Next Generation Adaptive Optics

DAVINCI Pupil Mask Size and Pupil Image Quality

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April 29, 2010

INTRODUCTION

3

This document discusses considerations for the DAVINCI instrument's pupil image quality and pupil mask selections. The DAVINCI instrument (Adkins et al., 2010) requires a cold pupil mask to control background, especially in the near-IR wavelengths. Different size masks may be required to balance throughput loss and background suppression, with additional masks required for the DAVINCI imager's coronagraphic mode. The intent of the DAVINCI instrument design is to limit the background sources seen by the imager and IFS detectors in DAVINCI to the telescope, AO system, and the entrance window of the DAVINCI dewar. This will be accomplished by cooling the interior of the instrument to 120 K and providing a high efficiency cold stop and stray light suppression baffles to control the background seen by the detectors.

AREA OF PUPIL

The telescope segments are regular hexagons 1.8 m across (corner to corner). Since each segment can be represented by a tessellation of six equilateral triangles, the total area of each segment is found using equation 1.

$$Area_{segment} = 6 \times \left(\frac{\sqrt{3}}{4} \times L^2 \right) = 2.10444\ \text{m}^2 \tag{1}$$

where:

L = length of one side of the hexagonal segment = 0.9 m

The area of the entire telescope primary is then 36 x 2.10444 m^2 or 75.76 m^2. An aperture that fully encloses the telescope primary is 10.948 m in diameter as shown in Figure 1.

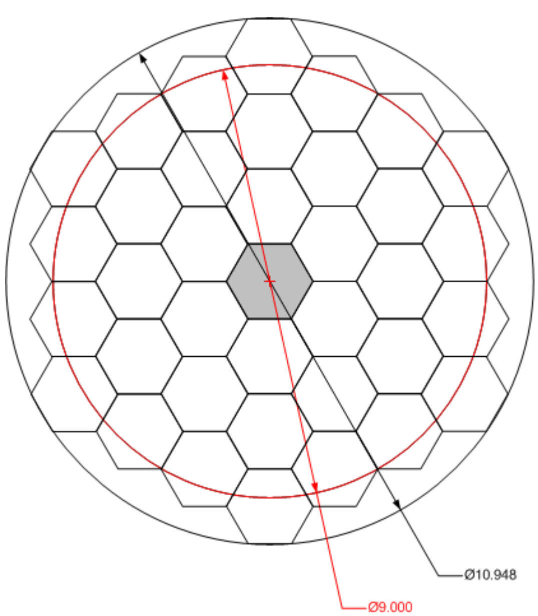

Figure 1: Keck telescope primary mirror apertures

A fully inscribed circular aperture overlaid on the primary mirror is 9 m in diameter, and the ratio of this aperture's area to the area of the telescope primary is 0.84:1, in other words the area of a fully inscribed aperture is 16% less than the actual telescope collecting area. Circular mask sizes intermediate in diameter between a fully inscribed circular aperture and the full size aperture result in correspondingly lower losses. For example, a 9.32 m diameter aperture results in 10% less area than the actual telescope collecting area, and allows only small amounts of background through at six points on the outer segment to segment vertices at the points where the fully inscribed circle would exactly intersect those vertices.

PUPIL MASK SHAPES AND SIZES

Pupil Mask Losses

The current DAVINCI imager throughput budget is shown in Table 1 with the pupil mask transmission set to 100%, that is, no pupil mask losses. Ideally we would achieve the condition of zero pupil mask losses with 100% cold stop efficiency, i.e. full suppression of the thermal background from the AO system and telescope.

