K1DM3 Design Note

Elevation Axis of the K1 Telescope

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I. Overview

It is a primary goal of the K1DM3 project to provide a new tertiary mirror system for the Keck I telescope that replicates, as best as can be acheived, the performance of the current M3 system. This includes image quality and repeatability in mirror positioning. It also includes reproducing the existing optical path to the instuments along the elevation axis (i.e. at Nasmyth and bent-Cass). To acheive this latter requirement, we must precisely characterize the as-built configuration of the K1 telescope. This Design Note describes new measurements that assess the position of M3 relative to M1, which defines the elevation axis of the as-built K1 telescope. These measurements indicate that M3 is approximately 6 mm farther from M1 then designed.

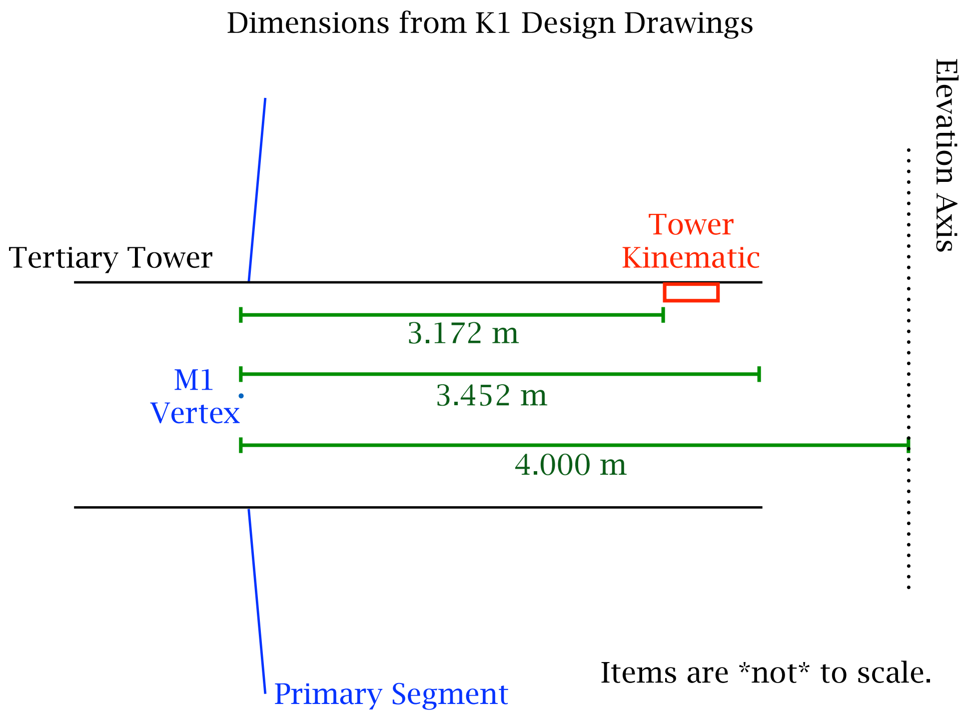

Fig. 1.— As-designed dimensions for several components of the K1 telescope taken from the K1 drawings.

II. K1 Elevation Axis: As Designed

The design of the K1 telescope places the elevation axis of the telescope at 4.000 m from the vertex of the M1 mirror surface to the intersection point between the reflective surface of M3 and the optical axis of M1 (e.g. Figure 1). The drawings for the tertiary tower [199-06-00-C] further specify that the tertiary tower extends 3.452 m from the M1 vertex. This is derived from the specification that the M1-facing surface of the steel tube defining the end of the tower lies 650 mm from the elevation axis. Given that the tube is 4 in. (101.6 mm) across, one recovers the above value.

Lastly, the drawings specify 3.172 m from the M1 vertex to the M1-facing surface of the 'blocks' that hold the tower-side kinematics which mate to the M3 module. Specifically, the drawings show

170 mm from the same M1-facing surface of the top steel tube to the farthest bolt on each block and an additional 8 mm from the bolt to the M1-facing surface. These dimensions are summarized in Table 1.

Thus far, the K1DM3 project has been designing its system to these measurements for the deployment of its mirror.

Table 1: Design Specifications for K1 Dimensions

Measurement	Value (mm)	Comment
M1 vertex to Elevation Axis	4000	
M1 vertex to Top of Tertiary Tower	3452	
M1 vertex to M1-facing surface of Kinematic Blocks	3172	

III. K1 Measurements: As Built

To precisely assess the as-built locations of key components in the K1 telescope, the K1DM3 project has performed a series of measurements. We describe each of these in turn.

