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Fabrication completion and commissioning of a deployable tertiary mirror for the Keck I Telescope

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ABSTRACT

The new deployable tertiary mirror for the Keck I telescope (K1DM3) at the W. M. Keck Observatory has been assembled, tested and shipped to the telescope site, and is currently being installed. The mirror is capable of reflecting the beam to one of six positions around the telescope elevation ring or to retract out of the way to allow the use of Cassegrain instruments. This new functionality is intended to allow rapid instrument changes for transient event observations and improve telescope operations. This paper presents the final as-built design. Additionally, this paper presents detailed information about our alignment approach in the attempt to duplicate the instrument pointing orientation of the existing M3.

Keywords: tertiary mirror, opto-mechanical design, opto-mechanical alignment, robotic mirror, Keck Telescopes

1. INTRODUCTION

The Keck I deployable tertiary mirror is a deployable tertiary mirror (M3) for the Keck I (K1) telescope. It provides a 5.0 arcminute field-of-view (FOV) to any instrument port, satisfying the observational needs of all current and planned instrumentation on K1 at this f/15 focus. This mirror shifts between states (retracted, deployed) in less than three minutes and provides observations with any K1 instrument on any given night. K1DM3 is a major enhancement of flexible observing at Keck, enabling rapid target of opportunity observations, cadence programs, and bad weather scheduling, using the suite of K1 instrumentation. The K1DM3 has the ability to switch between Nasmyth platforms or align to any desired instrument on the elevation ring. When retracted, it stays out of the FOV of the Cassegrain instrument below (LRIS or MOSFIRE) while also avoiding the vignetting of light between M1 and M2.

1.1 Overview of design

Figure 1 shows the overall configuration of the K1DM3 module in its deployed state and installed in the tertiary tower in its retracted state. Referring to Figure 1, the K1DM3 module consists of a fixed outer drum and an inner drum that can rotate about its cylindrical axis. The inner drum is supported at both ends by pre-loaded ball bearing assemblies that are approximately 1.2 meters in diameter. The inner drum has a ring gear that is driven by a pinion gear servo motor system mounted to the outer drum. A magnetic encoder is used to measure the position of the rotatable inner drum with arc-second precision.

The tertiary mirror is an elliptical shape (901mmx643mmx45mm thick) and is composed of a precision ground and polished Zerodur substrate with an aluminum reflective coating that was applied at WMKO. The mirror is supported by axial and lateral supports attached to a passive 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.

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The top of the inner drum supports the swing arm in the deployed position through a bipod weldment structure with kinematic interfaces. These kinematic interfaces provide highly repeatable positioning of the swing arm and mirror assembly. The swing arm is locked in the deployed position by pneumatic 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 kinematic interfaces (v-blocks), the deployment process is performed at the elevation angle where the kinematic coupling is oriented normal to gravity (67 degrees elevation angle). We can deploy and retract the mirror only at two specific inner drum rotation angles, where electrical power, compressed air and ethernet communication are supplied to the inner drum and swing arm.

Full rotation of the module inner drum is possible only with the mirror deployed. 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. There are also two additional positions not associated with observing instruments, but relate instead to operational requirements. The mirror needs to face up for mirror removal and needs to face down for retraction or shuttling through the tertiary tower. Each of these positions is held by a detent mechanism engaging a spherical roller into precision ground v-blocks. There are a total of eight v-blocks for the eight positions mentioned. The detent mechanism is engaged and disengaged using a pneumatic cylinder resulting in no power dissipation in the vicinity of M3 to maintain a precise inner drum position.

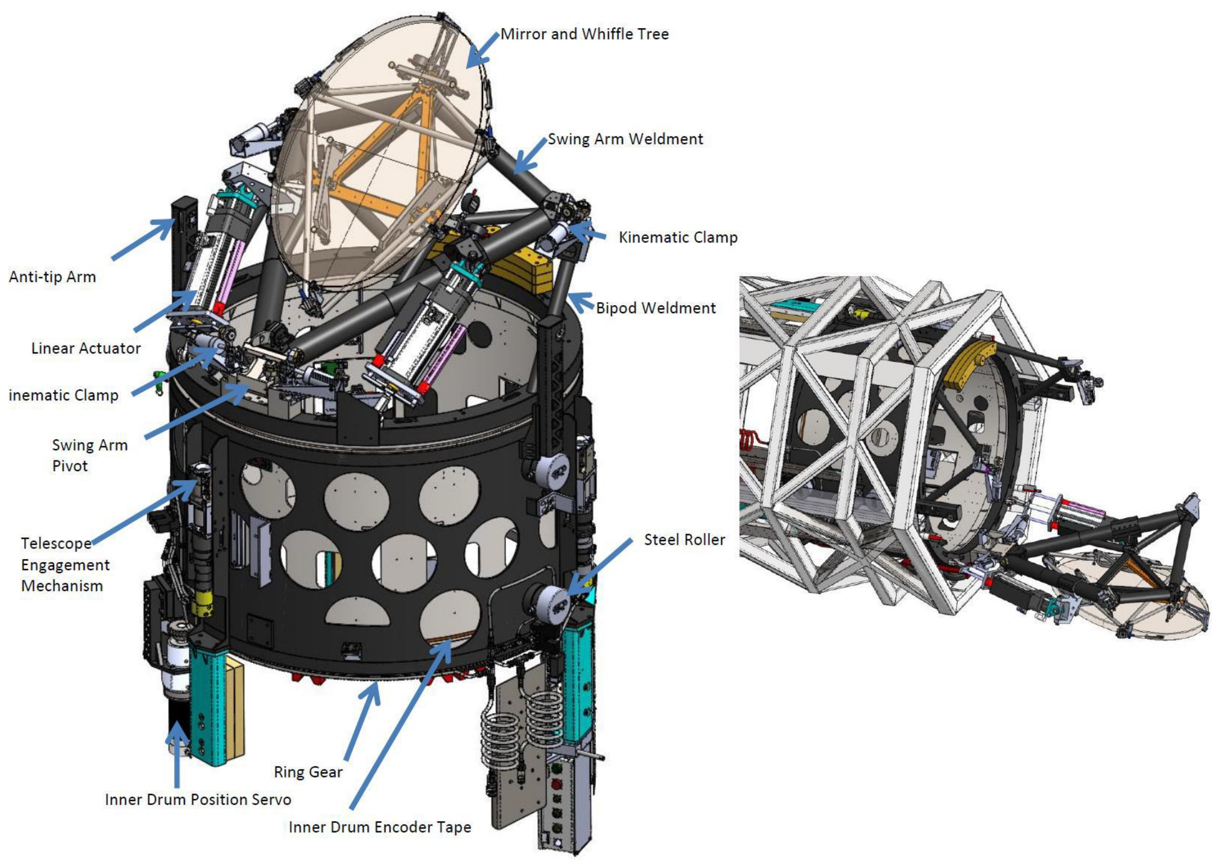

Figure 1: The Keck 1 Deployable Tertiary Mirror (K1DM3) in its deployed state (left) and in its retracted state installed on the tertiary tower (right)

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 steel rails. Steel wheels mounted on the outer drum support the module and allow it to roll on the rails. When the module is installed in the tower, it is held in position using three defining point mechanisms equipped with quasi-kinematic interfaces that are engaged and disengaged by three air motor screw and nut mechanisms. The engagement mechanism lifts the entire K1DM3 module free of the steel rails during engagement, and the quasi-kinematic interfaces ensure repeatable positioning while not imposing excessive contact stresses at these interfaces.

