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ISHELL TECHNICAL NOTE

PUPIL / COLDSTOP ALIGNMENT ANALYSIS

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Revision History

Revision No.	Author & Date	Approval & Date	Description
Revision X	Tim Bond Oct 1/12	Tim Bond Oct 1/12	Preliminary Release.

Contents

1 Introduction / Document Purpose

The purpose of this document is to describe the details of the procedures that was undertaken to analyze the pupil misalignment issues (telescope secondary mirror vs. cold stop) within the ISHELL instrument.

The exit pupil for the IRTF telescope is nominally the secondary mirror, but there is also a cold stop located within ISHELL, conjugated to the secondary. Any flexure between these two elements results in an effective shearing of the pupil, which in turn results in a reduction in instrument throughput. There is a science driven requirement that the throughput needs to be maintained to with a few percent.

This analysis will quantitatively examine the effects of the aforementioned misalignment on the throughput. Typically, such a misalignment would be caused by flexure during the course of an observation as the misalignment can be removed using standard calibration procedures at the beginning of an observation.

2 Summary of Analysis Procedures

The bulk of the analysis is performed using the optical design software package – ZEMAX. The telescope and the instrument are modeled within ZEMAX and a tolerance analysis is performed. Several iterations of the analysis are undertaken, and tolerance parameters are modified appropriately in order to determine to systems sensitivity to misalignment.

In summary, the following steps were performed to complete the pupil analysis:

- The original optical design in ZEMAX is modified to enable the application of tolerances to the design in such a way that realistic mechanical tolerances are being modeled.
- The tolerance analysis is run in a "sensitivity analysis" type mode, in order to determine which elements have the most dramatic effect on the misalignment.
- Individual tolerances are placed on the relevant optical elements and the tolerance analysis is performed in a "Monte Carlo" type mode with 25 trials. The tolerances are fine-tuned and the Monte Carlo repeated as necessary.
- When the final tolerances are established, a concluding "Monte Carlo" run is performed with 1000 trials. The 95th percentile of this run is examined to confirm the tolerances are tight enough.
- The analysis is repeated with the flexure of the secondary mirror added.

2.1 Refinement of the original ZEMAX design

The original ZEMAX optical design file is in a somewhat simplified form, compared to what is required for a full rigorous pupil analysis. Several modifications needed to be made in order to get the design into a suitable form.

2.1.1 Addition of an Entrance Pupil Location:

During normal use of the telescope it is standard procedure to "re-point" the telescope in order to maintain alignment on selected objects on the sky. By use of a coordinate break inserted at the telescope entrance pupil, we are able to simulate this procedure within ZEMAX during the tolerance runs.

2.1.2 Instrument (Optical Bench) Flexure Simulation:

As the telescope slews to different locations on the sky, the instrument moves into different orientations with respect to gravity. As this occurs, the mass of the instrument will invariably flex the main mounting trusses of the instrument, and the optical bench will move relative to the vacuum jacket and telescope. This was modeled in ZEMAX with the addition of several coordinate breaks, and by estimating the final instrument center of gravity location. It is assumed that the trusses are designed to hold the optical bench about the center of gravity.

2.1.3 Mirror Deflections:

Additional coordinate breaks were added around mirrors in order to correctly simulate the deflections of these mirrors within their mounts. Only relevant deflections were modeled (i.e. flat mirror decentration was ignored as well as axial rotations).

2.1.4 Image Rotator Flexure Simulation:

Similar to the instrument flexure, as the telescope slews to different locations on the sky, the instrument moves into different orientations with respect to gravity. As this occurs, the image rotator as a whole will flex with respect to the optical bench. This was modeled in ZEMAX with the addition of several coordinate breaks, and by estimating the final image rotator center of gravity location. Again, it is assumed that the image rotator flexes about the center of gravity.

2.1.5 Lens Barrel Flexure Simulation:

Similar to the instrument flexure, as the telescope slews to different locations on the sky, the instrument moves into different orientations with respect to gravity. As this occurs, the lens barrels as a whole will flex with respect to the optical bench. This was modeled in ZEMAX with the addition of several coordinate breaks, and by estimating the final lens barrel center of gravity location. Again, it is assumed that the image rotator flexes about the center of gravity.

