

# ALIGNMENT OF THE SPARTAN IR CAMERA FOR THE SOAR TELESCOPE

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The goal is to align the IR camera in the fewest steps using a 3×3 grid of image points. This procedure aligns the f/11 channel of the camera when it is attached to the SOAR Beam Replicator. All calculations assume a test wavelength of 630 nm.

Every camera element has up to five error parameters that affect the Strehl ratio of the images. The alignment errors produce image changes that, while not unique, are different enough to distinguish between a tilted fold mirror and a decentered collimator, for example. ZEMAX calculated the encircled energy within a 12- $\mu$ m radius about the center of the field points. The intensity of each field point is measured at the current best focus for the camera, which is not necessarily the best focus at alignment. This measurement ensures that the image error is not caused by a focus change, but by light entering and exiting the diffraction peak. The result is an alignment procedure that relies solely on the relative brightness of the images produced by the camera.

The following table gives a quick summary of the changes brought about by each error, assuming each error is twice the alignment tolerance. These changes are then grouped by the image changes

Table 1 Types of camera errors and their effects. The x-direction is the axis about which the collimator and camera mirrors are symmetric. The y-direction is perpendicular to the light path (z-direction) and the x-direction.  $I_n$  is the intensity of field n relative to that with perfect alignment (the alignment fields are numbered in Figure 12). “8 to 1 Disparity” means one field has an error opposite the other eight.

	L-R	$I_2$ & $I_3$	$I_5$ & $I_8$	$I_4$ & $I_6$ Parallel	8 to 1
Error	Non-Agreement	Unequal	Unequal	Adjustment	Disparity
Col. X Dec.	YES	YES	NO	NO	NO
Col. Y Tilt	YES	YES	NO	NO	NO
Fold 2 Y Tilt	YES	YES	NO	NO	NO
Col. Y Dec.	NO	YES	YES	YES	NO
Col. X Tilt	NO	YES	YES	YES	NO
Fold 1 X Tilt	NO	YES	YES	YES	NO
Col. Dist.	NO	YES	YES	YES	YES
Cam. Dist.	NO	NO	YES	NO	YES

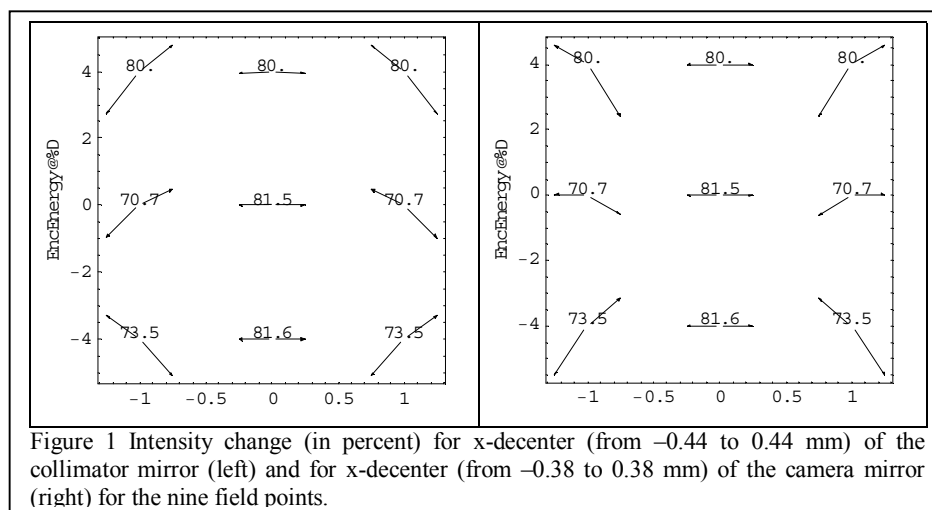
they produced and described in detail. Finally, there is a description of a test of this alignment procedure using a Monte Carlo simulation of a camera.

