K1DM3 Design Note

Tertiary Mirror in Beam Positioning Requirements
Version 1, October 3, 2013
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INTRODUCTION

The Keck I Deployable Tertiary Mirror (K1DM3) will replace the existing Keck I tertiary mirror. The baseline for in beam positioning performance is that the K1DM3 will provide identical positioning performance to the existing tertiary. This design note describes the analysis of the K1DM3 mirror positioning requirements first developed in version 1.0 of the requirements for the K1DM3. As the discussion that follows will show, some of those requirements were overly tight, and the modified positioning requirements are given in the conclusions to this design note.

BACKGROUND

The K1DM3 Concept

The current Keck I tertiary is removed from the telescope when a Cassegrain instrument is installed. The K1DM3 is designed to remain in the telescope when observing with a Cassegrain instrument and this requires that the K1DM3 not vignette the light reaching the telescope primary. When it is not deployed it also must not vignette the light reaching the part of the Cassegrain focus used by the current Keck I science instruments (LRIS and MOSFIRE). Vignetting of the primary can be avoided by keeping all parts of the K1DM3 inside the center obscuration (~2.6 m diameter). During the system design study for the K1DM3 it was realized that neither Cassegrain science instrument uses all of the 20' diameter field of view (FOV) supported by the Keck telescope and this could provide the space needed for the tertiary mirror and its mount and deployment mechanism when the mirror is retracted out of the telescope beam. Further consideration of this shows that since the Cassegrain instruments accomplish field de-rotation by rotating the entire instrument, the location of the available space also moves, making it necessary to rotate the K1DM3 in synchronization with the instrument rotators once it is retracted and positioned out of the instrument FOV.

Coordinate Systems

The coordinate system used in this design note is intended to match the conventions used by WMKO for the Keck telescope (Figure 1). With the telescope pointed at the horizon the x axis is the direction parallel to the telescope elevation axis (horizontal), the y axis is perpendicular to this (vertical), and the z axis corresponds to the telescope optical axis. The positive signs for each axis are defined by the right hand rule when standing behind the telescope (at the Cassegrain focus).

The tertiary mirror folds the light from the secondary into the telescope X-Y plane, centering the optical axis on the center of the opening in the elevation bearing where it then forms the Nasmyth focus as shown in Figure 1. Not shown in Figure 1 are the four “bent Cassegrain” (BC) focal stations. There are two of these on the two sides of the elevation ring that have their intersection on the telescope Y axis (this is the side of the elevation ring that is on top when the telescope is pointed at the horizon).

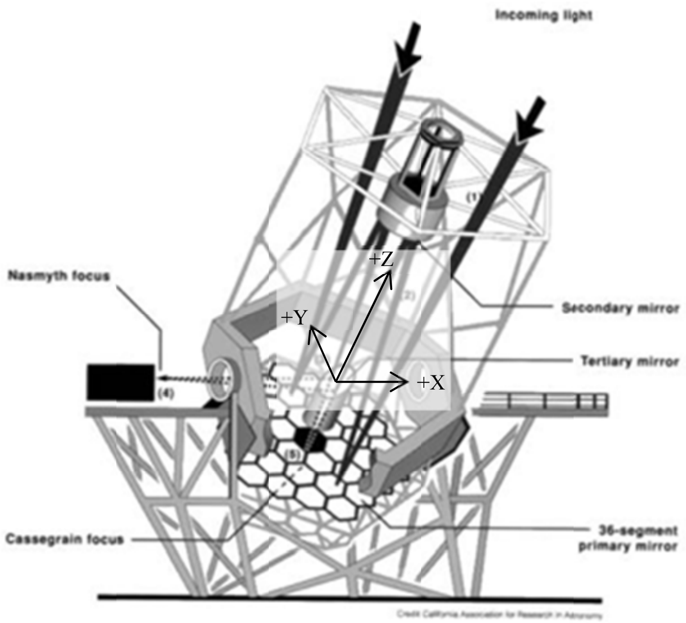

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Figure 1: Telescope coordinate system

Because the tertiary mirror rotates about the telescope Z axis to direct the light to either of the two Nasmyth focal stations or one of the four BC focal stations, in this design note we always consider the optical axis from the center of the tertiary mirror to the selected focal station as the X axis. The telescope Y axis is then defined as the perpendicular axis in the same plane as the X axis.

