primary, normal to the optical axis. For an ideal telescope with a desired circular FOV at the Nasmyth foci, an elliptical tertiary mirror should be inserted at a 45 degree angle with respect to the optical axis (telescope Z axis) and slightly off-center along the mirror's major axis. The reader may consult [2] for further details.

The current M3 is offset from this ideal position, because of the as-built locations of M1 and M2, the as-built tertiary tower, and/or errors in the original alignment procedure [3]. Because the Nasmyth instruments on K1 (HIRES, OSIRIS) have been aligned to the existing M1-M2-M3 telescope, we endeavor to replicate (to a specified tolerance) the position of the current M3. More details on this activity are provided in § 5.1.3 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 [2] 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 ($\delta X, \delta z$) and rotations about the minor axis of the mirror (tilt or $\delta\theta_{tilt}$) or the telescope Z axis (tip or $\delta\phi_{tip}$). Because the tertiary is tilted by 45 degree 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:

$$\delta\alpha = \frac{\delta_Z \text{ (or } \delta_X)}{0.7252\,\text{mm}} \text{ arcseconds} \quad (3.1)$$

$$= \left(\frac{\delta\theta_{\text{tilt}}}{11.5''}\right) \text{ arcseconds} \quad (3.2)$$

$$= \left(\frac{\delta\phi_{\text{tip}}}{16.5''}\right) \text{ arcseconds} \quad (3.3)$$

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 arcseconds. 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 arcseconds and tip to 16.5 arcseconds (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 arcseconds 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 a 1 arcsecond offsets of a source at the focal plane lead to very small additional vignetting in HIRES ($\approx 0.1\%$) 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 [2]. For reference, the existing tertiary allows repeatable positioning at the various focal stations with an error of < 5 arcseconds.

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

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

1. The K1DM3 mirror will position to an accuracy of 725 microns along the telescope X and Z axes (rms). We adopt the same requirement for repeatability. [§8.2.1, Table 9]
2. The K1DM3 mirror will position to the nominal rotations of tip and tilt to 11.5 arcsecond and 16.5 arcsecond (rms) respectively. We adopt the same requirement for repeatability. [2]
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 arcseconds and 0.46 arcseconds (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[1] 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[2] to that existing handler as possible. [§8.3.1.4]

[1] Note that WMKO intends to replace the current rails on K1 with a set more similar in design to those on K2. The K1DM3 will interface with either set.

[2] In fact, we intend to use the existing M3 mirror module handler since we will store the current module on the dome floor once K1DM3 is in service.

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]

3.2 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]

3.3 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]

3.4 COMPLIANCE MATRIX FOR REQUIREMENTS

See Appendix.

4 DETAILED DESIGN ACTIVITIES

4.1 OVERVIEW

The work performed in the DD phase is described in this report and represents the design of the K1DM3 system. The major activities may be summarized as:

1. Produce detailed designs for all K1DM3 sub-systems
2. Create fabrication drawings for K1DM3 sub-systems for all externally fabricated items
3. Place material fabrication orders for all of the K1DM3 optical components
4. Identify other long lead time items, identify vendors and obtain quotations
5. Place orders for long lead items if the critical path requires it
6. Perform prototype testing of K1DM3 kinematics
7. Perform prototype testing of K1DM3 outer drum fitting in the Tertiary Tower [4]

8. Build and test a prototype for the pneumatic interface
9. Build and test a prototype for custom communications (internet and power)
10. Prepare functional requirements documents for all software including use cases, test plans and validation plans
11. Prepare configuration control plans for documentation and software
12. Prepare final error budgets for optics, flexure, weight, thermal and power
13. Prepare operations concepts including observing scenarios
14. Identify cabling, power, and air interfaces with the tertiary tower
15. Perform a safety design and review (FMEA)
16. Develop a Preventative Maintenance plan and spare list
17. Develop a plan for coating (material, re-coating, handling, jigs)
18. Describe how alignment will be accomplished and establish requirements for alignment tests
19. Develop performance predictions and risk mitigation strategies
20. Review and update the project plan to completion, including the schedule and budget
21. Address issues raised at the PDR
22. Address issues raised at the Interim DDR

4.2 Significant Design Modifications since Preliminary Design

Following the Preliminary Design phase and review, the K1DM3 team has endeavored to bring all major subsystems to the Detailed Design level. In the process, a few areas of the design have seen significant modification. These have generally been to simplify the design and related fabrication. We summarize these modifications as follows (greater detail is provided in the following section):

1. Custom connections: We have abandoned the planned slip ring approach to connectivity (power and ethernet) between the outer drum and the upper assembly. Both the cost and complexity were considered prohibitive. Instead, we have designed a custom communications system – "hammers" pulled across Ag-coated "ramps" – that provide nominal and robust connectivity. We will install two such connections on K1DM3.
2. Pneumatic clamping: To minimize the spatial profile of the clamps for the deployable kinematics, we have adopted pneumatic clamps instead of electronically driven clamps. This requires a custom interface between the outer and inner drums for air supply.
3. Limited rotation when retracted (tower interference): As designed, the swing arm assembly interferes with the tertiary tower when retracted if the assembly is rotated by more than approximately 45 degrees from the retraction position. Our design, therefore, restricts the rotation of the module when retracted.
4. An effective reduction in the FOV: Although our design includes an over-sized mirror for a nominal FOV of 5 arcminutes, our vendor (Zygo) late in our discussions reported that their manufacturing methods for cutting the mirror imposes an approximately 15 millimeter "apron" around the outside circumference of the aperture with poorer surface quality. This effectively reduces the true clear aperture to yield a smaller 4.7 arcminute FOV [5].
5. Alignment plan: Inspired, in part, by the measurement procedures we adopted to measure the position of the K1DM3 outer drum in the K1 tertiary tower [4], we have developed a new plan for alignment of K1DM3 in the K1 telescope.

The remainder of the design follows the path laid out at PDR and several subsystems have since been fabricated.

5 Detailed Design

5.1 Optical Design

5.1.1 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 Zerodur glass and be shaped as an ellipse with major axis 2a = 901.1 mm and minor axis 2b = 643.0 mm, and a thickness of 44.5 mm (Figure 5.1). It will have an approximate mass of 51.23 kg. The K1DM3 project obtained the mirror blank from the TMT project, on permanent loan, and a second blank as a spare.

The mirror was fabricated by Zygo. The figured mirror has an apron of approximately 15 mm width around the outer circumference that has poorer image quality. This reduces the clear aperture FOV to approximately 4.7 arcminute (see [5] for further details).

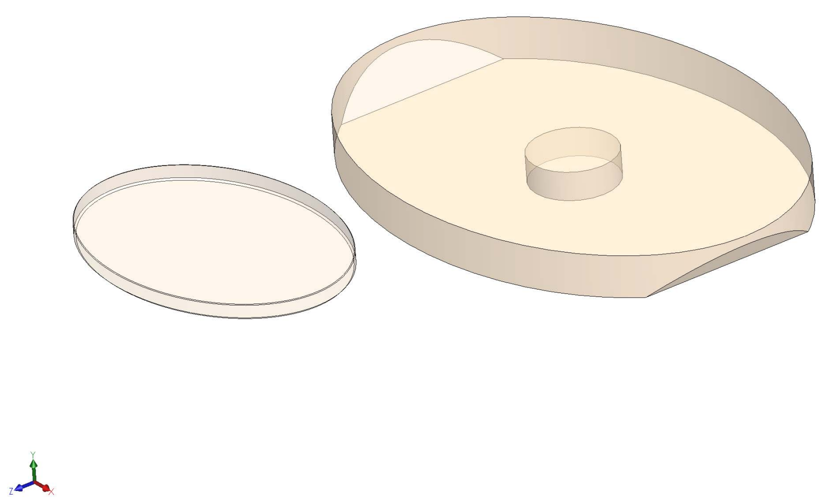

Figure 5.1: K1DM3 mirror (left) and the current K1 M3 (right). The K1DM3 mirror provides an approximately 4.7 arcminute FOV and is an ellipsoid having with major axis = 901.1 mm and minor axis = 643 mm. An apron of poorer surface quality related to the cutting procedure, however, reduces the high quality clear aperture to major axis = 870.8 mm and minor axis = 613.4 mm for an 4.7 arcminute FOV. The current K1 tertiary provides for a 20 arcminute FOV.

Within the clear aperture, the mirror was polished by Zygo to 0.2 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 was polished to a P-V of 57 nm and a surface error of 6 nm. These meet the slope error requirements.

The mirror will be delivered uncoated and later coated with bare Aluminum using the coating chamber at WMKO (see § 5.1.4).

Performance: The mirror design satisfies the optical requirements listed in § 3.1.1. Figure 5.2 shows the measurements on surface quality performed by Zygo.

Fabrication: The K1DM3 mirror was fabricated by Zygo.

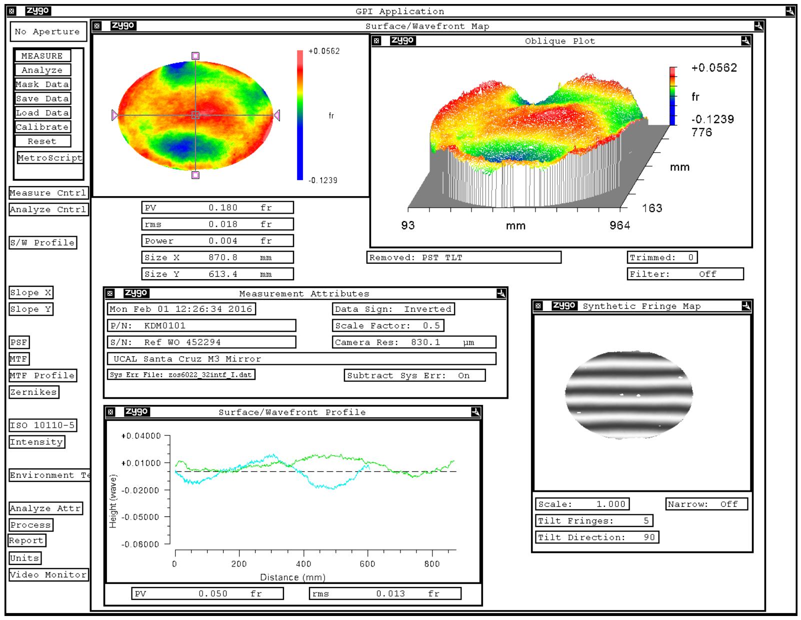

Figure 5.2: Surface quality measurements on the clear aperture of the as-built mirror for K1DM3.

Risks and Mitigations: We identify no further risks with this aspect of the design. The mirror has been delivered to UCO where it will be safely stored until gluing.

5.1.2 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 [2] for further details .

We face significant challenges when M3 is retracted to avoid vignetting the rays from M1 to M2 and, at the same time, avoid vignetting the rays from M2 to the Cassegrain instruments. An additional concern is vignetting related to the LRIS ADC (see [6] for further details). When M3 is retracted, it will be held above the module and the tertiary tower with the reflective surface facing away from the optical axis as shown on the left side of Figure 5.3). In this position, we must avoid the rays travelling to M1 and (more importantly) the converging rays from M1 to M2. We will retract the center of M3 to this position: a height of 267.16 mm above the elevation axis and radially offset by 759 mm from the optical axis, and at an angle $\alpha = 104.5$ degrees (where $\alpha = 45$ degrees is the deployed position and $\alpha = 90$ degrees is parallel to the optical axis). The result is no vignetting of the converging rays from M1 to M2 over the full 20 arcminute Cassegrain FOV.

Presently, there are two Cassegrain instruments commissioned on Keck I (with none additional currently planned): LRIS with a 6 arcminute x 8 arcminute FOV located 7 arcminute off-axis and MOSFIRE with an on-axis FOV of 6.14 arcminute x 6.14 arcminute. Each instrument has an off-axis guide camera. The rectangular fields of view of the science and guide cameras for LRIS and MOSFIRE generate rounded "footprints" normal to the optical axis that one must avoid to prevent vignetting (Figure 5.4). 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).

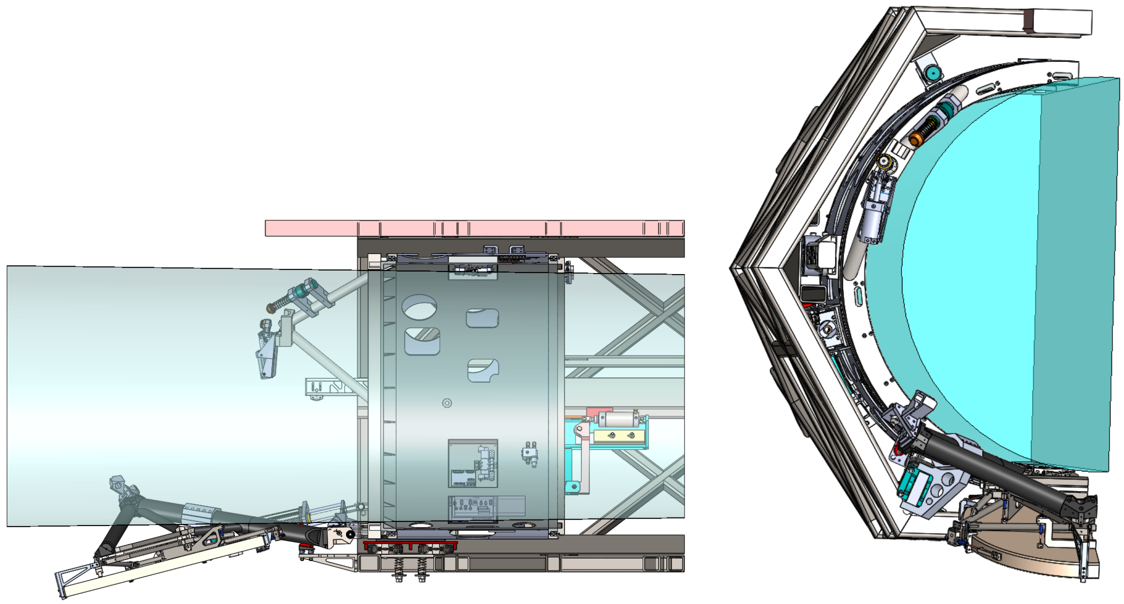

Figure 5.3: Two views of K1DM3 in the retracted position showing proximity of the M2 to Cassegrain beam footprint (colored shroud).

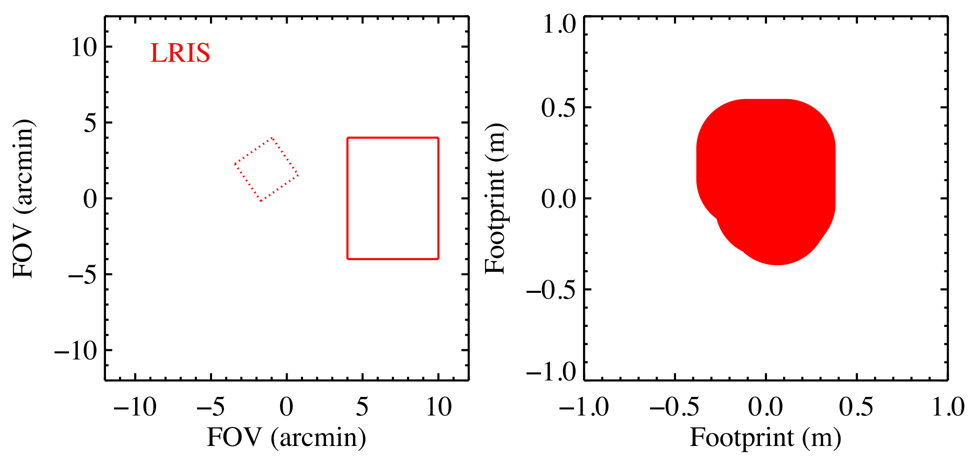

Figure 5.4: LRIS field of view for the science and guider cameras in the focal plane (left) and the footprint mapped at Z1 = 5 m above the primary mirror (elevation axis is 4 m above the primary). The latter was imported into SolidWorks to check whether K1DM3 vignettes LRIS when retracted.

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

Performance: The mirror design satisfies the optical requirements listed in § 3.1.1.

Risks and Mitigations: The sizing constraints imposed on the K1DM3 system are challenging and subject to the as-built dimensions of the Keck I telescope, but we are confident that the requirements are met by our design.

5.1.3 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 § 3.1.2.1, 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 alignment 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.

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. The activities to be performed at UCO are the same as described at PD and we do not repeat them here. We have, however, developed a new plan for the alignment effort at WMKO.

Table 5.1: Variables requiring matching during alignment

	Variables	**Number of Variables**
For one port:		
rotation axis	x,y,tip,tilt	4
mirror plane	z, tip, tilt	3
For 5 add'l ports:		
rotation	detent azimuth	5
		Total: 12

The concept of the alignment at WMKO is the same as at PDR - the goal is to align to the current M3 module. We assume (and will verify) that the oval K1DM3 mirror is properly centered and clocked for no vignetting. Only the plane of the mirror requires precision aligning, as well as the rotation axis and detents. The variables requiring an accurate solution are listed in Table 5.1. The steps are then:

1. We mount M3 and set an alignment telescope approximately on the rotation axis (as described below).
2. For each detent position (6 total), we mount a target (graph paper) and note the xy-position on the target using the alignment telescope. Each target then represents two observables (x,y on the target).
3. Replace M3 with K1DM3.
4. Repeat the observations for each detent using K1DM3 and the same alignment telescope.
5. Using the differences in the observed positions, solve for adjustments to the K1DM3 rotation axis and mirror plane.
6. Adjust the tower defining point mounts and/or deployable kinematics on K1DM3 (keeping in mind the effects of one adjustment on the others), and repeat steps 4-to-6 until desired accuracy is achieved.

In practice, this is not the most efficient procedure, because some variables are strongly coupled. In addition, note that for any one port, there are 7 degrees of freedom but only 2 observables - the input of all five additional ports is required to constrain the solution. Therefore:

- We plan to replace at least two of the targets with mirrors that have a tip-tilt adjustment in addition to a gridded reticle on their surfaces. These "gridded mirror" targets add two additional observables (the x-y of the collimator telescope reflection) each, raising our total observables to 16.
- We will align the rotation axis of K1DM3 to that of M3 as carefully as possible using the same procedure applied by the K1DM3 team to measure the alignment of the outer drum [4]. This process used a fixed gridded mirror on M3 to define its rotation axis (4 variables, 4 observables), as seen by a fixed alignment telescope on the rotation axis. Without moving the alignment telescope (and/or using crosshairs to verify/recover its location), we then observe the same mirror on K1DM3. Unlike with the outer drum alignment, only the one gridded mirror is needed since we will be able to rotate K1DM3 during this final alignment. We intend to make a number of modifications to the actual mechanical setup of the alignment telescope to improve stability. This initial alignment of the rotation axes will greatly improve the ease of the final alignment of the mirror planes.
- We will also do careful azimuthal placement of the K1DM3 rotation detents prior to arrival (i.e. at UCO).

At the time of the PDR, we envisioned using an Alignment Rig on the floor to hold both M3 and K1DM3. We realized that with the f/25 secondary (which has a central aperture) and a remotely-controlled alignment telescope (Davidson Model D-275-AAT), we could actually align K1DM3 in the telescope. This new approach has several pros and cons:

Pros:

- K1DM3 could be aligned at useful elevation angles. Its alignment could be verified at arbitrary elevation. In the other scheme, we would be aligning horizontally, and flexure differences could introduce errors relative to elevations for normal operation.
- We would be using the same kinematic mounts to the tower during alignment as will be used during operation.
- Cheaper than building a "simulated tower". (A mechanical mount for the alignment telescope at the f/25 secondary will be needed.)
- Cabling and control for M3 and K1DM3 would not need to be duplicated on the floor.

Cons:

- Scheduling difficulty: due to the need to change in-and-out not only M3 and K1DM3 but also the f/15 and f/25 secondaries, this would likely require us to give up one commissioning night so the f/25 secondary could remain on the telescope.
- Scheduling inflexibility: final alignment would be fixed in the telescope schedule, and there is some risk if things don't go according to plan.
- Access for gridded mirrors: it is unclear whether there is access for mounting a gridded mirror in front of the AO bench and/or HIRES. This is not crucial, but alignment is most critical for AO, and HIRES after that, so it makes sense to put these mirrors in those locations.

