K1DM3 Design Note

Positioning of M3 for the K1DM3 Project

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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. It is intended to retract, deploy and rotate the tertiary throughout any given night to enable observations with one or more K1 instruments. It is a basic requirement of the K1DM3 project that the mirror be positioned to nearly the optimal location. This is intended, in part, to insure that once the K1DM3 is properly and precisely aligned that it maintains a high-precision alignment. Significant offsets may degrade the image quality, cause vignetting, challenge object acquisition, complicate guiding, etc., as described below.

We are giving extra attention to these issues under the expectation that it could pose a major technical challenged to the K1DM3 design. Achieving high precision repeatability implies a very stiff (i.e. heavy) structure with minimal CTE and high-precision mounts and encoder systems. While these are all characteristics of the design under consideration, there will undoubtedly be trade-offs between performance and cost/complexity.

Throughout the document we adopt the Coordinate Systems defined in the K1DM3 Design Note (v1.4).

II. Optimal Positioning

This section describes the optimal positioning of the K1DM3 mirror in both retracted and deployed configurations.

A. Retracted

When the K1DM3 is retracted, it is intended that the device vignettes at most a trivial fraction ($\ll 1\%$) of the light that will feed the mounted Cassegrain instrument and guider system. Currently, and for the foreseeable future, there are 2 Cassegrain instruments on K1: MOSFIRE and LRIS. Here is a summary of the fields of view (FOVs) for each system:

MOSFIRE

The MOSFIRE imaging spectrometer has its science camera on-axis with a $6.14' \times 6.14'$ FOV, although the the camera delivers unvignetted images to only $6.8'$ radius. The MOSFIRE guider system lies $6.6'$ off-axis with a $2.8' \times 2.8'$ FOV. These were verified from the Zemax files provided by Harland Epps: `DIFF24_DIRECT.IMAGING.ZMX`, `REDUCER.062607AB.OFFSET.FOLD.Z.AS_BUILT.ZMX`.

LRIS

The LRIS $6' \times 8'$ FOV lies $7'$ off-axis. Its guide camera is clocked at 55 deg relative to the short side of the science FOV and is offset by 139.68 arcsec from the telescope optical axis. The guider FOV measures 180 arcsec on each side. These values were confirmed using the as-built Zemax models provided by Drew Phillips and Sean Adkins: `MAGIQ_offset_guider_model_062008_SMA.zmx`

The unvignetted beam that travels to any position in the Cassegrain focal plane is an oblique circular cone whose base is the pupil, a circle with diameter $D_p = 1.460$m centered and normal to the telescope optical axis (Z3) and located a height $z_p = 17.448$m above the primary mirror. The vertex of this cone is any point on the focal plane, located $z_f = -2.500$m above the primary and at x_f, y_f in the C1 system.

For any arbitrary footprint of an instrument at the focal plane (typically a set of rectangles defined by the camera and guider detectors), one can trace out the dimensions of the beam as a series of overlapping circles at any elevation z'. We have generated a simple IDL script (ccd_footprints.pro; available via SVN) to perform this calculation. Figures 1 and 2 show the LRIS and MOSFIRE footprints at the focal plane and at $z' = 5.0$m above the primary.

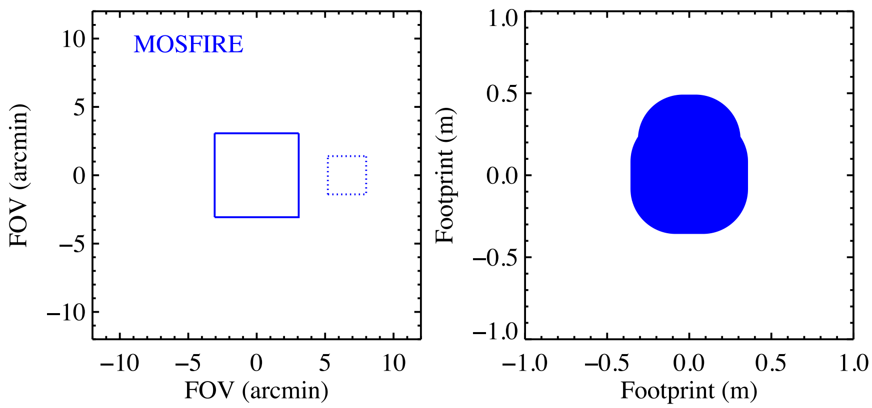

Fig. 1.— MOSFIRE field-of-view for the science and guider cameras in the focal plane (left) and the footprint as mapped at an arbitrary $z' = 5$m above the primary mirror (note that the elevation axis is 4m above the primary). The latter is used to insure that the K1DM3 system does not vignette MOSFIRE when retracted.

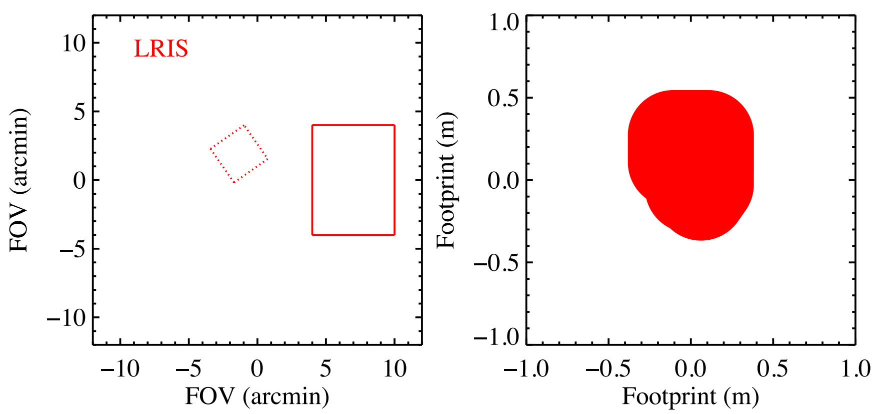

Fig. 2.— Same as Figure 1 but for LRIS.

From our script, we generated a User Defined Aperture (UDA) for each instrument and imported these into Zemax at an elevation of 5m above the primary. We then propagated rays from the corners of the field angles corresponding to the corners of the detectors for the science and guider cameras. The resultant footprint diagrams are shown in Figures 3 and 4. We confirmed that the percentage of primary rays through each UDA aperture matched the percentage at the secondary (i.e. no obscuration). The Zemax files and associated UDA files are available on the K1DM3 Twiki.

We then proceeded to generate the solids associated with the LRIS and MOSFIRE footprints at $Z1 = [2, 3, 4, 5, 6]$m above the primary and integrated this within SolidWorks (using CAD exports of the surfaces). The corresponding files (e.g. LRIS_5m_FOOT.UDA) are available on the K1DM3 Twiki and are being used to guide the design of K1DM3.