1.2 Mirror design and support system

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. The most demanding FOV to clear is related to the low resolution imaging spectrometer and atmospheric dispersion corrector (LRIS/ADC). 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 in Figure 2. In this position, the instrument must avoid the rays traveling from the sky to M1, M1 to M2 and (most importantly) the converging rays from M2 to LRIS, shown in Figure 2 as a semitransparent cone of light.

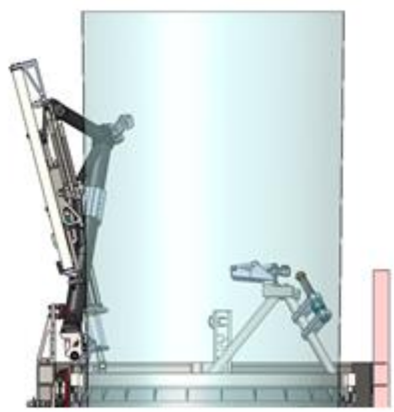

Figure 2 - M3 in retracted position and clearing the FOV to the Cassegrain instruments.

The mirror for K1DM3 requires a support structure that will:

- maintain the mirror's figure under varying gravity vectors and temperature changes
- interface the mirror with the deployment (swing arm) mechanism
- ensure the safety of the system during an earthquake
- 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 non-reflective back side of the mirror. These rods are 1.7 mm in diameter with 60 mm free length, and made of 17-4PH steel. The pucks are Invar and glued with an epoxy adhesive. The pucks were glued to the mirror by Keck in their segment repair lab. Keck has studied and researched the bonding of Invar to Zerodur and has developed extensive procedures and preparations. Pictures of the glue jig before bonding and immediately after are shown in Figure 3. The axial rods are screwed into the pucks. The layout of these six axial support rods is shown in Figure 4. The positions for the rods were determined from finite element analysis (FEA) to minimize deflections of the mirror normal to its surface.

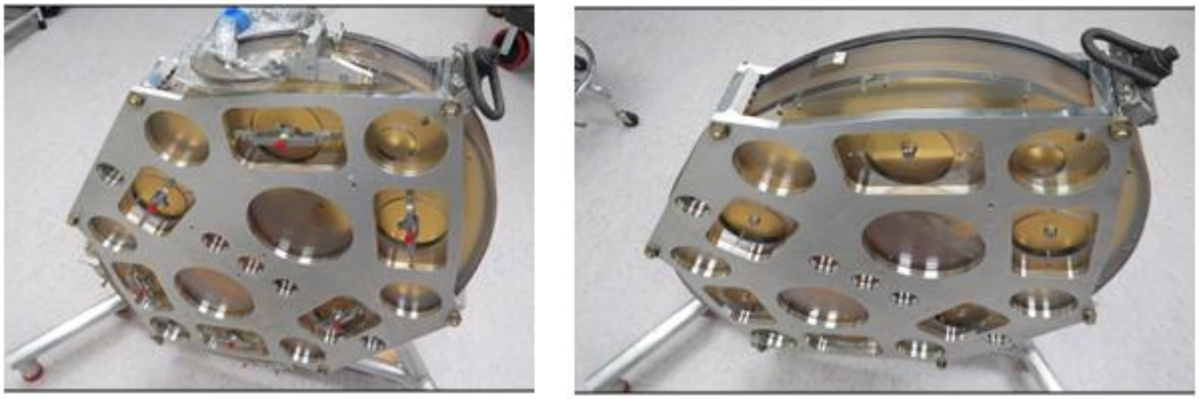

Figure 3 - Mirror at Keck in the glue jig fixture. The fixture is on a stand so that the tooling can rotate about the mirror center. This allowed positioning the three lateral pucks on edge to be individually upright for easy work access. Left image is mirror fixtured prior to bonding. Right image is after bonds sufficiently cured and with puck positioning hardware removed.

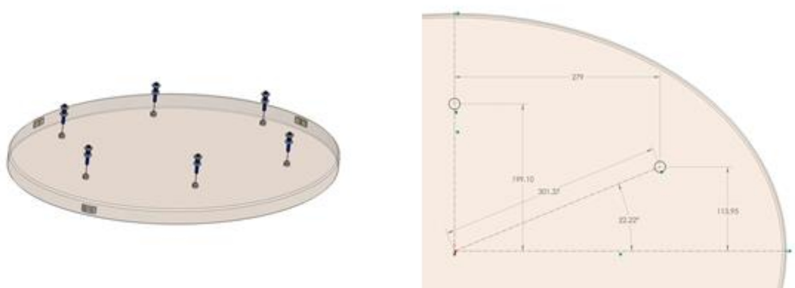

Figure 4 - The left CAD image shows the six axial support rods attached to the back of the K1DM3 mirror. The diagram on right shows the placement of two of the rods indicated by open circles. The measurements are referenced from the major and minor semi-axes of the mirror.

Lateral support is provided by three rods glued to pucks on the mirror edge at mid-plane, similar to the axial flexure rods. These are at approximately the major axis of one side and two other positions opposite (Figure 5). These rods are 125 mm long, 3.0 mm in diameter, and also 17-4PH. These rods use pucks designed for the curvature at the points of attachment. Their sizes were designed to ensure 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 for the worst case design loads. These stresses are significantly smaller than the estimated 3000 PSI of stress that the bonds can endure and the 1000 PSI limit imposed for Zerodur.

The axial and lateral rods are integrated within a whiffle-tree support system, shown in Figure 6. The whiffle tree is composed of 0.75 inch diameter struts (5/32 inches thick wall) 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 about 69.85 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 7). This configuration allows one to remove the mirror assembly from the K1DM3 system for coating. It then enables one to consistently and precisely reattach the mirror assembly to the swing arm assembly.

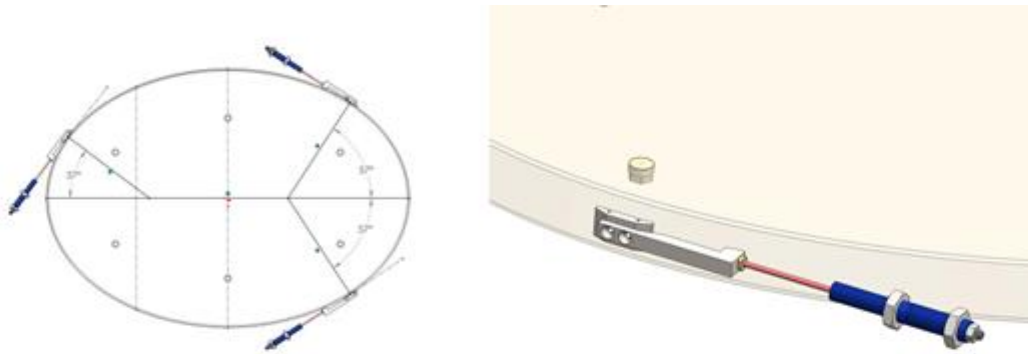

Figure 5 - Left diagram shows the placement of the three lateral supports along the outside edge of the mirror. Right image is a close-up view of one of the lateral supports screwed to a puck that is glued to the edge of the mirror.