The required precision of alignment is discussed in §3.1.2.1 of the PDR Report. Briefly, the mirror tip/tilt requirement is 11.5 arcseconds, corresponding to 1 arcsecond on the sky or 0.73 mm in the focal plane. The targets are likely to be mounted a little closer to K1DM3 than the focal plane, so conservatively we could say 0.5 mm accuracy is required at the target. The piston requirement is 0.75mm along the optical axis, and this translates directly to image motion at the target. Model D-275 alignment telescopes have a resolution of 5 arcseconds, corresponding to ~ 0.3 mm at the distance from the f/25 secondary to the targets, so the required measurement precision at the targets should be just achievable. Repeated observations, and the fact that the number of observables is greater than the degrees of freedom can be used to estimate the precision with which we have established the matching of each variable.

5.1.4 Coating of the K1DM3 Mirror

The going-in position from the PDR is that the K1DM3 mirror would be delivered bare to WMKO, where it would be coated with Aluminum in the WMKO coating chamber. We now consider this the default option. A detailed coating plan with appropriate fixturing and handling has been developed for in-house aluminizing [7]. We have recently received quotes for the fabrication of the “mirror grabber” and “flip fixture” that would be required. These are included in the budget to completion.

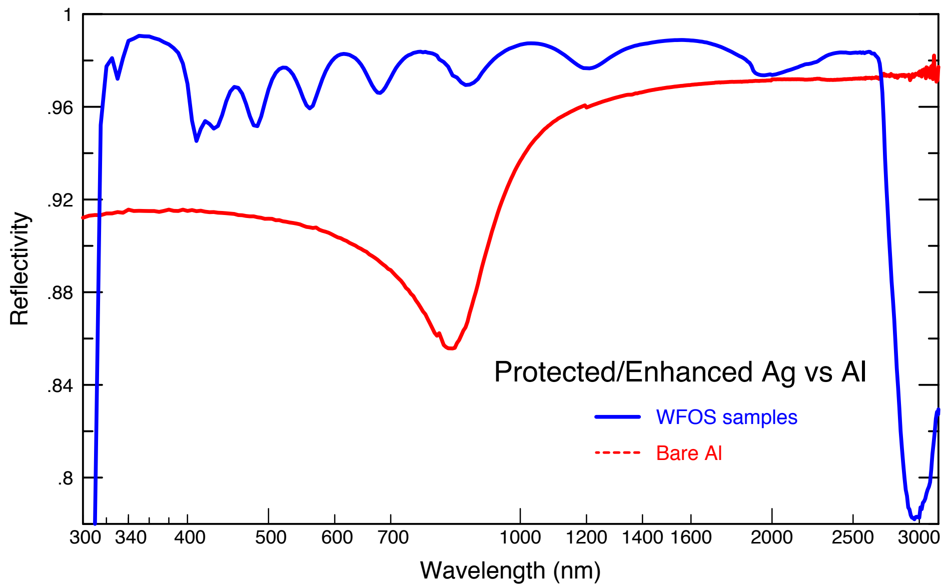

Figure 5.5: Comparison of a protected/enhanced Ag-based coating (a proposed WFOS coating) with fresh bare Al. This is near-normal incidence; the coating layers would need "tuning" for 45-deg incidence.

Since the PDR, it has been argued that we can improve throughput and possibly longevity by using a multi-layer-protected silver coating, along the lines of the LLNL coating used on the LRIS collimator. We have investigated this somewhat. The potential gains over bare aluminum are modest but significant. In Figure 5.5, we show measured curves for bare Al vs. a measured coating suggested for the TMT WFOS collimator; the gains are significant, particularly in the range 600-1000 nm. Note that these curves are for near-normal incidence, and the multi-layer coating would need "tuning" for the 45-degree incidence angle. We have requested a similar design from ZeCoat Corp, but modeled at 45-degree; this is shown in Figure 5.6. It looks quite similar to the WFOS coating, with minimum reflectivity of ~ 95% in the dips, and typical reflectivity of ~ 96.5% throughout.

Using a multi-layer Ag-based coating has disadvantages that offset the improved performance:

- Higher cost (ZeCoat estimates $42K, which includes $5K for tooling and $2K materials, so future recoating should be approximately $37K);
- The shipping of the mirror carries some risk;
- K1DM3 would be unavailable for one month or greater during an off-site recoat (although the existing M3 module could be used during this time).

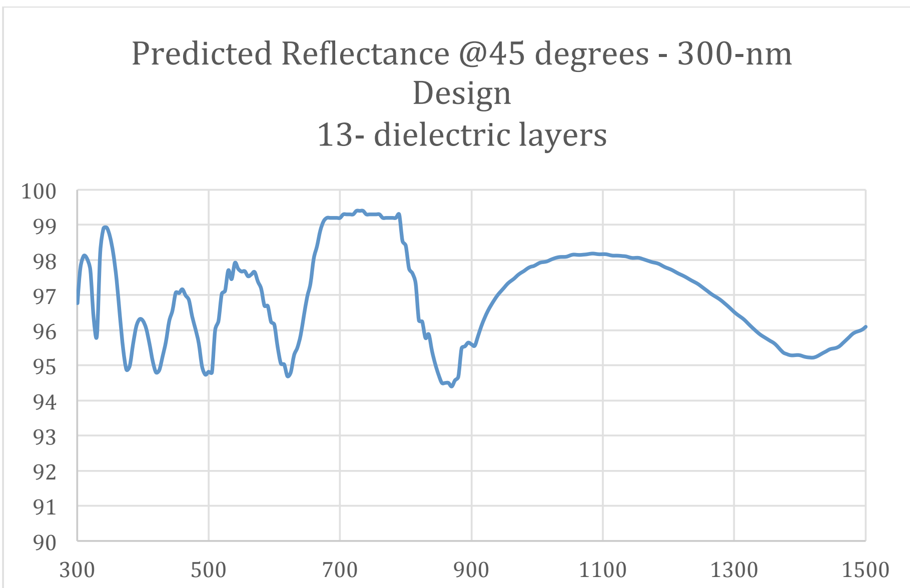

Figure 5.6: Predicted reflectivity of the ZeCoat design at 45-degree incident angle.

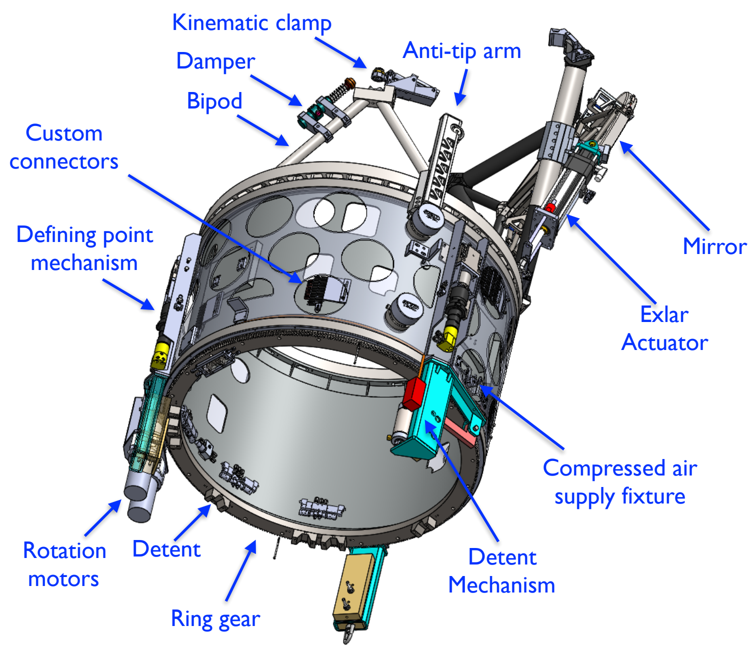

Figure 5.7: K1DM3 module as viewed from below, with callouts. See Figure 2.3 for a view from above.

5.2 Mechanical Design

The DD mechanical design is described in the following sections. Figure 5.7 shows an overview of the K1DM3 module with callouts for the major components. These figures provide a useful reference to the module as its key design features are discussed.

5.2.1 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 (swing arm) 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, have 60 mm free length, and will be made of AISI M2 steel. The pucks are Invar and will be glued with an epoxy adhesive. The axial rods are screwed into the pucks. The layout of these six axial support rods is shown in Figure 5.8. The positions for the rods were determined from finite element analysis (FEA) to minimize the deflections of the mirror normal to its surface. These were updated from PDR to reflect the final dimensions 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 5.9). These rods are 125 mm free-length and 3.0 mm in diameter, and are AISI M2 steel. These use pucks designed for the curvature at the points of fixture. Their sizes were designed to insure a less than 15 micron difference in the glue thickness across the surface. This yields 130 PSI (static) and 655 PSI (dynamic) of stress in the bonds and glass. These stresses are significantly smaller than the estimated 3000 PSI of stress that the bonds can endure. They are also significantly smaller than the 1000 PSI (static) and 8000 PSI (dynamic) limits that we wish to maintain for Zerodur.

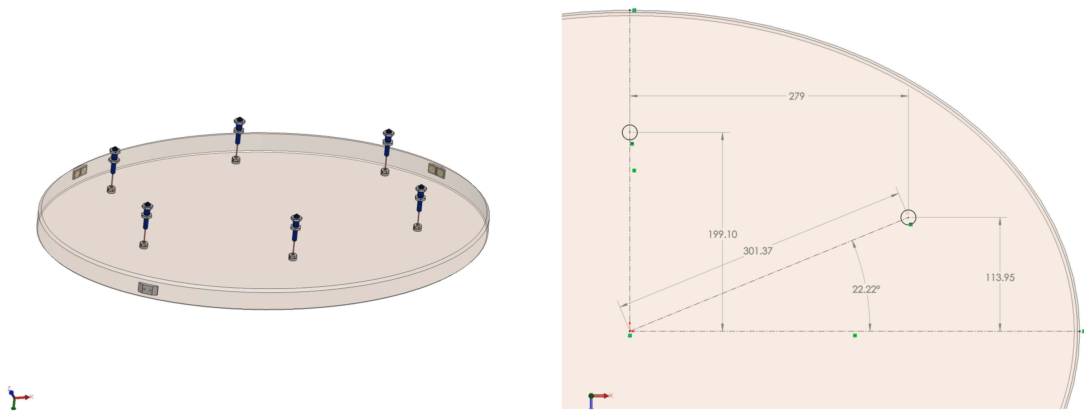

Figure 5.8: The left CAD image shows the six axial support rods attached to the back of the K1DM3 mirror. The diagram on right shows the placement of two of the rods indicated by open circles. The measurements are referenced from the major and minor semi-axes of the mirror.

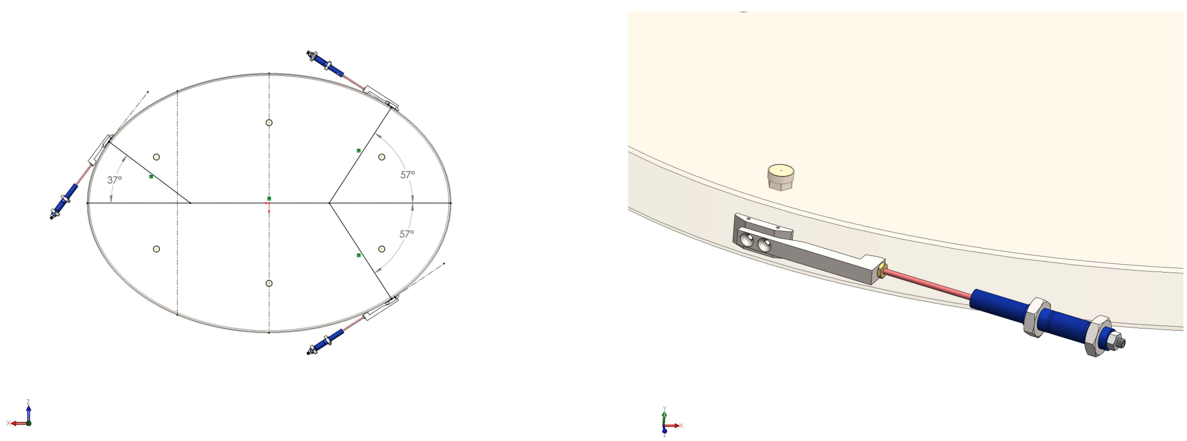

Figure 5.9: Left diagram shows the placement of the three lateral supports along the outside edge of the mirror. Right image is a close-up view of one of the lateral supports screwed to a puck that is glued to the edge of the mirror.

The axial and lateral rods are integrated within a whiffle-tree support system, shown in Figure 5.10. The whiffle tree uses 0.75 inch diameter struts (5/32 inches thick) in a determinate truss pattern. It allows the Mirror Assembly to be bolted to the Deployment System and then removed for re-coating. The total mass of the Mirror Assembly including the mirror is estimated to be 70 kg.

The mirror assembly includes three kinematic fixtures (0.5 meter radius spheres in v-grooves) that interface it with the swing arm assembly (Figure 5.11). This allows one to remove the mirror assembly from the K1DM3 system for coating. It then enables one to repeatably and precisely reattach the mirror assembly to the swing arm assembly. The design also allows for fine adjustment of the kinematics during the alignment phase.

We have designed an earthquake restraint system consisting of 6 “clamps” affixed to the mirror and the whiffle tree truss system (Figure 5.12). These are spaced approximately evenly around the circumference (Figure 5.10). They are made of Aluminum with Teflon pads positioned in normal operations with a gap (i.e. not touching the mirror). These are designed to take the static load of the mirror assembly in the event that the glue bonds fail during an earthquake.

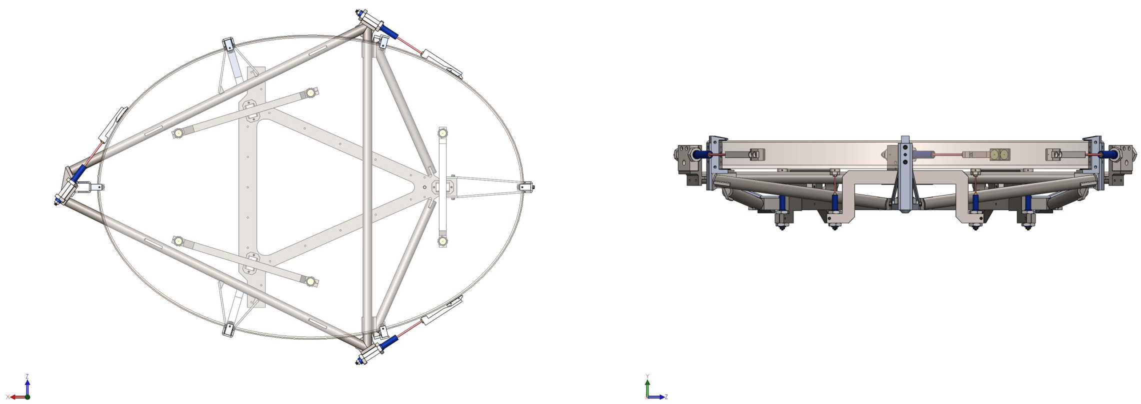

Figure 5.10: Top and side views of the whiffle-tree support structure for K1DM3.

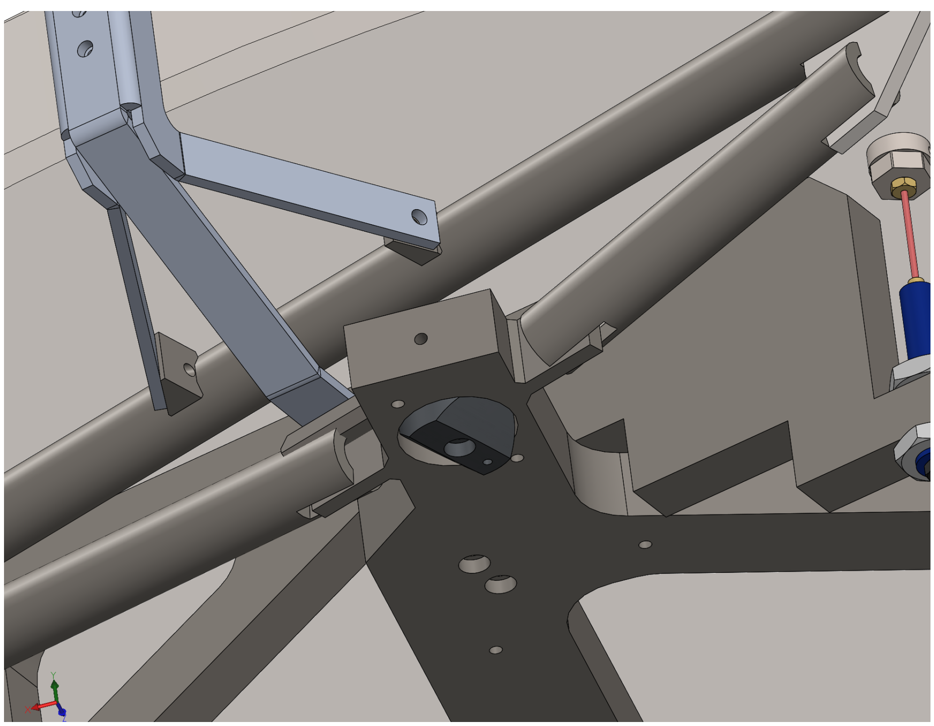

Figure 5.11: At the center of the image is the kinematic coupling (sphere) for attaching the mirror assembly to the swing arm assembly.

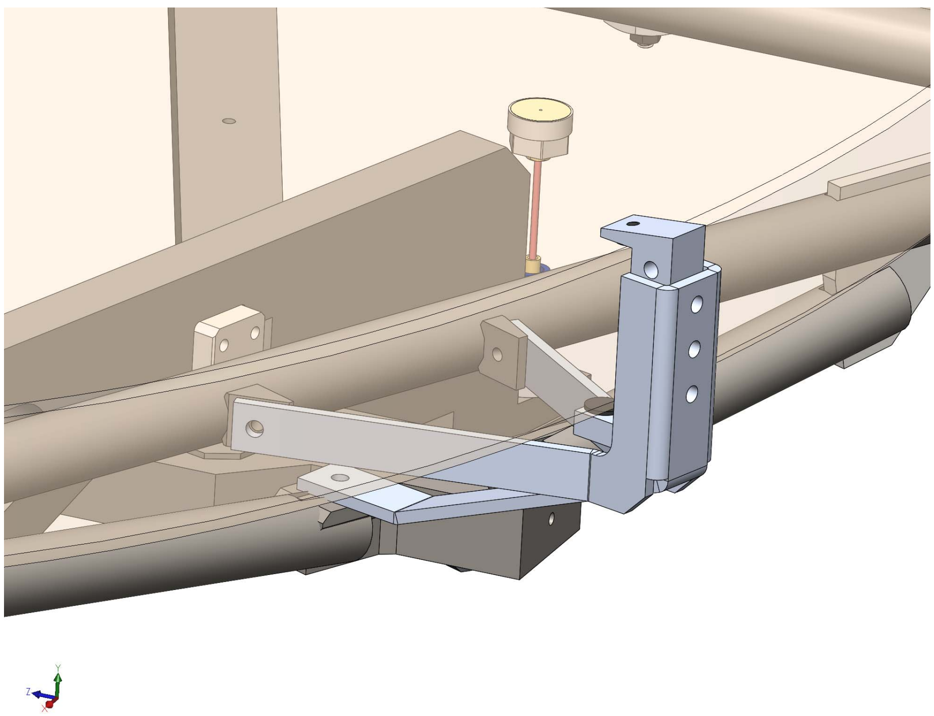

Figure 5.12: Earthquake restraint system (blue material) which will support the K1DM3 mirror in the event that its glue bonds fail. The restraint otherwise does not touch the glass.

Design Analysis:

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

Our first efforts reduced the previous M3 support structure design to six axial rods and lateral support assembly similar to that of the current M3. We believe this satisfied all requirements related to mirror stability. 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.

FEA Modeling:

The positioning of the axial rods was optimized iteratively in a series of FEA models processed with ANSYS. The modeling and static deflection analysis was performed with traditional 3D, 20-node brick elements which yield displacements (3 degrees of freedom) at the nodal locations. To obtain slopes (rotations) and reasonable statistics, the surface deformations of the top surface were mapped to a denser and uniform shell model. Results of this second model provided the surface slopes (and deflections) over a uniformly distributed surface. These results were exported to Excel for easy processing to obtain statistical values (max, min, rms, etc.). When possible, we constructed 1/4 and 1/2 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.

We implemented a mesh geometry for an ANSYS model of the current design. The model assumes the mirror properties described in § 5.1.1.