	%T						%R					
Surface	**I band**	**Z band**	**Y band**	**J band**	**H band**	**K band**	**I band**	**Z band**	**Y band**	**J band**	**H band**	**K band**
Dewar Window												
Infrasil 302, 25 mm thick	99.23%	99.23%	99.23%	99.23%	99.23%	99.23%						
Coating, 2 surfaces	97.83%	97.84%	94.95%	95.83%	95.50%	96.77%						
Coronagraph Mask												
Infrasil 302, 2 mm thick												
Coating, 2 surfaces												
FM1							97.65%	98.53%	98.79%	99.00%	99.03%	99.17%
OAP1							97.65%	98.53%	98.79%	99.00%	99.03%	99.17%
Pupil mask/cold stop	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%						
Filter	90.00%	90.00%	80.00%	88.00%	85.00%	95.00%						
OAP2							97.65%	98.53%	98.79%	99.00%	99.03%	99.17%
FM4 (hole to IFS)							97.65%	98.53%	98.79%	99.00%	99.03%	99.17%
FM5 (periscope)							97.65%	98.53%	98.79%	99.00%	99.03%	99.17%
OAP3							97.65%	98.53%	98.79%	99.00%	99.03%	99.17%
OAP4							97.65%	98.53%	98.79%	99.00%	99.03%	99.17%
Totals												
%T	87.37%	87.37%	75.37%	83.68%	80.55%	91.22%						
%R							84.68%	90.18%	91.80%	93.17%	93.40%	94.33%
Combined	73.99%	78.79%	69.19%	77.96%	75.24%	86.05%						

Table 1: DAVINCI imager throughput budget, no pupil mask losses

As the table shows, losses due to all other sources besides the pupil mask result in transmissions ranging from a minimum of 69% in Y band, to a maximum of 86% in K band. While it is clearly preferable to limit losses due to the pupil mask/cold stop, in practical terms we will be forced to make a compromise between the transmission losses due to making the pupil undersized, and ensuring 100% cold stop efficiency. This compromise will have the most impact in the near-IR bands are where the trade-off between cold stop efficiency and background suppression is most important. For example, assuming a pupil transmission of 98% in K band results in net transmission of ~84% through the instrument and the corresponding background limited exposure time is 280 s. For a fully inscribed circular pupil (pupil transmission of 84%) the net transmission through the instrument is ~72% and the corresponding background limited exposure time is 360 s.

Pupil Mask Shape and Size

When considering the size and shape of DAVINCI's pupil masks we assume that the Keck telescope's primary mirror image is fully transmitted by the AO system and therefore the maximum transmission is obtained by exactly matching the shape of the pupil mask to that image. A central obscuration, and perhaps masks for the telescope spiders should also be included, but these features would be common to all sizes of pupil mask. Table 2 shows the transmission and cold stop efficiency for matched pupil masks and various sized circular masks.

Collecting area (m^2)	Form	Diameter (m)	Transmission	Cold stop efficiency
75.760	Matched	-	100%	100%
74.245	Matched	-	98%	100%
72.017	Matched	-	97%	100%
74.245	Circular	9.723	98%	99.29%
72.730	Circular	9.623	96%	99.79%
71.214	Circular	9.522	94%	99.86%
69.699	Circular	9.420	92%	99.91%
68.184	Circular	9.317	90%	99.95%
66.669	Circular	9.213	88%	99.98%
65.154	Circular	9.108	86%	99.99%
63.617	Circular	9.000	84%	100.00%

Table 2: Pupil mask transmission and cold stop efficiency

The collecting area and diameter in Table 2 is with respect to the telescope primary mirror space. For the circular masks, the full inscribed 9 m diameter mask is taken as a 100% efficient cold stop since its footprint falls entirely on the primary mirror. For progressively larger circular masks the effect is to reveal background beyond the telescope primary mirror as indicated in Figure 2.

The area of the background revealed by the larger circular masks was approximated for the purpose of calculating the cold stop efficiency using an equilateral triangle to approximate the 6 symmetrical areas, and an oblique triangle for the other 12 asymmetrical areas.