## 1 Types of Misalignment

### 1.1 Decenter of the x-direction of the collimator and camera mirror

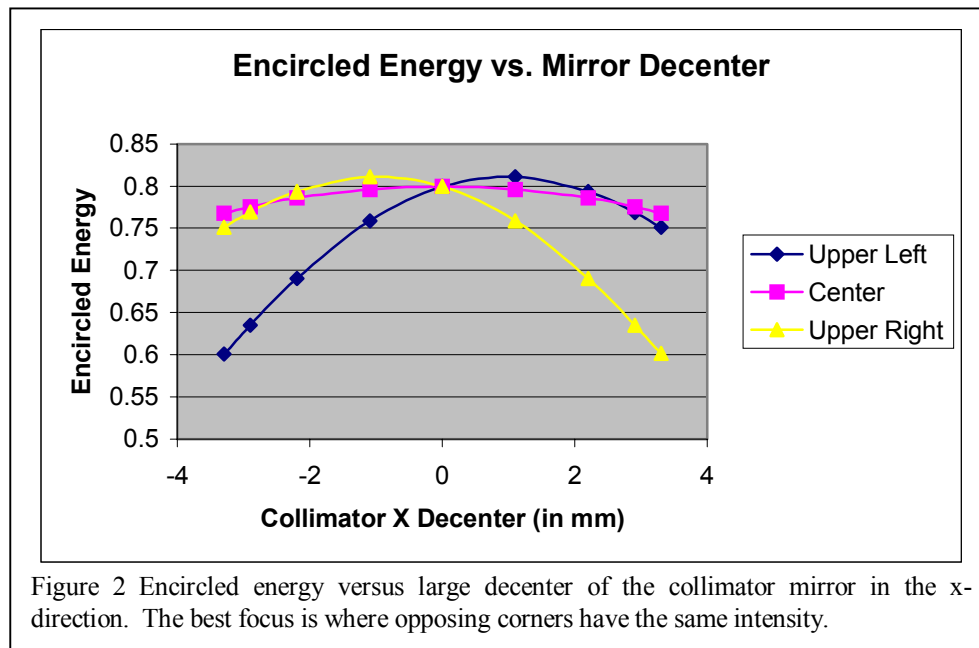
A collimator decenter error in the x-direction mostly affects the images on the sides. It is the first error described in this alignment procedure because of its ease of detection. Without decentering, the top corners are equally bright. The bottom corners are also equally bright, but slightly dimmer than the top corners. If the mirror is decentered in the x-direction, one corner becomes brighter, while the neighboring corner becomes fainter (see Figure 1 left). A corner becomes brighter because the optimal position of the mirror for all field points is not the same as the optimal position for each individual point. Figure 2 shows that the encircled energy in a corner reaches maximum if the collimator is slightly decentered. The optimal focus for all test points is where the encircled energy in each corner is equal. There is a negligible change in the three center points. Therefore, to ensure that the position of the collimator mirror is aligned in the x-direction, the Strehl ratios in the top or bottom corners must be equally intense (see Figure 2). In practice, there are many misalignments such that equalizing the left and right sides is not possible in one step. In that case, the intensity difference between right and left sides should be minimized to align this element.

If the camera mirror is decentered in the x-direction, the intensity change is virtually



indistinguishable from a similar decenter in the collimator mirror, aside from reversed signs (see Figure 1 right). Therefore, the image changes may be caused by the collimator or camera mirror

decentered in the x-direction. The x-position of both mirrors should be checked if this error appears in the image.



## 1.2 Tilt about the y-axis of the collimator, first fold, and camera mirror

A collimator tilt about the y-axis mostly affects the images on the sides. Without a y-tilt, the fields on the left are as bright as the fields on the right. If the mirror is tilted about the y-axis, two points on one side become brighter and one becomes fainter, while the two points on the other side become fainter and one becomes brighter (see Figure 3 left). There is a negligible change in the three center points from top to bottom. This error may be distinguished from a x-decenter by examining all nine field points. If the top and center points on a side get brighter while the bottom point gets dimmer, then the error is a x-decenter. If there is a marginal difference between top side points and a large difference between center side and bottom side points, then the error is a y-tilt. Alignment is reached when the intensity difference between images on the left side and images on the right is minimized.