2.1.6 Customized Merit Function was developed:

The default merit functions packaged within ZEMAX are all relevant to image quality and not useful within this analysis. A custom merit function needed to be built, that would rate a particular design based on the pupil decentration (from the secondary) at the cold stop. This is fairly simple, but it also needed to incorporate components for focusing the telescope and for repointing.

Another non standard procedure that was necessary when performing the analysis within ZEMAX was the use of a "scripted" tolerance analysis evaluation criterion for the Monte Carlo Analysis. A short script was invoked for each of the Monte Carlo trials that evaluated the randomly perturbed design and recorded the pupil decentration to an external text file. That text file was later used to determine the mean, standard deviation, and the 95th percentile result.

2.2 Sensitivity Analysis

Once the new ZEMAX file was constructed, a sensitivity analysis was performed in order to determine both relative sensitivity of the pupil shearing to the individual element perturbations, and to get first estimates for the actual magnitude of the perturbations themselves. This process took several iterations and during these iterations, it was discovered that the actual flexure of the secondary on the telescope might have a significant impact on the pupil misalignment.

At this point, it was determined that two individual analyses would be undertaken; one which would account for flexure of the secondary on the telescope, and one that did not. Preliminary results indicated that active collimation of the secondary (possibly via a hexapod) would be necessary in order to meet the desired pupil misalignment criteria.

2.3 Determination of Tolerances

After several iterations on the Monte Carlo analyses, a set of tolerances were determined that seemed reasonable based on semi-precision manufacturing tolerances and reasonable flexure requirements (see Appendix A). Below is a list of these tolerances and an indicator as to how sensitive each one is with respect to movement of the pupil.

	Nominal	Min	Max	Pupil shift	% of Diameter	% Reduction in Area
				(mm)	(%)	(%)
SECONDARY FLEXURE						
+/- 1 mm decentration in X	0	-1	1	0.04	0.39	0.247
+/- 1 mm decentration in Y	0	-1	1	0.04	0.39	0.247
+/- 0.03 deg tilt about X	0	-0.03	0.03	0.15	1.48	0.925
+/- 0.03 deg tilt about Y	0	-0.03	0.03	0.15	1.48	0.925
INSTRUMENT FLEXURE (about CofG)						
+/- 0.2 mm decentration in X	0	-0.2	-0.2	-		
+/- 0.2 mm decentration in Y	0	-0.2	0.2	-		
+/- 0.02 deg tilt about X	0	-0.02	0.02	0.13	1.28	0.801
+/- 0.02 deg tilt about Y	0	-0.02	0.02	0.13	1.28	0.801
+/- 0.05 deg tilt about Z	0	-0.05	0.05	-		
+/- 0.1 mm despacing along Z	0	-0.1	0.1	-		
FIRST FOLD MIRROR						
+/- 0.2 mm despacing along element axis	0	-0.2	0.2	-		
+/- 0.02 deg tilt about X	0	-0.02	0.02	0.184	1.81	1.134
+/- 0.02 deg tilt about Y	0	-0.02	0.02	0.262	2.58	1.615
COLLIMATOR MIRROR						
+/- 0.2 mm despacing along element axis	0	-0.2	0.2	-		
+/- 0.05 mm decentration in X	0	-0.05	0.05	0.052	0.51	0.321
+/- 0.05 mm decentration in Y	0	-0.05	0.05	0.052	0.51	0.321
+/- 0.02 deg tilt about X	0	-0.02	0.02	0.276	2.72	1.701
+/- 0.02 deg tilt about Y	0	-0.02	0.02	0.276	2.72	1.701
SECOND FOLD MIRROR						
+/- 0.05 mm despacing along element axis	0	-0.05	0.05	0.08	0.79	0.493
+/- 0.05 deg tilt about X	0	-0.05	0.05	0.04	0.39	0.247
+/- 0.05 deg tilt about Y	0	-0.05	0.05	0.08	0.79	0.493

2.4 Post - Monte Carlo Analysis

During the Monte Carlo analysis, the custom made ZEMAX script file writes all of the decentration results out to an external file for post analysis. That file was analyzed with Microsoft EXCEL and appropriate plots were derived.