Degrees of Freedom

The K1DM3 tertiary mirror's six degrees of freedom have varying impact on the optical performance of the telescope. These impacts may be summarized as follows:

1. Translation of the mirror on the telescope X axis displaces the image and moves the focus by an amount that is equal in each case to the amount by which the mirror is translated. For a sufficiently large movement in either direction along the X axis the telescope beam will begin to fall off the edge of the mirror.

2. Translation of the mirror in either direction on the telescope Y axis has no effect until the mirror has moved far enough that the footprint of the telescope beam begins to fall off the edge of the mirror. Motion along this axis corresponds to motion in the plane of the mirror.

3. Translation of the mirror on the telescope Z axis displaces the image and moves the focus by an amount that is equal in each case to the amount by which the mirror is translated. With increasing movement towards the telescope secondary the telescope beam will begin to fall off the edge of the mirror.

4. Rotation of the mirror around the telescope X axis has no effect until the mirror has rotated far enough that the footprint of the telescope beam begins to fall off the edge of the mirror.

5. Rotation of the mirror around the telescope Y axis will move the center of the telescope focal plane up or down as seen from the selected focal station.

6. Rotation of the mirror around the telescope Z axis moves the center of the telescope focal plane left and right as seen from the selected focal station. Motion in this degree of freedom is used to direct the light to each of the focal stations.

From the point of view of the tertiary mirror there are two degrees of freedom in the mirror plane that are not accounted for by the above:

1. The translation of the mirror along an axis that is perpendicular to the telescope Y axis and rotated into the mirror plane, this would be the mirror Z axis using the same orientation of axis used for the telescope. Translation of the mirror along this Z axis has no effect until the mirror has moved far enough that the footprint of the telescope beam begins to fall off the edge of the mirror. Motion along this axis corresponds to motion in the plane of the mirror.

2. Rotation of the mirror about an axis that is normal to the mirror plane (see Figure 2). This rotation has the same effect as rotation about the telescope X axis.

TERTIARY MIRROR POSITIONING REQUIREMENTS

The positioning requirements for the K1DM3 can be separated into requirements that apply when the K1DM3 is in beam, and requirements that apply when the K1DM3 is out of beam. When the mirror is in beam we are concerned about the unvignetted FOV supported by the mirror, and the accuracy, repeatability and stability of positioning in beam as it affects positioning of the image and the telescope pupil at each focal station served by the tertiary mirror. When the mirror is out of the beam we are concerned with out of beam location repeatability and K1DM3 rotation performance in order to ensure that the light to the Cassegrain instruments is not vignetted.

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 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.

Original Requirements for the Tertiary Mirror

The Keck Observatory design report (Nelson et al., 1985, p. 11-8) gives the following requirements for the tertiary mirror:

Clear aperture: 1040 mm x 1430 mm
Distance to primary: -4000 mm
Displacement Tolerances
    Tilt < 3"
    Piston normal to surface 1.3 mm (0.15" of defocus)
    In plane of mirror ∞

The evolution of the telescope constants during the design and construction process resulted in some changes to the telescope parameters established in Nelson et al. (1985) including those that that drive the tertiary mirror clear aperture. In addition we can observe that allowing any amount of displacement in the plane of the mirror is not actually practical since even allowing moderate displacements with the specified clear aperture would result in vignetting of the 20' FOV at the Nasmyth focal stations.

For the purposes of this design note we assume the optical properties for the Keck I telescope shown in Table 1.

Table 1: Relevant optical properties of the Keck I telescope

Parameter	*Min.*	*Typ.*	*Max.*	*Units*	*Notes*
Primary mirror diameter	-	10949	-	mm	
Focal length	-	149583		mm	
Plate scale	-	0.7252	-	mm/"	
Focal ratio	-	*f*/13.6618	-	N/A	
Pupil location	-	19948	-	mm	1
Pupil diameter	-	1460	-	mm	

Notes:
1. Nominal pupil location (before focus) with respect to the focal plane.

Field of View

The tertiary mirror is installed in the telescope when using the Nasmyth and BC focal stations. With the f/15 secondary the Nasmyth focal stations support the full 20' FOV of the telescope, while the BC focal stations provide a smaller FOV (7.46' maximum science field diameter, determined by the opening in the BC rotator).