If the first fold or camera mirror is tilted about the y-axis, the intensity change is not easily distinguishable from that caused by the collimator mirror tilted about the y-axis (see Figure 3 center and right). There are two major differences between the three possibilities. A collimator tilt causes larger changes in the center side fields than a fold1 or camera mirror tilt. A fold1 tilt causes changes in the center side fields that are larger than a camera mirror tilt, but smaller than a

collimator tilt. Therefore, the collimator, first fold, or the camera mirror may cause these changes in the image. The tilt of these mirrors about the y-axis should be checked if this error appears in the image.

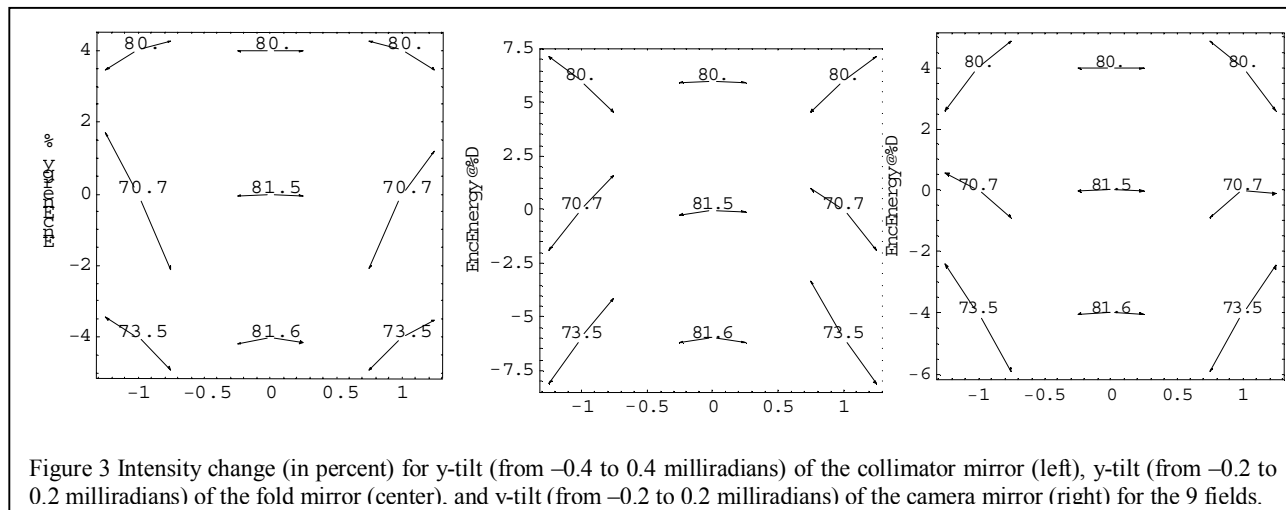


Figure 3 Intensity change (in percent) for y-tilt (from  $-0.4$  to  $0.4$  milliradians) of the collimator mirror (left), y-tilt (from  $-0.2$  to  $0.2$  milliradians) of the fold mirror (center), and v-tilt (from  $-0.2$  to  $0.2$  milliradians) of the camera mirror (right) for the 9 fields.

### 1.3 Tilt about the y-axis of the second fold mirror and the lens

A fold2 tilt about the y-axis mostly affects the images on the sides. Without a y-tilt, the fields on the left are as bright as the fields on the right. If the mirror is tilted about the y-axis, the bottom of one side becomes brighter, while the bottom of the other side becomes fainter. The top side and the middle side images become fainter with a y-tilt (see Figure 4 left). There is a negligible change in the three center points from top to bottom. Alignment is reached when the intensity difference between the bottom left and bottom right field is minimized.

