K1DM3 Design Note

Zygo Quote for the K1DM3 Mirror

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I. Overview

The K1DM3 project has been generating a quote for the fabrication and polishing of its mirror (M3) with Zygo. The current quote specifications are for an 901.1mm × 643.0mm ellipsoidal figure with a 44.5 mm thickness (the latter dimension is set by the thickness of the TMT Zerodur blank which begets our mirror). Zygo has informed the project that the surface quality in the outer 'apron' (15 mm wide around the full circumference) may be poor, $\approx 1/2$ wave. This is due to the polishing procedure, and it could imply a clear aperture as small as 871.1mm × 613.0mm.

This document details the impacts and trade-offs related to this mirror quote.

II. Field-of-View

The Requirements Document (v3.1; October 17, 2014) specifies that the K1DM3 system will deliver an unvignetted field-of-view (FOV) of $5'$-diameter to the Nasmyth foci, when deployed. The dimensions of the ellipsoid that precisely captures the entire beam of a $5'$-diameter FOV for a perfect telescope with a pupil diameter of $D_p = 1.460$ m that would be located a height $z_p = 17.448$ m above M1 and for an elevation axis located at $z_e = 4.00$ m above M1 are given by: $2a = 881.1$ mm and $2b = 623.0$ mm. This optic must be aligned slightly off-center from the optical axis (13.7 mm). See the K1DM3 Positioning Design Note for further details. The full size of the quoted optic from Zygo exceeds this ideal ellipse by 20 mm in each axis, but if the outer apron (15 mm) is deemed optically unacceptable then the clear aperture would be reduced by 30 mm in each axis, i.e. 871.1mm×613.0mm. This would reduce the FOV provided by K1DM3.

To first order, changes in the linear dimensions of the mirror along the major axis lead to angular changes in the focal plane according to the approximate scaling of $10''/7$ mm, e.g. increasing the major axis by 7 mm increases the FOV by $10''$. The ratio for the minor axis is $10''/5$ mm (ie. scaled by $\sqrt{2}$). This follows from simple geometric considerations and may be verified by a full Zemax analysis.

Therefore, if we assume that all of the apron will be masked[1], then the clear aperture of the optic would be $2a = 871.1$ mm and $2b = 613$ mm leading to an unvignetted FOV=$280''$ (a reduction of $20''$ from the nominal $5'$ or approximately 7%). This would still well exceed the FOVs used by the existing instrumentation at the Nasmyth foci of Keck I (HIRES, OSIRIS). The choice of $5'$ was partly to accommodate a possible, additional guide camera for HIRES which no longer has Observatory priority. Another important consdieration is to feed any future instrument at the bent-Cass foci. Even at $5'$ the K1DM3 FOV would not feed the full $8'$ FOV opening in the bent-Cass facility rotator. With a $5'$ FOV, one may provide a science FOV of $\approx 2'$ when coupled to a guider with its own FOV of $\approx 1.2'$. Reducing the K1DM3 FOV to $\approx 4.7'$ would further reduce the science FOV at bent-Cass. Currently, the only concept being discussed for bent-Cass requires only an approximately $1'$ FOV (KRAKENS), yet we wish to maximize the potential for other opportunities.

[1]Possibly as part of a system for Earthquake restraint. If the project does mask this apron, special attention must be given to minimize scattered light. We may decide instead to accept the slightly poorer image quality.

We may consider the effects of mis-alignment of the M3 optic in a similar fashion. Assuming only 'in-the-plane' mis-alignment, i.e. in a plane parallel to its reflective surface, one maintains nearly the same FOV (to first order) but offset by the same scaling as provided above (e.g. $\approx 10''$ for every 7 mm of mis-alignment along the major-axis). Instruments utilizing only a small portion of the K1DM3 FOV (e.g. OSIRIS, HIRES) would have no change in performance. Instruments accepting a larger than K1DM3 FOV would receive an off-centered beam with a tolerably shifted pupil (see the Positioning Design Note for further details on mis-alignment). An instrument matched to the K1DM3 FOV would lose a portion of the field.

III. Surface Deformation and Flexure

The K1DM3 project has designed a mirror assembly system to maintain the flat surface of the M3 optic under varying gravity loads. This system envisions six rods glued to the back of the mirror for axial support and 3 additional rods glue to the mirror edge for lateral restraint. Our FEA of the design indicates that the performance is sensitive to both the size and mass of the mirror.

We had originally designed the assembly for an optic with $2a = 881.1$ mm and $2b = 623.0$ mm and achieved surface deformations of ≈ 42 nm RMS, well within the requirements. After discussing the mirror design with Zygo, we modified the mirror assembly for an over-sized optic and re-optimized the FEA. Surprisingly, the slope errors and surface deformations decreased slightly (e.g. ≈ 39 nm RMS). We conclude that our design can handle this over-sized optic and presumably one that was even somewhat larger.