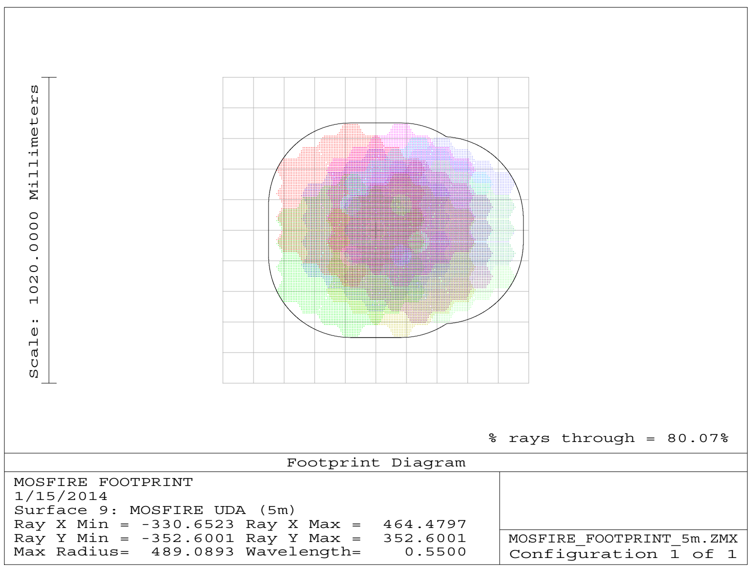

Fig. 3.— Zemax output of the footprint for the UDA of MOSFIRE (also shown in Figure 1), set at a height of 5m above the primary. The dots indicate the rays propagated by Zemax from the corners of the detectors of both the science and guider cameras. The software reports 80.07% rays through the aperture which matches the fraction captured by the secondary. Note that this shows only one orientation of the primary mirror but that the end result of rays through is insensitive to primary rotation.

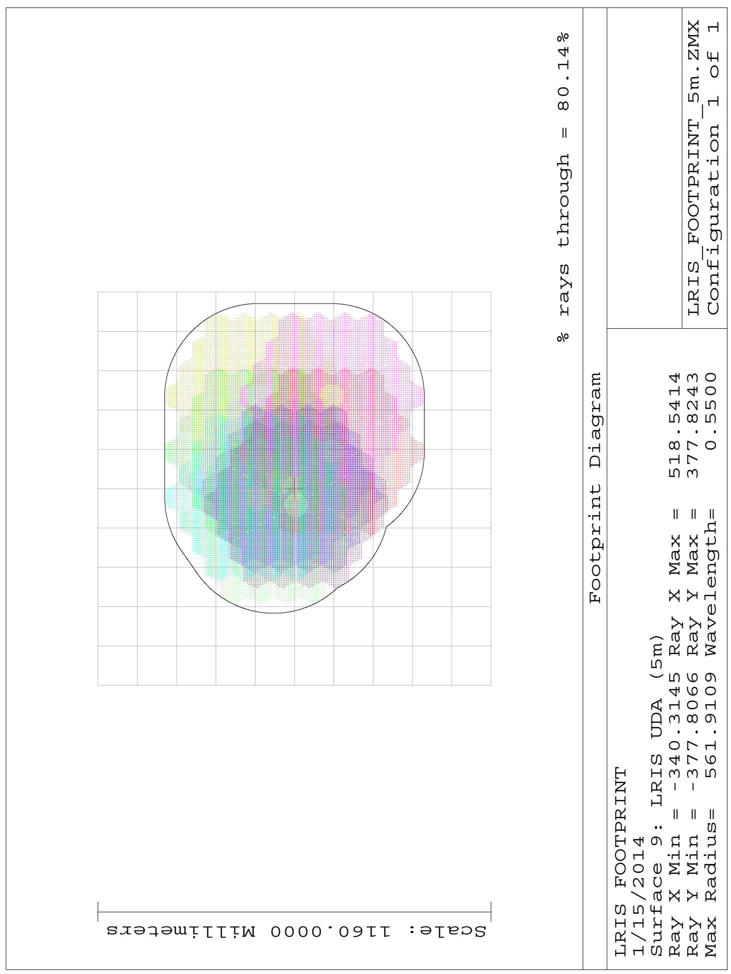

Fig. 4.— Same as Figure 3 but for LRIS.

In our current design, the M3 mirror extends slightly beyond the side edge of the tertiary tower when retracted and therefore may vignette rays travelling to the primary mirror (M1) and/or rays from M1 to M2. The impact is determined by the size of the tertiary tower, the size of the K1DM3 deployment mechanism, the size of the secondary structure, and the requirements described above to avoid vignetting the Cassegrain instruments.

We have analyzed the vignetting of the M1/M2 system by K1DM3 with Zemax with the following assumptions/simplifications:

- We have modeled the tertiary tower as a hexagonal obscuration at a height of 3451.6 mm above the primary mirror.
- The half-length of the hexagon (measured side-to-side) is 762.46 mm. The half-width of each hexagon side is 440.207 mm.
- In the telescope coordinate systems (C1), the K1DM3 mirror center (reflective side) is located at a height z_1 above the primary and a separation from the optical axis y_1.
- The K1DM3 mirror is tilted at an angle α defined as the angle between its XM-axis (given by mirror's major axis) and the elevation axis (X1). A value of 90 degrees correponds to the mirror plane lying parallel to the optical axis (0 degrees is normal).
- The obscuration ellipse is slightly larger than the K1DM3 mirror to account for its lateral mounts. Specifically, we assume an ellipse with semi-minor axis of 320 mm and semi-major axis of 450 mm.
- We assume that the mirror tips out over the side of one hexagon (tipping over a corner generally reduces the vignetting).
- We assume the secdonary mirror (M2) is held by a hexagonal structure co-aligned with the tertiary tower (and M1) with a side of 1.32 m. In Zemax, we implement this as a series of obscuring rectangles with half-widths of 660 mm and 1143 mm.

We have estimated the vignetting for two configurations:

1. No LRIS/MOSFIRE vignetting – This configuration retracts the mirror sufficiently such that K1DM3 would not vignette the LRIS FOV at any rotation angle. This places the center of the K1DM3 mirror at $y_1 = 836.5$ mm and $z_1 = 4245.7$ mm with an angle $\alpha = 110$ degrees. We find that the rays through the M1/M2 system reduce from 78.22% to 78.07% due to vignetting by K1DM3.
2. No MOSFIRE vignetting – This configuration retracts the mirror sufficiently such that K1DM3 would not vignette the MOSFIRE FOV at any rotation angle. It would vignette the LRIS FOV and would likely need to be rotated during observing. This configuration places the center of the K1DM3 mirror at $y_1 = 690.02$ mm and $z_1 = 475.86$ mm with an angle $\alpha = 99.5$ degrees. We find that there is no vignetting of the M1/M2 system in this position as the mirror is fully shadowed by the secondary structure.