A. Truman's Measurements of Kinematic Locations: On XX HT, Truman Wold used tape measures and scales to measure the distances from the top of the teritary tower to the M1-facing surfaces of the blocks that hold the tower kinematic mounts for the tertiary module. These values are presented in Table 2 and are the dimensions labeled as "Dim A" in Figure 2.

We may compare these measurements against the design drawings. The latter specify 3452 mm − 3172 mm = 280 mm from the top of the tower to the M1-facing surfaces of the kinematic blocks. This exceeds Truman's measurements by 13 to 19 mm implying a notable difference between the designed and as-built locations of the kinematic blocks relative to the top of the tower.

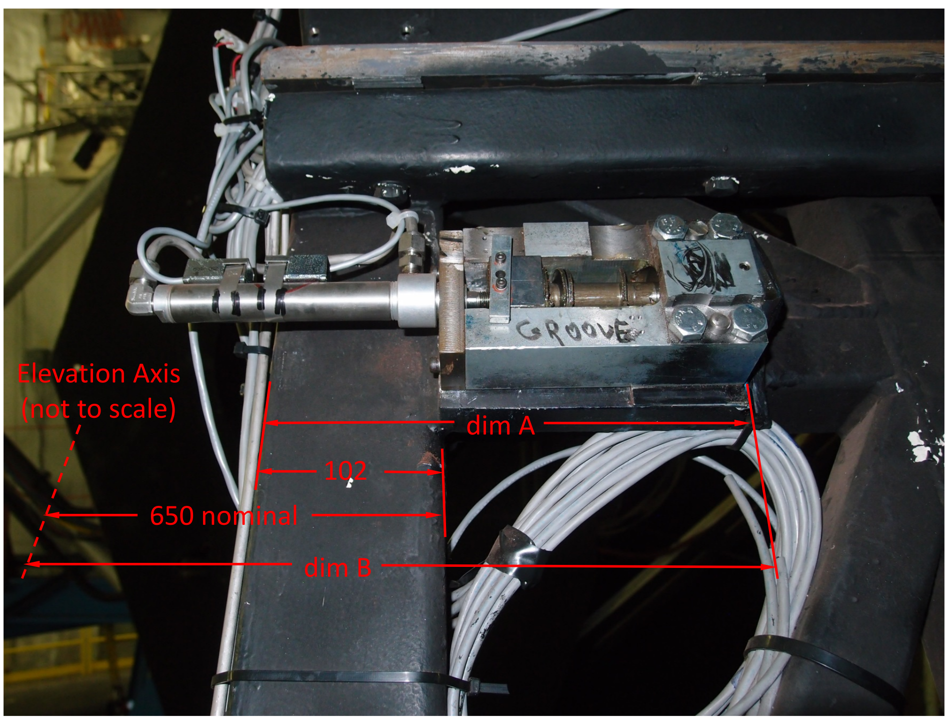

Fig. 2.— V-groove kinematic mount at the top of the tertiary tower in K1. Truman Wold measured the distance labeled as Dim A for each of the kinematic mounts on the tertiary tower, as given in Table 2.

Table 2: Truman Wold Measurements of Tower Kinematic Mounts relative to Top of Tertiary Tower

Measurement	Value (mm)	Comment
Top of Tower to M1-facing surface of kinematic block (Cone)	265	Dim A
Top of Tower to M1-facing surface of kinematic block (V-Groove)	261	Dim A
Top of Tower to M1-facing surface of kinematic block (Flat)	267	Dim A
As Designed	280	