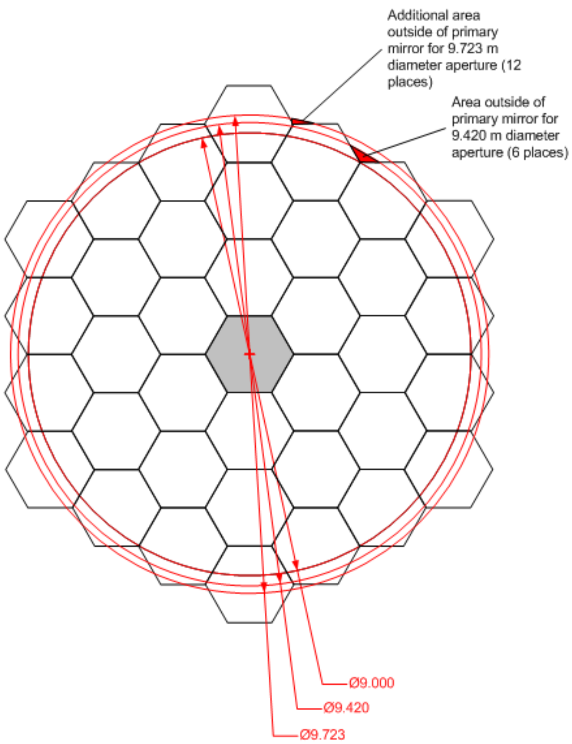

Figure 2: Various size circular masks on the Keck telescope pupil

Although the reductions in cold stop efficiency for circular apertures appear small, for the near-IR H and K bands (1.49 to 1.78 μm and 2.03 to 2.37 μm respectively for the photometric bands) the difference in thermal emission between the telescope primary mirror and other background objects is quite significant. For example, at a temperature of 274.8 K the telescope primary emits ~1000 photons/s/arcsecond^2/m^2 over the photometric passband in K. An average emissivity of 7.7% is assumed for the telescope primary over the passband. A surface with an emissivity of 90% (a typical dark background object outside of the telescope primary mirror footprint) emits ~11,660 photons/s/arcsecond^2/m^2 in the same photometric passband in K. This background needs to be suppressed by a properly sized pupil mask, even if the cold stop efficiency reduction appears modest for the larger circular apertures. At the long end of the H band there is a small background contribution from thermal emission, ~1.3 photons/s/arcsecond^2/m^2 for the telescope primary assuming an average emissivity over the passband of 8.4%. For a background object with an emissivity of 90% the background contribution is ~13.8 photons/s/arcsecond^2/m^2. For the J band and shorter wavelengths there is no significant thermal background contribution.

Based on the expected thermal background contributions a matched mask is required for the H and K bands and as we discuss in the next section this mask will need to be slightly undersize, so we assume 97% transmission for this mask. A circular mask with 98% transmission appears to be appropriate for the Y and J bands, and we assume a circular mask that includes 100% of the primary mirror area for I and Z bands.

Pupil Image Quality

DAVINCI's nominal pupil size is 25 mm corresponding to the clear aperture required to enclose the entire primary mirror (10.948 m). This means that 1 mm of image shift at the primary mirror corresponds to 25/10948 or 2.3 μm at DAVINCI's pupil plane.

The off-axis parabolas (OAPs) used in the NGAO system's AO relay result in a pupil image that exhibits a field point dependent shift in position. This makes the location of the pupil appear uncertain with respect the total field of view (FOV), effectively blurring the edge of the pupil image. In the current design of DAVINCI, the pupil image is formed at the pupil mask location by a first OAP is used at an off-axis angle that matches the final OAP in the AO system. This angle matching allows the pupil blur to be controlled. In the present design the blur is well controlled. The maximum pupil image shift is 58 μm for the 25 mm pupil diameter in the current DAVINCI optical design. Since this shift is symmetrical for points on opposite sides of the optical axis the pupil mask should be undersized by two times the maximum pupil shift, or 99.5% of the desired clear aperture to ensure that the pupil image is fully masked for all field points.