The Zemax files used to perform this analysis are available on the K1DM3 TWiki. We caution that we found some unusual and unexplained performance by Zemax but we are confident this didn't affect the above calculations.

B. Deployed

When deployed, the K1DM3 will be designed to provide a $5'$ FOV to either of the Nasmyth foci and any of the four bent-Cass foci. The K1DM3 is currently required to support a 5' diameter FOV (Nelson & Cabak, 2009). This was determined by the anticipated maximum FOV ($\approx 4'$ diameter) that would be required if a second, offset, guiding channel was added to the HIRES instrument. Assuming the f/15 secondary, the maximum available science FOV at the right BC focal station 2 (RBC2) which is equipped with a visitor port, is $4.2'$, but the facility guider pickoff which is before the rotator at RBC2 requires a FOV of $8.68'$. The current K1DM3 FOV will not support this focal station.

As built, the elevation axis of the Keck I telescope is located 4.000 m above the primary mirror. The Appendix to this document describes the nominal dimensions for the tertiary for the K1 telescope given this FOV. These are an ellipse with semi-major axis $a = 0.4406$m and semi-minor axis $b = 0.3115$m whose center is located $z3 = 0.0097$m above the elevation axis and $x3 = -0.0097$m along away from the optical axis (along X3).

We have verified with Zemax using the Keck I model (taken from the as-built Zemax model for the LRIS guider) that a tertiary mirror with these dimensions captures all of the rays incident upon it from field points offset by $5'$ from the telescope axis. This is illustrated in Figure 5. The associated Zemax file (`simple_tertiary.ZMX`) is on the Twiki.

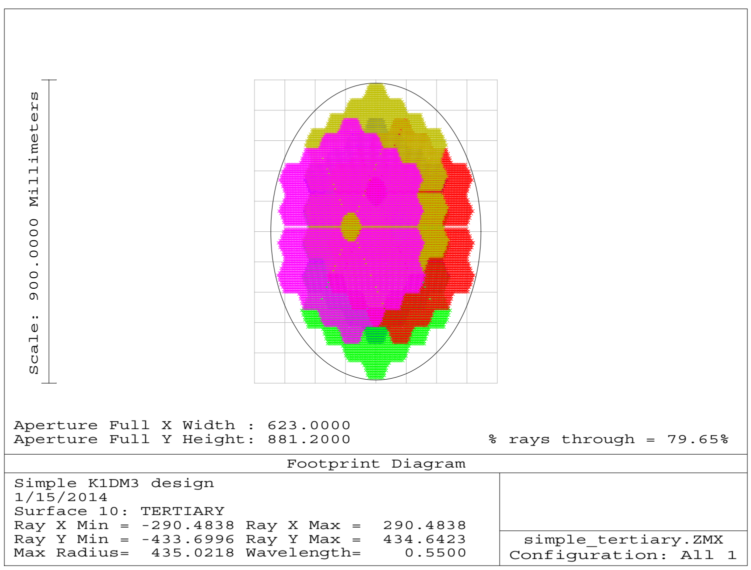

Fig. 5.— Zemax output of the footprint for four field endpoints of a $5'$ FOV on the surface of the K1DM3 tertiary mirror. The software reports 79.65% rays through the aperture which matches the fraction captured by the secondary in this calculation.

III. Cases of Misalignment

The following defines the complete set of misalignments that may occur for K1DM3 when deployed.

1. Rotation about Y3 (tilt): This is akin to a rotation about the minor axis of the mirror[1]. When optimally deployed, M3 will be rotated by 45 deg around Y3 with 0 deg defined to have XM parallel to Z3. Let $\delta\theta_{\rm tilt}$ be the offset in degrees from $\theta_{\rm tilt} = 45\,{\rm deg}$. This misalignment leads to the partial capture of the telescope beam. It displaces the image from the instrument focal plane by misaligning X3 and X1 by $\delta\theta_{\rm tilt}$.

2. Rotation about Z3 (tip): There will be a nominal rotation angle of the K1DM3 bearing (around Z3) to deliver the beam to the instrument on the elevation axis. Define this angle as $\phi_{\rm tot} = 0\,{\rm deg}$. Define the offset from nominal as $\delta\phi_{\rm tip}$. This misalignment leads to partial capture of the telescope beam. It also displaces the image from the instrument focal plane by misaligning X3 and X1. It also rotates the image at the focal plane.

3. Rotation about the center of the tertiary mirror: This implies a rotation about ZM. Let $\psi_{\rm tot} = 0\,{\rm deg}$ be the optimal orientation and $\delta\psi_{\rm rot}$ define an offset from nominal. The only effect of this rotation is to lead to the partial capture of the telescope beam.

4. Translation of the mirror along the X3 axis. This displaces the focus by the degree of translation δx_3. This misalignment also leads to the partial capture of the telescope beam. This misalignment also displaces the image in the focal plane.

5. Translation of the mirror along the Y3 axis. This misalignment δy_3 only leads to the telescope beam not being fully captured.

6. Translation of the mirror along the Z3 axis. This misalignment δz_3 is very similar to that for δx_3. It displaces the focus by the degree of translation. If the motion is towards the secondary, it can lead to partial capture of the telescope beam. This displacement moves the image in the focal plane, shifting its center by δz_3 off the elevation axis.

IV. Impact of Misalignments

The effects of misalignment have different impacts for spectroscopy and imaging and for systems that make use of Adaptive Optics (AO). We examine each of these in turn, with quantitative estimates for existing instruments. We begin, however, with a discussion of the effects at the telescope focal plane.

For the purposes of this analysis we are concerned only with how the K1MD3 in beam performance affects positioning of the image and telescope pupil. It is appreciated that there are other potential sources of error that could affect this positioning such as improper tilt of the telescope secondary and actual motion or non-repeatable positioning of the instruments with respect to the telescope optical axis. In this regard it is helpful to know that all of the instruments that will be served by the K1DM3 are at fixed locations and presumably have been aligned to a satisfactory degree of accuracy with the telescope using the existing tertiary. Anecdotal evidence suggests that performance of the current tertiary is satisfactory, but no routine checking of alignment at each focal station is

[1]Formally, the CM coordinate system travels with the tertiary mirror.

performed. At present the Keck I AO science instrument OSIRIS has inscribed pupil masks without a center obscuration so the sensitivity to pupil alignment is probably lower than it would be if a matched pupil mask were used.

Nighttime observing procedures are used to collimate the telescope with the result that small night to night tertiary positioning errors are not noticeable because the secondary adjustments made during collimation will compensate for such errors.