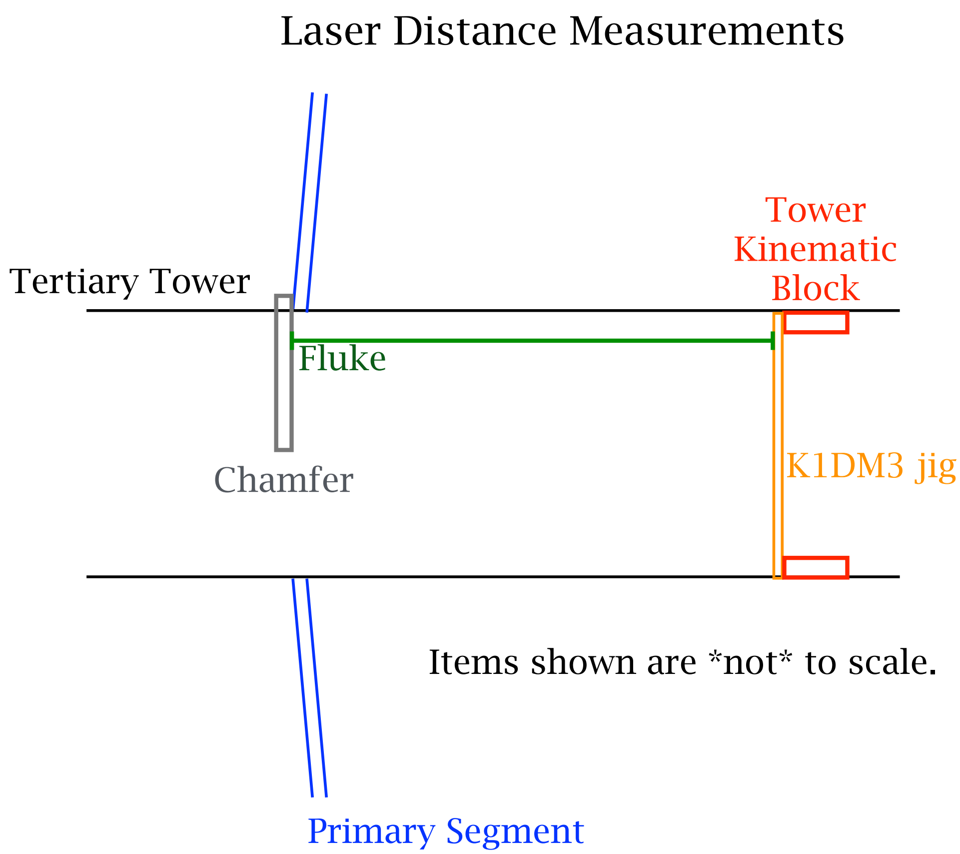

Fig. 3.— Setup for performing the laser distance measurements on K1.

B. Laser distance measurements: On June 27, 2015 (HT), Dave Cowley and Sam Park performed a series of distance measurements using a Fluke laser distance meter. They aligned the Fluke to the chamfer on the back of the M1 at the edge of the central, 'missing' segment to reference its position (Figure 3). They then measured the distances to the fixtures on the K1DM3 jig[1] when it was installed. Separately, Dave and Sam measured distances to the M1-facing surfaces of the kinematic blocks that hold the tower kinematic mounts. Lastly, they measured the distance from the back of M1 to the end of the tertiary tower. These measurements are listed in Table 3.

Let us first compare the positions of the blocks holding the tower kinematics measured by Dave/Sam to the drawings. Taking the differences between the end of the tower to the M1-facing surfaces and converting to millimeters, we have: 259.8 mm, 261.6 mm, and 272.0 mm for the Cone, V-

[1]A custom fixture brought to WMKO to establish the spacings between the tower kinematics.

groove and Flat respectively. These are 20 mm to 8 mm offset from the design specification of 280 mm. These measurements are similar to the values measured by Truman (Table 2), with offsets ranging from $1-5$ mm. We expect that these latter differences represent error in the measurement techniques.

Finally, consider the measurement from the back of M1 to the end of the tower: 138.02 in.=3505.71 mm. To compare against the design specification, we must estimate the distance along the M1 optical axis from the M1 vertex to the back edge of the segments around the 'missing' M1 segment. The M1 primary has a radius of curvature of 35 m. Approximating the mirror shape as spherical, we can estimate the 'sag' of the vertex relative to the inner segment corners or edges. We estimate the vertex is 11.6 mm below the inner segment corners and approximately 8.7 mm below the inner segment edges. Lastly, the mirror segment thickness is 75.0 mm (WMKO drawing 22A1016B).

Combining these quantities, the laser distance measurements from the back of M1 to the top of the tower gives a distance from the M1 vertex to the top of the tower of 3439.4 mm, i.e. 12 mm shorter than the design. For this estimate, we assumed that Dave/Sam measured to the edge of the inner segment and not the corner (yielding an uncertainty of several mm).

Table 3: Laser distance measurements on the K1 Telescope

Measurement	Value (in.)	Comment
Back of M1 to jig fixture on Cone	123.23	
Back of M1 to M1-facing surface of block holding Cone	127.79	
Back of M1 to jig fixture on V-groove	123.30	
Back of M1 to M1-facing surface of block holding V-groove	127.72	
Back of M1 to jig fixture on Flat	123.13	
Back of M1 to M1-facing surface of block holding Flat	127.31	
Back of M1 to end of tower	138.02	

C. Laser-Tracker: On XX HT, Sam Park oversaw laser-tracking measurements of the K1 telescope performed by the company API. They provided three sets of measurements, two[2] of which (A,B) are illustrated in Figures 4, 5.