Figure 6 - Top and side views of the whiffle-tree support structure for K1DM3.

The design also allows for fine adjustment of the kinematics during the alignment phase.

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

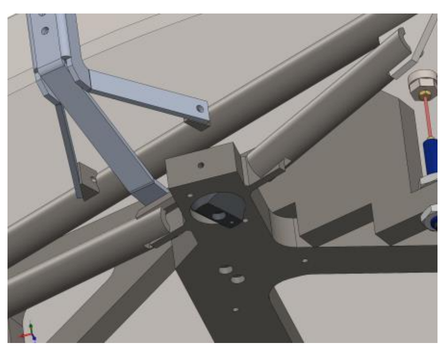

Figure 7 - At the center of the image is the kinematic coupling (canoe sphere) for attaching the mirror assembly to the swing arm assembly.

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

Figure 8 is a deflection contour map of displacement (m) normal to the surface. The load is gravity normal to the mirror surface. This is the most severe loading condition encountered by the mirror during normal operating conditions. The peak-to-valley displacement is approximately 124 nm.

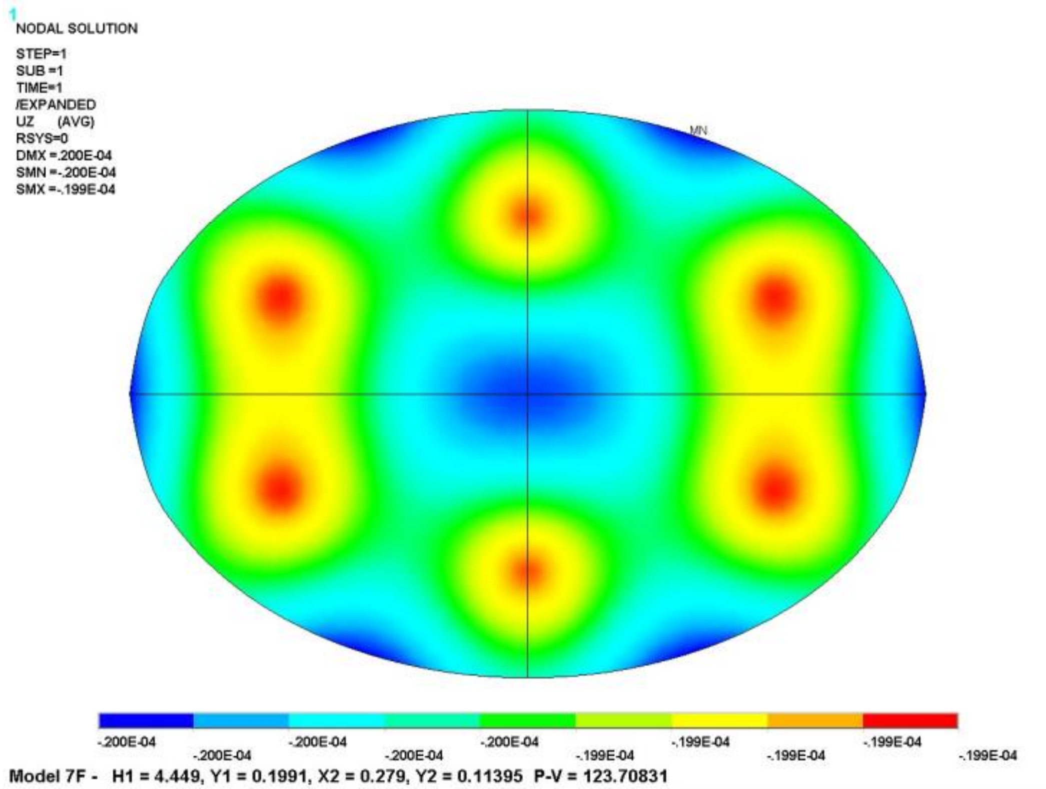

Figure 8 - Surface deformation map for the six point support system due to gravity normal to the mirror. Deflections are in meters. The contour map is for the entire mirror surface. The peak-to- valley range is 124 nm. RMS deflection of the entire surface is 39 nm.

A pseudo spot diagram shown in Figure 9 is an assessment of the worst-case deformations reported above. The basis for this diagram is the deformation response of the mirror due to normal gravity. Surface deflections of the model (Figure 8) are mapped to a uniform shell mesh.

The plot is an aggregate of all the points on the uniform mesh. Each dot on the graph represents the two out of plane rotations of the point. X Slope is about the mirror major axis. Y Slope is about the minor axis. For a perfectly flat mirror all points would be at the center. This shows that the rotations are small and the overall image blur is negligible.

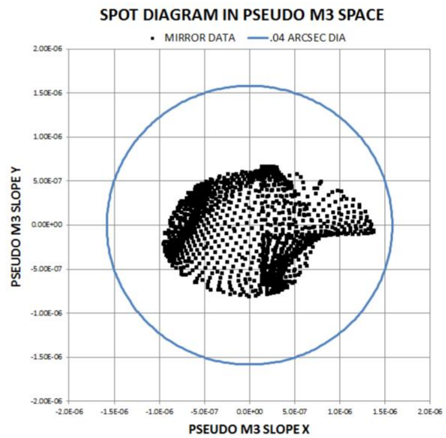

Figure 9 - Spot diagram based on results shown in Figure 9. This diagram represents where light reflected by the mirror would strike the focal plane. The image is a family of points which are calculated based on the slope error throughout the mirror. If the mirror were not deformed (perfectly flat) the image would be single point at the center.

Once the locations of the direct contact supports to the mirror were established, the rest of the support structure needed design and optimization. FEA models were made of the mirror assembly attached to the swing arm and connections to the bipods. This led to an iterative process for the design of the placement, size, and material of the swing arm struts.

Figure 10 shows the FEA model. This model includes the mirror with its support by the axial and lateral flex rods along with the whiffle tree system and finally to the mirror support structure. 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 with appropriate boundary conditions.

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.

Worst case gravity orientations were modeled for when the mirror is pointed to Nasmyth and bent Cassegrain instruments. Net piston and mirror rotation was calculated from nominal position (telescope pointed at Zenith) for the extreme case of observing at 72 deg off Zenith. Results of the static gravity cases are shown in Table 1. Only the displacements causing out of plane motion of the mirror are reported. These are piston, tip (rotation about the minor axis), and tilt (rotation about major axis) of the mirror.

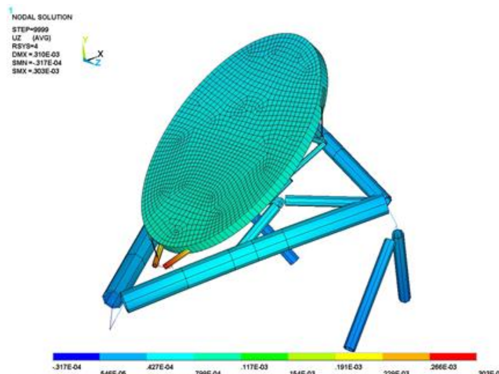

Figure 10 - FEA model of the combined swing arm and mirror assembly.