A. Telescope Focal plane

It is both conceptually and quantitatively easiest to calculate the effects of misalignment at the focal plane of the telescope. Most of these effects then impact performance of the guider and imaging cameras. These also affect performance of the slit mechanism for spectrometers, which are often located at the telescope focal plane (e.g. HIRES).

It is common for Nasmyth instruments to use an image rotator to orient and maintain a desired position angle of the sky at the focal plane. Indeed, both HIRES and OSIRIS have such mechanisms. These are designed to rotate the field while keeping fixed all angular separations. Therefore, image rotators impose no additional effects from misalignment aside from the possibility of vignetting (i.e. the bean is not fully captured by the mechanism).

Both translations and rotations will displace the image at the focal plane and modify the focus. The latter may be corrected by re-positioning the secondary and the former by re-pointing the telescope. For translations, therefore, the mitigated effects of misalignment are nearly negligible. For rotations, the image will be tilted (and possibly rotated) with respect to the focal plane. Therefore, only one point in the image (or a line) will truly be in focus at the slit mechanism.

i. Image Displacement

It is straightforward to estimate the image displacement due to misalignments of the tertiary. For translations $\delta x_3, \delta z_3$, a source at the center of the field will be displaced at the focal plane by

$$\delta\alpha_y = 1'' \, \frac{\delta x_3}{0.7252\,\mathrm{mm}} \tag{1}$$

and the same for δz_3. For a tilted mirror $\delta\theta_{\rm tilt} > 0$, the resultant linear offset in the focal plane is given by the small angle approximation for a separation of 6.5m: $\Delta y = (2\delta\theta) 6500\,\mathrm{mm}$. Converting to an angular offset on the sky with the plate scale at the telescope focus $(0.7252\,\mathrm{mm}/1'')$, we have:

$$\delta\alpha_y = 1'' \left(\frac{\delta\theta_{\rm tilt}}{11.5''} \right) \tag{2}$$

This corresponds to a misalignment of the tertiary by

$$\Delta z = (2a)\delta\theta_{\rm tilt} = 85\,\mu\mathrm{m} \left(\frac{\delta\theta_{\rm tilt}}{20''} \right) \tag{3}$$

Meanwhile, a rotation of $\delta\phi_{\rm tip}$ yields an offset that is 1/2 that for $\delta\theta_{\rm tilt}$, i.e.

$$\delta\alpha_x = 1'' \left(\frac{\delta\phi_{\rm tip}}{23''} \right) \tag{4}$$

Image displacement will mimic a mis-pointing of the telescope. Therefore, these may be corrected by offsetting the telescope accordingly. In this respect, misalignment of K1DM3 will have no effect.

ii. Focus

We may estimate the offset from focus (roughly along the elevation axis or ZF of the CF coordinate system), as follows. For small angles, a tilt rotation of the tertiary $\delta\theta_{\rm tilt}$ will displace a source offset by ΔX from the 'line of focus' (given here as angular offset on the sky) by

$$\Delta f = \delta\theta\Delta X = 15\mu\text{m}\left(\frac{\delta\theta}{30''}\right)\left(\frac{\Delta X}{2.5'}\right) \tag{5}$$

Therefore, even at the edge of the nominal FOV for K1DM3, the offset from the focal plane will be negligible.

iii. Distortion

Another consideration is distortion of the field, i.e. a change in the plate scale at the focal plane. This could lead to the misalignement of sources on a slit mechanism (e.g. a slit mask) and/or incorrect positioning of the telescope using guider offsets.

Let's estimate the change in the angular separation $\delta\rho$ of two sources separated by $\Delta\psi$ on the sky for a tilt of the tertiary $\delta\theta_{\rm tilt}$. We assume that the sources are oriented along XM, i.e. the position that maximizes the error. The image plane is now tilted with respect to the original focal plane and one calculates the change in separation of the sources as projected onto the focal plane as:

$$\delta\rho = \Delta\psi[1-\cos(\delta\theta)] = \frac{1''}{315149}\left(\frac{\Delta\psi}{5'}\right)\left(\frac{\delta\theta}{30''}\right)^2 \tag{6}$$

Such an effect is immeasurable. One derives similar results for a tip of the tertiary.

A tip of the tertiary will also cause a rotation of the field at the focal plane. To first order, the field rotation equals $\delta\phi_{\rm tip}$. This will affect blind offsets and guider performance. Regarding the latter, consider a $1'$ offset of the telescope with the tertiary misaligned by $\delta\phi_{\rm tip} = 30''$. In this case, the source will be offset from the desired location by

$$\delta\alpha_x = 60''(1-\cos\delta\phi_{\rm tip}) = 6\times10^{-7}\,\text{arcsec} \tag{7}$$

and

$$\delta\alpha_y = 60''\sin\delta\phi_{\rm tip} = 0.009'' \tag{8}$$

from the desired position on the focal plane. These are negligible for any application on Keck.

iv. Zemax

To confirm the above estimations, we have calculated the offsets $\delta\alpha_x, \delta\alpha_y$ of three field angles $(\beta_{x,i}, \beta_{y,i}) = [0'', 0''], [0'', 30''], [30'', 0'']$ relative to the chief ray. For each calculation, we curved the focal plane to have a radius of 2192.1mm. If the misalignments offset the focus, then we moved the focal plane (instead of adjusting the secondary). The Zemax file used to generate these misalignments is provided on the Twiki (`simple_tertiary_tilt.ZMX`).

Table 1 summarizes the effects. We also calculate $\delta\rho_{ij}$, the separation between sources and $\delta\eta_{ij}$, the rotation in the focal plane. The offsets were estimated using the spot size centroids reported by Zemax at the focal plane. Similarly, the RMS refers to the spot sizes. In agreement with our estimations above, we find the sources are displaced but that the change in separations and spot sizes are negligible.

Table 1: Offsets from Misalignment (all quantities in arcsec)