Set A scanned several positions on the back of M1 (on the edges of the innermost segments) and portions of the mating surfaces on the tower kinematic mounts. We have made a representation of the M1 optical axis using the rear edges and assuming a hexagonal configuration for the 'missing' segment. Using this axis, we have measured the distances to the kinematic mounts listed in Table 4. These are in good agreement (matching to within 3 mm) with the values obtained with the laser-ranger (Table 3).

Set B scanned the tertiary module from several viewing angles when it was on its handling cart. From these data, locations of the ring gear of the M3 module, the non-reflective surface of M3, and the M3 module kinematics were determined. A representation of the module center axis was derived from a best fit to the ring gear, using its designed inner diameter. Because the gear is a thin piece, this measurement will have more Abbe or sine error. Traveling along this axis, we measure 1209.9 mm from the ring gear to the back surface of M3. Adopting a thickness of 4.921 in. for M3 (from WMKO K1 drawing 22A8874A), we calculate a distance of 1386.7 mm from the ring gear plane to the intersection

[2]Set C measures the cross-hairs and are not discussed here.

of its rotation axis with the reflective surface of M3. We define this point as lying upon the elevation axis of K1.

The two scan sets were mated by matching the kinematic mounts of the tower and module. We estimate that this procedure is accurate to approximately 1 mm. Impressively, we find that the M1 optical axis and the module axis (defined as above) are co-aligned to within 0.03 deg. Furthermore the M1 optical axis intersects the ring gear at only 2.2 mm offset from nominal.

After mating the two sets, we measure a distance along the M1 optical axis from the back of M1 to the ring gear on the module of 2685.7 mm. This gives 4072.4 mm from the back of M1 to the elevation axis. Allowing for the thickness of an M1 segment and the shape of the M1 mirror (as described above), we derive 4006 mm from the M1 vertex to the elevation axis. This matches (to within 0.5 mm) the measurement performed on the SolidWorks model generated from the tracker CAD models. We therefore conclude that the elevation axis of K1 is offset by ≈ 6 mm from the nominal design.

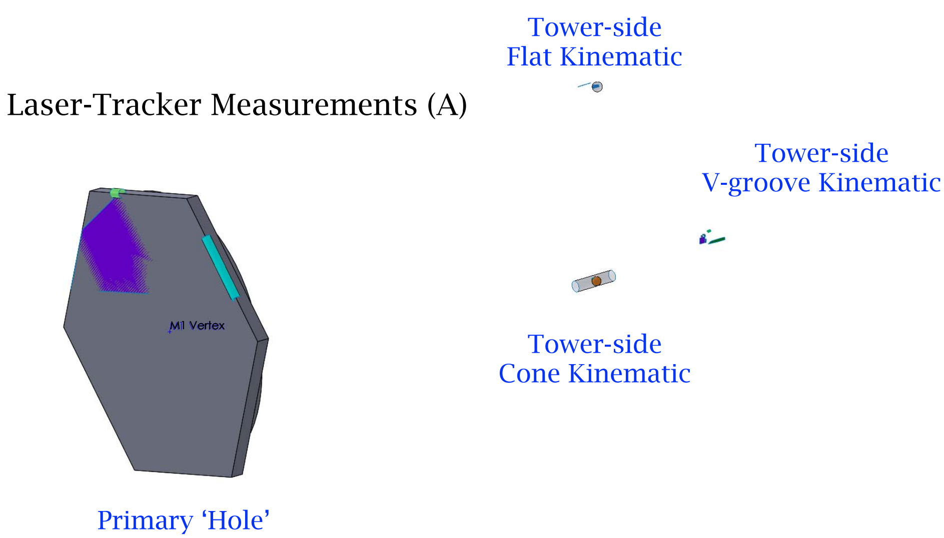

Fig. 4.— CAD of the laser tracker measurements from Set A.

Table 4: Laser tracker measurements on the K1 Telescope

Set	Measurement	Value (mm)	Comment
A	Back of M1 to tower kinematic (Cone)	3245.3	
A	Back of M1 to tower kinematic (Flat)	3243.3	
A	Back of M1 to tower kinematic (V-Groove)	3249.3	
B	Ring gear plane to back of M3	1209.9	
B	Ring gear plane to elevation axis	1386.7	Calculated