Figure 5.13 is a deflection contour map of displacement (nm) normal to the surface. The load is gravity normal to the mirror surface. This is the most severe loading condition encountered by the mirror during normal operating conditions. The peak-to-valley displacement is approximately 124 nm with an rms of 29 nm.

A pseudo spot diagram shown in Figure 5.14 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 5.13) 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.

CTE:

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

Vibrational Analysis:

A full description of the vibrational analysis is given in the next section where we consider the combined mirror and swing arm assemblies.

Deformation Summary:

The error budget for the mirror is shown in Table 5.2. 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:

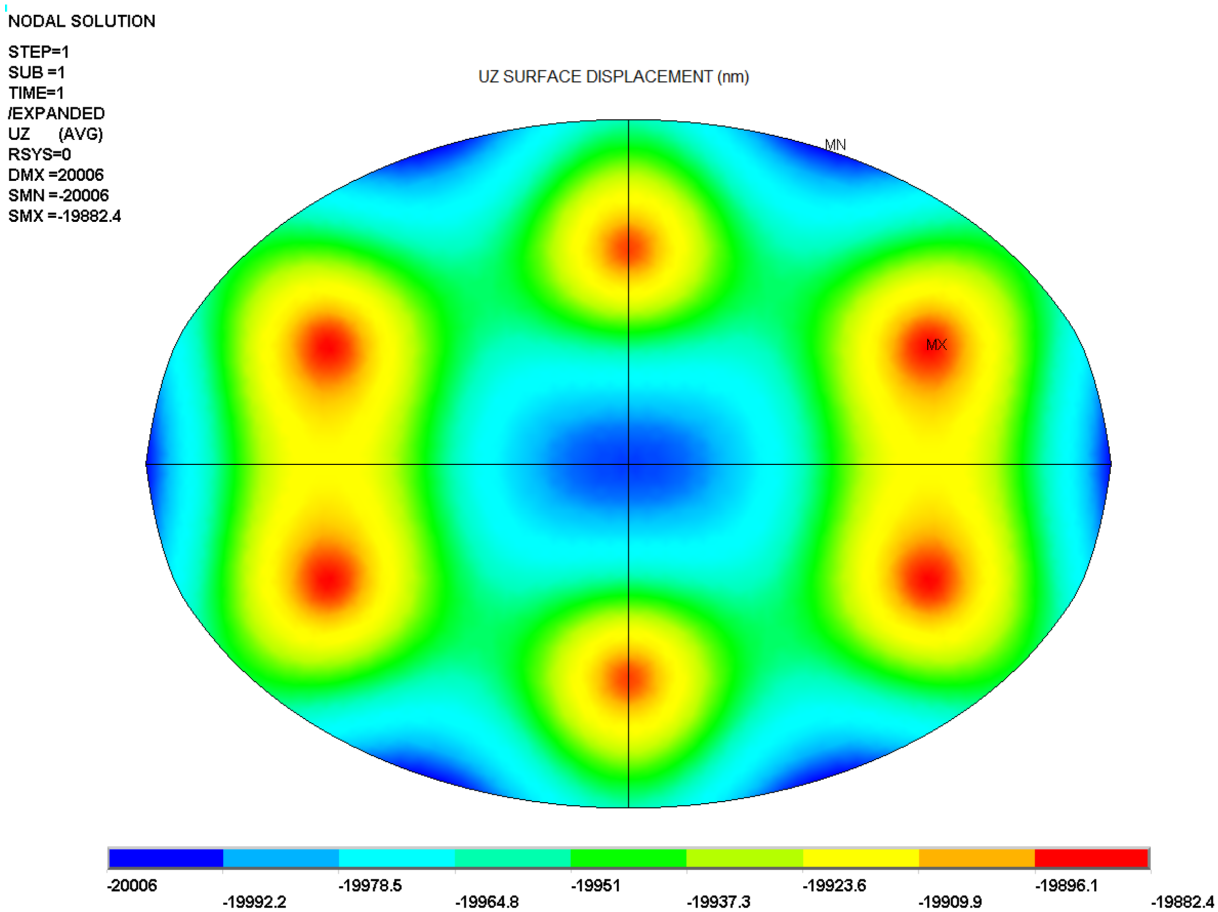

Figure 5.13: Surface deformation map for the six point support system due to gravity normal to the mirror. Deflections are in meters. The contour map is for the entire mirror surface. The peak to valley range is 124 nm. Rms deflection of the entire surface is 39 nm.

$$Maximum\ permissible\ rotation = \sqrt{\theta_x^2 + 2 * \theta_y^2} = 1.68 \times 10^{-6} \text{ radians} \tag{5.1}$$

Table 5.2 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 through 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 refer to a 1N load in plane 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.

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.

The subtotal listed in Table 5.2, which is the quadrature sum of the error terms, is well below the maximum allowed value. Therefore, the support system satisfies the requirement.

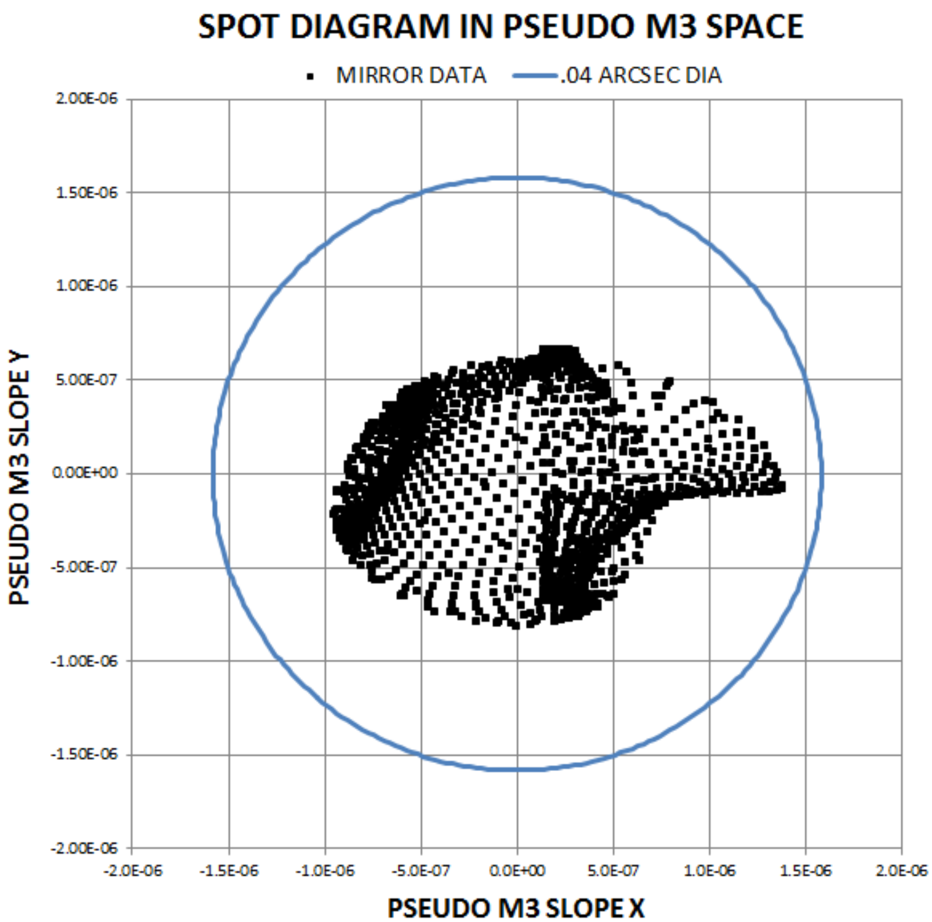

Figure 5.14: Spot diagram of based on results shown in Figure 5.13. This diagram represents where light reflected by the mirror would strike the focal plane. The image is a family of points which are calculated based on the slope error throughout the mirror. If the mirror were undeformed (perfectly flat) 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 arcseconds in diameter. The image spread for this case is well within the tolerance.

Table 5.2: Mirror Deformation Error Budget

Item	**Combined Error** (radians)	**Comments**
Polishing	4.85E-7	Based up as-built surface measurement data; still conservative
Support design	4.85E-7	Largest gravity normal to mirror
CTE Axial	2.73E-8	Glue & pucks
CTE Lateral	1.33E-9	Glue & pucks
Fab errors axial	1.06E-8	1N force error allowed in plane of mirror
Axial pivot error	4.00E-8	1 mm error in pivot location
Fab error axial moments	1.35E-7	0.2 N-m moment allowed
Fab errors lateral	8.07E-8	1 N force error allowed
Fab error lateral moments	1.06E-7	0.2 N-m moment allowed
SUBTOTAL	7.13E-7	In quadrature
CUSHION	9.67E-7	
TOTAL	1.68E-6	Maximum allowed

Kinematic Fixtures:

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

Gluing:

A critical aspect of the mirror assembly is the gluing of the lateral and axial support pucks to the glass. The project has chosen to rely on the extensive expertise of WMKO for this process. Their staff has performed extensive research [8, 9, 10, 11, 12, 13, 14] into adhesive selection, application, and strength performance testing which resulted in their choice of the preferred gluing agent (Hysol Loctite E-120HP), finding that it performed well in strength tests and is substantially easier to mix and apply. It will be necessary to etch the glass with a solution produced by Schott prior to gluing, which follows a rigorous cleaning and surface preparation regimen.

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

Earthquake restraints:

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

<u>Fabrication:</u>

- The whiffle tree assembly (mirror support frame) will be cut and welded by an external vendor. We have received a quotes on our design from Tapemation and Martinez & Turek, Inc.. The delivery time is estimated at 8 weeks.
- We will purchase the kinematics from Motion Industries.
- UCO will fabricate the rods and pucks.
- UCO will fabricate the earthquake restraints
- Gluing of the pucks to the glass will be performed by the mirror segment repair lab at WMKO, led by D. McBride.

<u>Risks and Mitigations:</u>

- Adhesion strength – The design effort at WMKO has been focused on the mirror segment repair and has not specifically considered the K1DM3 project. We will perform our own stress tests with the proposed adhesion process using test samples at UCO.
- Adhesion schedule – Gluing at WMKO bears the risk of schedule delay as priority may be given to the segment repair activity. We will endeavor to schedule the K1DM3 effort during an optimal time for that project.
- 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.

5.2.2 Mirror Deployment Design

<u>Design Description:</u>

The K1DM3 system is designed to deploy and retract its mirror upon software command. In the following, we describe the parts critical to the actuation of K1DM3 with the exception of details on the bipods and kinematic couplings that position the assembly during deployment. Those are discussed in § 5.2.3.

The Mirror Assembly described in the previous section will fasten to a tripod swing arm fabricated with ASTM-A36 steel. Figure 5.15 illustrates the shape and overall dimensions of this part. It is a weldment of several steel members with varying diameter designed to maintain rigidity while minimizing profile. At the end points of the main arms are the kinematic couplings (canoe spheres made by Baltec, division of Micro Surface Engineering, Inc.) that enable repeatable, precise positioning of the system. This swing arm is attached to a pivot on the top ring of the K1DM3 module. This pivot is compliant (≈ 1 mm) to allow the kinematic coupling to determine the deployed position of the mirror. The pivot mechanism consists of a shoulder screw that is supported by two spherical-rolling element bearings, each supported by O-rings. (see Figure 5.16).

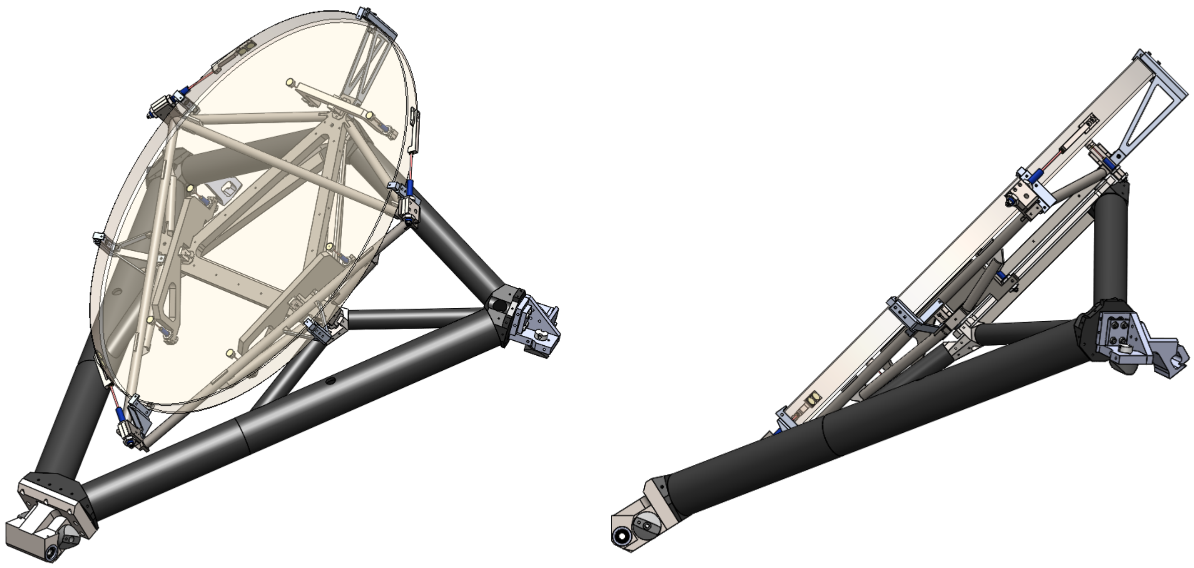

Figure 5.15: Perspective and side views of the mirror support swing arm.

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. To minimize their profile, we will remove a set of unnecessary parts standard to the Exlar actuator. We have tested this modified actuator in the UCO lab and have verified that performance is nominal.

Design Analysis:

Motor torque: The two linear actuators need sufficient torque to deploy and retract the Actuation assembly and Mirror assembly under gravity. The required torque will be less at the elevation angle designed for deployment (68 degrees) and at the nominal drum rotation angle of 90 degrees (where 0 degrees faces K1DM3 towards the AO system), but we have calculated the torque required assuming a worst-case configuration. Specifically, this implies a force of 6860 N. Each of the linear actuators has a manufacturer reported force of 9450 N. We therefore expect the system can be actuated with even a single actuator.

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 at any rotation angle of the K1DM3 module (e.g. Acme screw presenters, forward baffle mounts). The current design satisfies all of these constraints.

FEA analysis: FEA models were made of the mirror assembly attached to the swing arm and connected to the bipods. This led to an iterative process for the design of the placement, size, and material of the swing arm struts.

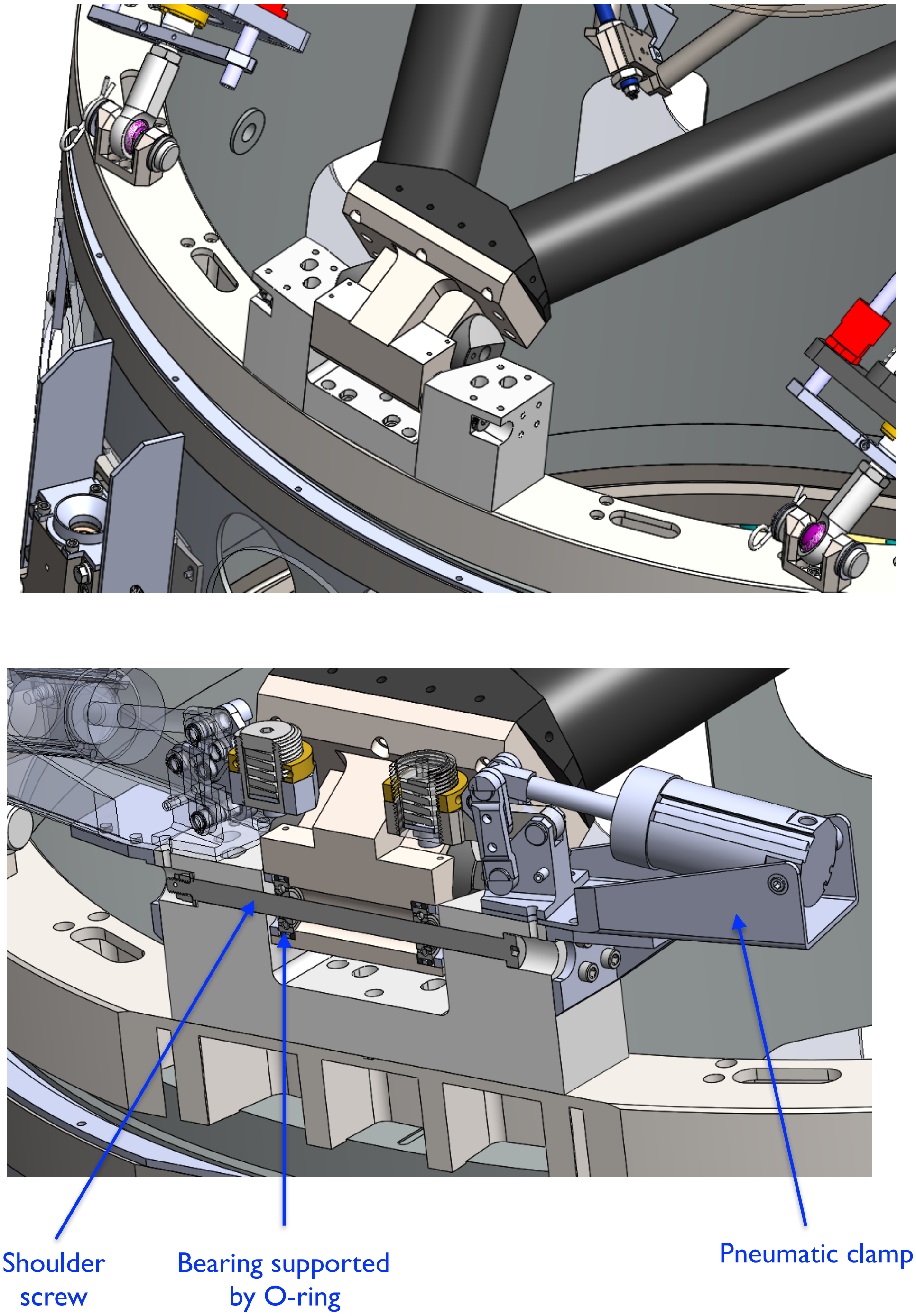

Figure 5.16: (Top) View of the swing arm pivot. (Bottom) View of the pivot in cross-section, and with the kinematic clamps.

Figure 5.17 shows the FEA model. This model more accurately represents the mirror with its support by the axial and lateral flex rods. The swing arm structure was modeled as a series of beams with full elastic properties reflecting the materials of construction. The kinematic restraints at the v-groove are modeled as pin connections. The bases of the bipods, which connect to the upper ring, are fixed to ground. The pivot is also included.

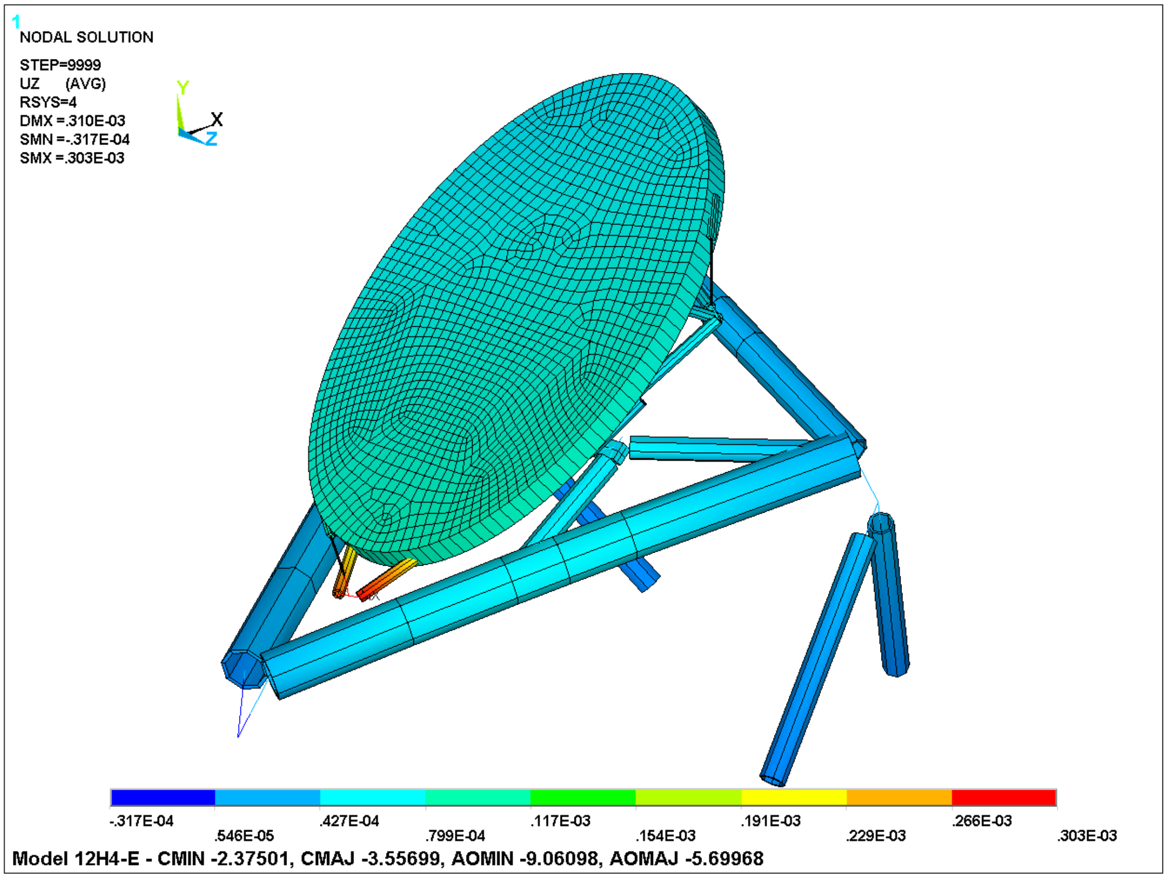

Figure 5.17: FEA model of the combined swing arm and mirror assembly.

