K1DM3 Design Note

Mirror Specifications for the K1DM3 Project

Version 1.3, September 2, 2014

By J. Xavier Prochaska, Jerry Nelson, Harland Epps, David Hilliard, Drew Phillips, Sean Adkins

I. Overview

The tertiary mirror (M3) on the Keck I telescope (K1) feeds light into the Nasmyth and bent-Cassegrain foci of the telescope. The Keck I Deployable Tertiary Mirror (K1DM3) will replace the existing Keck I tertiary mirror with a new optical element designed to provide a field-of-view (FOV) of $5'$ at the Nasmyth foci.

This document details the specifications and requirements for the mirror and will guide RFQ requests to vendors. These specifications are (or will be) summarized within the Design Requirements document for K1DM3.

II. Material

The highest quality material for a flat optic is the Clearceram-Z glass from Ohara. This is the preferred material. Alternatively, Zerodur standard will suffice.

The specification is Clearceram-Z glass or equivalent.

III. Dimensions

A detailed calculation of the nominal dimensions of M3 are discussed in the K1DM3 Design Note on Positioning. To capture the full beam of a $5'$ FOV, one requires an elliptical mirror with major axis $2a = 881.1$mm and minor axis $2b = 623.0$mm. If $5'$ FOV were considered a strict requirement, then we may choose to oversize the mirror by a few mm in each axis to compensate for small misalignments. However, this FOV is not strictly defined (i.e. by any specific technical or scientific requirement) and we adopt these nominal values.

Lastly, we require a thickness of 50mm as a compromise between weight and stiffness[1].

The specifications are an elliptical mirror with $2a = 881.1$mm and $2b = 623.00$mm and a thickness of 50mm.

IV. Surface Flatness

The standard requirements are typically expressed (and measured) in units of a fringe, analyzed interferometrically with a laser tuned to a specific wavelength (often 632.8nm). This is the traditional method, but we caution that the conversion of fringe measurements to physical deviations in the surface depend on the exact technique(s) used to measure the fringes. Therefore, we primarily express our requirements in physical quantities (i.e. distances and angles). For a vendor, these may need to be converted to requirements on fringes but should be done only after one fully understands their interferometric setup.

In the following, we estimate requirements relating to both imaging (with seeing-limited and adaptive optics, AO) and spectroscopy. We then adopt a requirement on surface flatness taking all of these calculations into consideration.

[1] A report on the fine-element analysis (FEA) of this mirror is provided in the Design Note *Mirror FEA*.

A. Spectroscopy (rule-of-thumb)

To minimize the effects of astigmatism in a spectrum, the rule-of-thumb is that the wavefront be coherent to within 1/4 of a wave. This needs to be achieved across the seeing-limited size of the image (r_0) at the tertiary for a point source. For the estiamte, we adopt $r_0 = 1\,\mathrm{m}$ at the primary or $(1\,\mathrm{m}/10.949\,\mathrm{m})\,476\,\mathrm{mm} = 44\,\mathrm{mm}$ at the projected tertiary. On K1 the HIRES spectrometer provides spectra down to 300nm. Setting the requirement at 1/4 of a wave at 300nm for the RMS wavefront error σ_λ (or 1/8 for surface error σ_S, we have

The rule-of-thumb specification is 32nm (RMS) surface error for spectroscopy, across any 44 mm diameter on the tertiary mirror.

A. Imaging

i. AO:

We may generate a specification on optical flatness by demanding that the Strehl contribution be 0.9 or greater at 1μm (the shortest wavelength assumed for high-performance AO observations). Using the standard definition of Strehl, $S = \exp[(-2\pi\sigma_\lambda/\lambda)^2]$ with σ_λ the RMS wavefront error over the aperture of the wavefront, we recover the RMS wavefront error to be $\sigma_\lambda < 52$nm. As the AO system corrects for low frequency errors for sizes exceeding 1 m (the actuators have 0.5 m separation), the requirement corresponds to a 44 mm diameter on the tertiary. This yields the following requirement on the RMS surface error:

The specification is 26nm (RMS) surface error for high-performance AO Strehls, measured across any 44 mm diameter on the tertiary mirror.

ii. Seeing-limited:

If we assume the mirror is smooth (next section), then a slope requirement is appropriate for seeing-limited imaging. The original Keck specification for the tertiary allows only 0.054 arcsec for 80% enclosed energy. Adopting a Gaussian profile to relate the encircled energy to the slope error, EE80=3.59σ_s, and therefore $\sigma_s = 0.054''/3.59$. This gives an RMS wavefront slope error of σ_s=7.3e−8 radians on the sky as viewed by the primary mirror.

Ignoring tilt, the slope error allowed at the tertiary is 23× larger (the ratio of 10.949m/0.476m) giving σ_s =1.68e−6 radians. Allowing for the tilt (which doubles the error in one dimension), we adopt a requirement that is $\sqrt{3}$ smaller or a 9.7e−7 slope error. This total error budget includes polishing, thermal, and gravity errors with polishing most likely to dominate.

iii. Summary:

Given that any AO system will automatically remove low order aberrations in the tertiary, we consider the slope specification on the projected wavefront of 9.7e−7 radians to be sufficient.

The final surface flatness specification is 9.7e−7 (RMS) slope error, measured across any 44mm diameter on the tertiary mirror. For AO observations, we require a 26 nm (RMS) surface error across the same diameter.

IV. Surface Roughness

From the previous section, we derived a slope specification of 7.3e-8 radians at the primary giving a specification of 9.7e−7 radians at the teritary mirror. The latter implies a height difference of 4nm over a lateral distance of 2.4mm. [Why 2.4mm??] We therefore require that projected wavefront errors be under 4nm on all scales < 10mm. We also note that a 4nm rms wavefront errors gives a Strehl at 1μm of 0.9994 and 0.9975 at 500nm wavelength, so scattered light should be small.

With optical-grade polishing (i.e. using pitch and standard machining), one can achieve this and we impose:

The specification is to polish the (uncoated) reflective surface of the tertiary to less than 2nm (RMS) surface roughness.

V. Dig/Scratches

The mirror will be inspected for small imperfections. We specify requirements on the size and frequency of these imperfections.

The specification is (60-40) scratch/dig surface quality per MIL-PRF-13830B.

VI. Non-optical surface finish

To minimize stress on the mirror, one requires a relative high quality finish on the entire optic. This is achieved by machine polishing.

The specification is R2 ground flat, 400 grit finish or better.

VII. Modifications to the back surface

At present, the design does not require holes in the back surface.

VIII. Coating

Given the requirement of high reflectivity from the atmospheric cut-off through the visible (HIRES), and into the near IR (AO), bare aluminum is the only viable choice for the mirror coating. This will be applied at WMKO in their coating chamber.

[Provide a Summary Table]