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

Mirror position	Piston (µm)	Minor axis rotation (arcsec)	Major axis rotation (arcsec)
Bent-Cass	114	2.4	3.6
AO	64	9.1	5.7

1.3 Repeatable positioning of the mirror

Ensuring repeatable positioning of the mirror was a key driver in many aspects of the K1DM3 design. For good overall repeatability, it is essential that we ensured good repeatability of three separate subsystems: 1) the deployment subsystem called the deploy kinematic coupling mechanism (DKC), 2) the inner drum positioning subsystem called the inner drum detent mechanism (IDD), and 3) the tertiary tower engagement subsystem, called the defining point mechanism (DPM). For all of these subsystems, the combined error budget was tight for most degrees of freedom, the most demanding of which is the 11.3 arcseconds (rms) for mirror pointing accuracy and repeatability. Following, each subsystem is described in more detail.

1.3.1 Deploy kinematic coupling mechanism (DKC)

The K1DM3 system is designed to deploy and retract its mirror upon software command. In the following narrative, we describe the parts critical to the actuation of the K1DM3 swing arm and the key components used to achieve micron level repeatability for deployment. As mentioned previously, the mirror assembly is fastened to a tripod swing arm fabricated with ASTM-A36 steel to match the coefficient of thermal expansion of the telescope and major support structure of K1DM3. Figure 11 illustrates the shape and overall dimensions of this part. It is a weldment of tubular steel members designed to maintain rigidity while minimizing profile. At the end points of the main arms are the canoe spheres (highlighted in blue) that enable repeatable, precise positioning of the mirror. Each of the six hemispherical surfaces of the canoe spheres (0.5 m radius) engage with precision ground flat surfaces rigidly attached to the bipod weldment. This swing arm is attached to a pivot mounted to the bipod weldment. This pivot is compliant (roughly 1mm in any direction) 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. The deployed swingarm is held in position by a set of four over-center locking pneumatic clamps. These clamps do not require pneumatic pressure to maintain their locked position.

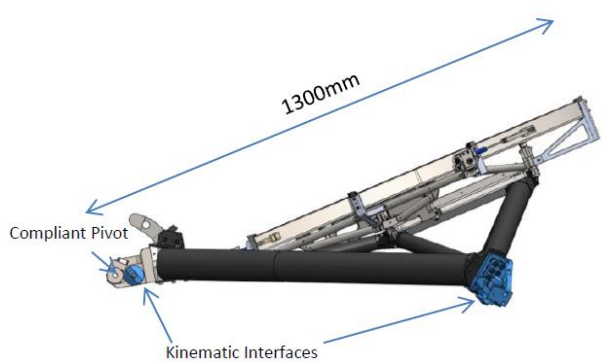

Figure 11 - Views of the mirror support swing arm, dimensions are in millimeters, canoe sphere kinematic interfaces highlighted in blue.

The swing arm is lowered into place (or lifted from the deploy position) by a pair of brushless planetary roller screw linear actuators, each providing up to 9000N of force. Such high force actuators were used to due to limitations in where we could place the actuators. It was important to place them where they would not cause vignetting when retracted. The less-than-ideal actuator placement results in a mechanical advantage of approximately 0.25, meaning approximate 4x the gravitational load of the swing arm is required of the actuators. Each actuator is attached to the swing arm by a compliant universal joint. The opposite end of the linear actuator is attached to the inner drum with a compliant spherical bearing joint. The compliance at each end is on the order of 1mm which allows the kinematic coupling to function as intended and not over constrain the swing arm. The positioning accuracy of the linear actuator is roughly 25 microns to ensure that we are well within this compliance range every time.

1.3.2 Inner drum detent (IDD) positioning system

Repeatable positioning of the inner drum is just as critical as the repeatable positioning of the swing arm. Our inner drum detent (IDD) position system achieves this requirement with no steady state power dissipation. At the bottom of the module, as shown in Figure 12, there is a ring gear driven by a pinion gear servo system as well as a detent mechanism. When changing to a new instrument, the detent disengages from the v-block and the servo system is commanded to drive to the v-block corresponding to the new instrument position. While servo-ing, position information regarding the inner drum is fed back to the control system from both a rotary encoder on the servo motor and a magnetic load encoder attached directly to the inner drum. The resolution of the magnetic load encoder is 5 microns. After the servo system positions the inner drum to within 100 microns of the desired v-block position, the final position is achieved by engaging the high precision spherical roller into one of the eight v-block detents (hardened and precision ground 440C steel). The engagement is accomplished by an air-pressure driven actuator mounted to the outer drum, resulting in no heat dissipation at M3 to maintain this high precision positioning.

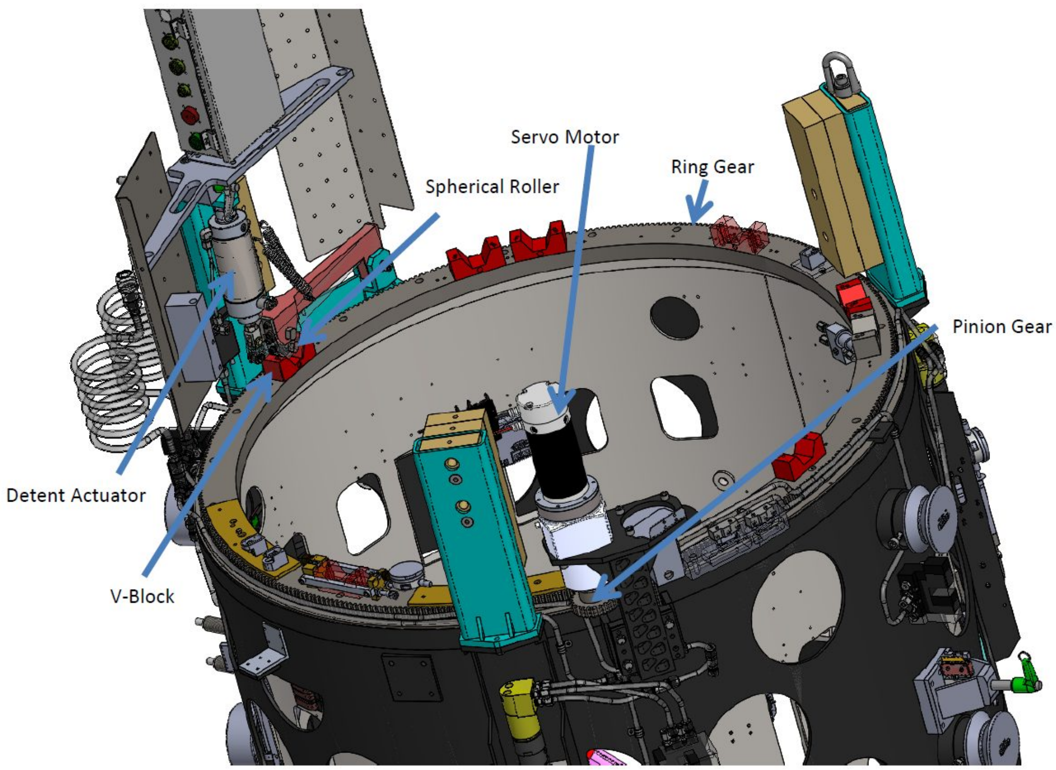

Figure 12: Azimuth/instrument positioning system, spherical roller engaging in v-block