3 Analysis Results

3.1 Summary

The following tolerances were established during the modeling of the pupil decentration errors on the cold stop:

TELESCOPE SECONDARY MIRROR FLEXURE
- Maximum decentration ±1.0 mm
- Maximum tilt ±0.03°

INSTRUMENT FLEXURE
- Maximum tilt ±0.02°

FIRST FOLD MIRROR (DICHROIC)
- Maximum tilt ±0.02°

COLLIMATOR MIRROR
- Maximum decentration ±50 µm
- Maximum tilt ±0.02°

SECOND FOLD MIRROR
- Maximum decentration ±50 µm
- Maximum tilt ±0.05°

Results from the ZEMAX Monte Carlo run with secondary mirror deflections can be summarized as follows:

- We can anticipate decentration errors of around $\mu = 0.419$ mm
- But we can say with 95% confidence that the errors will be less than $2\sigma = 0.815$ mm

Note that the deflection numbers given are the decentration of the pupil at the cold stop (cold stop nominal diameter = 10.136 mm).

Results can be expressed as reductions in pupil area (proportional to flux transmitted) and can be summarized as follows:

Cold Stop Diameter	***10.136 mm (100% flux)***	***10.034 mm (98% flux)***	***9.879 mm (95% flux)***
Mean Case (µ)	2.8 % reduction	2.45 % reduction	1.95 % reduction
95^{th} Percentile (2σ)	5.4 % reduction	5.1 % reduction	4.55 % reduction

Table 1: Results Summary

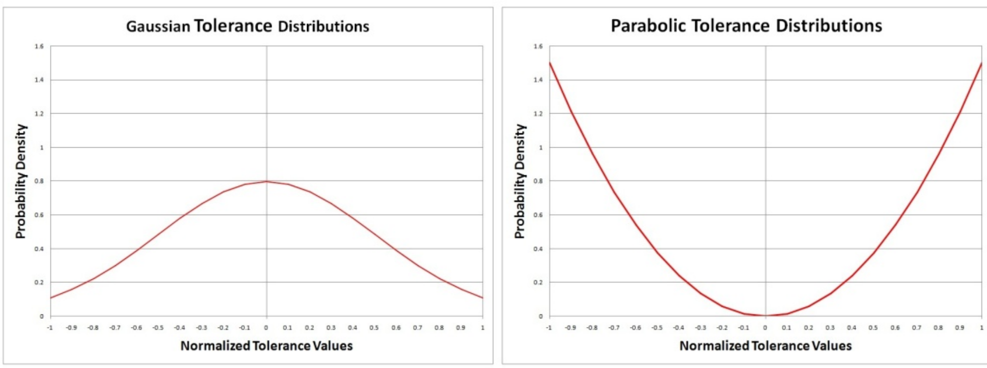
Note that we can reduce the effect slightly by reducing the size of the cold stop – effectively stopping down the telescope collecting area (See Appendix C). Table 1 also presents the results of the stopping down versions of the analysis.

3.2 Discussions

3.2.1 Distribution Form of Individual Tolerances:

During the Monte Carlo analysis, the value for each of the individual perturbations is chosen from a probability density. ZEMAX allows the user to select from several predefined distributions (Gaussian, Uniform, and Parabolic) or to even specify a custom distribution. The default is Gaussian, but we chose to switch to a parabolic distribution as this would more accurately model real world manufacturing processes.

Individual Pertubation Selection Based On Tolerances



3.2.2 Discussion of the 95th Percentile Standard:

Due to the large number of tolerances involved and the random nature in which they are likely to interact with each other, a statistical analysis of these tolerances is required. If all of the tolerances were simply “stacked” as would be done in a worst case scenario, it would simply be too difficult (and expensive) to meet the desired requirements. It is standard practice in the optics industry to employ a statistical tolerance scheme to help relax some of the tolerances that need to be attained.

In our case, the mean result is reported (expected value) as well as the 95^{th} percentile case (within 2 standard deviations).

3.2.3 Reduction of the Cold Stop Diameter:

One suggested method of alleviating the effects of the decentering of the pupil is the use of a slightly undersized cold stop. This will allow the pupil to decenter for a small length of travel before any effect begins to take place. One must balance the fact that a reduced cold stop will also reduce the total flux allowed to pass through the system, and we are in essence stopping down the size of the telescope.