This intensity change may also occur if the lens is tilted about the y-axis, or if the lens is decentered in the x-direction (see Figure 4 center and right). Therefore, the second fold mirror or lens may cause these changes in the image. The y-tilt of the second fold and the lens, and the x-position of the lens should be checked if this error appears in the image.

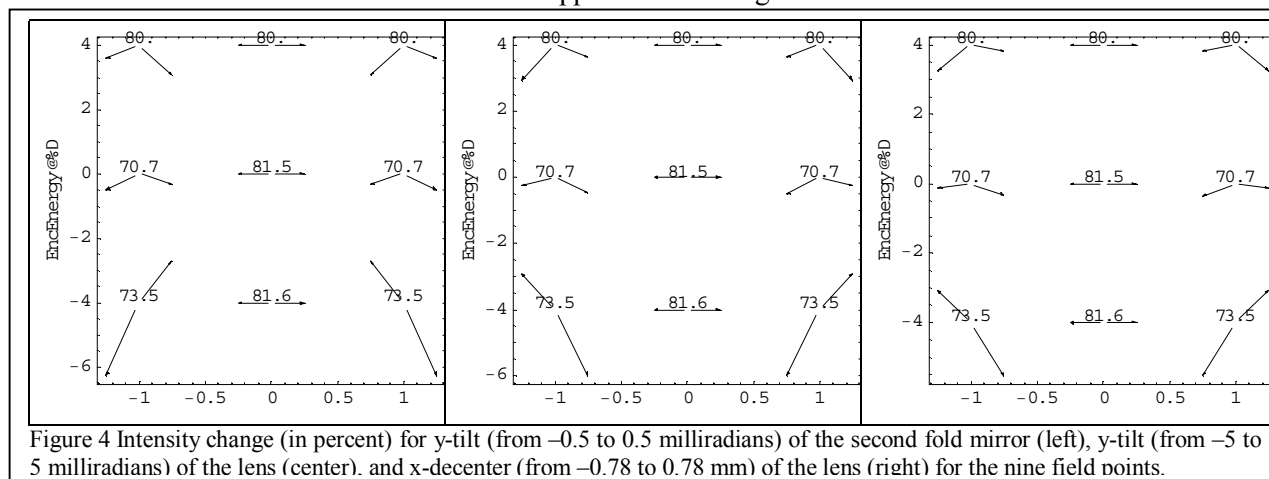
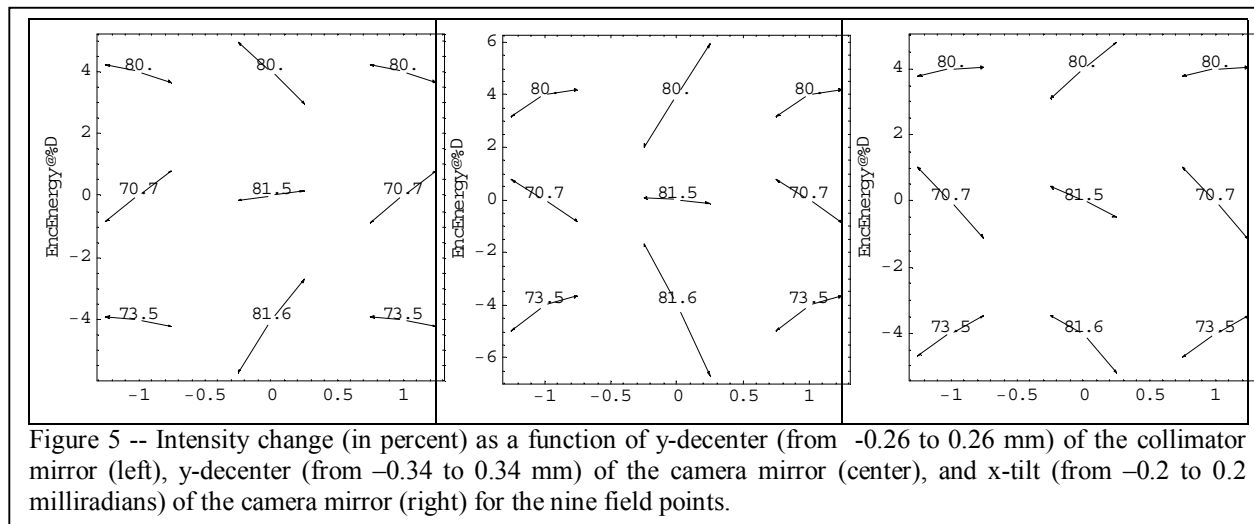