1.3.3 Tertiary tower engagement subsystem AKA defining point mechanism (DPM)

After mirror recoating or other off-telescope servicing, K1DM3 must re-engage with the tertiary tower in a repeatable manner. The engagement mechanism is referred to as the defining point mechanism (DPM), and the complete DPM system includes both a tower side Acme screw mechanism and a K1DM3 side Acme nut mechanism. The three Acme screw and nut mechanisms work together to load a quasi-kinematic coupling consisting of the following engagement geometries: (1) sphere-in-cone; (2) cylinder-in-groove; and (3) flat-on-flat. The flat-on-flat and the cylinder-in-groove are not kinematic per se, but provide increased stiffness and less Hertzian stress compared to using a sphere-on-flat and a sphere-in- v-groove, hence we are quasi-kinematic in this case, but the repeatability has proven to be satisfactory. The K1DM3 cone portion of the DPM is shown in Figure 13. Each defining point mechanism that is mounted on the tertiary tower incorporates a rotationally fixed Acme thread lead screw that is pushed into the corresponding K1DM3 Acme nut 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 an Acme nut in the center of the mating half of the DPM. The nut is rotated by a reversible air motor incorporated in the K1DM3 half of the DPM. Once the two halves of the three defining points are all in initial contact (brought in close contact by a telescope technician), each part of the mechanism is mated in sequence, starting with the sphere, then the cylinder, and then the flat. Each Acme nut is unconstrained in the x and y directions so it only provides a clamping force in the z direction. It should also be noted that upon full Acme screw engagement, the DPM lifts K1DM3 off of the steel installation rails so K1DM3 is fully unconstrained except by the DPM.

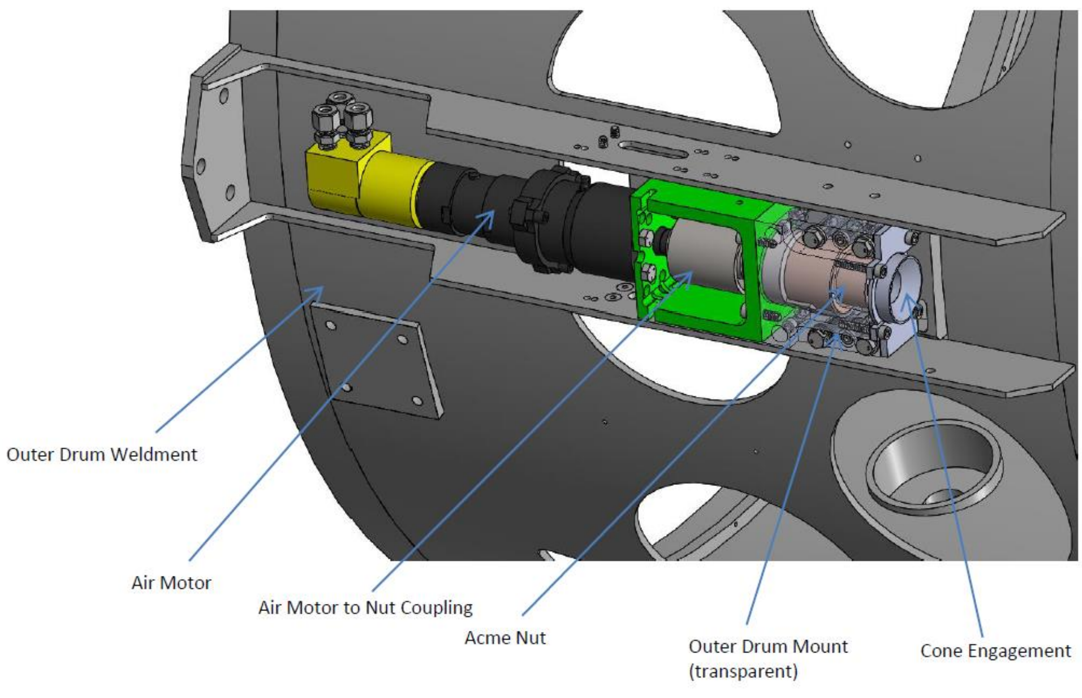

Figure 13: K1DM3 tertiary tower engagement mechanism, cone type. Outer drum mount shown as transparent to show internal parts

1.4 Control system highlights

This section highlights the most distinctive aspects of the K1DM3 control system.

The non-vignetting requirement did not allow room for a cable wrap that could connect the inner drum with an external motion controller. There is enough room to provision a low profile slip ring solution for a handful of electrical connections, but not enough room to carry a full set for motor power, encoder, limit signals, and so on. Instead, a motion controller for the swing arm is mounted on the inner drum wall, rather than a conventional location in a separate electronics enclosure. Only power, a network connection, and two additional signals are provided between the inner and outer drums. Full slip rings were prohibitively costly, so the module has electrical contacts only at each instrument position.

The requirement to minimize heat load means that the swing arm controller has to be powered off between moves. Yet, the control system has to be able to power up and be ready to move the swing arm in a matter of seconds, so that the entire module can meet the requirement for moving between any two instrument positions within two minutes. We do not meet this requirement for a worst case move at this time. It takes us about 2.4 minutes for a worst case move.

The two swing arm actuators have a very high force capacity, as a result it is important to move them synchronously -- if they get out of sync, the swingarm will bind and excessive mechanical stress is imparted. An independent module, a PLC-like Galil RIO-47142, monitors a pair of absolute encoders that are mounted on the swing arm actuators, and interrupts motion if the actuators get out of sync. Like the swing arm controller, the safety-enforcing RIO is mounted on the inner drum.

The drum rotation controller, a second Galil DMC-4040, is in an external electronics enclosure behind the primary mirror. The enclosure is cooled by a glycol system, and therefore this controller can remain constantly powered.

Successful and safe operation of the K1DM3 module imposes strict sequencing requirements among the rotation detent mechanism, rotation motor operations, inner drum compressed air supply, inner drum power, swing arm clamps, swing arm actuators, *etc*. On the other hand, the telescope control system expects the M3 subsystem to operate correctly with just four simple commands (*Halt, Standby, Init, Move*), and therefore the K1DM3 control system includes software sequencers that implement the complex motion steps. The same sequencing must be followed when using the simple manual control paddle that is provided for operations and engineering support, and so the paddle doesn't directly command the low-level components, but instead signals high-level requests such as “move to next position.”

2. ALIGNMENT

2.1 Alignment functional requirements

The overall approach is to align K1DM3 to the old M3 rather than realigning each instrument to the new K1DM3. This approach allows Keck to use either K1DM3 or the old M3 without reconfiguring the telescope while the other mirror is being recoated or serviced. Although good for Keck 1 operations, matching K1DM3 to the old M3 alignment for all degrees of freedom poses challenges.