Pupil Alignment Errors

Another factor in selecting the size of the pupil masks is the impact of errors between the actual telescope pupil location and the location of the pupil mask. The main sources of error are alignment of the AO relay to the telescope optical axis, alignment of the instrument to the AO relay optical axis, and errors in tracking field rotation for the matched mask.

Field Rotation Errors

The maximum elevation at which the Keck telescope can track the sidereal motion of the sky is 89.25° and is determined by the telescope's maximum azimuth tracking rate of ~0.3°/s (Neyman, 2010). Based on the location of the Keck II telescope (University of Hawaii Institute for Astronomy, 1998) the maximum rate of field rotation is given by equation 2.

$$R = \omega \times \cos(\varphi) \times \frac{\cos(Az)}{\cos(El)}$$

where:

R = rotation rate in °/s

ω = sidereal tracking rate of 4.178×10^{-3} °/s (2)

φ = observatory latitude

Az = azimuth angle of observation in °

El = elevation angle of observation in °

The maximum rate of 0.30025°/s occurs at the maximum elevation of 89.25° and azimuth angles of 0° and 180°.

For a matched pupil mask that is 3% smaller than the primary mirror aperture, the maximum tracking error before the mask drifts past the edge of the primary mirror image is 1.24° as shown in Figure 3.

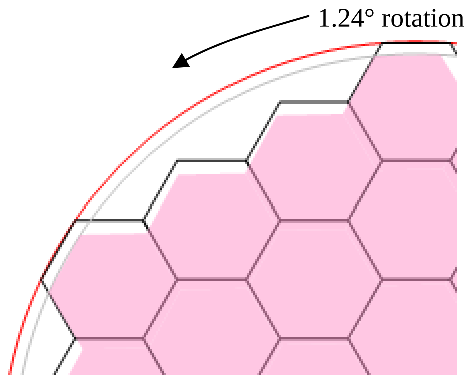

Figure 3: 1.24° CCW rotation of a 3% undersize matched mask (pink) with respect to telescope primary image

Pupil Registration Errors

For the same 3% undersized mask the maximum shift of the pupil in x is ±107.5 mm in X at the primary mirror, and ±95 mm in Y. At the instrument pupil this corresponds to ±247.25 μm in X, and ±281.5 μm in Y.

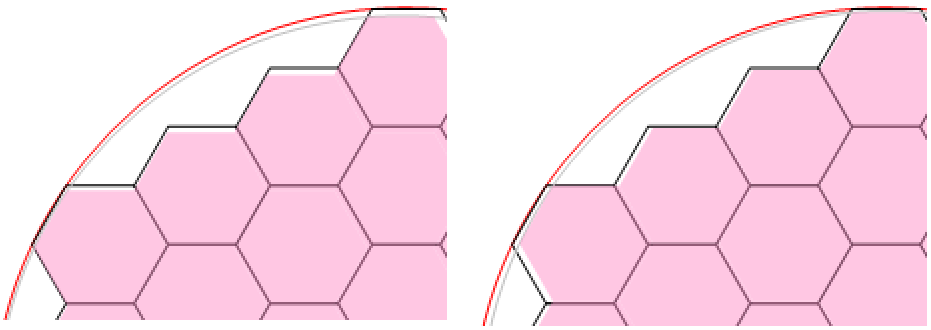

Figure 4: Pupil mask registration margin at the telescope primary for a 3% undersize matched mask (pink) with respect to telescope primary image.
X axis registration error (left side), Y axis registration error (right side).

Pupil Alignment Error Budget

An error budget based on a combination of pupil rotation errors and pupil mask registration errors has been determined by arbitrarily setting the maximum rotation error to ±0.3°. The corresponding maximum offsets are then ±52 mm in X and Y, or ±119.6 μm in X and Y at DAVINCI's pupil plane. Figure 5 shows the effect of maximum offsets in X and Y combined with CCW and CW rotation errors of 0.3°. The other two combinations of maximum offsets result in zero clearance for the mask at the opposite corners from that shown in Figure 5.