Misalignment	$\delta\alpha_{x,1}$	$\delta\alpha_{y,1}$	RMS_1	$\delta\alpha_{x,2}$	$\delta\alpha_{y,2}$	RMS_2	$\delta\rho_{12}$	$\delta\eta_{12}$
None	0.0000	0.0000	0.0007	0.0000	-29.9997	0.0007	0.0000	0.00
z3=-7.252mm	0.0000	-10.0000	0.0010	0.0000	-39.9996	0.0035	-0.0001	0.00
tilt=30”	0.0000	2.6071	0.0007	0.0000	-27.3927	0.0005	0.0001	0.00
tip=60”	-2.6071	0.0000	0.0007	-2.6158	-29.9997	0.0007	0.0000	-59.73
Misalignment	$\delta\alpha_{x,1}$	$\delta\alpha_{y,1}$	RMS_1	$\delta\alpha_{x,3}$	$\delta\alpha_{y,3}$	RMS_3	$\delta\rho_{13}$	$\delta\eta_{13}$
None	0.0000	0.0000	0.0007	29.9997	0.0000	0.0007	0.0000	0.00
z3=-7.252mm	0.0000	-10.0000	0.0010	29.9997	-10.0000	0.0010	0.0000	0.00
tilt=30”	0.0000	2.6071	0.0007	29.9997	2.6071	0.0007	0.0000	0.00
tip=60”	-2.6071	0.0000	0.0007	27.3927	0.0000	0.0005	0.0001	0.00
Misalignment	$\delta\alpha_{x,2}$	$\delta\alpha_{y,2}$	RMS_2	$\delta\alpha_{x,3}$	$\delta\alpha_{y,3}$	RMS_3	$\delta\rho_{23}$	$\delta\eta_{23}$
None	0.0000	-29.9997	0.0007	29.9997	0.0000	0.0007	0.0000	0.00
z3=-7.252mm	0.0000	-39.9996	0.0035	29.9997	-10.0000	0.0010	-0.0001	-0.48
tilt=30”	0.0000	-27.3927	0.0005	29.9997	2.6071	0.0007	0.0001	0.47
tip=60”	-2.6158	-29.9997	0.0007	27.3927	0.0000	0.0005	0.0062	-30.33

The three sources are at field locations $(\beta_{x,i}, \beta_{y,i}) = [0'', 0''], [0'', 30''], [30'', 0'']$ relative to the chief ray.

iv. Summary

Based on the very small effects in the focal plane, we propose the following requirements from these considerations alone, as regards accuracy and repeatability.

Requirement: *Displace the image by no more than* $3''$ *(RMS) in the focal plane. This is driven primarily by the decision to contribute only modestly to pointing errors in the telescope.*[2]

Goal: *Displace the image by no more than* $1''$ *(RMS) in the focal plane.*

[2] In practice, we believe that these errors may be corrected for in the telescope pointing model.

B. Imagers

i. AO

Misalignments of K1DM3 will affect the performance of the AO system on Keck I. Of greatest concern is the misplacement of the pupil image. The repeatability of the pupil image position is important for two reasons. First, the adaptive optics system requires that the telescope pupil fall on the AO system's deformable mirror (DM). Second, in order to suppress the thermal background from the telescope, infrared instruments use matched cold pupil masks with center obscurations to block unwanted light from the telescope secondary obscuration and from around the primary mirror while also minimizing the loss of the desired light from the telescope.

The clear aperture of the DM is 146 mm, corresponding to 11732.5 mm in primary mirror space. The 10949 mm diameter primary mirror image could therefore be shifted by as much as 783 mm in primary mirror space and remain on the DM. However, before this limit is reached the change in the pupil image position will alter the correspondence between DM actuators and the pupil image to an extent that makes it necessary to update the wavefront reconstructor to take into account the new correspondence between DM actuators and the pupil image. The AO system uses the illumination pattern in the outer sub-apertures of the high-order wavefront sensor to determine when the wavefront reconstructor needs to be updated. This is an automatic procedure, so operation of AO from one tertiary mirror pointing to another should be unaffected. This does not appear to be a driving constraint on pupil image positioning.

The use of matched pupil masks may be a driver for pupil image positioning. If the telescope optical axis is misaligned with the AO systems k-mirror image de-rotator axis because of tertiary mirror pointing errors, the telescope pupil image, which appears to rotate when seen through the de-rotator, will also appear to nutate around the optical axis. This nutation offsets the primary mirror image relative to the matched pupil mask in the instrument, resulting in increased background and reduced throughput. Mis-registration can also affect the instrumental point spread function (PSF). A stable and repeatable PSF is becoming more important for precision astrometry using AO, as well as allowing more advanced methods of reducing source confusion in crowded fields such as the Galactic Center.

Matched pupil masks are designed with some margin for alignment error. For example, Figure 6 shows the telescope primary mirror and the central obscuration (gray circle) overlaid with an image showing the transmitting portion of a matched pupil mask (pink area) that is 3% undersized with respect to the telescope aperture and also 3% oversized with respect to the central obscuration. The addition of margin to the mask provides tolerance for error in the alignment of the mask to the pupil image, but it also results in additional loss of light. Optimization of the mask design will balance the effectiveness of the mask in the presence of misalignment against the loss of light.

If we define the maximum allowable position shift as one that keeps the outer edges of the telescope primary and the central obscuration fully masked, then in primary mirror space, with the example pupil mask shown here, the maximum shift in the position of the telescope primary mirror image relative to the centered position is 66 mm (see Adkins, 2010 for details on this determination). The ratio of the primary mirror diameter to the pupil diameter is 7.5, and with the image plane at 6500 mm from the tertiary mirror and the pupil image at 19948 mm from the image plane, the pupil image is 13448 from the tertiary mirror, a ratio of ~ 2. The product of these two ratios is 15, meaning that

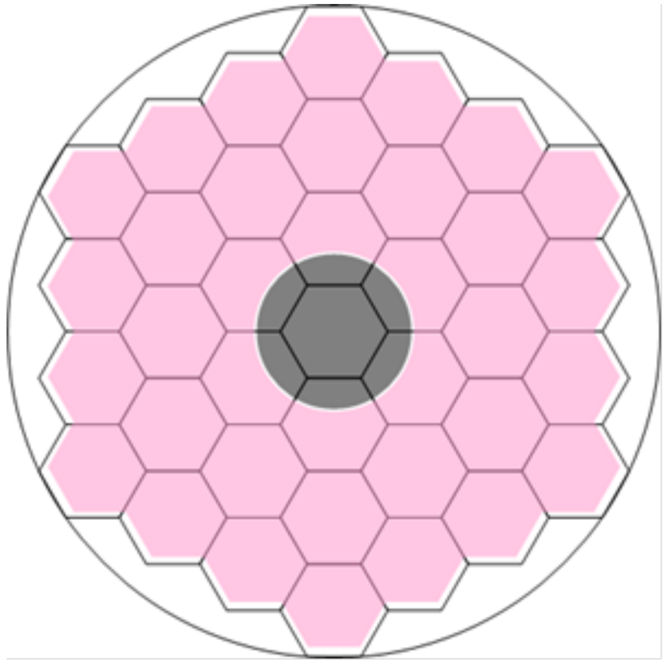

Fig. 6.— Example matched pupil mask for the Keck I telescope.

the pupil displacement at the primary is 15 times that of the image displacement for a given tilt of the tertiary mirror. Stated another way, if the matched pupil mask allows a shift of 66 mm at the primary, the allowable image shift is 4.4 mm, corresponding to a tilt of $\approx 70''$.