Extensive analysis of the deformation of the mirror surface has been conducted by independent analysis covered earlier. The purpose of the model and analysis described here is to determine the performance of the supporting structure and rigid body displacement and rotation of the mirror.

We then measured the deflections in the mirror from nominal position (telescope pointed at Zenith) for the extreme case of observing at 72 degrees off Zenith. Results of the static gravity cases are shown in Table 5.3. 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. These values are satisfy the requirements for positioning and repeatability of the mirror.

Table 5.3: Out of plane displacement and rotations to due gravity for the mirror when observing at 72 degrees off Zenith.

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

Vibrational analysis:

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

There are two particular requirements that the K1DM3 design must satisfy regarding vibrations and the stresses that result:

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

We examined the predicted performance of the current K1DM3 design in a range of environments. Specifically, the K1DM3 team was provided a set of forcing functions that are intended to describe the random motions as a function of frequency that the module would experience in three conditions: (1) during transportation; (2) during handling at WMKO (e.g. installation, removal for coating); (3) during normal operations when installed on the telescope. These three functions are illustrated in Figure 5.18, presented as power spectral density (PSD) curves as a function of frequency. As one would expect, the transportation function presents the most severe motions with PSD amplitudes many orders-of-magnitude higher than standard operation conditions.

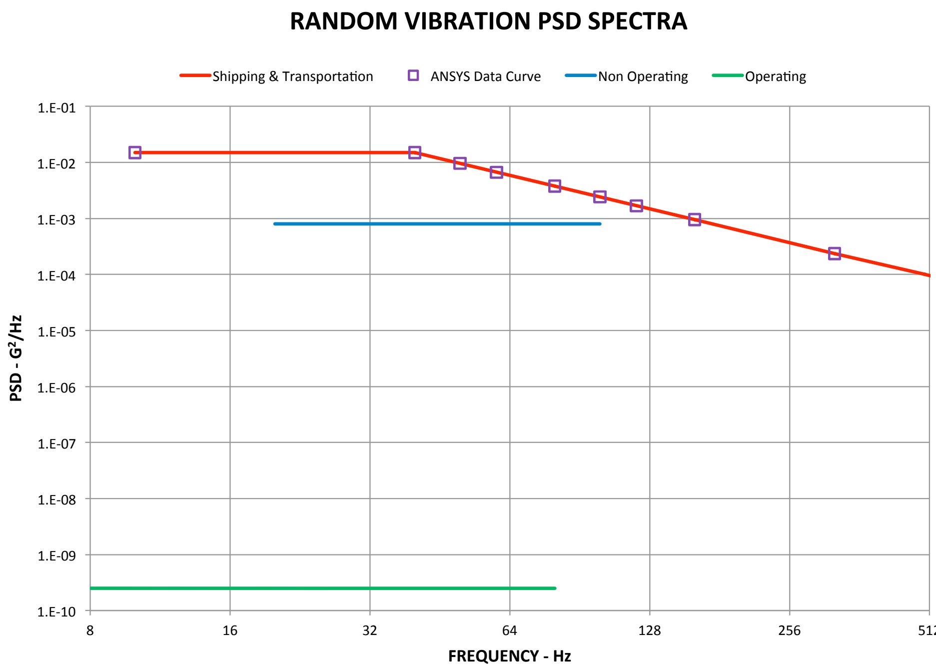

Figure 5.18: PSD spectra used for the vibrational analysis of the K1DM3 design. There are three separate functions for (i) transportation; (ii) handling at WMKO; and (iii) normal operations of K1DM3 on the telescope.

Table 5.4 summarizes the results of our vibrational analysis for mirror stress (see [15] for further details and analysis). Not surprisingly, the stresses on the mirror during transportation would nearly exceed our 500 PSI limit. We will design the shipping crate and packing materials to reduce the stress to tolerable levels.

Regarding normal operations when deployed, we estimate 0.3 arcseconds (rms) of tilt and tip motions and 1 micron of translation. The stress of 0.1 PSI is far within tolerance and we predict maximum accelerations of less than 0.05 g.

The forcing function provided by WMKO for handling also yield acceptable, maximum stresses. on the mirror assembly. The K1DM3 team, however, was concerned that this forcing function was overly pessimistic. We therefore decided to monitor the stresses incurred by current M3 module during installation and removal. Indeed, the accelerations measured are only approximately 3G which would give acceptable stresses (with a significant safety factor) to the mirror assembly. Nevertheless, the procedures developed for handling K1DM3 will demand special care to insure its safety. And, we note that K1DM3 – unlike the current M3 module – is only intended to be handled very rarely, i.e. for re-coating once every several years.

Table 5.4: Results of vibrational analysis

Mode	Condition	Max. Stress (PSI)
Deployed	Transportation	444
Deployed	Handling	163
Deployed	Observing	0.1
Retracted	Transportation	860
Retracted	Handling	215

Vignetting: § 5.1.2 provides a discussion of vignetting of the beam by K1DM3. Figure 5.3 shows that neither the struts nor the retracted mirror vignettes the LRIS or MOSFIRE footprints. We are required, however, to rotate the mirror to face one corner of the hexagonal face of the tertiary tower to avoid the beam from M2 to M1 (when the secondary baffle is not installed). This is the nominal parking position for K1DM3 when retracted. We discuss additional issues related to tower clearance below.

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

Our goal has been to limit the effects from thermal expansion to be the same or less than those experienced by the current M3 system. The key to reducing the sensitivity is to pick materials with coefficients of thermal expansion that match the rest of the telescope structure. The predominant material used in the telescope structure is ASTM-A36 steel which has a CTE of 11.7 ppm/ degrees C. This material and material with very similar CTEs have been selected for the K1DM3 design (see Table 5.5). We estimate that there will be an approximately 12 mm change in the height of the struts, but all three will move together maintaining the geometry.

Table 5.5: List of materials used for K1DM3 and their coefficients of thermal expansion (CTE)

Material	Use	CTE (ppm/deg 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

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

Tower clearance: To avoid vignetting in certain configurations of the M2 baffles, we must rotate the K1DM3 mirror when retracted to the parking position indicated in Figure 5.19. During DD, WMKO approved and executed the removal of the forward baffle tracks on the K1 tertiary tower. This reduced the potential for interference between K1DM3 and the tower. The only remaining source of significant, potential interference are the Acme screw presenters associated with the tower defining points. We have modeled in SolidWorks the top of the tertiary tower using the WMKO drawings and measurements by our team during DD. We have also modeled the three mechanisms for the telescope half of the tertiary module/K1DM3 defining points that are located 659.5 mm from the optical axis, 35 mm diameter in diameter, and extend 100 mm above the tower.

We then confirmed using SolidWorks that the swing arm assembly of the K1DM3 design clears all of these obstructions when rotating to the parking position. This required us to reduce the profile of the Exlar actuators and use a clever orientation for mounting these devices (e.g. Figure 2.3). There is a potential interference with the magnetic switches on the cylinders (Figure 5.19, right) which may require us to rotate these prior to installation of K1DM3.

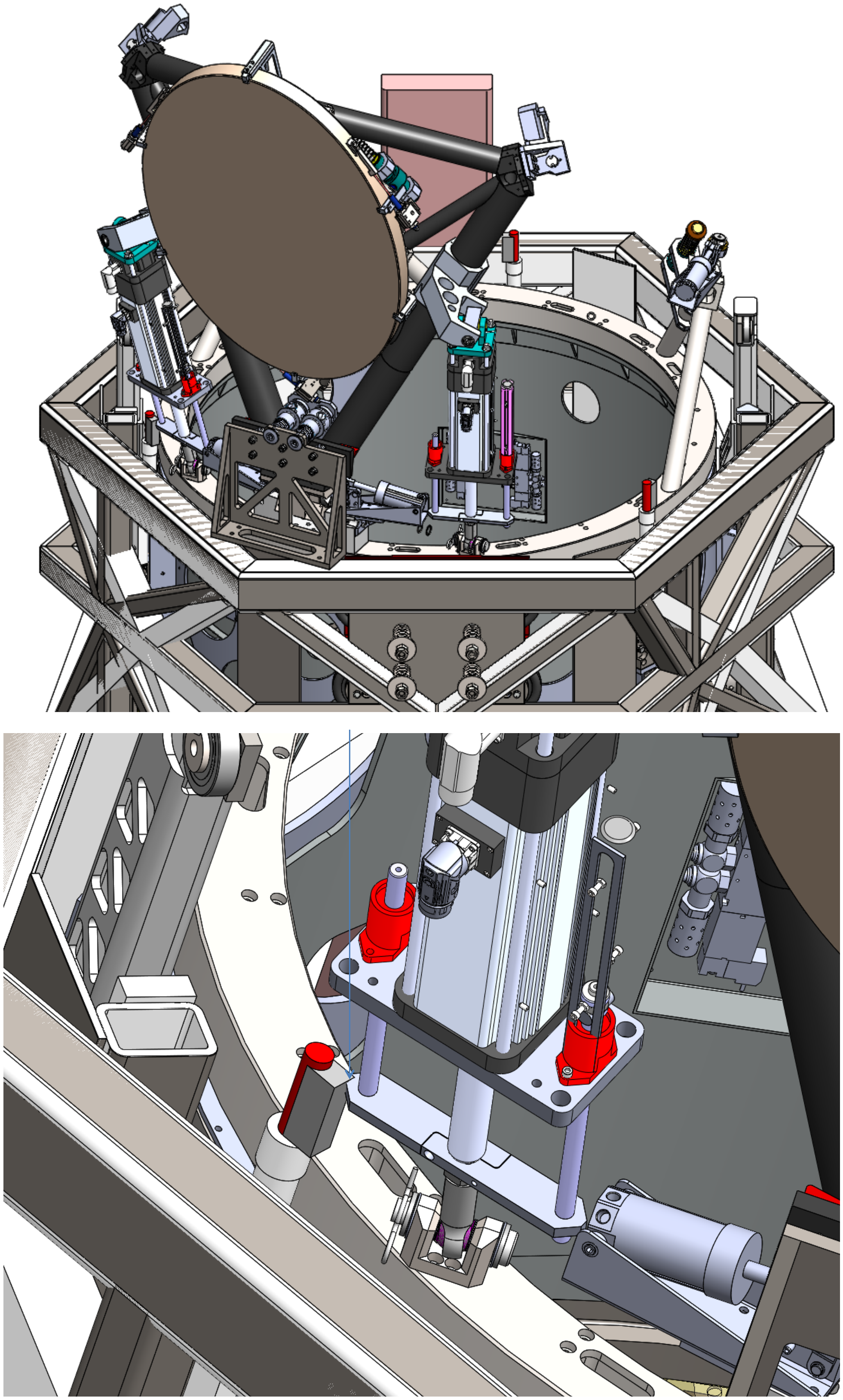

Figure 5.19: (left) Parking position of the K1DM3 mirror when retracted. In this position, no portion of the assemblies vignettes the light traveling to the Cassegrain instruments nor the light from M1 to M2. (right) Zoom in on potential interference between K1DM3 and the magnetic switch on one of the Acme screw presenters of the DMP system. We may need to rotate these switches to avoid interference.

Prototyping:

We have constructed a prototype swing arm assembly at UCO for testing the linear actuation and the kinematic couplings (next section).

Fabrication:

- Swing arm: The swing arm weldment will be cut and welded by an external vendor. We have received quotes from Tapemation and Martinez & Turek, Inc.
- Actuators: Both actuators have been purchased from Exlar.
- Pivot: The pivot will be manufactured by UCO.

Risks and Mitigations:

- Actuation failure – In the event that the actuation K1DM3 fails (e.g. loss of one or more actuators), we have developed a procedure that allows for the manual deployment of K1DM3. One can then remove the module from the tertiary for maintenance (see [16] for details).

5.2.3 Upper Assembly Design

Design Description:

Upper ring: At the top of the two drums is an upper ring (structural steel) which supports the swing arm (described in § 5.2.4). This part has an inner diameter of 1104 mm, an outer diameter of 1240 mm, and is 56.4 mm wide. It is manufactured with a recess that centers it on the inner drum.

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

As a safety measure, we will attach an Enidine damper to each of the bipod struts to "catch" the swing arm assembly in the event of a major software or hardware failure. This will insure that the kinematics engage with the swing arm moving at a speed of less than 10 mm per second. Figure 5.20 shows the designed damper system.

Deploy kinematics (DKs): We will employ 3 sets of canoe-sphere/v-groove fixtures (Figure 5.21) in the kinematic coupling used for positioning the K1DM3 mirror when deployed. The canoe spheres will have a radius of 500 mm. Two of these are mounted at the ends of the swing arm and the third is mounted on the under-side of the swing arm at approximately 44 mm from the pivot point.

The v-grooves will be 25.4 mm wide and 49 mm long. Two of these will be held at the ends of the bipod struts in a common plane. The third v-groove is mounted to the end of the pivot mechanism for the swing arm. Its axis lies in a plane parallel to that defined by the struts but offset by 655 mm.

All of the DK fixtures will be made with 440 stainless steel, polished to 0.2 micrometer rms roughness, and plated with chromium nitride and tungsten di-sulfide (WS_2). The former is to prevent rust and the latter is to achieve a low coefficient of friction.

Clamps: When engaged the DKs will be clamped with a pneumatic clamping mechanism that maintains 1500 N of sustained forced on each canoe sphere/v-block interface (Figure 5.20). There is 1 clamp on each bipod strut and a pair at the pivot (Figure 5.16). These air actuated mechanisms will be controlled via a solenoid valve which holds the coupling in place even with a loss of air pressure. It will be important for the actuation assembly to bring the kinematic fixtures in close contact, but this pneumatic mechanism will be relied upon to fully engage the coupling. Feedback switches will be provided to verify that each clamp is open or closed.

Design Analysis:

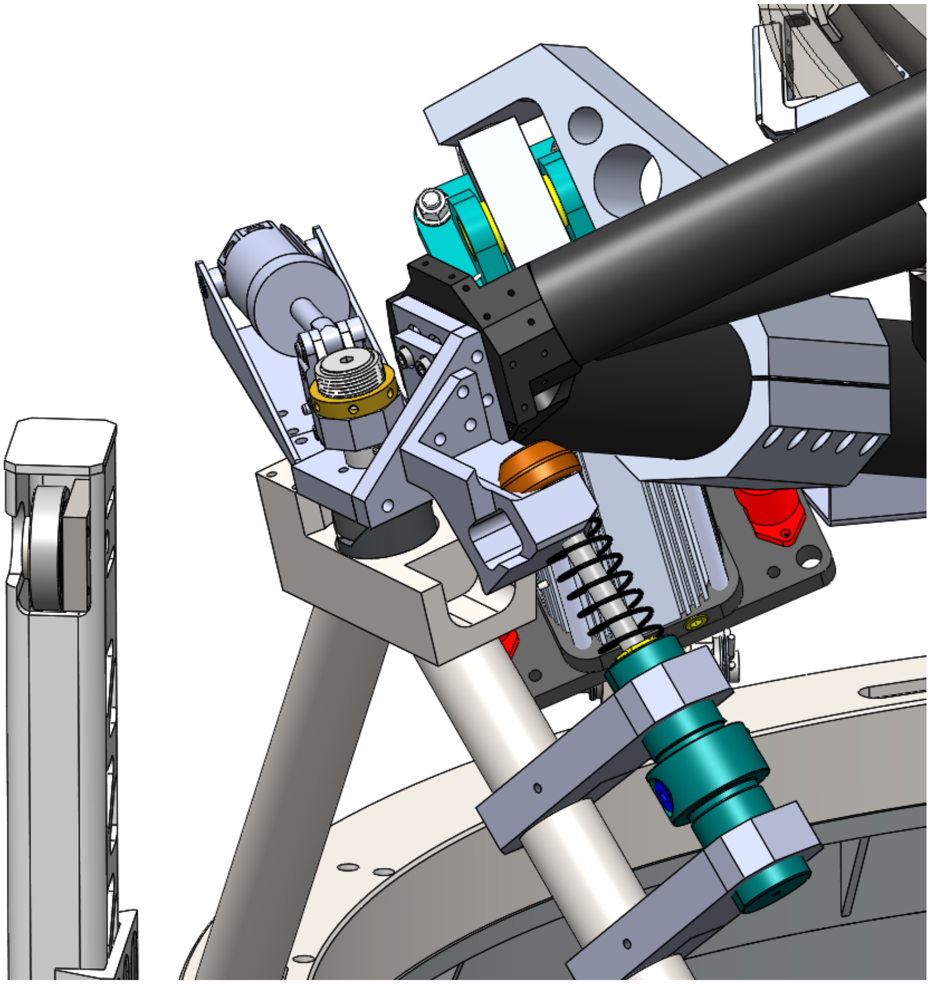

Figure 5.20: In the foreground, one views the damper attached to the bipod strut which will slow the K1DM3 swing arm in the event of a failure of the actuators. The clamp mechanism which holds tight the kinematic coupling at the top of the bipod struts is also shown.

Deploy Kinematics (DKs): After studying the standard reference on kinematic couplings [17], we decided on a canoe-sphere/v-groove coupling system for the DKs. These have advantages over the more traditional cone-flat-groove couplings. We then researched vendors that manufacture these fixtures and selected Baltec. We have analytically estimated the precision for repeatable positioning as described in [2].

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

Clamping:

For positional stability, each DK will be clamped with a sustained force of 1500 N by a clamping mechanism (Figure 5.20). We estimate less than 1.0 microns of motion with any change of gravity. This satisfies the requirements on stability.