The K1DM3 is currently required to support a 5' diameter FOV (Nelson & Cabak, 2009). This was determined by the anticipated maximum FOV (~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.

Tertiary Mirror Size

The size of the Keck I tertiary mirror is given in various references as being between 1040 mm x 1430 mm (Nelson et al., 1985) and 1068 mm x 1439 mm (Nelson & Cabak, 2009, p. 7). The interface control drawing for the Keck I tertiary mirror blank (drawing number CP 0003, “Tertiary Mirror Interface Control”, April 17, 1988) indicates the size of the mirror as 1090 mm x 1540 mm. These dimensions agree with the QC document supplied by Schott when the blank was fabricated and with the assembly drawing for the tertiary mirror (LBNL drawing number 22A9153, revision A, “Tertiary Mirror, Mirror with Bonded Attachments”, dated August 10, 1989).

The current Zemax model for the Keck telescope, as provided by WMKO optical engineer Sergey Panteleev, indicates that the tertiary mirror should have a clear aperture of 1016 mm x 1499 mm with the appropriate offset of the mirror center (~10.2 mm away from the optical axis along the plane of the mirror). Using the as-built values for the Keck I tertiary, the mirror is 7.3% oversize in the minor dimension, and 2.7% oversized in the major dimension.

It is desirable to make the K1DM3 mirror no larger than absolutely necessary, and for some degrees of freedom we can trade precision of positioning off against the clear aperture to optimize the mirror size and mechanism performance requirements. The clear aperture required for a 5' diameter FOV is 580 mm x 879 mm offset ~12.7 mm away from the optical axis along the plane of the mirror.

Errors due to decenter of the mirror in plane are a simple function of the margin allowed on the clear aperture. If we wish to allow a 5 mm margin around the FOV, the result is a mirror that is 590 mm x 889 mm in size, offset ~13.7 mm away from the optical axis along the plane of the mirror. This allows up to 5 mm of decenter in the mirror plane. With this size of mirror the amount of allowable rotation around a normal to the mirror plane is 2° as illustrated in Figure 2.

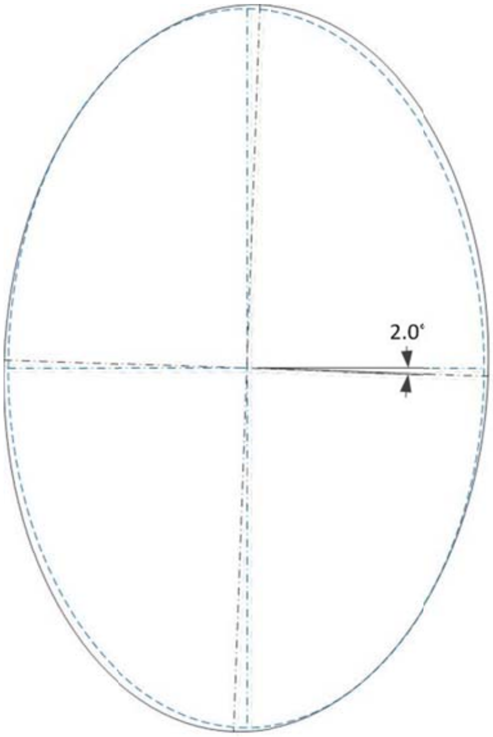

Figure 2: K1DM3 mirror rotated about the optical axis
This figure shows a view of the K1DM3 mirror along the normal to the mirror plane (black outline) rotated by 2 degrees around the optical axis with respect to an outline corresponding to the maximum beam footprint (blue dashed outline) for a 5' diameter FOV.

In beam positioning

In beam positioning requirements are driven by five performance concerns:

1. Unvignetted FOV
2. Accuracy and repeatability of image positioning at the Nasmyth and BC focal stations
3. Accuracy and repeatability of the pupil image position at the Nasmyth focal station (particularly the left Nasmyth with adaptive optics)
4. Stability of the image at the Nasmyth and BC focal stations
5. Stability of focus at the Nasmyth and BC focal stations

Unvignetted FOV

The unvignetted FOV is baselined at 5', mirror size considerations relative to positioning tolerances are discussed in the previous section of this design note.