One also wants the pupil (the image of the primary) to be repositioned to a small fraction of the sampling subaperture. Current Keck AO systems sample the pupil about 20 times across its diameter. Future AO systems might sample more densely, perhaps 100 times across the diameter. If we allow alignment variations 10% 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 arcsec and tip to 22 arcsec. We should decide whether this is RMS, or not to exceed. RMS is likely adequate.

It is probably most important to know where the pupil is. This can be easily measured by monitoring the flux in the AO subapertures; those at the edge are sensitive to the exact pupil location. This is routinely done at PCS where pupil location is particularly important. If pupil location becomes important for some future AO instrument, the instrument will probably have its internal way to adjust the pupil location; this is done by PCS.

ii. Image Stability

Ideally the K1DM3 will not contribute to image motion when deployed. In practice a small amount of mirror motion due to vibration can be tolerated by seeing limited observations when it is root square summed with the atmospheric seeing. The Keck I AO system is capable of removing the blurring due to image motion caused by motion of the tertiary but it is preferred that the K1DM3 not be a source of additional image motion that the AO system must correct.

Established convention is to allow uncorrelated effects on image quality at the level of 10% of the seeing disk. Based on this convention, for $0.4''$ seeing, translation of the mirror along the telescope X or Z axes should be no more than 29 microns (RMS). Confining the motion to $\sim$29 microns (RMS) places a stability requirement on tip and tilt of the tertiary of $0.92''$ and $0.46''$ (RMS).

C. Spectrometers

The first section below offers some general and incomplete discussion of the impacts of misalignment. I currently recommend that the reader skip to the HIRES sub-section which was informed by Zemax analysis.

i. Overview

A standard spectrographic design for the Nasmyth platform may consist of:

- An image rotator to maintain field orientation
- A slit mechanism at the focal plane
- A series of lenses and dispersing elements
- The detector
- A guide camera

Image Rotator:
An image rotator is designed to capture the full beam of a given FOV and rotate as the telescope tracks to maintain a specific orientation at the focal plane. Misalignments of the tertiary will displace the beam from nominal. For δx_3, δz_3 translations, the beam will be parallel but offset from the preferred axis. Typically, the observer will 'correct' for this offset by adjusting the pointing of the telescope, e.g. recentering the target of interest along the preferred axis. Vignetting will result if the offset is sufficiently larger and is the primary impact of misalignments for the image rotator alone.

For rotations (tip/tilt), the considerations are similar (i.e. vignetting of the incoming beam) although the beam is now incident to the image rotator at a non-optimal angle. Therefore, it is possible that the beam could be fully captured by the first optical element but not by one or more that follow.

For HIRES, the entrance optic of the image rotator (a dove prism) is located XX from the focal plane and has diameter $D_i = XX$m. The axis of the beam is intended to intersect this prism at an angle XX. [Discuss tolerances for offsets]

The Slit Mechanism:
Generally, a spectrometer has a slit (or a set of slits/slitlets) at the focal plane to isolate a finite set of sources and insure/achieve a desired spectral resolution.

The Camera:
The spectrograph camera is designed to gather the light passed through by the slit mechanism and then collimate, disperse, and image the light onto the detector. This camera is designed for a nominal FOV with considerations on throughput and image quality at the detector. Misalignments of the tertiary will modify the path (and size) of the beam passing through the camera, imposing several negative consequences: (i) the beam may not be fully captured by one or more of the optical elements, implying light loss; (ii) image quality may be degraded; (iii) the pupil will intersect the dispersing elements at different positions, shifting the spectrum at the detector and modifying the spectral resolution. We consider each of these in turn:

(i) Light loss:
Translations and rotations modify the position and path of the beam within the camera. Similar to the image rotation (see above), an offset may imply rays that fall off one or more optical elements. This is analogous to vignetting. For a slitted observation, the qualitative effect would be a gradient in flux across the portion of the slit that becomes 'vignetted'. If the misalignment is small relative to the nominal FOV of the camera and the slit of interest lies near the field center, then this will not be an issue. More generally, we conclude that a spectrometer designed to capture the full $5'$ FOV provided by K1DM3 would not suffer significantly from light loss for offsets of the focal plane of a few arcseconds.

For HIRES, the camera was designed to capture a FOV of XX$''$, allowing observers to employ such a slit. Aside from the reddest observations, order overlap precludes slits longer than $7''$. For observations with a $7''$ long slit (or shorter), even a misalignment of $3''$ (translation at the focal plane) implies no light loss. Similarly, a rotation (tip) of $10''$ does .. [Use Zemax here]

(ii) Image quality:
The camera should be designed to deliver high quality images at the detector for science targets within the FOV. Generally, one designs a camera to produce spot sizes that are smaller than the best seeing (i.e. $< 0.5''$ at WMKO) for a defined spectral coverage. Degradation of image quality affects both S/N (the light is spread spatially across more pixels incurring greater noise from sky and detector) and spectral resolution. The effects of misalignment of the tertiary on the resultant spectra will depend on the position of the source relative to field center, the wavelength of interest, and the configuration of the dispersion elements.

Consider a few simple examples for HIRES: [Do 1 near detector center and 1 towards the edge for $\Delta X = 1''$ and $\delta\theta = 10''$]

(iii) Spectral distortions:
Both translations and rotations of the tertiary will modify the spectrum recorded at the detector of the spectrometer. This is true even when the telescope is offset to recenter the source in the slit because the source will now lie off the optical axis and therefore enter the camera along an axis offset from nominal. This will offset the resultant spectrum at the detector and modify (slightly) the spectral resolution. We focus on the former here.

For HIRES, a translation of $1''$ at the focal plane shifts light at 5000Å on the detector by XXμm or XX pixels with the CCD mosaic. If one calibrates the exposure solely with an internal source (i.e. an arc exposure), this results in an error of XX km/s. One can mitigate the majority of this area, in principle, with atmospheric lines. And, if absolute calibration is not required then one can adjust in software when combining multiple exposures. Use of the iodine cell, of course, mitigates these issues. [Do tip of $10''$ too]

Guiding:
To enable long integrations on-source, most spectrometers are equipped with a guide camera system. The camera may 'view' the slit during observations by imaging a reflective slit. Or the guide camera may view a field that is offset from the science FOV, typically in the same focal plane as the slit mechanism. [is that true?]

The effects of misalignment of the tertiary on guiding performance is twofold. First, the plate scale at the guider will be modified. This is a very minor effect as described above (Equation 6). We ignore this effect going forwards. [this should mean that blind offsets are fine, at least in magnitude]

Second, misalignments of the tertiary will offset the optical axis from nominal, leading to a misalignment between the actual rotation... All of the Keck I science instruments and guide cameras are provided with a means to compensate for the field rotation that results from the telescopes altitude-azimuth mount. HIRES uses a rotator equipped with a Dove prism. This rotator is deployable, but is used for most observations. The Keck I AO system uses a rotator based on a k-mirror that is always in the beam and is ahead of all of the rest of the AO system optical path including the feed to the acquisition camera. The Keck I visitor port is equipped with a rotator drive that rotates the offset guide camera and the instrument to accomplish image de-rotation.