Damper system:

We selected a set of Enidine damper devices (OEMXT 1.5Mx3) that have a damping force that will slow the K1DM3 swing arm assembly to less than 10 mm per second in the event of a complete loss of the actuators. This speed was estimated assuming the total weight of the swing arm assembly is borne by the dampers. These were also chosen

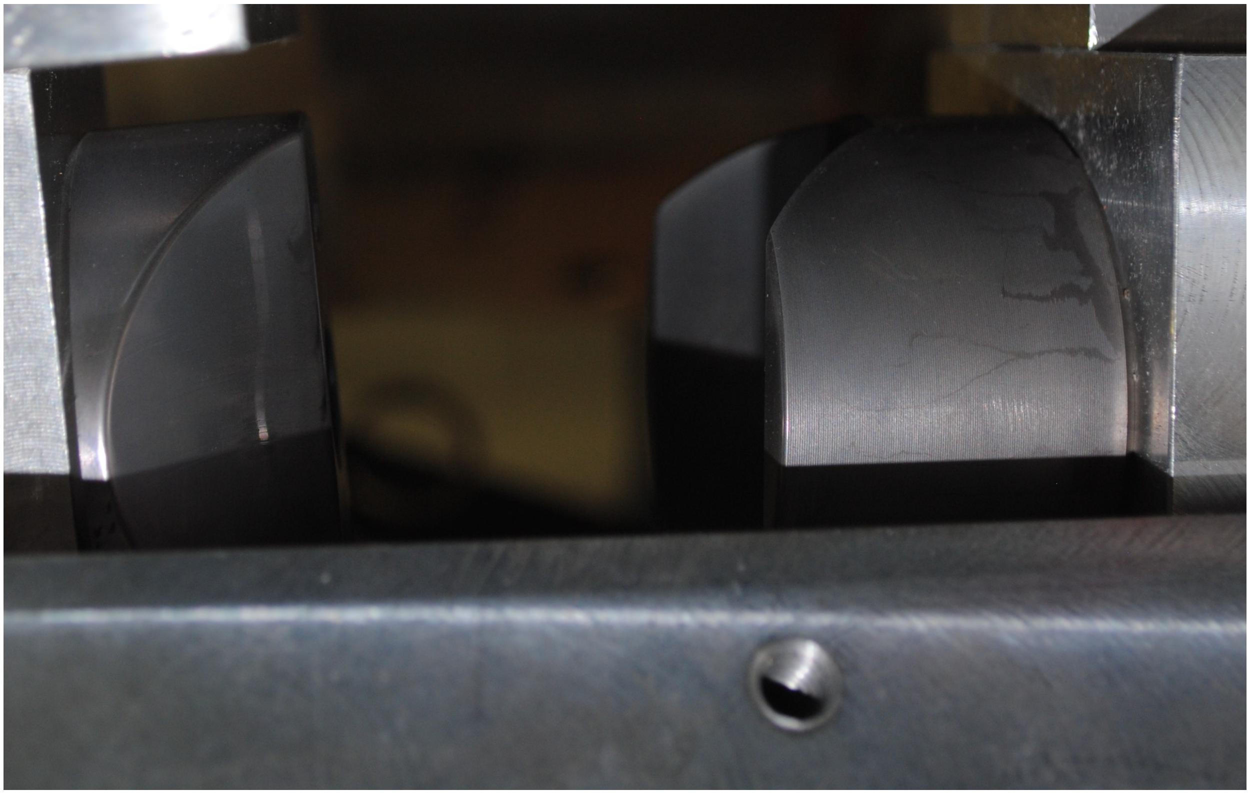

Figure 5.21: Photo of the existing canoe-sphere/v-grove couplings for the K1DM3 deploy kinematics installed on the prototype testbed.

because of their small profile, i.e. to avoid vignetting the light path.

Prototyping:

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

Fabrication:

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

Risks and Mitigations:

- 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 have plated the fixtures with CrN and WS_2. We will test their resistance to environmental conditions in the next phase.

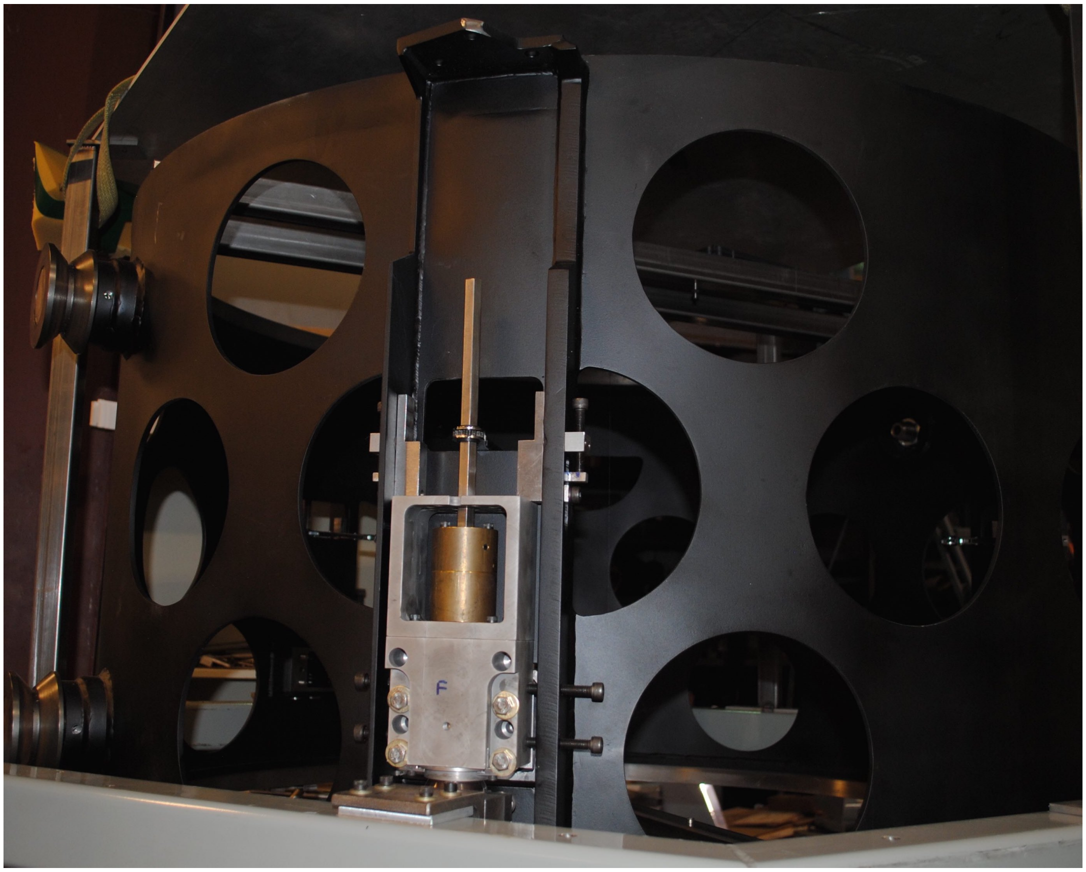

Figure 5.22: Photo of the fabricated outer drum for K1DM3 (at UCO).

5.2.4 Drum Assembly Design

<u>Design Description:</u>

Outer drum:

The backbone of the K1DM3 system is an ASTM A36 steel drum, 1/4 inch rolled plated precision machined to have an outer diameter of 1240 mm. The drum has holes to reduce its mass without compromising its stiffness (Figure 5.22). The drum is approximately 737 mm long.

Wheels:

For installation and removal of K1DM3 in the K1 tertiary tower, we have purchased (from Osborn) 4 steel wheels each with a diameter of 4.5 inch. These are now attached to the outer drum (Figure 5.23).

Anti-tip arms:

As designed, the center of mass of the K1DM3 module when the mirror is deployed lies 63 mm behind the forward wheels (those closest to the mirror) toward the rear set of wheels. In principle, this implies the system is stable to tipping. To further mitigate against tipping during installation, we have designed bronze counter-weights attached to the lower end of the assembly and a pair of anti-tip arms which can bear the full weight of the system (Figure 5.24). These will be affixed to the outer drum as an additional safety measure.

Defining points:

Fixtures attached to the exterior of the K1DM3 module to position it within the tertiary tower. These are referred to as the Defining Point Mechanism (DPM), and the complete kinematic coupling includes the tower fixtures. These

Figure 5.23: Photo of one of the 4 fabricated wheels (Osbourne) attached to the outer drum. These have been verified to interface with the K1 tertiary tower.

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

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

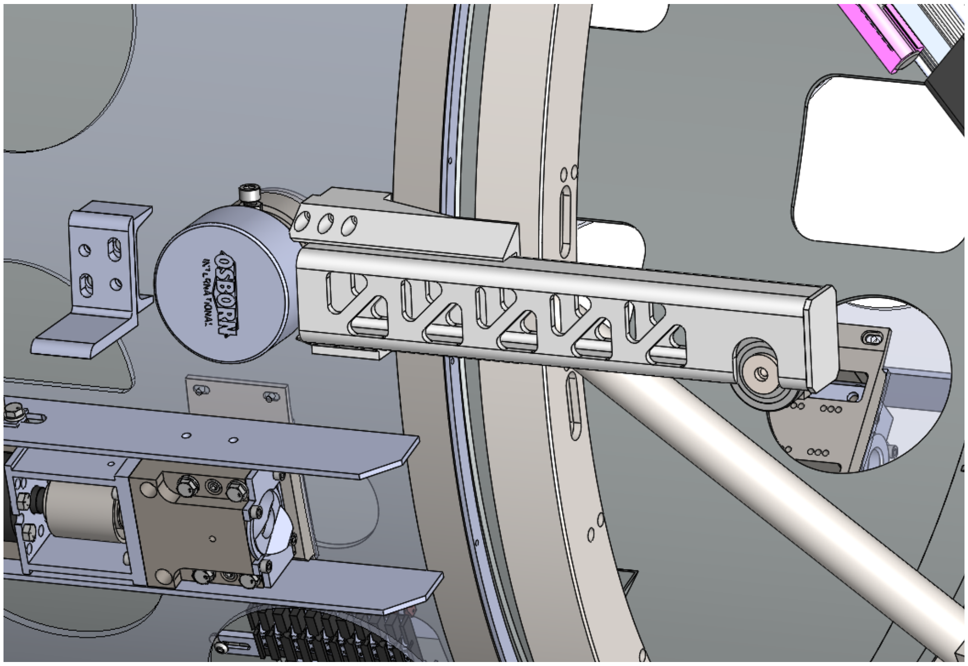

Figure 5.24: At the center of the figure is one of the anti-tip arms, attached to the outer drum. Both arms have been fabricated by Tube Service.

excess of 2000 kg. Position sensors are incorporated in the system to ensure proper positioning before the defining sequence is started.

Figure 5.25 shows the as-built sphere-in-cone DMPs, now mounted on the outer drum of K1DM3. Each of the DPMs are made of AISI 4130, Hardness Rockwell C 50 minimum, chrome plated to QQ-C-320, Type 1, class 2 material. Each allows for adjustment for 6 degrees of freedom (3 translational and 3 angles). These will have an end-to-end positioning range of about 12 mm.

Ring bearings:

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

Inner drum:

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

Compressed Air supply: To provide air pressure to the pneumatic clamps, we have designed a custom fixture that connects an air supply on the fixed, outer drum to plumbing on the inner drum. There will be a pair of these mechanisms at 0 and 180 degrees rotation angles. The latter is the orientation when the mirror is deployed/retracted and the former is for removing the mirror for coating. Figure 5.27 shows one device in the assembly and a photo of our prototype. The system will engage when oriented to within 1 degree of alignment.

Cabling: The drawings shown in this report do not display the network of cables and wiring that will cover the assembly. Nevertheless, we have anticipated the quantity of wire harnesses and where they expect to be routed. We have provided access holes and slots where we expect to need them and sized them for the largest wire harness

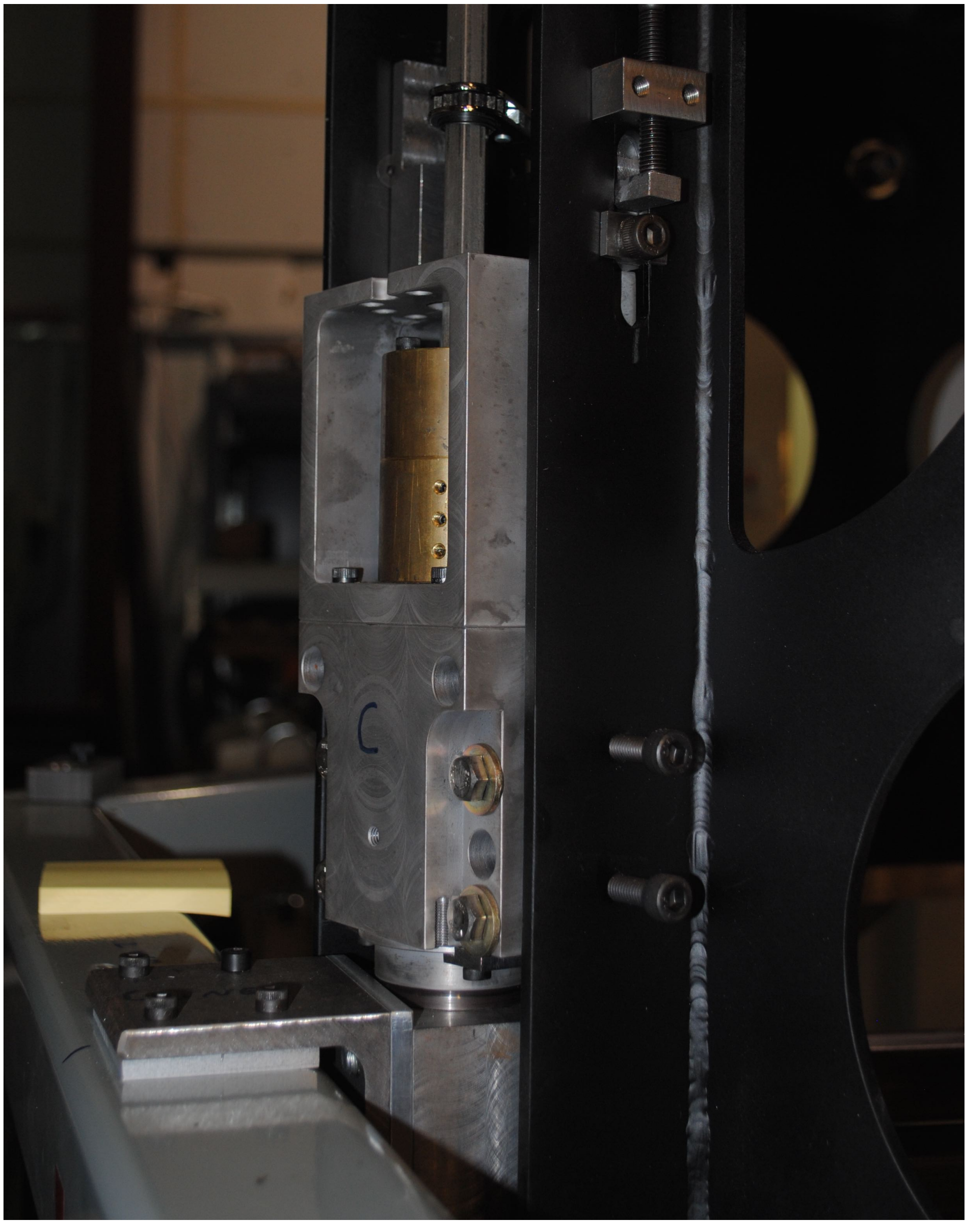

Figure 5.25: Photograph of the sphere-in-cone DPM attached to the outer drum of K1DM3. This does not include the air motors.

required. We have through slots on the top ring for wire harnesses and tubes that provide clamp-end detection, pneumatic actuator compressed air, linear actuator power and feedback signals.

Our next and final effort on this is to model these items within the layout. This will occur at the start of full scale development.

Ring gear and detents:

As shown in Figure 5.28, 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 1075 mm, and 378 teeth around the full circumference. Two pinions gears turned by two DC servo motors using harmonic drive gear heads will drive the ring gear. One of the two servo motors will lag the other slightly to eliminate backlash between the drive pinions and the ring gear.

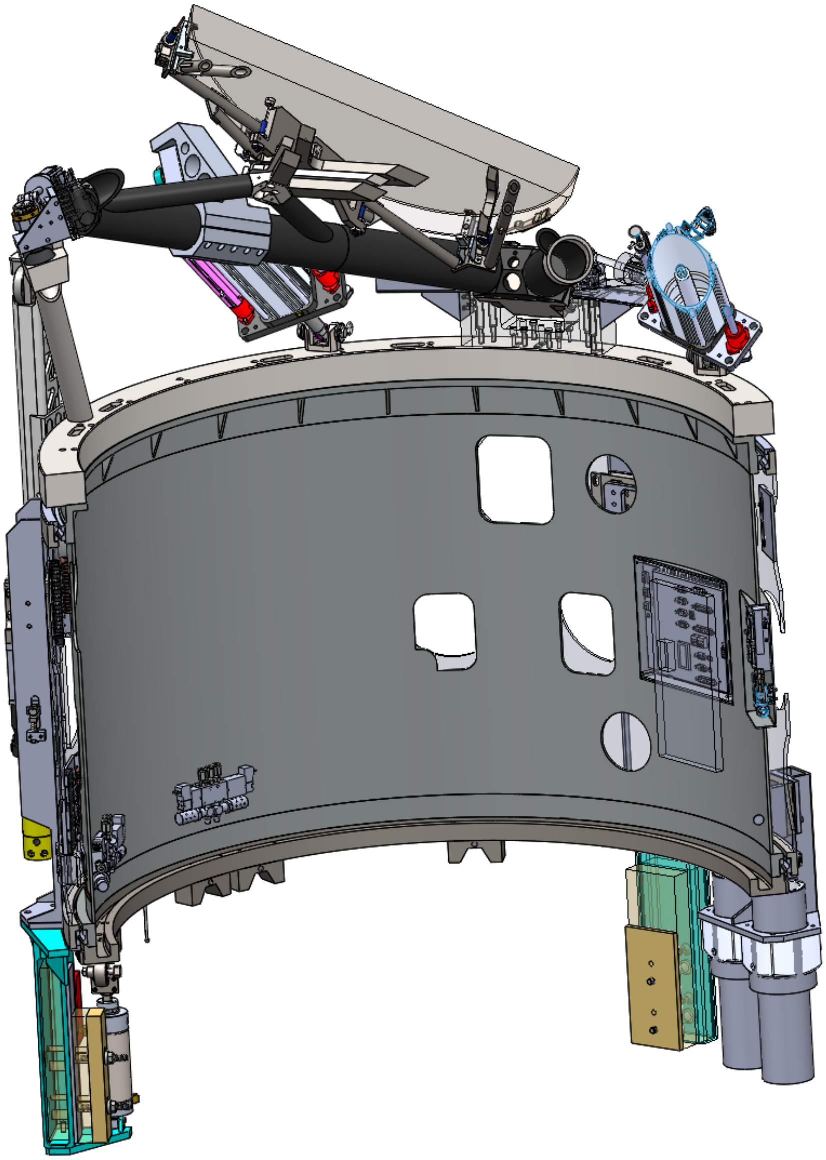

Figure 5.26: Cross-sectional view of the inner drum. One notes “pockets” for the Galil and RIO mechanisms and fixtures for air supply and electric connectivity.

There will be eight detent blocks made of steel hardened to 45 to 50 Rockwell Scale C and will be v-grooves that are 88 mm long and 40 mm wide. These will be pinned to the ring gear during alignment at WMKO (§ 5.1.3). This coupling will be engaged by an air-pressure driven detent mechanism mounted below the module (see Figure 5.28).

Encoder:

The rotation angle of the K1DM3 module will be monitored by reading a Renishaw magnetic tape attached to the drum, approximately 78 mm above the bottom edge as noted in Figure 5.29. We will use a single read head with an incremental encoder with distance coded reference marks for precise and continuous reads.