Accuracy and Repeatability of Image Positioning

The repeatability of image positioning is important because the guider coordinate system for each FOV relies on guider pixel coordinates to define the pointing origin for the guider and in turn for the associated science FOV. This approach is reliable from one tertiary mirror pointing to the next only if the same part of the telescope FOV is returned to the same location on the guider detector each time the tertiary mirror is deployed and rotated to the desired focal station.

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 telescope's 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 instrument's 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.

There is another very important aspect of rotator alignment for rotators based on a Dove prism or a k-mirror. In the case of these rotators the angle of deviation of the output beam, and therefore the amount of motion that results from any error in angle of the input beam to the rotator, is double that of the error in the input angle.

There are four tertiary mirror degrees of freedom that affect image positioning. These are translation along the telescope Z axis, translation along the focal station X axis, rotation of the tertiary mirror around the telescope Y axis, which we define as mirror tilt, and rotation around the telescope Z axis, which we define as mirror tip. To appreciate the magnitude of these effects we need to understand what amount of motion at the focal plane is significant.

The telescope plate scale determines the relationship between angular measurements on the sky and linear measurements (in this case mm) at the telescope focal plane. Since pointing coordinates are defined in integer numbers of guider pixels, the plate scale of the guider determines the physical distance at the focal plane that corresponds to a resolution element in guider coordinates. For the Keck telescope the plate scale is 0.7252 mm/" and the pixel scales and equivalent pixel size at the telescope focal plane for the Keck I facility cameras are summarized in Table 2.

Table 2: Keck I facility camera plate scales

Camera	**Plate scale ("/pixel)**	**Pixel size at the telescope focal plane. microns**
HIRES slit guider	0.086	62.4
Keck I visitor port	0.216	91.4
Keck I star stacking camera (SSC)	0.166	120.4
Keck I AO acquisition camera	0.135	97.9

As Table 2 shows there are a range of facility camera plate scales in use on Keck I. The main consideration for pixel size on the sky is to have a size that provides the best centroiding accuracy when guiding, where smaller pixels are better if the image SNR is above a threshold of ~10. The impact of changes in position of the guider field on the sky due to the deployable tertiary primarily affects the relationship between guider fiducials and the instrument's science field. In practice offsetting relative to known fiducials should be reliably accomplished to within ~0.5" to avoid adding overhead to the fine acquisition process. The corresponding requirement for repeatable positioning at the focal plane is then within 363 microns for the telescope plate scale of 0.7252 mm/".

For translation of the mirror in the Z and X axis, the position shift at the focal plane is exactly equal to the amount of translation. We therefore require the repeatability from one tertiary pointing to the next at a given focal station to be +/- 181 microns on the telescope Z and X axis.

The nominal distance from the center of the tertiary mirror reflecting surface to the telescope focus is 6500 mm. The resulting constant for focal plane motion due to tip-tilt of the tertiary is 31.513 microns of focal plane motion for every 1" of tertiary tip or tilt. Motion of +/- 181 microns corresponds to +/- 5.75" of tip or tilt. However, for focal stations that see the mirror motion through a Dove prism or k-mirror which doubles the amount of motion due to tip-tilt of the tertiary mirror, motion of +/- 181 microns then corresponds to +/- 2.88" of tip or tilt. From this we can derive values for tertiary position accuracy and repeatability. Accuracy and repeatability of +/- 0.25" on the sky will correspond to an in beam tip-tilt positioning accuracy requirement of +/- 2.88". The result will be pointing origins and other guider fiducials that once calibrated with the K1DM3 will be repeatable from K1DM3 installation to installation, and pointing to pointing within 0.5" on the sky.

Accuracy and Repeatability of the Pupil Image Position at the Nasmyth Focal Station

The repeatability of the pupil image position is important for two reasons. First, the adaptive optics (AO) 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 in 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 subapertures 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 system's 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. Misregistration 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 3 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% undersize with respect to the telescope aperture and also 3% oversize 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 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 ~140".