Results for three cases are provided:

1. No area reduction at the cold stop (same size as pupil)
2. 2% area reduction at the cold stop
3. 5% area reduction at the cold stop

3.2.4 Active Collimation of the Telescope Secondary Mirror:

Two distinct cases were analyzed regarding the secondary mirror. One case considered the secondary mirror to remain aligned at its nominal locations (see Appendix B1) and a second case applied tolerances to the secondary mirror.

The analysis showed that somewhat tight tolerances are required on the tip/tilt, but that decentrations were less sensitive. It is important to note that this may be the case if the pupil misalignment were considered alone, but one needs to also consider the loss in image quality with the decentration of the secondary in order to draw any final conclusions.

Regardless, the numbers found indicate that we can make improvements of up to about 0.35 % (total variations in flux) to the numbers specified in Table 1 of this document, if some form of active secondary collimation is utilized. Details can be found in Appendix B1 and Appendix B2 and are summarized as follows:

With the following secondary tolerances:

- Maximum decentration ±1.0 mm
- Maximum tilt ±0.03°

Pupil misalignments were found to be:

- Expected decentration errors of around $\mu = 0.419$ mm
- 95% confidence that the errors will be less than $2\sigma = 0.815$ mm

If we were able to hold the secondary perfectly (i.e. if we had no tip/tilt or decentration errors) the pupil misalignments were found to be:

- Expected decentration errors of around $\mu = 0.397$ mm
- 95% confidence that the errors will be less than $2\sigma = 0.766$ mm

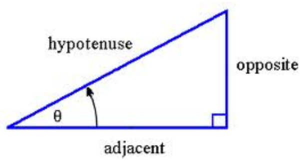
4 Appendices

4.1 Appendix A: Example Tolerance Considerations

The following general calculations are used as a basis for determining reasonable tolerances.

<u>CASE 1:</u> A 15um deflection over 40mm baseline

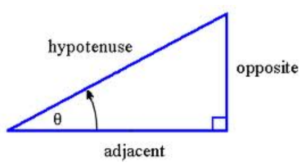
A typical optical element diameter is 40mm and it may be possible to hold the deflections on one edge of that element to a potential 15um.



$$\emptyset = \tan^{-1}\left(\frac{opposite}{adjacent}\right)$$
$$\emptyset = \tan^{-1}\left(\frac{0.015}{40.0}\right)$$
$$\emptyset = 0.021°$$

<u>CASE 2:</u> A 250um deflection over 750mm baseline

The distance from the center of gravity of the instrument out to one of its extreme ends is 750mm and it may be possible to hold the deflections on one edge of the instrument to a potential 250um.



$$\emptyset = \tan^{-1}\left(\frac{opposite}{adjacent}\right)$$
$$\emptyset = \tan^{-1}\left(\frac{0.250}{750.0}\right)$$
$$\emptyset = 0.019°$$

<u>CASE 3:</u> Total Instrument deflections might be in the range of ±0.150mm

Considering, for example a total instrument mass of 500kg and a G10 support truss system with 2 arms. It is conceivable that each arm might carry loads up to:

$$F = \frac{1}{2}(500)(9.81) \quad \Leftrightarrow \quad F = 2452\,N$$

Considering members that are 50mm x 12.5mm x 500mm long, with a Young's Modulus of E=18.0 GPa, one can expect deflections of the order:

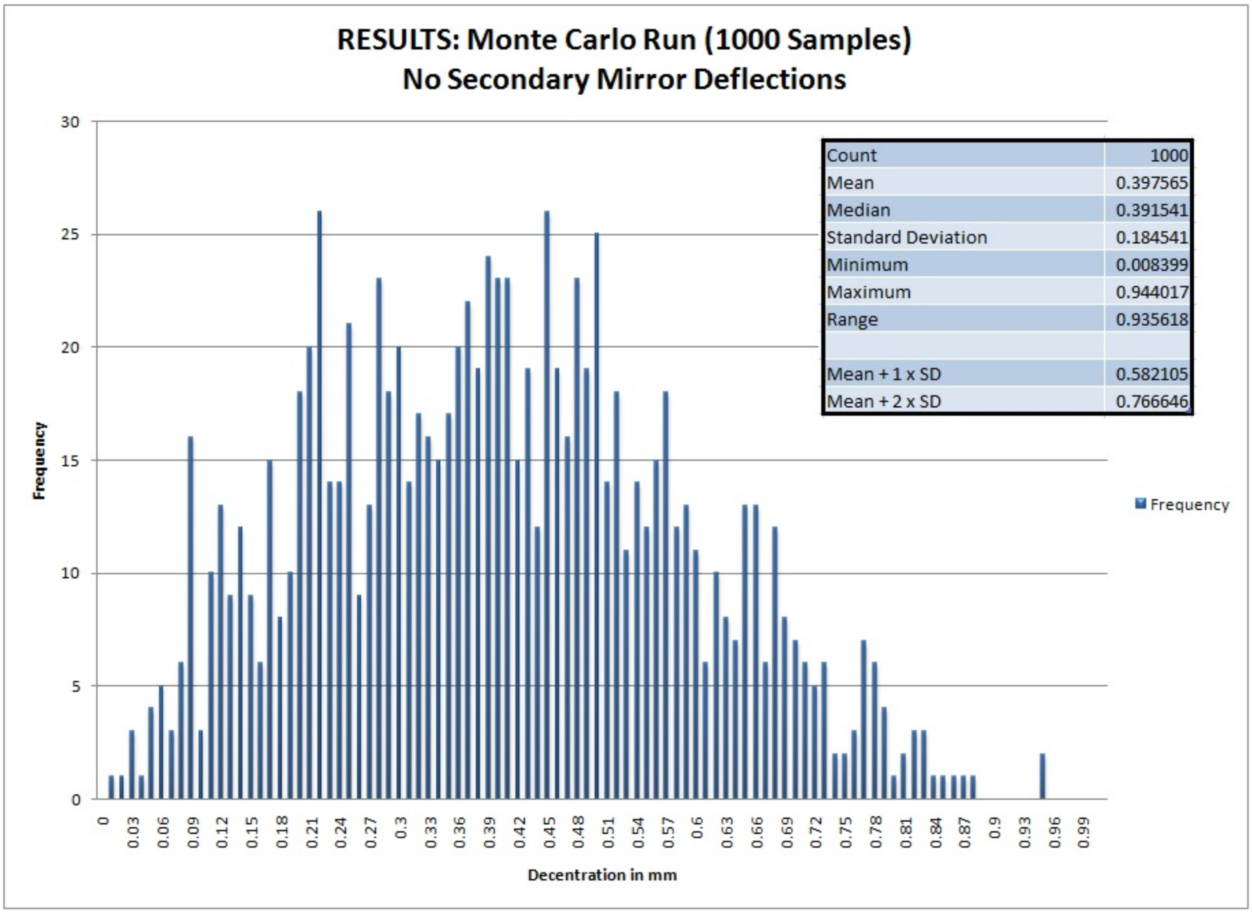
$$\delta = \frac{(2452)(0.500)}{(0.050)(0.0125)(18.0 \times 10^{6})} \quad \Leftrightarrow \quad \delta = 0.109\,mm$$

Note: this only accounts for the elongation/compression of the truss member. Lateral flexure is usually significantly higher than the elongation/compression component.

4.2 Appendix B1: Monte Carlo Results (Excluding Secondary Mirror)

Results from the ZEMAX Monte Carlo run with no secondary mirror deflections included. . The deflection number given is the decentration of the pupil at the cold stop (cold stop nominal diameter = 10.136 mm)