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

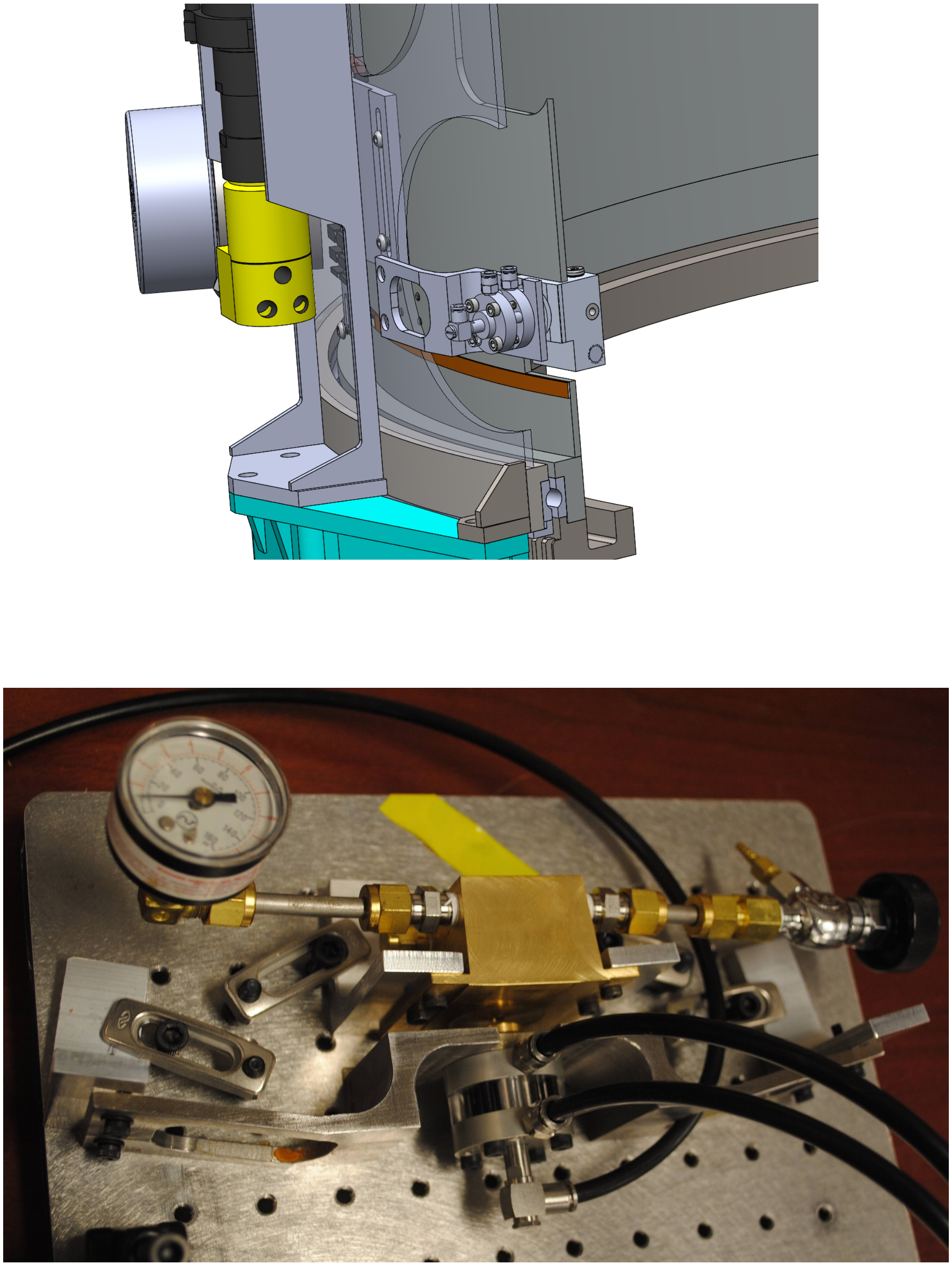

Figure 5.27: Figure showing the fixture supplying compressed air to the upper assembly (top) and a photo of the prototype of the fixture (bottom).

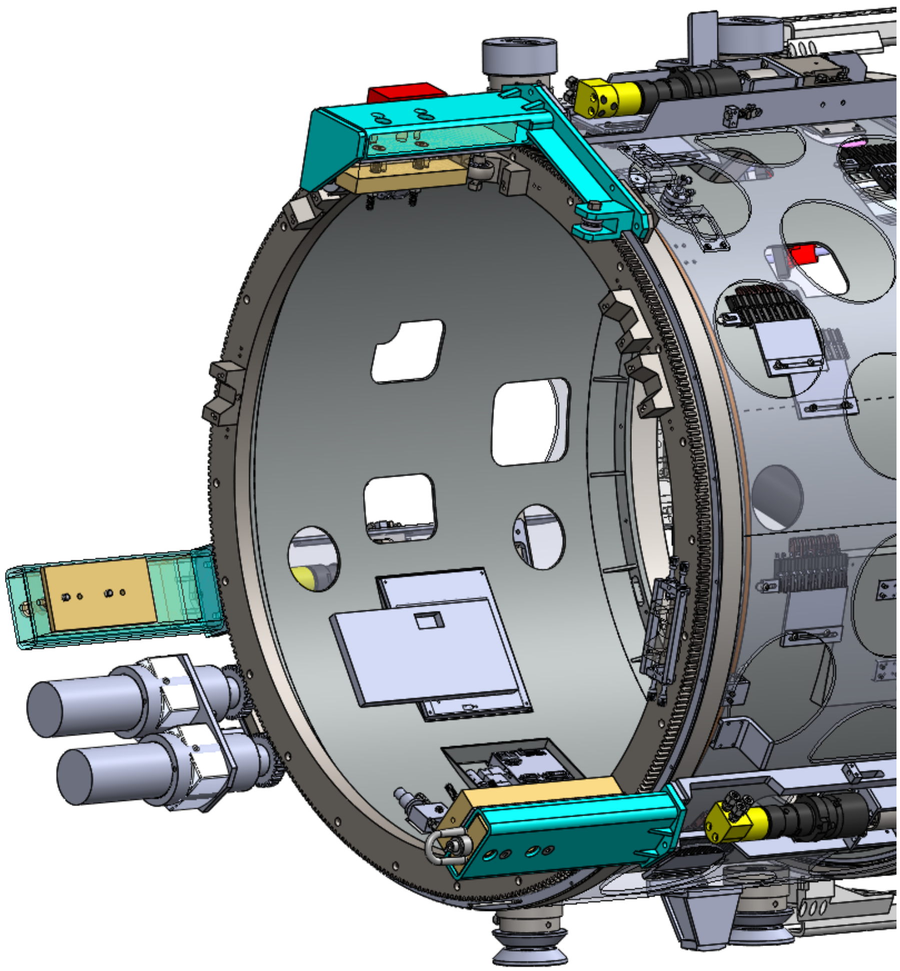

Figure 5.28: Ring gear, detents (v-grooves) and detent mechanism (cyan, top).

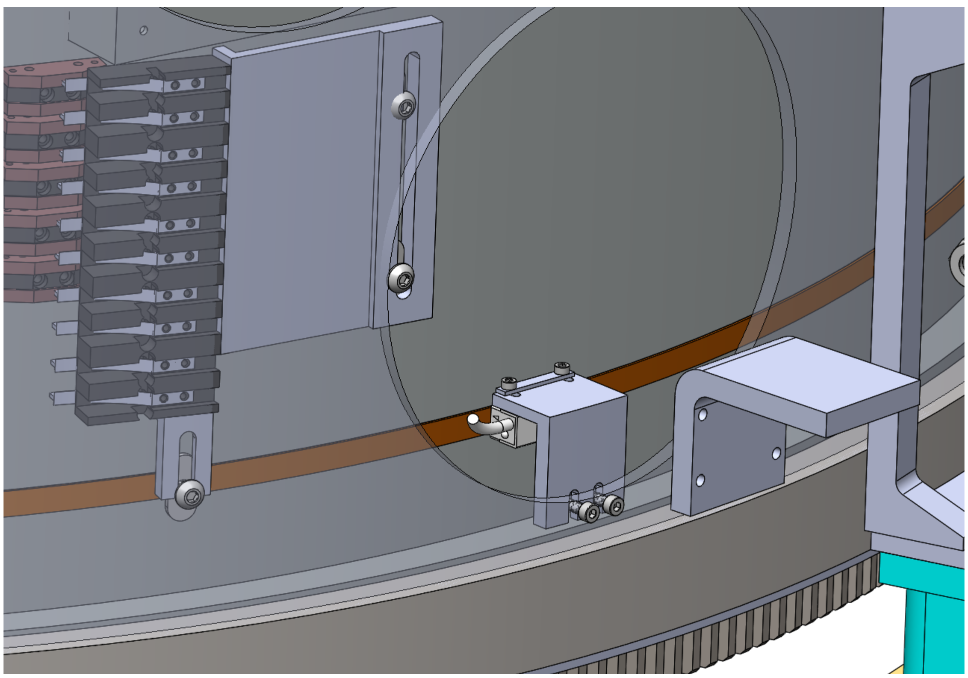

Figure 5.29: Renishaw tape (brown) on the inner drum. The figure also shows the readhead in the assembly.

Design Analysis:

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

During Detailed Design, we fabricated these fixtures and the outer drum. We delivered them to WMKO to test clearance and perform initial alignment of these fixtures (e.g. test that they coupled to the tower fixtures). We successfully mounted the outer drum on the K1 tertiary tower defining points and measured that its center of rotation lay within several mm of the current tertiary module (see [4] for further details).

Our design will allow for 12 mm of positioning of the DPMs to facilitate the alignment of K1DM3 (see § 5.1.3).

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

Vignetting: Unlike the drum of the current tertiary module, the Drum assembly of K1DM3 must be sized to avoid vignetting the converging beam from M2 to the Cassegrain focus. For example, the ring gear designed for the current existing tertiary module has too small of an inner diameter and we have re-designed it accordingly. § 5.1.2 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 the tower and existing tertiary module. This mitigates against the effects of thermal expansion.

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

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

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

Prototyping:

- We had the outer drum fabricated during DD and delivered it to WMKO to test its integration [4]. This includes our coupling the K1DM3 defining points to the K1 tertiary tower defining points.
- For the DPMs, we have mounted the outer drum with the fabricated K1DM3 DPMs on the K1 tertiary tower in October 2015.
- We have fabricated at UCO the custom fixture for providing air to the clamping mechanisms. This has been tested under the environmental conditions (e.g. low temperature) relevant to WMKO.

Fabrication:

- Outer drum: The outer drum was manufactured by Wilcox. The wheels were made by Osborne and the anti-tip mechanism was manufactured by Tube Service.
- Bearings: The pair of rotation bearings were manufactured by Kaydon.
- DMPs: The defining point mechanisms were manufactured at UCO and have been attached to the outer drum.
- Inner drum: We have submitted the detailed design to several vendors for quotes, including Wilcox and Tapemation.
- Pneumatic connector: We will manufacture the pneumatic coupling fixtures at UCO. One unit is complete.
- Ring gear: The ring gear will be made by an external vendor. We have received quotes from Cage Gear and Machine and Wilcox.
- Detent mechanism: The detent mechanism and detents will be manufactured by UCO.

5.3 Electric/Electronic Design

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

5.3.1 Deployment Stage

Design Description:

The deployment stage electronics are located on the rotating drum portion of K1DM3. These electronics are responsible for mirror deployment and mirror retraction. Power and communication to the deployment stage will be provided through custom contacts, affixed at two rotational positions on the outer drum. All of the deployment stage electronics will be powered off except when the mirror is being deployed or retracted. An overview of the deployment stage electronics is shown in Figure 5.30.

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

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

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

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

An independent safety monitoring system will insure the safe operation of deploy and retract movements. The safety monitor system will be based on a Galil RIO PLC. The safety monitor system will monitor the position and speed of the deployment stage. If excessive speed is detected motor power will be cut and the brakes set. Maximum allowable speed is reduced when approaching stops at either the deployed or retracted position.

Prototyping: During DD, we have purchased and connected a Galil controller to one Exlar linear actuator. After significant interaction with Galil, we have determined how to initialize the actuator using the Hall effect sensors. This allows us to initialize the system with the swing arm in any position at power-up.

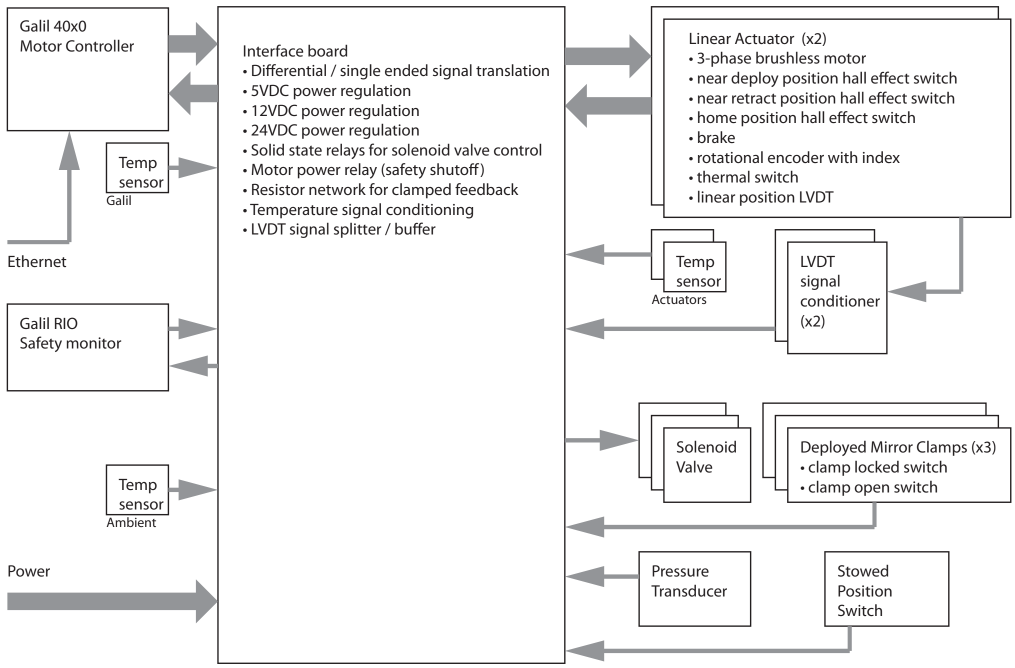

Figure 5.30: Deployment stage electronics

Risks and Mitigations:

Power dissipation: Drum rotation and mirror deploy/retract use a significant amount of power. With the designed system, we estimate 2700 Joules of energy for one deploy. This is based on peak dissipation for the approximately 5 seconds that the actuators are at full power (2x270 Watts). Other motors, controllers add negligible additional heat. To meet the requirement on heat dissipation (5 Watt average), the frequency of deployment/retraction should be less than once per 10 min.

Kinematics: Failure of the Galil controller could potentially run the stage into the kinematics with excessive force damaging the kinematics or mirror mount. The safety monitor system and a mechanical dampener have been added to prevent high speed movement into the kinematics.

5.3.2 Custom Contacts

Design Description: After careful consideration of a slip ring for communications, the team chose to develop a set of custom communications to minimize cost, minimize complexity and to enable easier servicing.

Our design uses a set of spring contacts (or brushes) that are pulled across a set of contact ramps (Figure 5.31). The contacts are carbon impregnated with silver. The ramps will be made from copper and plated with silver. We will also likely coat the ramps and brushes with a product formerly called ProGold. Our tests show the contact resistance dropped from 100 mOhms to 3 mOhms when using this product and it is reported to inhibit oxidation.

Prototyping: During DD, we manufactured a prototype of the custom contacts to test connectivity, longevity to environmental conditions (i.e. tarnishing), and robustness to wear during usage. We considered several designs for the ramps and spring contacts and also several coatings for the ramps (Cu, Ag, Au). We achieved optimal performance with Ag.

For the duration of our tests, we recorded a resistance of less than 100 mOhms. If the contacts were left idle for longer than 14 days, there was modest tarnishing but the resistivity held at less than 100 mOhm. Furthermore, the performance quickly returned to nominal after the contacts were engaged several times.

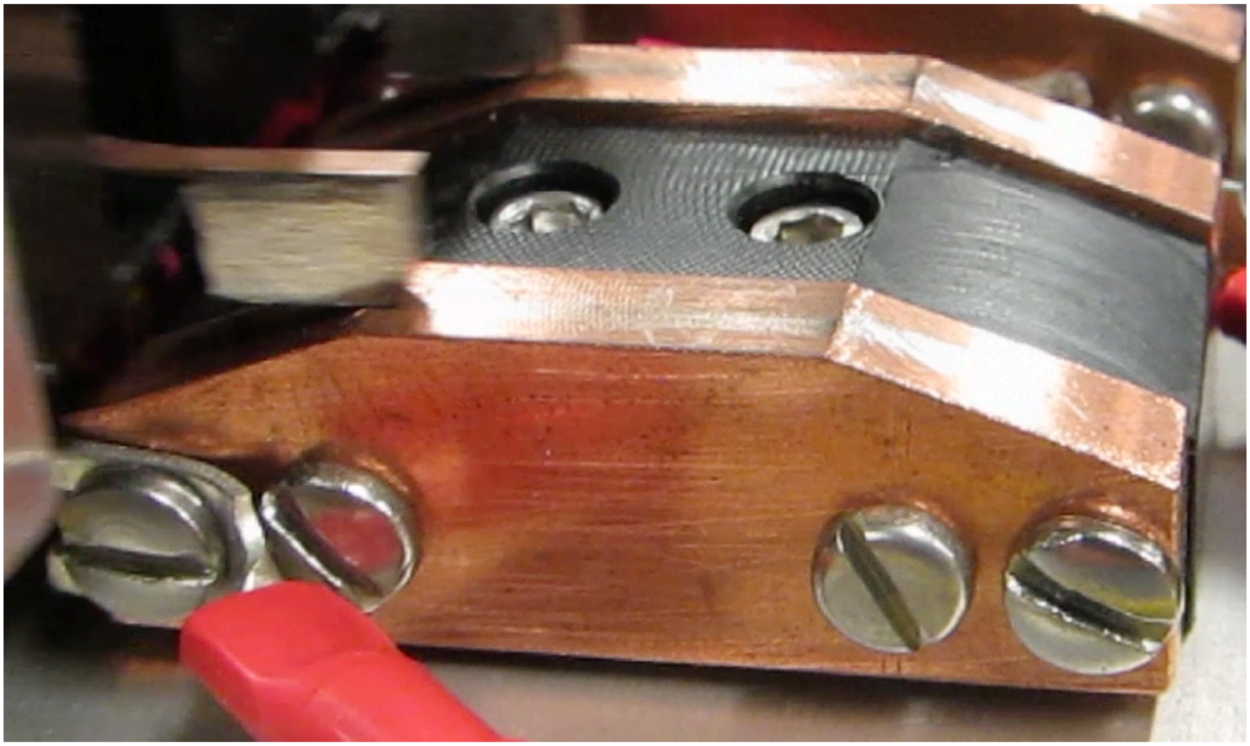

Figure 5.31: Image of a prototype of the custom contacts, brush on ramp. The final system will consist of a series of these contacts coated in Ag with a slightly modified brush design.

Fabrication: We will manufacture the ramps for the custom contacts at UCO. The brushes will be manufactured by Contact Technologies, Inc.

Risks and Mitigations:

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 the telescope in an inoperable state. Possible mitigations: Spare controllers and wiring harnesses. A hand paddle or portable controller will be provided to allow manual operation of K1DM3 (see [18] for details).

5.3.3 Rotation Stage

Design description:

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 5.32.

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

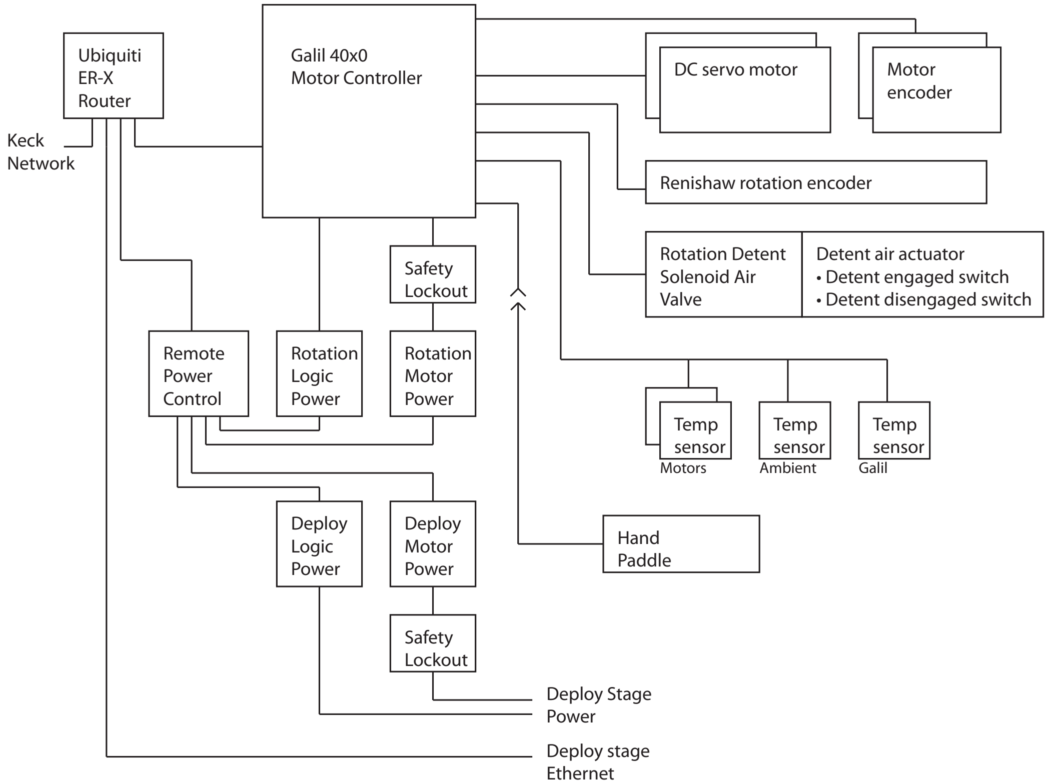

Figure 5.32: Block diagram for the rotation electronics

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.