Figure 4 Intensity change (in percent) for y-tilt (from  $-0.5$  to  $0.5$  milliradians) of the second fold mirror (left), y-tilt (from  $-5$  to  $5$  milliradians) of the lens (center), and x-decenter (from  $-0.78$  to  $0.78$  mm) of the lens (right) for the nine field points.

#### 1.4 Decenter of the y-direction of the collimator and camera mirror

A collimator decenter error in the y-direction affects all fields but the center. If the top row gets brighter, then the left center and right center will get dimmer, the bottom corners will get slightly brighter, and the bottom center will get dimmer. These changes are reversed for a positive decenter. The easiest way to check y-alignment is to look at all fields but the bottom left and bottom right (see Figure 5 left). The top center of the focal plane will appear brighter than the top left and top right. There is a negligible change in the center of the focal plane, but the left center and right center fields will appear dimmer relative to the center. The bottom center will appear dimmer than the center. Alignment is reached when the intensity difference between top center and top left/right is minimized, and when the difference between center and bottom center is minimized.

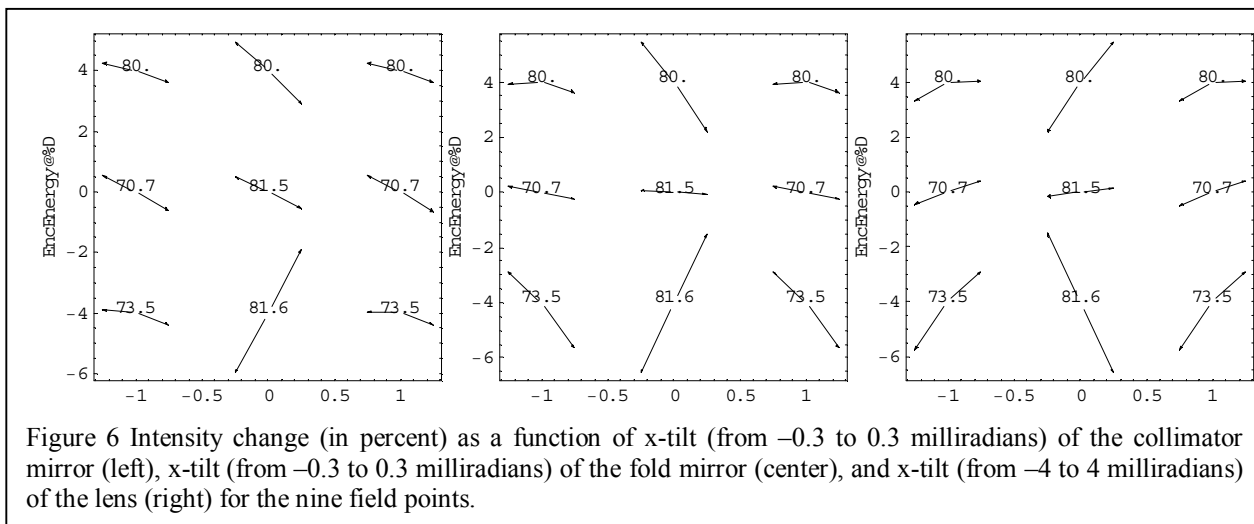


If the camera mirror is decentered in the y-direction or tilted about the x-axis, the intensity change is virtually indistinguishable from the collimator mirror decentered in the y-direction (see Figure 5

right and center). Therefore, either the collimator mirror or the camera mirror may cause these changes in the image. The y-positions of both mirrors and the x-tilt of the camera mirror should be checked if this error appears in the image.