The driving requirement for matching K1DM3 to the old M3 mirror position is matching alignment to the AO system. The desire is to have the pupil image of the primary remain in the same position to within a small fraction of the sampling sub-aperture. The current Keck AO system samples the pupil about 20 times across its diameter. Future AO systems will likely sample more densely, maybe 100 times across the diameter. After deliberation and calculations, the mirror positioning requirements were set so K1DM3 should match the existing M3 normal to within 11.3 arcseconds in tip (rotation about mirror minor axis) and 22.6 arcseconds in tilt (rotation about major axis). In addition, it was also important to match the mirror pointing alignment to HIRES on the opposite side of the elevation axis and also to the four instrument ports on the elevation ring as close as is practical. There are other requirements for positioning in piston and in plane positioning, however the tip and tilt requirements proved to be the most demanding and will be the focus in this paper.

After some thought and experimentation, our alignment procedure was turned into a three step process, which is described in detail below. The first step was to align the inner drum axis of rotation of K1DM3 to the old M3. Step two involved matching K1DM3 mirror in tip/tilt and piston to the old M3. Step three involved matching the position of each of the six instrument stopping positions of K1DM3 to the old M3.

2.2 Step 1: rotation axis alignment

The first step in aligning the rotation axis is to identify the axis of rotation of the old M3. This is done using an alignment jig and ring gear fixture, a schematic is shown in Figure 14.

The ring gear attachment fixture is rigidly clamped to the old M3 ring gear, and the collimation telescope alignment jig is attached to the Keck telescope tertiary tower structure. The interface between the alignment jig and the tertiary tower is kinematic allowing highly repeatable placement of the alignment jig relative to the tertiary tower. After the alignment jig is in place, we commence to rotate the old M3 and adjust the tip/tilt of OM3 to be normal to the rotation axis. In practice, we will often start with a laser in place of the collimation telescope to "rough in" OM1, OM2 and OM3 to get things aligned to within half of the 30 arcminute FOV of the collimation telescope. This process ensures that we can see our auto-collimation pattern with the CCD camera mounted to the collimating telescope. We then switch from the laser to the collimation telescope and CCD camera. With these components, we can achieve a much higher precision identifying our rotation axis with respect to the collimation telescope axis. An example of this auto-collimation return signal is shown in Figure 15. The bull's eye light pattern represents the OM3 mirror normal angle relative to the cross hairs that represent the collimation telescope axis. We can magnify the auto-collimation return signal and identify the center of the circular pattern to about 0.5 pixels, each pixel represents about 2.2 arcseconds of angular resolution.

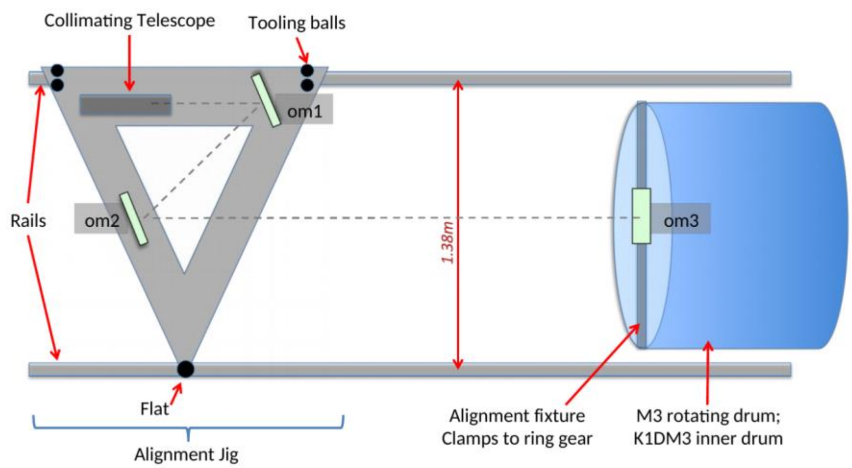

Figure 14: Schematic of Alignment Jig, Alignment Fixture and Module for alignment of module rotation axes. OM1 and OM2 redirect the beam from the collimating telelscope to the module and OM3 has tip/tilt adjustments to align normal to the rotation axis

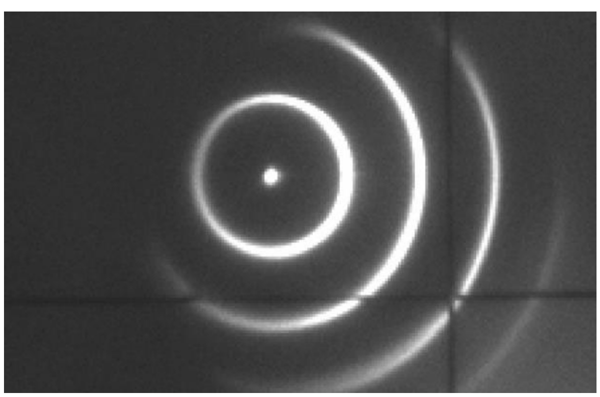

Figure 15: Autocollimation image. The rings are at radii 1,2,3 ..arcminutes. We can locate the center of the "bull's eye" to about 0.5 pixels which is 1 arcsecond resolution.

In rotating both K1DM3 and the old M3 one full rotation, significant axis wobble is apparent, approximately 10-20 arcseconds is the typical deviation from a perfectly circular auto-collimation trace. This wobble is likely due to the runout (deviation from a perfect circle) on the inner and outer drums. The runout on the drums is about 0.05 mm as manufactured. This anomaly alone could contribute about 20 arcseconds given the geometry of the situation.

We could likely improve on the 10-20 arcsecond wobble if the inner and outer drums were machined with a higher precision milling machine. Improved fixturing and handling would also likely also be required to eliminate the possibility of ovaling during bearing installation and lifting/assembly procedures.

Given that both the old M3 and K1DM3 have axis wobble, we made it our goal to align the centroid of the 360 degree K1DM3 auto-collimation pattern to the centroid of the old M3 360 degree pattern.

After defining the rotation axis angular orientation on the old M3, the next step is to identify its center of rotation. This is done by taking the alignment telescope out of collimation mode and focusing on a target scribed on OM3. By making a full rotation, we can identify the center of rotation relative to the alignment telescope axis to within 0.2 pixels, which corresponds to approximately 0.1mm position precision at M3. The method to find the center of rotation is to fit a circle to the scribe mark positions for one full rotation, the center of this best fit circle is the location for the center of rotation.

Figure 16 shows the alignment jig in more detail. The collimating telescope is a Davidson Optronics D-275 fitted with a CCD camera at the focus. Optical mirror 1 (OM1) is mounted to a 2 axis tip/tilt flexure stage and optical mirror 2 (OM2) is mounted to tip/tilt flexure stage and a preloaded x-y translation stage.

Figure 16: Alignment jig on rails of Keck-I. Autocollimation telescope with CCD camera

Figure 17 shows the ring gear attachment fixture in more detail. OM3 is mounted to this fixture on a tip/tilt stage to allow adjustment of OM3, to get it perpendicular (or nearly so) to the rotation axis.