5.3.4 Miscellaneous 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.

5.3.5 Safety

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

5.4 Software Design

5.4.1 Software Architecture

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

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

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

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

Figure 5.33: K1DM3 software layers

5.4.2 Control and Client Software

The software components for K1DM3 include the following:

1. A KTL service to control the drum rotation and swing arm deployment. One Galil DMC-4040 controls drum rotation, and another Galil DMC-4040 controls the swing arm deployment and retraction. Each Galil is controlled by a separate dispatcher daemon, but both dispatchers are part of the same *k1dm3* KTL service.
2. A Galil RIO safety system that normally operates entirely standalone, with no network connectivity with external software.
3. An engineering user interface.
4. A DCS or TCS control row, or other user interface paradigm. (Note: this is to be written by WMKO staff, and is not covered in this document.)

In order to keep cable lengths short, and avoid the need for a large cable bundle going through a cable wrap, the swing arm is controlled by a Galil DMC-4040 that is mounted on the inner drum. Heat is minimized by powering off this Galil except when deploying or retracting the mirror. The drum is controlled by a second Galil DMC-4040, which is mounted below the primary mirror and is not turned off.

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

K1DM3 includes 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 time stamped 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.

5.4.3 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. Development of the K1DM3 system started on a computer running CentOS 6, but is now being done on a CentOS 7 host.

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.

5.4.4 *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 systems, 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. 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.

5.4.5 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 using custom routines for specific motions, 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.

- For K1DM3, e-stop signal handling is done with a combination of electronics that directly cut motor power and activate brakes, and dedicated inputs to the Galils that are handled by the Galil firmwith with response times in the millisecond range. If there should be a need for other signals that are handled faster than the 250 ms maximum time for the dispatcher software to be notified, the handling is implemented in an on-board Galil interrupt routine that will respond in under 10 ms.
- *Galildisp* automatically recovers from loss of network connections, or resets of the Galil controller.

5.4.6 Motion Constraints

To ensure safe and accurate motion, the software observes a number of constraints on both rotation and swing arm deployment:

- Interference with items at the top of the tertiary tower limit the rotation when K1DM3 is retracted. Therefore, the software normally permits rotation only if the swing arm assembly is clamped in the deploy position. The clamps are continuously monitored by the rotation software, and rotation will stop if any of the three clamps is no longer engaged.
- When K1DM3 is on the handling cart, or for rare trouble-recovery situations when installed in the telescope, it may sometimes be necessary to rotate the drum while the swing arm assembly is not in the deployed and clamped position. Therefore, the requirement for a deployed-and-clamped swing arm can be bypassed when the hand paddle is connected *and* its bypass button is pressed.
- Stable, accurate, and repeatable deployment of the swing arm assembly requires the assembly to move only in a vertical plane. The software normally enforces this restriction and will reject requests to move the swing arm when the drum is not in the deploy position, whether or not the deployment Galil is powered.
- Again, in special situations it may be necessary to deploy or retract the Galil when it is not in the normal position. Therefore, this requirement is bypassed when the hand paddle is connected and its bypass button is pressed.
- Highly accurate and repeatable positioning of the swing arm assembly into the V-blocks requires the telescope to be at the same elevation for any deployment. Therefore, when K1DM3 is installed in the telescope, the software will not normally deploy the swing arm except when the telescope is at the configured elevation. This is not an issue of safety, however, and one *may* command swing arm deployment whenever the drum is in the deploy position.

5.4.7 General Safety and Monitoring

In addition to the constraints described above, there are many signals and rules that are used to enforce safe operation and provide performance feedback.

K1DM3 handles all safety-critical signals, such as e-stops, in one of two ways: either low-level electronics directly cut power and apply brakes (with a supplementary signal going to the Galil purely for informative purposes), or the signal goes to the Galil's 'Abort Input', and is processed by Galil firmware without reference to any program code.

The Observatory E-stop signal and the instrument e-stop signals will be connected to the Abort Input of both the rotation Galil and the swing arm Galil. A Galil responds to an Abort Input by shutting off any motors that have the Off-On-Error function enabled, and letting them coast. Motors that do not have Off-On-Error enabled are stopped as quickly as possible, and then servo to hold position.

The drum motors do not have brakes, and merely cutting power to the motors would let the drum coast. The KDM3 drum will use different configurations for the two motors so that the drum will not coast. The primary drum drive motor (see Drum Control, below) will be configured with the "Off-On-Error" function, which is important for safety if the drum stage itself is misbehaving. To prevent coasting of the drum, the secondary drum drive motor will be configured without the Off-On-Error function. Normally, this drive will be slaved to the primary motor, so it will not need a separate Off-On-Error function. Should an Abort Input occur, the secondary motor will stop and hold the drum, preventing coasting.

The swing arm actuators have brakes, so in this case we will ensure that motor power is cut and brakes activated on an e-stop signal. We have not yet chosen using the Abort Input, or directly wiring the e-stop signal to cut a power relay.

When K1DM3 is connected to either telescope or handling cart, loopback signals will indicate where the module is connected, so that the software can apply different rules as needed.

The two swing arm actuators must stay synchronized to within 0.75 mm at all times, so our software will continuously monitor their relative positions, and apply brakes if they differ.

The software will not command the swing arm clamps to open or close unless the swing arm assembly is in the V-blocks. The software will not attempt to retract the swing arm unless the clamps are open. In an engineering mode, this restriction can be bypassed for servicing or recovery from serious problems.

Although the swing arm Galil is powered off most of the time, the alway-on rotation Galil will monitor an analog signal that will indicate if all clamps are active. Rotation will normally be forbidden unless the swing arm is deployed and the clamps are closed.

All motors will have temperature sensors on them, to detect overheating problems. Several additional temperature sensors will be placed on the drum and possibly swing arm, to enable environmental monitoring. These will all be simple thermocouples with 0.1 C accuracy.

5.4.8 Drum Control

The drum is controlled by two DC servomotors, and position feedback from a Renishaw incremental encoder tape. The encoder tape includes distance-coded reference marks, which allow the drum to be homed by passing over any two marks, with a maximum of about 20 mm of motion at the tape, or about 2 degrees of rotation. The drum is held at any of the observing stations or the deploy/retract position by a detent mechanism.

When installed in the telescope, the swing arm assembly is always clamped in its deploy position when the drum is rotated. One motor is designated as the primary drive of the drum, while the second motor is used to remove backlash. The second motor is slaved to the primary motor, but delayed in phase by slightly more than the maximum backlash. Its maximum torque will be limited to a low value that is just enough to prevent free rotation of the drum when it is at its most-unbalanced condition, but can be readily overcome by the primary drive motor.

The rotation control algorithm is as follows:

- The drive motors are powered up. The primary motor holds position at its power-up location, and the second motor is commanded to be slaved to the primary motor, but at low torque and phase-delayed to remove backlash.
- The detent is retracted.
- The primary motor is commanded to the detent position.
- The secondary motor is commanded to stop being slaved to the primary, and instead to independently hold its current position.
- The torque limit of the primary drive motor is reduced to the same low level as the secondary motor. At this point, both motors are simply holding the stage from drifting out of position while the detent is being engaged, but their torque can be overcome by the detent mechanism as it engages.
- The detent is engaged.
- The drive motors are shut off.

5.4.9 Swingarm Assembly Control

The swing arm assembly is driven by two linear actuator arms. Each actuator has a brushless servomotor with Hall effect sensors, an index mark that triggers every 8192 counts, and a linear variable displacement transducer that provides rough absolute position. Sinusoidal commutation is used instead of trapezoidal commutation, partly because it provides more power, but more importantly because it eliminates "stuttering" during motion.

There are several notable control issues with the swing arm actuators. Because the Galil is typically powered off after each deployment or retraction, the brushless phase information has to be re-measured every time the Galil is powered up. Since the two actuators are coupled to the same swing arm, their positions must always be synchronous to better than 1 mm, which is the amount of compliance in the swing arm hinge. At the deploy position, the swing arm must gently engage hard stops, *ie.* the V-blocks. There are no clamps to hold the swing arm in the retract position, so it is has to be forced against dampers and then brakes are applied before turning off the motor.

The swing arm control algorithms are:

Sinusoidal Commutation. When first powered up, the Galil has no precise commutation phase information for the actuators, but can control them using trapezoidal commutation with the Hall sensors. The software initializes sinusoidal commutation by simply commanding both actuators to move about 0.5 mm while the Galil monitors the Hall sensors. Within 0.5 mm, the Galil will detect a Hall transition, and will immediately switch to using sinusoidal commutation.

Homing. Homing is done by combining the transducer voltage to provide absolute location that is accurate to better than 0.25 mm, with the index marks that provide a precise trigger every 2.5400 mm. A lookup table stores the value of transducer voltage and encoder position at each index mark of each actuator. The transducer voltage indicates the direction to move for homing: the swing arm moves away from the hard stops and towards the center whenever it's homing. First, one actuator is commanded to find its next index mark, and the lookup table is used to determine the absolute encoder location. The other actuator is slaved to the first actuator, so that they remain in phase during this motion. Next, the actuators exchange roles, and the second actuator seeks its index mark and absolute position. The worst-case homing requires about 0.58 mm of motion.

Deployment. For all normal motions, one actuator is designated as the primary actuator, and the other is designated as the secondary actuator. The secondary actuator is commanded to be slaved to the primary actuator, and thereafter motion commands are only sent to the primary actuator. The primary actuator is commanded using the Galil "Contour Mode". The software defines up a motion track (contour) in which the actuator moves slowly while it's within ~1 cm of either the deploy or or retract position, and full speed in between. After reaching the deploy position, the clamps are engaged, the motors' brake are activated, and the motor is turned off.

Retraction. Retraction is done quite similarly to deployment. The secondary actuator is slaved to the primary, the motors are turned on, the clamps are released, and then a contour-mode motion profile is used. At the retract position, the brakes are engaged, and the motors are turned off.

5.4.10 Safety Monitor System

In addition to the general safety features described above, a dedicated, redundant, safety Galil is provided to ensure safety in the event of certain rare failures of a Galil:

- The K1DM3 mirror can be severely damaged if it runs into the retract or deploy stops at high speed. The scenarios under which this could occur are the misbehavior or failure of either the dispatcher software or the Galil motion controller.
- The swing arm actuator motors are quite powerful, and are capable of bending the mirror assembly if they try to drive at high power — high speed is not needed — beyond the V-blocks.

K1DM3 will take several steps to prevent any of these occurrences.

- At the retract position, dampers will prevent the swing arm from hitting the kinematics at excess speed.

- At the deploy position, limit switches will be employed to cut motor power if an actuator arm moves beyond the deploy point.
- An independent Galil RIO, with only a few dozen lines of embedded code and no external software, will monitor the speed at both retract and deploy positions, and cut motor power and apply the brakes if the speeds are too high.

Several considerations lead us to implement an entirely separate and simple safety system, even though the primary control system is the latest iteration of a software and controller combination that has an excellent track record for moving stages reliably and accurately.

Our standard Galil dispatcher is a large general-purpose package, with tens of thousands of lines of code. It evolves over time, to provide features needed for new systems, to support new Galil models, and to fix bugs. The dispatcher is driven by instrument-specific configuration files. Naturally, these configuration files are edited from time to time as the system is developed. This is not suitable to a safety system that must be proven to work correctly, and then be known to remain correct and unmodified thereafter.

Furthermore, our dispatcher downloads code to the Galil at startup, and therefore the contents of the Galil itself cannot be guaranteed to be stable. This, too, is not suitable for a safety system. Finally, we have recently seen a rare instance wherein a Galil misbehaved by accepting and acknowledging a command from the dispatcher, but then ignored the command!

Collectively, this leads to the decision to provide a simple safety system that is independent from the primary motion controller.

We have demonstrated that the testbed actuator's brake will reliably stop the testbed in ~0.3 mm. ÂăThe same single brake will stop the full-up system in about 0.6 mm. Therefore, the safety system can implement the backup system by simply cutting motor power and enabling the actuator brakes.

The safety system will run on a standalone Galil RIO 471xx, and will have the following characteristics.

1. The safety system will monitor the transducer voltages of the two swing arm actuators, and two digital signals that indicate if any motor power is on or both brakes are on.
2. The safety system will have an output signal that it will toggle at approximately 100 Hz to indicate that the safety system is alive and that it is OK for the motors to operate. If the output signal is not toggling, the electronics will cut motor power and apply brakes.
3. The safety system will have additional output signals to indicate its overall state, and these signals will be monitored by the swing arm Galil. For example, two signals indicate when the safety system detects that the swing arm is close to the retract location, close to the deploy location, or somewhere in between. However, those signals are for reporting only, and are not needed for it to operate correctly.
4. The output signal will stop toggling if:
    - the safety Galil software isn't running.
    - the actuator voltages don't agree with each other.
    - the actuator voltages are out of range.
    - the rate of change of voltage (= speed of arm) is too large for that part of the motion profile. There will be three speed zones: a slow speed when moving into or out of the retract position; a high speed when moving between ends; and a slow speed when moving into or out of the deploy position.
5. The safety Galil code will be burned into the Galil, and will run immediately at power-up.
6. Our prototype monitor code has about 12 lines of configuration values, and its monitoring loop is also about 12 lines of Galil code. By keeping it short and simple, it should be readily understood and tested. The loop will grow by perhaps 10-20 lines to deal with our observation that the swing arm actuator can present noisy transducer voltages.

Table 5.6: Deployment of the mirror to any instrument station, from the Cassegrain position

Action	Max Time (s)	Notes
Slew the telescope elevation to 68 degrees.	30	From any elevation >= 30 deg.
Power up the deployment Galil	(20)	Occurs in parallel with telescope slew
Start dispatcher software	(10)	Occurs in parallel with telescope slew.
Brushless motor sinusoidal commutation	10	2 x 5 seconds per motor
Home the actuator motors	10	2 x 5 seconds per motor
Move slowly out of retract position	6	
High-speed move to deploy position	6	
Move slowly into deploy position	6	
Apply 3 clamps	2	
Move to target elevation	30	To any elevation >= 30 deg.
Rotate drum to correct detent, and activate detent	(25)	In parallel with telescope slew.
Shut off power to deployment Galil and motors	(1)	In parallel with telescope slew.

Table 5.7: Retraction of the mirror from any instrument station, to the Cassegrain position

Action	Max Time (s)	Notes
Release detent, rotate drum to retract position, and activate detent	25	
Power up the deployment Galil	20	
Start dispatcher software	10	
Brushless motor sinusoidal commutation	10	2 x 5 seconds per motor
Home the actuator motors	10	2 x 5 seconds per motor
Move slowly out of deploy position	6	
High-speed move to retract position	6	
Move slowly into retract position	6	

7. The monitor code will not depend on a network connection, and will be normally operated without one. Nonetheless, it will regularly send status messages via UDP to a burned-in IP address, which can be monitored for engineering purposes.

5.4.11 TIMING

K1DM3 is required to move between any two positions within 2 minutes. Here we summarize the time to carry out various moves.

5.4.11.1 From Cassegrain (Retracted) to Any Deployed Station

Total deployment time: <= 100 s.

5.4.11.2 From Any Deployed Station to Cassegrain (Retracted) Position

Total retract time: <= 93 s.

5.4.11.3 Moving between Any Deployed Stations

Total move time: <= 50 s.

Table 5.8: Retraction of the mirror from any instrument station, to the Cassegrain position

Action	Max Time (s)	Notes
Release detent, rotate drum to new position, and activate detent	50	

5.5 Interfaces with the 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, [19]). 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 [20]. 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.

6 Management Plan

6.1 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.

6.2 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, this effectively implements the WMKO development process and project oversight of the K1DM3 at the PI level.

An Organization Chart of the full team is presented in Figure 6.1. Dave Cowley serves as the Project Manager of UCO activities, managing a modest workforce of engineers and technical staff.

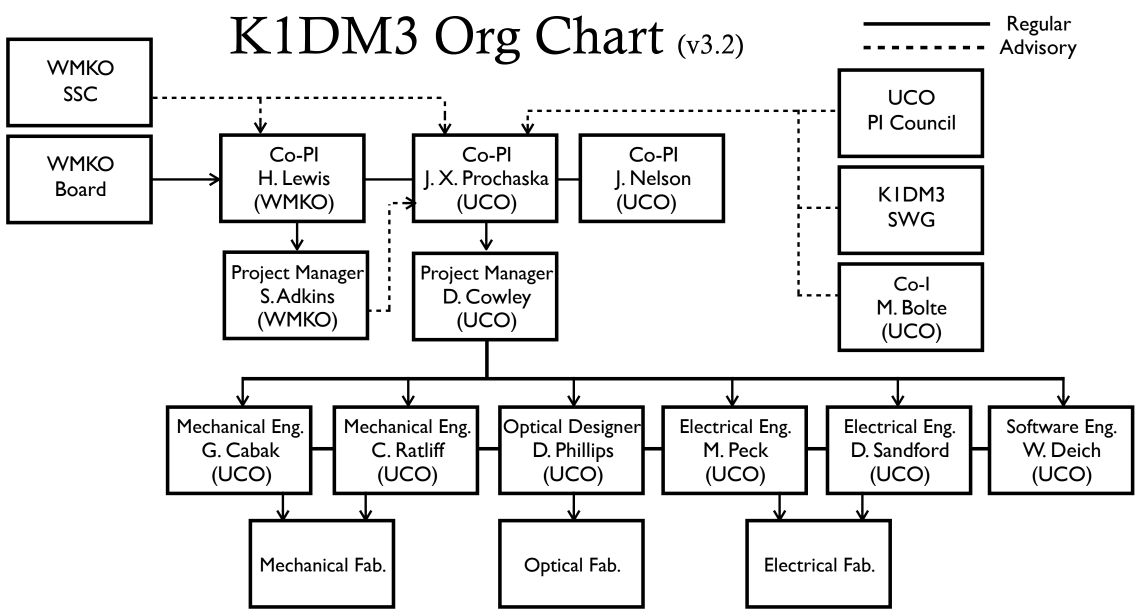

Figure 6.1: Org Chart for the K1DM3 project.

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 DD, 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: Lisa Ellis (financial), Betsy Lee (purchasing), Graseilah Coolidge (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:

- Keck Science Steering Committee (SSC): 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.
- UCO PI Council: 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.
- National Science Foundation: The NSF requires annual reports on the project status, budget, and schedule. The K1DM3 project submitted its second report in July 2015, which was approved by the program officer.

6.3 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 (v2.3) 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 6.1 presents the top risks identified by the project and their likelihood, impact, and mitigation. One may review the FMEA document for a detailed discussion of loss of observing capability, nights, etc.

6.4 Work Breakdown Structure and Schedule

A detailed Work Breakdown Structure (WBS) to Level 5 detailing 121 activities including DD is provided on the TWiki as the basis for a project plan in Microsoft Project format. 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 6.2 shows the project plan and WBS to Level 2.

As we complete Detailed Design, the project has slipped approximately 5 months from the projected completion date at the start of DD. This was driven primarily by the project's decision to perform an on-site test of fitting the outer drum into the Keck tertiary tower and to mount it on the tower's defining points. It was also due to the unexpectedly large effort to detail the as-built tower and the extra time required to fully detail the design per the criteria for DDR (complete drawings, especially for parts that will be fabricated externally).

We project a commissioning date of March 2017.