In order for the rotator to work properly the telescope optical axis must be centered on, and co-linear with the axis of the rotator. If the telescope optical axis is not centered on the rotation axis then a star centered in the field of view will follow a circular track around the rotator center as the telescope tracks the sidereal motion of the sky. Objects off axis will appear to orbit this central star. In turn, with misalignment of the rotator axis, if a given pixel is defined as the center of rotation at one rotator position, it will not be at the center for any other rotator position. This will cause the guider pointing origin and other guider fiducials to change position on the sky as a function of the instruments rotator position angle.

If the rotator is misaligned the fact that the field is not completely stable is usually not noticeable for any instrument where the science field and guider field share the same rotator (true for all Keck I instruments at present). In this case the guiding process will correct for the additional motion that results from the rotator misalignment by applying an adjustment to the azimuth and elevation of the telescope. This shows that if the rotator is not properly aligned with the telescope optical axis, the impact can be quite significant for telescope pointing and offsetting when the telescope is not being guided.

ii. HIRES

We have studied the effects of misalignment of the tertiary through Zemax anaysis using the hires33rev5 Zemax model (which does not include the image rotator). Specifically, we displaced the tertiary in the telescope X1 and Z1 axes by 0.7252 mm (equivalent to $1''$ in the focal plane) and rotated the mirror (tip and tilt) to offset a center-field image by $1''$. All of the analysis was performed for a point source emitting at 700nm in an HIRES configuration that placed that light near the center of the detector. The Zemax files are available on the Twiki.

For the displaced configurations, we analyzed sources offset from the field-center by the same (and opposite) displacement at the focal plane. This is equivalent to re-pointing the telescope to account for a misaligned tertiary such that the source remains at the center of the HIRES slit. In each case, we recorded the percentage of rays that passed through the system to assess vignetting and the RMS of the spot centroid. These are listed in Table 2. We find additional vignetting of $\approx 0.1\%$ and a degradation of the spot size by $\approx 0.5 - 1$ micron. We have discussed this analysis with HIRES PI S. Vogt who agrees that they may be considered insignificant. We conclude that requirements on K1DM3 related to HIRES will be much more tolerant than those imposed by the AO system.

Table 2: Analysis of K1DM3 Misalignment on HIRES Performance

Misalignment	Rays Through (%)	Spot size (RMS; microns)
None	78.53	21.4
Z1 offset by 0.7252 mm	78.39	22.8
X1 offset by 0.7252 mm	78.39	22.8
tip=22”	78.41	21.9

The sources are placed at field locations such that the light passes through the center of the HIRES slit. All analysis was done at 700 nm with HIRES configured such that this light hits the center of the detector.

Appendix

The tertiary mirror is sized and positioned to deliver an unvignetted beam to the Nasmyth or bent-Cass foci. The beam is defined by the pupil at one end and the focal region at the other. In general this frustum is axisymmetric around the optical axis (Z1). The tertiary mirror intersects this beam at 45 deg, to send the light to the focus along the X3 axis. The intersection of a plane with a cone is an ellipse, but in general it is not centered on the optical axis. The following notes and diagrams specify the size and optimal position of the tertiary mirror.

We will define quantities primarily in the C1 coordinate system whose origin is the center of the primary mirror. We define the following quantities and refer to Figure 7 for a diagram of the configuration:

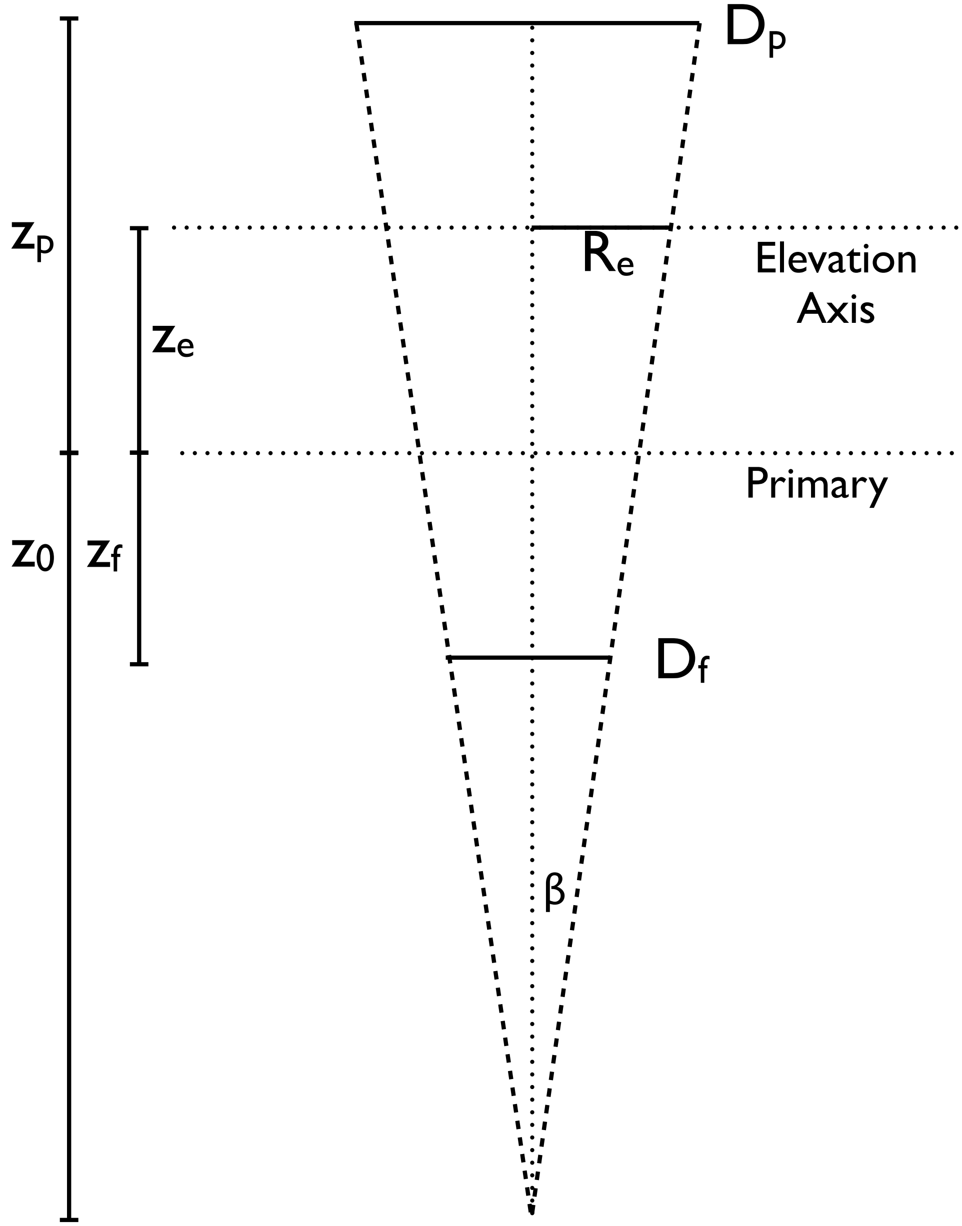

Fig. 7.— Sketch of the telescope positions

- D_p: Diameter of the pupil (1.460m for K1)
- D_f: Diameter of the focal plane (0.2176m for 5′ FOV)
- β: Half-opening angle of the cone encompassing D_p and D_f (1.7837 deg)
- R_e: Radius of the cone at the elevation axis (0.3112m)
- z_p: Height of the pupil above the primary (17.448m)
- z_f: Height of the focal plane above the primary (−2.500m)
- z_e: Height of the elevation axis above the primary (4.000m)
- z_0: Height of the cone apex above the primary (−5.9938m)

The known/defined quantities for Keck I are D_p, D_f, z_p, z_f and z_e. The half-angle β is then given by differencing

$$\frac{D_p}{2} = (z_p - z_0)\tan\beta \qquad (9)$$

$$\frac{D_f}{2} = (z_f - z_0)\tan\beta \qquad (10)$$

giving

$$\frac{D_f - D_p}{2(z_p - z_f)} = \tan\beta \quad . \qquad (11)$$

We calculate $\beta = 1.7837$ deg. From this, we may calculate $R_e = (z_e - z_0)\tan\beta$, as above, and calculate $R_e = 0.3112$m.

Nominally, the tertiary mirror is placed at the height of the elevation axis z_e at an angle of 45 deg from the optical axis. The intersection of a plane with a cone is an ellipse and we will find that the center of this elliptical mirror lies a small height above z_e and to negative X1.

To calculate the dimensions of the ellipse required to capture the full beam and its optimal position, define the following quantities (and refer to Figure 8):

- d_2: Length of the tertiary from the optical axis, in negative X1.
- d_1: Length of the tertiary from the optical axis, in positive X1.
- R_2: Length of the long segment (d_2) projected along X1
- R_1: Length of the short segment (d_1) projected along X1
- μ_0: Offset of the mirror, in its plane (i.e. to negative X3)

Additionally, define:

$$\delta R_1 \equiv R_e - R_1 \qquad (12)$$

$$\delta R_2 \equiv R_2 - R_e \qquad (13)$$

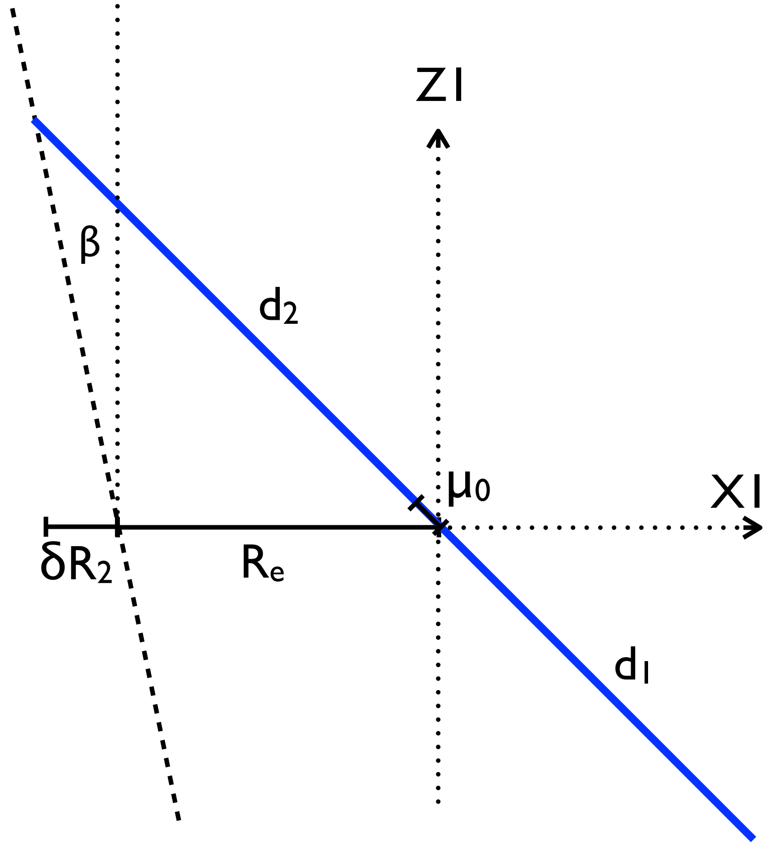

Fig. 8.— Sizing the tertiary mirror

Referring to Figure 8, we have:

$$\frac{\delta R_2}{R_2} = \tan\beta \tag{14}$$

Rearranging and using Equation 13, we recover

$$\delta R_2 = R_e \, \frac{\tan\beta}{1 - \tan\beta} \tag{15}$$

Similarly,

$$\delta R_1 = R_e \, \frac{\tan\beta}{1 + \tan\beta} \tag{16}$$

It is then straightforward to recover

$$\begin{aligned} d_2 &= \sqrt{2}\,\frac{R_e}{1 - \tan\beta} \qquad (17)\\ &= \sqrt{2}\,(z_e - z_0)\,\frac{\tan\beta}{1 - \tan\beta} \qquad (18) \end{aligned}$$

and

$$d_1 = \sqrt{2}\,(z_e - z_0)\,\frac{\tan\beta}{1 + \tan\beta} \tag{19}$$

The sum of these lengths defines the major axis of the ellipse:

$$2a = d_1 + d_2 = 2\sqrt{2}\,(z_e - z_0)\,\frac{\tan\beta}{1 - \tan^2\beta} \tag{20}$$

We calculate $a = 0.4406$m. We also find that the center of the mirror is offset by $\mu_0 = a - d_1$ from the optical axis. We calculate $\mu_0 = 0.0137$m.

The minor axis of the ellipse may be defined by the eccentricity $e^2 = 1 - b^2/a^2$ which is given from projective geometry by $e = \sin(45)/\cos(\beta)$. We prefer an alternate approach. The center of the mirror will be an additional $z_3 = \mu_0/\sqrt{2} = 0.0097$m above the elevation axis. At this location, the mirror must have size

$$b = (z_3 + z_e - z_0)\,\tan\beta \tag{21}$$

to capture the full beam. We calculate $b = 0.3115$m.

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