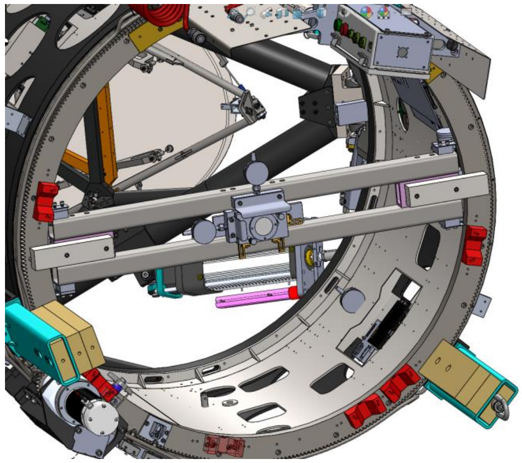

Figure 17: Ring gear attachment with OM3 on tip/tilt/translation stage

After defining the rotation axis angle and center of rotation on the old M3 , we remove the alignment jig, remove the old M3 and install K1DM3, attach the ring gear alignment fixture to K1DM3, remount the alignment jig on the rails to re-establish the axis definition, and adjust the tip/tilt/translation of the OM3 attached to K1DM3 to define its rotation axis. At this point, the differences in position between the auto-collimation images of the two modules, and those between the position of the center of rotation for the two modules, give us the inputs necessary to determine the required adjustments to the defining point blocks (solved with a computer program created by A. Phillips). Adjustments are then made to the K1DM3 DPM using jacking screws and indicator gauges. Finally, the new alignment is verified by rechecking the position of each M3 center of rotation and rotation axis angle.

Figure 18 shows the defining point mechanism (DPM) as well as the alignment tooling used to adjust position .

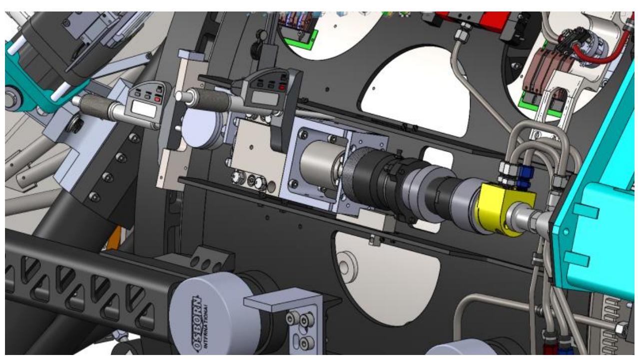

Figure 18: Defining point mechanism assembly with adjustment tooling

In making the alignment adjustments, it should be noted that the axis parallelism is the more demanding requirement. The positioning of these DPM mount blocks along the telescope axis need to be positioned with a precision of approximately 10 microns. We found that 40 micron precision moves were not so difficult, but 10 microns required iterations of the same move. In hindsight, it would have been better to add measurement tooling surfaces when the defining point block assembly parts were designed to ensure smooth high precision repeatable surfaces to measure from.

2.3 Step 2: Optical alignment, matching position of mirror relative to rotation axis

The portion of the alignment described below has not yet been completed and may be subject to change. After the rotation axes are aligned, it is time to move on to aligning the tip/tilt and piston of K1DM3 to match the tip/tilt and piston of the old M3 relative to the rotation axis. This part of the alignment uses a different hardware configuration where an alignment telescope is mounted to the f/25 secondary socket as shown in Figure 19. Figure 20 shows a photograph of the alignment telescope mounted in the f/25 mirror position. In this situation, we have decided to use a motorized alignment telescope to change focus or switch to auto-collimation mode remotely given the secondary socket swings approximately 12 meters above the Nasmyth Deck and 24 meters above the dome floor.

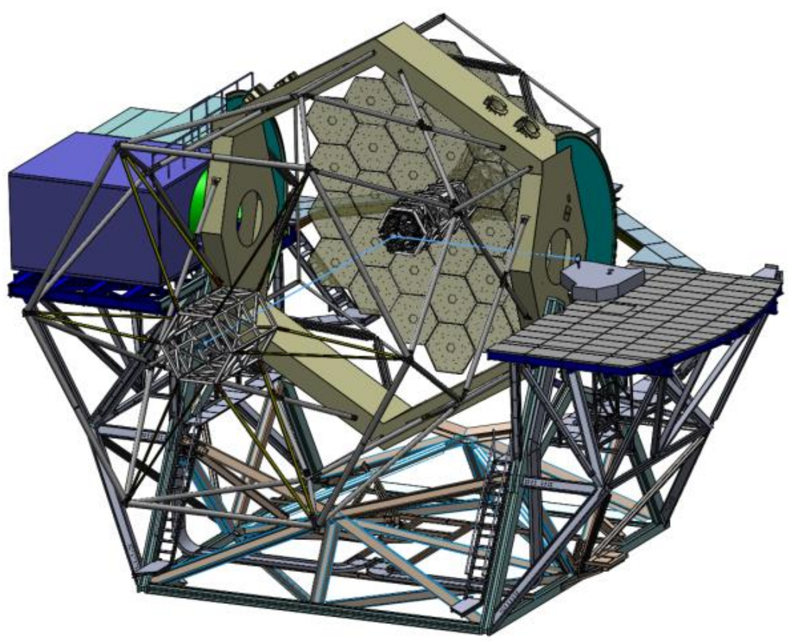

Figure 19: Setup of secondary socket mounted alignment telescope on Keck 1, blue highlighted line represents center ray from alignment telescope to K1DM3 to AO system mounted auto-collimation mirror

The initial step here is to mount a scribed mirror on the AO bench near the telescope center ray. This will allow us to match the (nearly) 45 degree pointing angle of the old M3.

With the old M3 installed first, we "rough in" the system with Keck 1 pointed at horizon. During this step, the tip and tilt of this AO mirror is adjusted so the mirror normal is within roughly 3.8 arcminutes of the alignment telescope axis.

This "rough in" ensures the auto-collimation return signal will be in the field of view for the CCD camera and is sufficiently luminous. The tip and tilt of the AO mounted mirror is adjusted using two remote controlled piezo motors (Pico-Motors ^{TM}), due to the difficult access to this mirror on the AO bench. Next, the alignment telescope is put into auto-collimation mode and an angular position of the old M3 is taken relative to the alignment telescope axis. The center of this pattern can be identified to within 1 arcsecond angular measurement precision for this motorized alignment telescope configuration. The auto-collimation return signal x-y pixel location is identified and becomes the optical axis target for positioning the K1DM3.

At this point, the old M3 is removed and K1DM3 is installed. Figure 21 shows the K1DM3 tip/tilt/piston adjustments relative to the swing arm. Jacking screws in combination with precision indicators are used. We then turn on the motorized alignment telescope in auto-collimation mode. At this point, we measure the angular position of the K1DM3 mirror and determine how much it needs to move to match the angular position of the old M3. K1DM3 is then removed from the tertiary tower, the adjustments are made and after reinstalling K1DM3, the angular position is verified to be accurate.

Figure 20: Automated alignment telescope mounted to Keck-I f/25 secondary, looking through the central hole in the mirror. Tested August 2017. There are tilt-tip adjustments in the mounting bracket, but the actual pointing of the alignment telescope is not critical as long as the targets can be clearly seen.