The other key issue related to mirror support is for the swing arm and kinematic struts to hold the optic rigidly when deployed under a varying gravity load. This is especially challenging design requirement when combined with the constraints related to vignetting. We had originally designed to the 'ideal' optic with a 50 mm thickness but have now considered the quoted over-sized optic with the smaller thickness of the TMT test blank; the mass of this optic is actually slightly smaller. With great effort we have modified the swing arm design to achieve flexure results that are comparable to that of the original optic while avoiding vignetting.

IV. Vignetting

Perhaps the greatest challenge of the K1DM3 project has been to design a sufficiently rigid system that also: (i) fits within the existing tertiary tower (both during installation and operation); and (ii) retracts to a position that does not vignette the FOVs of the existing Cassegrain instruments. Indeed, this 'jigsaw puzzle' has driven the design of the K1DM3 system since its inception. To guide the design, we have generated a non-vignetting "shroud" that includes the dimensions of the beam traveling from M1 to M2 and the beam traveling from M2 to the Cassegrain focus, extending to the outer corners of the LRIS FOV (MOSFIRE encompasses a smaller FOV). With the over-sized optic quoted by Zygo and our current swing arm design, we find that the assembly just fits within the non-vignetting shroud (see Figure 1).

If we cannot keep the retracted mirror and swing arm fully within the non-vignetting shroud, we would likely choose to retract to a position that would potentially vignette the corners of the LRIS FOV. This choice is driven by the following considerations:

- The corners of the LRIS FOV are already partially vignetted
- Because LRIS is off-axis, random orientations of the instrument with respect to K1DM3 should

give no vignetting approximately half of the time.

- Given two positions for retraction, the observer could choose a position (or rotate LRIS 180 deg) that would not vignette LRIS for nearly all situations. This may incur a small overhead ($\lesssim 60$s).

Because the K1DM3 is held in a fixed position when retracted (with respect) to the tertiary tower, the vignetting of LRIS would vary with time in cases where the observer rotates LRIS to maintain a fixed position angle on the sky (standard).

IV. Summary

Although the quoted optic from Zygo is over-sized with respect to the ideal aperture required to provide a $5'$ FOV, their quote allows for an outer margin of 15 mm that may have degraded surface quality. If the entire 15 mm is compromised (unlikely), the resultant clear aperture would be ≈ 10 mm smaller diameter in each ellipsoid axis than optimal yielding an $\approx 4.7'$ diameter FOV.

Even with the quoted over-sized optic, the project is greatly challenged to fit the entire swing arm assembly within a shroud that represents zero vignetting of the Cassegrain instruments (at any rotation of those instruments). Significant modifications to the swing arm design lead to large and unacceptable flexure in the structure. We are doubtful that we could avoid vignetting if we adopted an even larger optic.

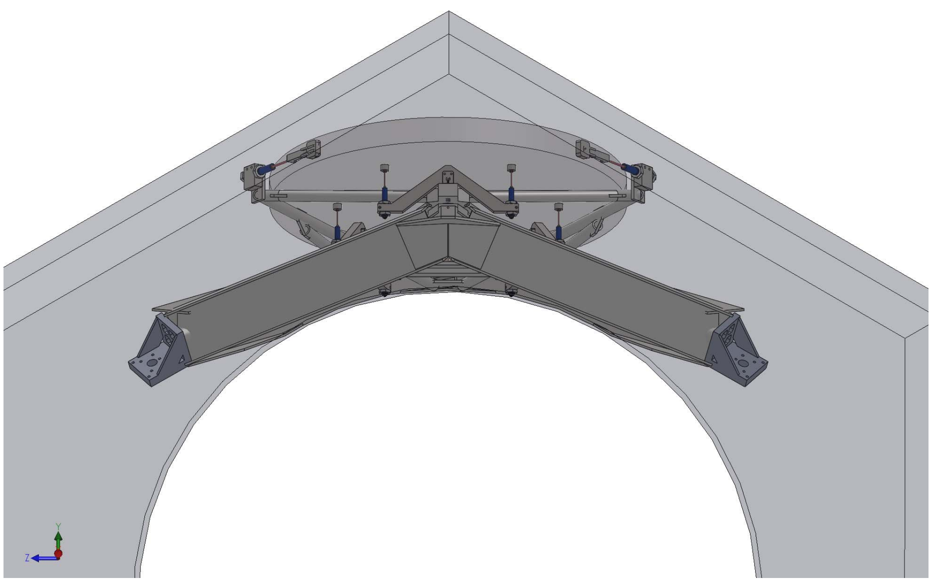

Fig. 1.— View of the swing arm assembly when retracted. The gray solid that surrounds it indicates the "shroud" that the assembly must lie within to avoid vignetting the Cassegrain instruments (specifically LRIS). The current design (barely) fits fully within that shroud.