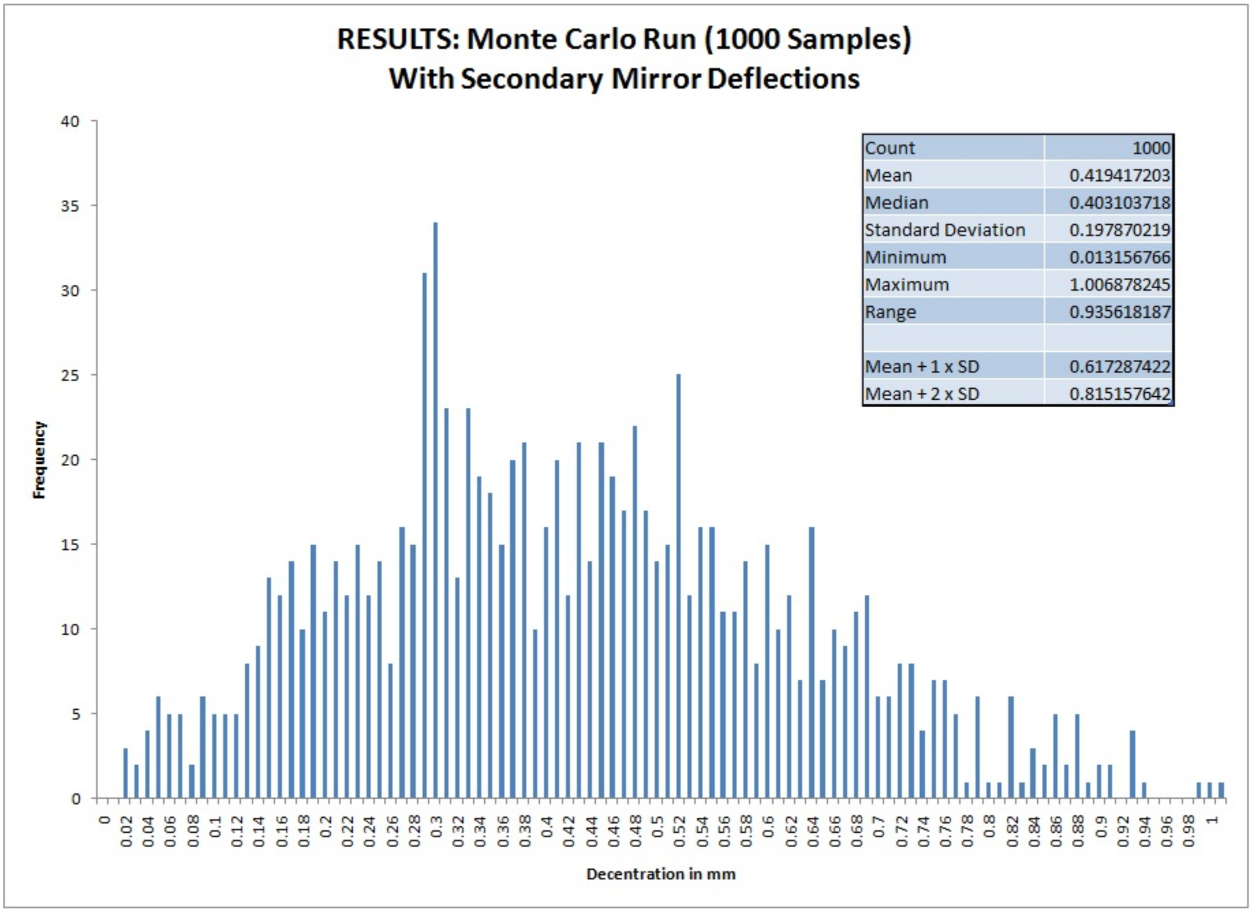
- We would anticipate decentration errors of around μ = 0.397 mm
- But we can say with 95% confidence that the errors will be less than 2σ = 0.766 mm



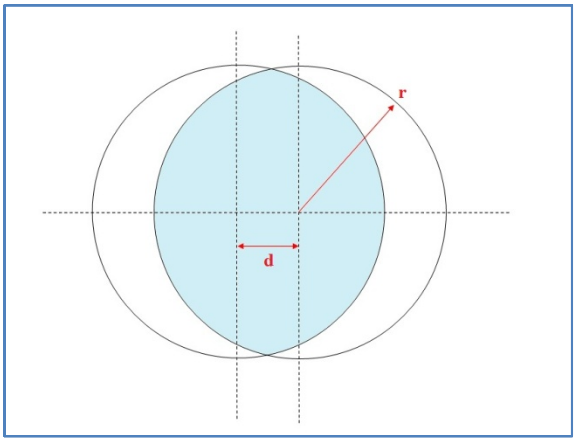
4.3 Appendix B2: Monte Carlo Results (Including Secondary Mirror)