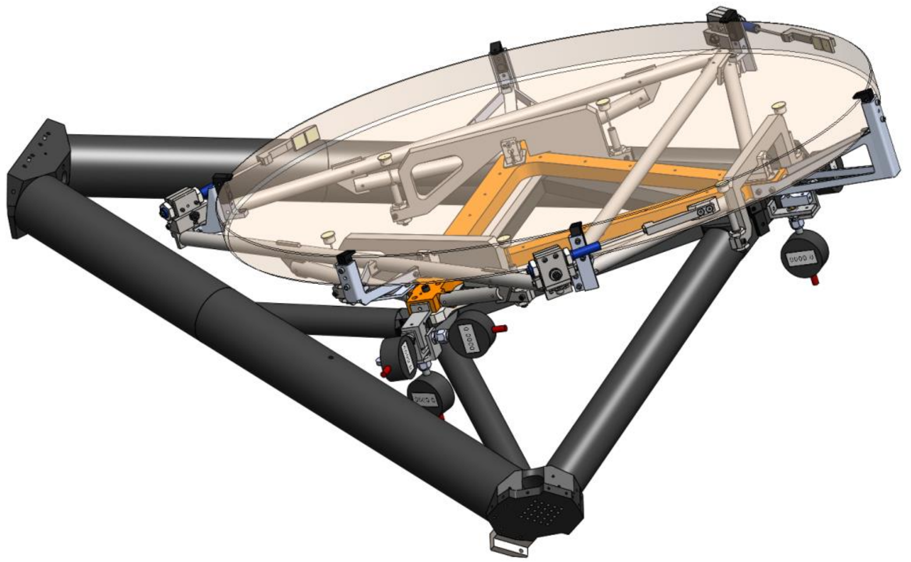

Figure 21: K1DM3 Tip/Tilt/Piston M3 Adjustment Tooling Relative to Swing-Arm

For the next step we adjust the piston of K1DM3 to match the old M3. With the old M3 installed we go out of auto-collimation mode and change to focus on the mirror at the AO bench that also has a scribe mark used a target. The scribe x, y position is noted to approximately 0.2 pixels resolution, the goal is to adjust the new M3 in piston so the scribe mark will match this x, y position to as close as is practical.

2.4 Step 3: Alignment of instrument positions

With targets also mounted at the five remaining Nasmyth and bent-Cassegrain foci, we then aim at each of these five foci, then screen capture the pixel location for each of these other five targets with the old M3 still installed. These five scribe pixel x, y positions (relative to alignment telescope center ray) are screen captured on a laptop and will be used to position the same five detent V-blocks on K1DM3.

The plan is to adjust the position of the detent V-blocks for each focus while K1DM3 is installed in the tertiary tower. The adjustment setup is shown in Figure 22. This positioning system uses a high precision spherical detent to push into each surface ground v-block that is attached to the ring gear and drives the inner drum into position. The system provides repeatable, high precision instrument positioning of the inner drum to each of the six elevation ring instruments. Here the goal is to move each v-block tangentially to best align to each instrument.

To adjust the position of each v-block, first the v-block is loosened from the ring gear by loosening two screws on the backside of the v-block. Next the adjustment mechanism, also shown in Figure 22, is installed. The v-block is then pushed relative to the ring gear with a extra fine pitch screw until the scribe mark pixel position lines up with (as close as possible/axis wobble will allow) to the old M3 pixel position. The positioning ability of this pushing mechanism is on the order of 5 microns, which translates in to about 1.7 arcseconds of azimuth instrument alignment resolution.

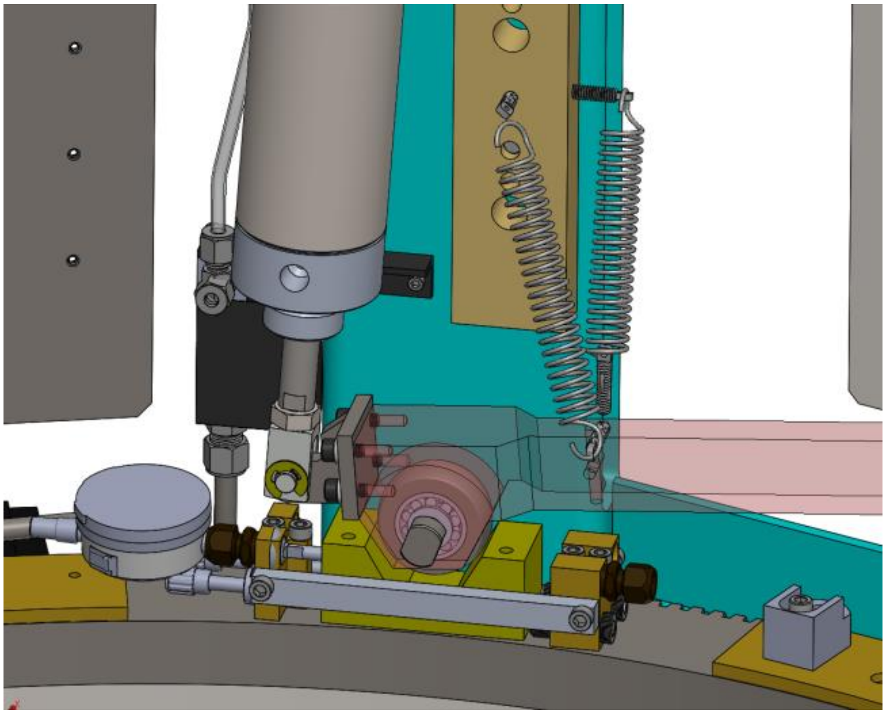

Figure 22: K1DM3 Instrument Position Detent Adjustment Mechanism

3. CONCLUSION

In conclusion, we have discussed some of the interesting topics regarding the design and alignment of K1DM3. K1DM3 should make the Keck 1 Telescope more agile for both science and the summit operations. K1DM3 has been fabricated and shipped to Keck Observatory, and we are still in the process of installation. Installation has taken longer than expected since we have not been allocated dedicated telescope time. It has been necessary to work around both scheduled and unscheduled telescope operations. Allocated telescope time certainly would be more efficient for the engineers and technicians who are installing this telescope upgrade.

We hope this project serves as an example for future telescopes and also for upgrades of existing telescopes. The goal is to be able to use any telescope instrument on demand to improve the scientific capability of the Keck Observatory.

In designing, fabricating and installing this new deployable tertiary mirror there were some important take-aways from this project that may seem obvious, but should always be remembered and not taken lightly.

1) Create mock-ups and test fit items on the telescope. Test fitting is especially important if the telescope was designed and built prior to computer aided design (CAD) and there are missing geometries and volumes in the project CAD layout.
2) Take lots of photos of both the new project build and of relevant mechanisms on the telescope. People typically suffer forgetfulness at 14,000 feet elevation. Photos can be invaluable.
3) Practice the act of installation and alignment before the trip. Practice helped us a great deal and resulted in better installation tooling and more efficient alignment procedures.
4) Establish good functional requirements early on in the project. They should be scrutinized and questioned. It is important to revise the requirements document and verify the product can meet key functional requirements and be within cost targets.

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