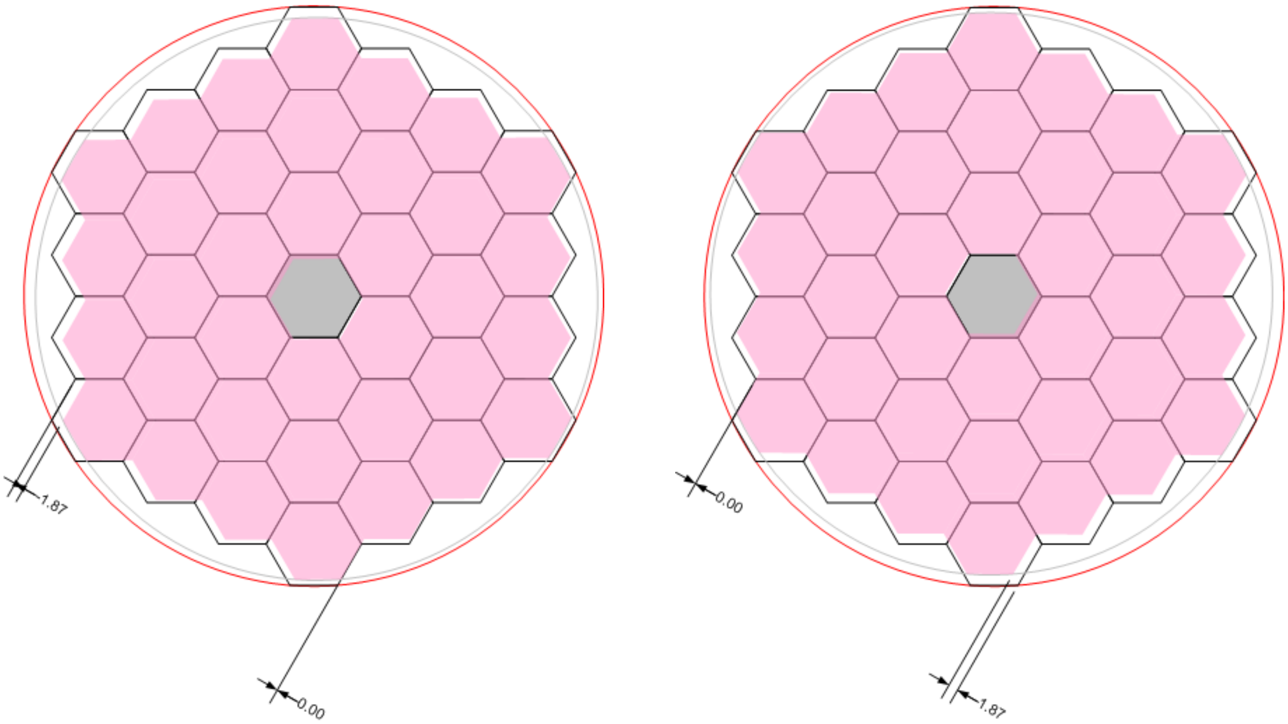

Figure 5: Rotation error of 0.3° CCW with offsets of +52 mm, -52 mm (left) and 0.3° CW and offsets of -52 mm, +52 mm (right)

A rotation error of 0.3° is 1 part in 1,200 for the control of the instrument's pupil mask position and tracking. The drive system will be a stepper motor with at least 400 steps per revolution and a gear drive with at least a 10:1 reduction this performance level should be easily achieved.

The X and Y positioning requirements are much more demanding. It is unlikely that we can mechanically position the entire DAVINCI dewar to the required level of accuracy. A tip/tilt mirror inside DAVINCI appears to be required. One possible candidate is the fold mirror located after OAP1 in the current optical design (Adkins et al., 2010, p. 26).

REFERENCES

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