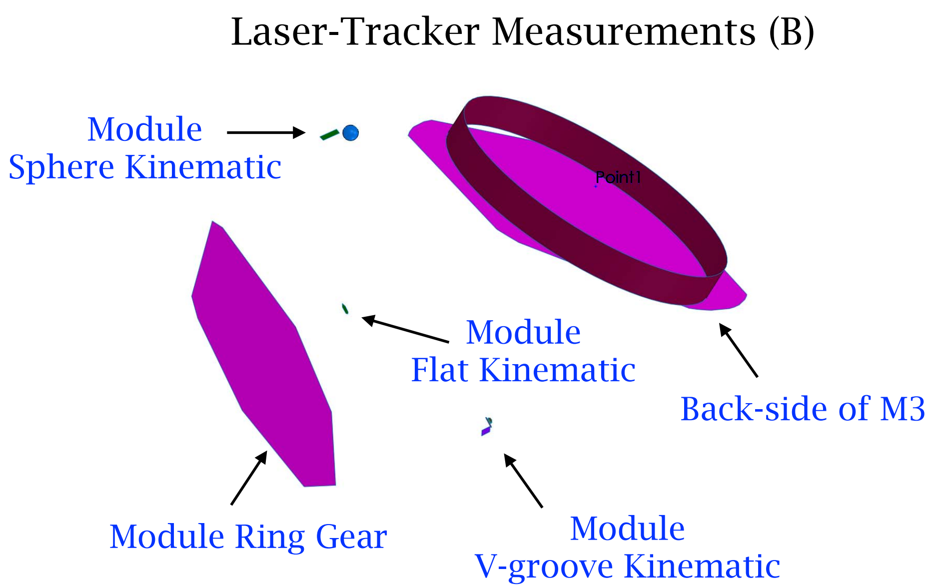

Fig. 5.— CAD of the laser tracker measurements from Set B.

IV. K1 Elevation Axis: As Built Summary

The K1DM3 project has performed a series of measurements on components of the K1 telescope. These are consistent to within $1-3$ mm, i.e. within measurement error. Adopting the laser tracking data, which has the highest precision, we estimate that the K1 elevation axis as built lies 4006 mm from the vertex of M1. This represents an offset of 6 mm and bears an uncertainty of ≈ 1 mm.

Appendix: Historical Measurements

Both during the commissioning of the Keck I telescope and in the few years that followed, measurements were made of the Elevation Axis relative to the primary mirror. Four archived Keck interoffice memorandums were found that contained information specifically regarding the as-built z-axis location alignment of the Keck I elevation axis: "Survey of Forward Cassegrain Defining Point Fixture" dated July 2, 1993 (Memo 1); "Z-Location of Tertiary Module with respect to Elevation Axis (Phase II)" dated February 24, 1994 (Memo 2); "Effect of 10mm Z-offset on Tertiary and Fwd Cass Modules" dated February 28, 1994 (Memo 3); "K1 Tertiary, Elevation Axis Survey Note" dated July 31, 1996 (Memo 4).

The original Memo 1 indicates that the K1 telescope elevation axis is at a height of $z = 10.0$ mm from the x-axis, whereas the K2 elevation axis and the x-axis are coincident. An update to memo 1 dated February 22, 1994, as attached as an addendum to Memo 3 clarifies The Keck I mirror cell is located 10 mm lower $(-z)$ than it is designed to be which makes the x-axis 10mm lower $(-z)$ than the elevation axis. Whereas the x-axis and elevation axis are near collinear in the Keck II telescope. We were unable to find further explanation on what was the source of the 10 mm offset.

Memos 2 and 3 discuss the implications of the 10mm difference between Keck I and Keck II and the interchangeability of the forward-cassegrain and tertiary modules. The Memo 3 indicates that the 10mm correction was made to the forward-cassegrain defining points in the tertiary tower. To clarify, the forward-cassegrain defining points in the tower are the same tower defining points for the tertiary mirror module. Having the offset on the tower side allowed interchangeability of the tertiary module between the two telescopes, according to the memo.

Memo 4 summarizes a repeat measurement of the 10mm offset in 1996 in preparation for HIRES alignment. In July 1996 9.96mm was measured compared to the previous 10.03mm. These measurements were performed using theodolites shooting crosshair targets located on the elevation ring (to establish the coordinate system) and through the elevation axis at right and left Nasmyth platforms.

Unfortunately, we do not have the ability to conduct direct measurements through the elevation axis at the right and left Nasmyth platforms in the same manner due to the in-situ instruments now stationed on the platforms. Such measurements would overly disrupt the telescope schedule.

The ~ 6 mm reported in the above document from the combination of laser tracker and CAD data is qualitiavely consistent with the historical documents although the K1DM3 team measurements are smaller. Measurement errors and assumptions of nominal CAD data (vs. as-built tolerance stackup of assembled components) can reasonably account for the difference.