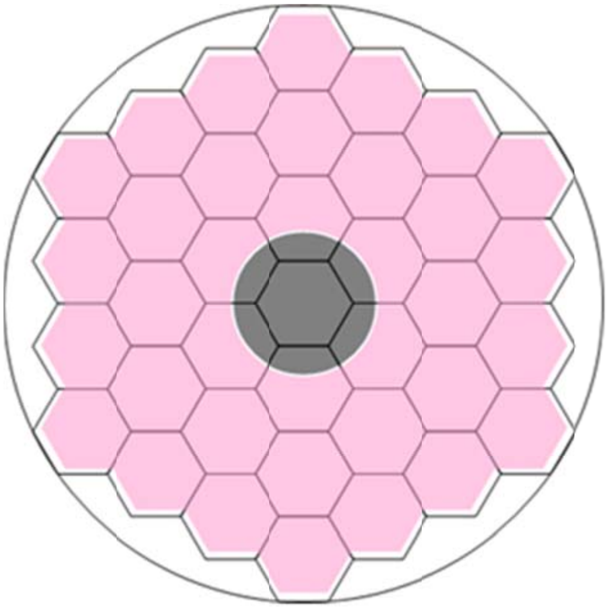

Figure 3: Example matched pupil mask for the Keck telescope

However, since the AO system rotator uses a k-mirror the tilt at the output is doubled, or stated another way, if the allowable tilt is 140" at the output of the rotator, then the allowable error for the angle of the beam entering the rotator is 70". The tolerance for pupil position error greatly exceeds the allowable error for image position, meaning that we can ignore pupil image positioning when considering the accuracy and repeatability requirements for the K1DM3 mirror.

Stability of the image at the Nasmyth and BC focal stations

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. Table 3 summarizes the diameters corresponding to 10% of the seeing disk from 0.4" to 1.0" which encompasses most of the range of seeing variations normally encountered at WMKO.

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. For tip tilt, since every 1" of tertiary tip or tilt results in 31.513 microns of focal plane motion, with the effect being multiplied by 2 by the Dove prism in the HIRES rotator, confining the motion to ~29 microns would place a stability requirement on tip and tilt of +/- 0.25".

Table 3: 10% sizes for typical WMKO seeing disks

Atmospheric seeing, "	**10% of the seeing disk at the focal plane, microns**
0.4	29.0
0.5	36.3
0.6	43.5
0.7	50.8
0.8	58.0
0.9	65.3
1	72.5

Stability of focus at the Nasmyth and BC focal stations

Motion of the tertiary mirror alters the image position and the focus. However, for reasonable amounts of focus shift, typically 1 mm, refocusing of the telescope using the secondary mirror introduces no significant increase in aberrations. The requirement placed on decenter on the telescope X and Z axes as it affects focus is much looser than the requirement for image position repeatability and does not require separate consideration.

CONCLUSIONS

The resulting requirements for K1DM3 mirror in-beam positioning are summarized in Table 4. These requirements are given in terms of the mirror plane for decenter and about an axis normal to the mirror plane for rotation of the mirror. Tip is given in terms of motion around the telescope Z axis, and Tilt is given in terms of motion around the telescope Y axis.

The accuracy requirements apply to initial positioning each time the K1DM3 is installed in the telescope. The repeatability and stability requirements apply to each positioning of the K1DM3 when it is installed in the telescope.

Table 4: K1DM3 mirror in beam positioning requirements

Parameter	***Min.***	***Typ.***	***Max.***	***Units***	***Notes***
Mirror in beam positioning					
Accuracy					
Decenter in the mirror plane	-2.5	-	2.5	mm	
Decenter from the telescope X and Z axes	-0.181	-	0.181	mm	
Tip-tilt	-2.88	-	2.88	"	1
Rotation about mirror surface normal	-1	-	1	°	
Repeatability					
Decenter in the mirror plane	-2.5	-	2.5	mm	2,3
Decenter from the telescope X and Z axes	-0.181	-	0.181	mm	2,3
Tip-tilt	-2.88	-	2.88	"	1,2,3
Rotation about mirror surface normal	-1	-	1	°	2,3
Stability					
Decenter in the mirror plane	-1	-	1	mm	2,3,4
Decenter from the telescope X and Z axes	-0.015	-	0.015	mm	2,3
Tip-tilt	-0.25	-	0.25	"	1,2,3
Rotation about mirror surface normal	-1	-	1	°	2,3

Notes:

1. Tip refers to motion around the telescope Z axis and tilt refers to the motion around the telescope Y axis
2. Repeatability and stability requirements apply over a temperature range of ±5 °C with an average rate of change of 1.6 °C/hour
3. Repeatability and stability requirements apply only when the mirror is defined in beam
4. The stability of decenter in the mirror plane should be determined by the constraint of the mirror mass needed to achieve the other stability requirements.

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