6.5 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
  - Spares for critical and difficult to obtain parts that are expected to require repair or replacement during the useful life of the K1DM3. These are listed on the TWiki.
- Software
  - Low-level control software
  - A system to diagnose (and archive) the status of K1DM3

Table 6.1: Risk table

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.
Deploy kinematics do not achieve required precision on pointing	Moderate	Poorer image quality; misalignment of pupil resulting in increased sky background for observations	Moderate	Test kinematic coupling during full scale development. Verify precision at UCO before delivery.
Damage to mirror when handling at WMKO	Small	Mirror is compromised	Critical	Develop cautious handling procedures; consider additional protection for assembly when handling
Interference of K1DM3 with tertiary tower during installation	Moderate	Cannot install K1DM3	Critical	Design to apron constructed during outer drum fitting [4]; trim edges of tower and/or K1DM3
Misalignment of K1DM3	Moderate	Poor image quality, misalignment of pupil resulting in higher backgrounds for observations.	Moderate	Extensive testing at UCO prior to delivery. Verification of performance at WMKO during commissioning.
Leak in air supply fixture	Small	Insufficient air pressure to kinematic clamps	Severe	Extensive testing of fixture at UCO under observatory conditions
Contamination of custom connections	Moderate	Reduced or insufficient power/ethernet	Moderate	Comprehensive testing at UCO prior to delivery; develop PM plan
Insufficient documentation of K1DM3 software	Small	WMKO unable to modify/update software	Moderate	Hold independent reviews at WMKO and UCO on software prior to delivery
Exceed MRI budget	High	Unable to complete project	Critical	Request supplemental funds from NSF; request UCO cover in-kind labor costs at UCO; request WMKO contribute to over-run

- 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

Keck 1 Deployable Tertiary Sun 2/21/16

ID	Task Name	Duration	Start	Finish	Work
1	**K1DM3**	**327 days**	**Mon 11/9/15**	**Fri 2/10/17**	**5,250 hrs**
2	DDR	0 days	Mon 3/7/16	Mon 3/7/16	0 hrs
3	Prep for PSR	2 wks	Fri 11/18/16	Thu 12/1/16	0 hrs
4	PSR	0 days	Thu 12/1/16	Thu 12/1/16	0 hrs
5	First Light	0 days	Wed 2/8/17	Wed 2/8/17	0 hrs
6	**completion of DD**	**78 days**	**Mon 11/9/15**	**Mon 2/29/16**	**1,532 hrs**
42	**Full Scale Development**	**173 days**	**Tue 3/22/16**	**Thu 11/17/16**	**3,118 hrs**
43	**Mechanical Fabrication**	**137.5 days**	**Tue 3/22/16**	**Thu 9/29/16**	**1,824 hrs**
65	**Electronic/Electrical Fabrication**	**94.1 days**	**Tue 3/22/16**	**Mon 8/1/16**	**434 hrs**
77	**Software**	**15 days**	**Mon 7/18/16**	**Mon 8/8/16**	**264 hrs**
83	**Assembly**	**44.5 days**	**Tue 8/9/16**	**Mon 10/10/16**	**356 hrs**
90	**Testing**	**28.5 days**	**Mon 10/10/16**	**Thu 11/17/16**	**240 hrs**
95	**Installation and commissioning**	**28 days**	**Fri 12/30/16**	**Tue 2/7/17**	**576 hrs**
96	**Shipping**	**16 days**	**Fri 12/30/16**	**Fri 1/20/17**	**144 hrs**
102	**Installation**	**12 days**	**Mon 1/23/17**	**Tue 2/7/17**	**432 hrs**
103	unpack	1 day	Mon 1/23/17	Mon 1/23/17	24 hrs
104	assemble on Observatory floor	1 day	Tue 1/24/17	Tue 1/24/17	24 hrs
105	hoist to N platform	2.67 hrs	Wed 1/25/17	Wed 1/25/17	8 hrs
106	installation of electronics on telescope	2 days	Tue 1/24/17	Wed 1/25/17	48 hrs
107	installation of pnumatics on telescope	2 days	Tue 1/24/17	Wed 1/25/17	48 hrs
108	initial installation into telescope	1 day	Thu 1/26/17	Thu 1/26/17	24 hrs
109	initial fuctional tests	2 days	Fri 1/27/17	Mon 1/30/17	64 hrs
110	initial alignment	2 days	Tue 1/31/17	Wed 2/1/17	64 hrs
111	optical alingment including F25 secondary	2 days	Thu 2/2/17	Fri 2/3/17	64 hrs
112	final functional tests and comfirmation of alignm	2 days	Mon 2/6/17	Tue 2/7/17	64 hrs
113	Commissioning	3 days	Wed 2/8/17	Fri 2/10/17	24 hrs

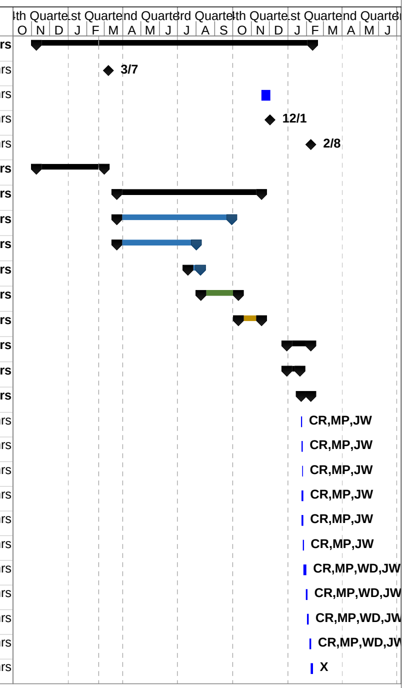

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Figure 6.2: Project Plan (overview) with WBS

6.6 Milestones and Reviews

Prior to installation and commissioning, the project will hold a pre-ship review at UCO to assess the as-built performance of K1DM3. This review will be managed by WMKO.

6.7 Budget

6.7.1 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 Vice Chancellor for Research (VCR)

- During DD, the project performed a prototyping exercise at WMKO (installing the outer drum in the K1 tertiary tower [4]). This was not part of the original NSF proposal and UCO agreed to fund approximately $128k of those activities.

6.7.2 Expenditures During Detailed Design

The DD phase of the K1DM3 project began on October 1, 2014. 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 6.3 summarizes the expenditure profile during this phase of the project at UCO, split between labor and materials.

Table 6.2 shows a breakdown of the costs integrated over the DD phase including projections for January-March 2016 and including liens. The second column shows the awarded funds from NSF, UCSC cost-share, and UCO in-kind. The third column shows the funds at the start of DD. The fourth column shows the balance

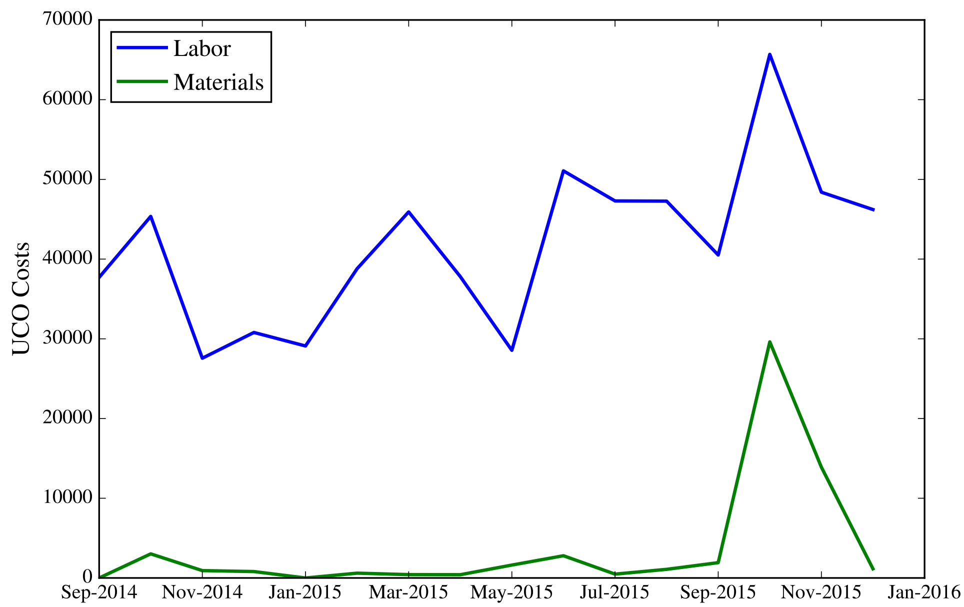

Figure 6.3: Expenditure profile for UCO Costs during DD.

Table 6.2: Summary of PD and DD Costs (in Thousands)

Description	**PD Expenses**	**PD Proposed**	**DD Expenses**	**DD Proposed**
UCO Labor	252	180	648	242
UCO Materials	29	10	155	61
WMKO Subaward	43	52	148	74
ODF Prototype	N/A	N/A	124	0

The total labor and materials costs of 953$k greatly exceeds the total budgeted amount for the DD phase as proposed to the NSF ($377K). The overrun is related to several factors:

- the prototype activity at WMKO to test-fit the outer drum The costs of this activity has largely been covered by new funds from UCO;
- we have purchased a number of long-lead items (e.g. the mirror, outer-drum, bearings) during DD
- the project spent considerable resources to accurately measure the as-built dimensions of the K1 tertiary tower;

- the project took longer than planned to achieve a swing arm design that was sufficiently stiff yet does not vignette the light paths;
- the project struggled with Galil operation of the hall effect sensors on the linear actuators;
- the project spent several weeks exploring a passive actuation system for the swing arm that was eventually discarded;

Regarding cost-share, we have booked 40% of the required amount to the project to date. Several large cost-share items are planned for late in the project (e.g. commissioning nights, expenditure of $70k of the UCSC VCR funds). We are therefore confident to meet the required cost-share.

6.7.3 Budget to Completion

Table 6.3 summarizes the awards funding K1DM3 and the costs broken down by phase. The DD costs include estimates for January-March 2016 (i.e. these are not yet recorded in the UCSC system). The full scale development (FSD) and delivery and commissioning (DC) estimates are based on the quotes in hand and labor expenses based on the WBS presented in Figure 6.2.

Table 6.3: Budget to Completion (in Thousands)

Description	**Awarded**	**PD Costs**	**DD Costs**	**FSD Estimate**	**DC Estimate**	**Net**
UCO Labor	894	252	648	236	56	−298
UCO Materials	172	29	155	130	25	−167
WMKO Subaward	400	43	148	61	61	87
UCSC VCR	96	6	15	0	0	75
UCO ODF	128	0	124	0	0	4
Total	1690	330	1093	426	140	−299

Table 7.1 lists the costs of the major purchased items for K1DM3. These total $258,216. Note that this list does not include materials costs for the items that will be fabricated at UCO which will total several thousands of dollars.

Table 6.4: Component Costs

Description	Unit Cost	#	Total Cost	Supplier	Comments
Mirror	32810	1	32810	Zygo	
Dummy Mirror	2000	1	2000	In house, buy stock	
Swing arm	35000	1	35000	Tapemation	
Mirror support frame	30000	1	30000	Tapemation	
Earthquake clips and attachments	1000	1	1000		
Inner Drum	19750	1	19750	Wilcox	Lowest quote
Ring Gear	11543	1	11543	Cage Gear and Machine	
Spur Gear	1000	1	1000		
Renishaw encoder tape	818	2	1636	Renishaw	Distance coded reference marks
Renishaw read head	391	2	782	Renishaw	
Inner Drum Servos	795	2	1590		custom 4 pole brushed motor
Harmonic Drive Reducer	2237	2	4474		
Inner Drum pneumatic actuator	150	1	150	Motion Industries	
Rotation bearings	30007	2	60014	Kaydon	
Exlar Actuator	10994	2	21989	Exlar	
Outer Drum	24958	1	24958.13	Wilcox	
Defining Point Air Motors	2033.66	4	0	Ingersoll Rand	Donated
Defining Point couplings	252.37	4	1009.48	Motion Industries	
Clamps (kinematics)	375.22	5	1876.1	Motion Industries	
Modifications to clamps	500	4	2000	UCO	
Canoe spheres (kinematics)	300	4	1200	Motion Industries	
V-Blocks (kinematics)	300	4	1200	Motion Industries	
Coatings (kinematics)	1506.7	1	1506.7	Brycoat	
Dampers	233	5	1165	Enidine	
Mirror grabber	4700	1	4700	Southwest Metalcrafts	
Flip fixture	5320	1	5320	Southwest Metalcrafts	

7 GLOSSARY

Table 7.1: Glossary

Term	Description
ADC	Atmospheric Dispersion Corrector
AO	Adaptive Optics
COTS	Commercial Off The Shelf
CTE	Coefficient of Thermal Expansion
DCS	Drive and Control System (used as an alternate for TCS)
DK	Deploy Kinematics
DPM	Defining Point Mechanism
FEA	Finite Element Analysis
FOV	Field Of View
FSD	Full Scale Development
GUI	Graphical User Interface
HIRES	High Resolution Echelle Spectrograph ICD Interface Control Document
K1DM3	Keck 1 Deployable Tertiary
KSD	Keck Software Document
KTL	Keck Task Library
LRIS	Low Resolution Imaging Spectrograph
LVDT	Linear Variable Differential Transformer
M1	First mirror in a system, here it refers to the telescope primary
M2	Second mirror in a system, here it refers to the telescope secondary
M3	Third mirror in a system, here it refers to the telescope tertiary
MOSFIRE	Multi-Object Spectrometer for InfraRed Exploration
MRI	Major Research Instrumentation (Program)
NEBS	Network Equipment Building System
OSIRIS	OH Suppressing InfraRed Imaging Spectrograph
SSC	Scientific Steering Committee
TBC	To Be Completed
TBD	To Be Determined
TCCB	Telescope Change Control Board TCS Telescope Control System
TCSU	Telescope Control System Upgrade TDA Time Domain Astronomy
TDA	Time Domain Astronomy
ToO	Target of Opportunity
UCSC	University of California, Santa Cruz
WBS	Work Breakdown Structure WMKO W. M. Keck Observatory

8 APPENDIX

8.1 INSTALLATION AND COMMISSIONING

The commissioning plan for K1DM3 will consist of three main phases: (1) verification of the system functionality; (2) alignment; (3) on-sky testing (and pointing model). The first phase will exercise and verify all of the primary modes of function for the K1DM3 system, on the telescope. We will insist that all systems are nominal before proceeding with the latter phases. We emphasize that we shall test the K1DM3 system extensively at UCO prior to shipping to WMKO. Therefore, the tests at WMKO are primarily to confirm that the system behaves as measured in the lab.

The second phase will align K1DM3 to the K1 telescope and the existing instrument suite at the Nasmyth foci (AO, HIRES). Full details are provided in § 5.1.3. Note that the telescope may need to be re-balanced during this phase (K1DM3 weighs several hundred kilograms less than the current module).

The final phase is to perform on-sky tests with K1DM3 on a set of science targets. We will test its performance as integrated with the K1 telescope control system and its instrumentation. We may also generate a new pointing model for the K1DM3 module.

8.1.1 VERIFICATION

We now list the series of tests to be performed during commissioning to insure K1DM3's functionality.

8.1.1.1 Installation

Goals:

- Confirm K1DM3 fits on handling cart
- Confirm K1DM3 slides on the rails through the K1 tertiary tower
- Confirm K1DM3 mounts on the K1 tertiary tower defining points
- Confirm K1DM3 may be removed from the K1 tertiary tower
- Confirm K1DM3 installs repeatably to the same location (< 1 mm tolerance)

Procedure:

1. Mount K1DM3 on its handling cart on the K1 Nasmyth platform and verify it has proper clearance and balance.
2. The tower side fixtures will be coated in blue "goo". This allows us to confirm that the K1DM3 kinematics are fully engaged.
3. Roll K1DM3 on the K1 tertiary tower rails and down the tower, verifying no interference restricts travel. Reference photos should be taken.
4. Mount K1DM3 on the K1 tertiary tower defining points with the air cylinder motors.
5. Take K1DM3 off the defining points and remove from tower.
6. Inspect the kinematics for uniform goo. Photograph.
7. Reinstall K1DM3 with a target affixed to its lower side.
8. Insert the tertiary tower cross-hairs
9. Align an alignment telescope (AT) to the cross-hairs
10. Measure the position of K1DM3 module as viewed by the AT.

11. Unmount, and remount K1DM3. Measure the position of K1DM3 module as viewed by the AT.
12. Verify that the location of K1DM3 remains stationary, to measurement precision.

8.1.1.2 Test Connectivity

Goals:

- Confirm K1DM3 control system communicates with the module
- Verify power, ethernet, and diagnostic systems

Procedure:

1. Install K1DM3
2. Rotate K1DM3 to align to the custom connections
3. Connect all cabling
4. Power up K1DM3
5. Confirm that Galil devices are nominal
6. Confirm that computer can communicate with Galil
7. Confirm that all electronic diagnostics can be monitored

8.1.1.3 Rotation

Goals:

- Confirm K1DM3 rotates at its nominal speed
- Confirm K1DM3 rotates to arbitrary positions
- Confirm K1DM3 rotates repeatably to sub-arcsecond precision

Procedure:

1. Power up K1DM3
2. Under computer control, rotate K1DM3 by 360 degrees. Measure the speed of rotation.
3. Identify preferred rotation angle for engaging the custom connections (i.e. the retract/deploy position). Record.
4. Rotate to the nominal angle, under computer control
5. Rotate away from the nominal angle and back. Measure the precision of repeatability.
6. Rotate to other angles of interest (approximate), e.g. Nasmyth foci.

8.1.1.4 Test Pneumatics

Goals:

- Confirm mechanism to deliver compressed air is nominal
- Confirm air pressure is nominal
- Confirm clamps engage/dis-engage

Procedure:

1. Rotate K1DM3 to deploy/retract position
2. Engage compressed air pressure mechanism. Monitor air supply.
3. Measure air pressure within K1DM3 system. Confirm > 100 PSI.
4. Dis-engage 1 kinematic clamp. Verify success (man lift?).
5. Confirm that electronic diagnostic is reading correctly.
6. Engage that clamp. Verify.
7. Verify all 3 kinematic clamps dis-engage.
8. Verify all 3 kinematic clamps engage.
9. Confirm that all electronic diagnostics are nominal.

8.1.1.5 Test Retraction

Goals:

- Confirm linear actuators lift mirror off the kinematics
- Confirm linear actuators can hold the mirror
- Confirm mirror may be retracted fully
- Confirm mirror may be rotated to parking position

Procedure:

1. Rotate K1DM3 to deploy/retract position
2. Elevate telescope (only if necessary)
3. Engage pneumatic mechanism
4. Dis-engage all 3 kinematic clamps
5. Power on Galil for actuators
6. Power on actuators
7. Lift mirror a few cm. Verify
8. Retract mirror slowly. Inspect for interference (man lift)
9. Fully retract mirror. Inspect for potential interference
10. Rotate slowly towards park position. Inspect for interference.
11. Rotate mirror fully to park position.
12. Repeat using computer scripts

8.1.1.6 Test Manual Deployment

Goals:

- Confirm manual deployment process

Procedure:

1. Rotate K1DM3 to deploy/retract position
2. Engage pneumatic mechanism

3. Dis-engage all 3 kinematic clamps
4. Retract mirror approximately half way
5. Power down actuators
6. Perform manual procedure (see [16] for details)
7. Remove K1DM3 and re-attach actuators

8.1.1.7 Test Hand-Paddle

Goals:

- Confirm hand-paddle functionality

Procedure:

1. Power down K1DM3
2. Attach hand-paddle mechanism
3. Exercise all modes (rotation, retraction, etc.)

8.1.2 Alignment

See § 5.1.3 for details. Note that this procedure will test the accuracy, precision, and repeatability of K1DM3 positioning (on-sky tests would almost surely be compromised by uncertainty in telescope pointing/tracking/guiding).

8.1.3 On-Sky Performance

8.1.3.1 Pointing Model

Goals:

- Assess the pointing of K1 with K1DM3
- Generate a new pointing model, as necessary

Procedure:

1. Retract K1DM3
2. Perform standard Keck pointing model procedure with LRIS

8.1.3.2 HIRES/HIRES Test

Goals:

- Confirm repeatability of K1DM3

Procedure:

1. Deploy K1DM3
2. Rotate to HIRES focus
3. Acquire bright star on HIRES slit; observe
4. Maintain telescope tracking
5. Rotate to AO

6. Rotate back to HIRES
7. Measure offset of star relative to slit
8. Retract K1DM3 (this will require a telescope slew)
9. Deploy K1DM3; rotate to HIRES focus
10. Point telescope at original field
11. Measure offset of star relative to slit

8.1.3.3 HIRES/LRIS/HIRES Test

Goals:

- Verify integration of K1DM3 within K1 Telescope Control System
- Check/modify HIRES pointing origin

Procedure:

1. Deploy K1DM3
2. Rotate to HIRES focus
3. Measure pointing origin
4. Perform HIRES observation
5. Retract K1DM3
6. Perform LRIS observation on same field.
7. Measure offset in pointing and/or pointing origin
8. Perform LRIS observation on new field
9. Deploy K1DM3, rotate to HIRES, point at original field
10. Note offset in pointing
11. Perform HIRES observation

8.1.3.4 MOSFIRE/AO/MOSFIRE Test

Goals:

- Verify integration of K1DM3 within K1 TCSU

Procedure:

1. Retract K1DM3
2. Measure pointing origin on MOSFIRE
3. Perform MOSFIRE observation
4. Deploy K1DM3, rotate to AO
5. Measure pointing origin
6. Perform AO observation on same field. Measure offset in pointing
7. Retract K1DM3
8. Note offset in pointing with MOSFIRE

9. Perform MOSFIRE observation