Results from the ZEMAX Monte Carlo run with secondary mirror deflections included. The deflection number given is the decentration of the pupil at the cold stop (cold stop nominal diameter = 10.136 mm)

- We would anticipate decentration errors of around μ = 0.419 mm
- But we can say with 95% confidence that the errors will be less than 2σ = 0.815 mm



4.4 Appendix C: Area Reduction Calculations:



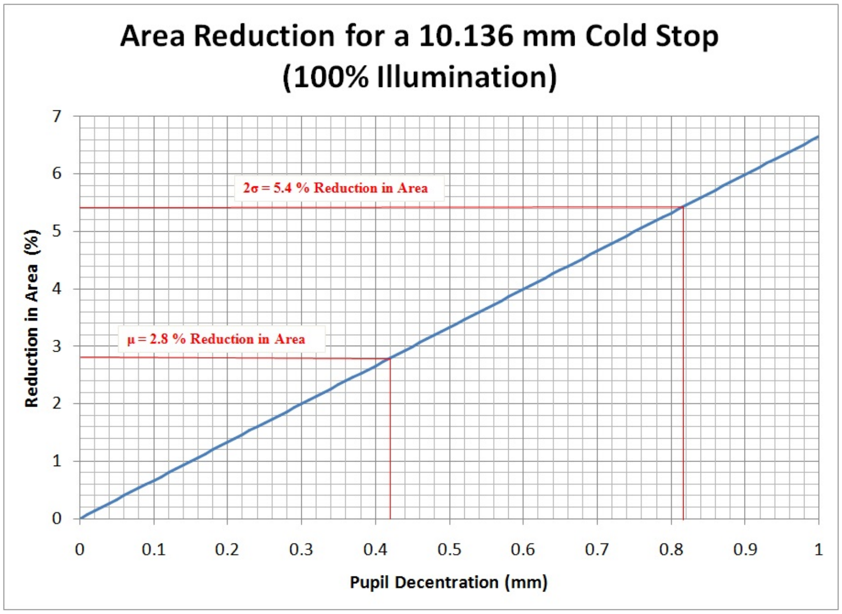
The overlapped area is given by the equation:

$$A^* = 2r^2 \cos^{-1}\left(\frac{d}{2r}\right) - d\sqrt{\left[r^2 - \left(\frac{d}{2}\right)^2\right]}$$

And the percent reduction in illumination is given by:

$$\%\,Reduction = 1 - \frac{A^*}{\pi r^2}$$

For a pupil size of 10.136 mm and a variety of pupil displacements, the following graph shows the relation between area reduction and pupil decentration:

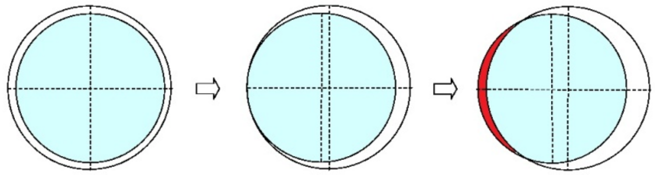


As can be seen from the above chart:

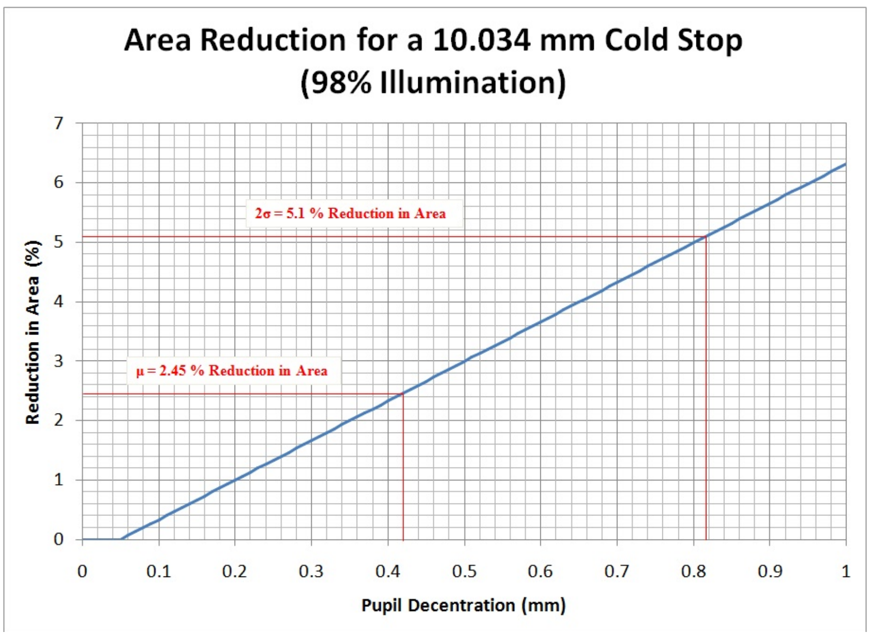
- A pupil decentration of 0.420 mm corresponds to an illumination reduction of 2.8 % (expected value).
- A pupil decentration of 0.815 mm corresponds to an illumination reduction of 5.4 % (95th percentile case).

It is possible to reduce the effects of a pupil misalignment by reducing the diameter of the cold stop slightly (effectively stopping down the telescope). This allows for some decentration to occur before the shearing of the two patches begins to reduce the flux.

An exaggerated diagram of the effect is shown below.

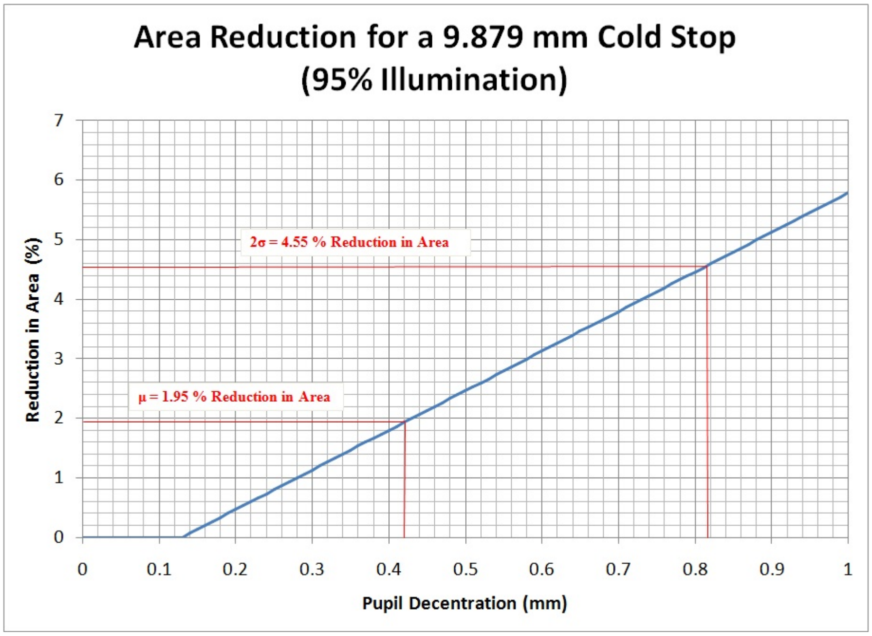


The result can be approximated fairly accurately by simply shifting the line in the above plots to reflect the fact that no effect will take place until the pupil from the secondary decenters enough to reach the side of the undersized cold stop. Plots with a 2% reduced area and a 5% reduced area are given below.



As can been seen in the chart above - by reducing the cold stop diameter to 10.034 mm (i.e. reducing the cold stop area by 2%), the variations in illumination reduce to:

- A pupil decentration of 0.420 mm corresponds to an illumination reduction of 2.45 % (expected value).
- A pupil decentration of 0.815 mm corresponds to an illumination reduction of 5.1 % (95^{th} percentile case).



As can been seen in the chart above - by reducing the cold stop diameter to 9.879 mm (i.e. reducing the cold stop area by 5%), the variations in illumination reduce to:

- A pupil decentration of 0.420 mm corresponds to an illumination reduction of 1.95 % (expected value).
- A pupil decentration of 0.815 mm corresponds to an illumination reduction of 4.55 % (95th percentile case).