### 1.5 Tilt about the x-axis of the collimator, second fold mirror, and lens

A collimator tilt about the x-axis affects top and bottom fields more than the center. If the top row gets brighter, then the bottom row gets dimmer, while the center row is relatively unaffected. These changes are reversed for a tilt in the opposite direction. The best way to check x-tilt alignment is to look at all fields but the bottom left and bottom right (see Figure 6 left). Although the fields used to check x-tilt alignment are the same as those used to check y-decenter alignment, an examination of all nine fields will differentiate between the two cases. If the top row gets brighter and the left and right center fields get dimmer, then the error is a y-decenter. If the top row gets brighter and the left and right center fields get brighter, then the error is a x-tilt. To ensure that the collimator mirror is aligned about the x-axis, the intensity difference between the top center and top left/right fields must be minimized.



This intensity change may also occur if the second fold mirror or the lens is tilted about the x-axis, or if the lens is decentered in the y-direction (see Figures 6 and 7). Therefore, the collimator mirror, camera mirror, or lens may cause these changes in the image. The x-tilts of both mirrors and the lens, and the y-position of the lens should be checked if this error appears in the image.

## 1.6 Tilt about the x-axis of the first fold mirror

A fold tilt about the x-axis mostly affects the center row of the image. This tilt causes the center row to become much brighter than normal, so that the brightness of the left center and right center fields can approach the brightness of the bottom left and bottom right fields (see Figure 8). The center field is also brighter than the bottom center field. The easiest way to ensure alignment is to concentrate on the center and bottom center fields. The first fold is aligned about the x-axis when the intensity difference between these two fields is minimized.

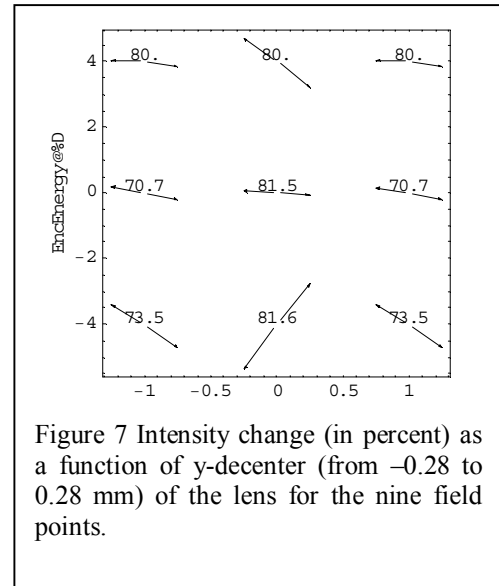


Figure 7 Intensity change (in percent) as a function of y-decenter (from  $-0.28$  to  $0.28$  mm) of the lens for the nine field points.

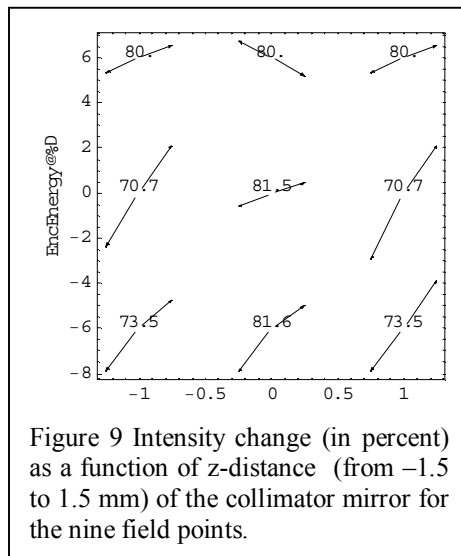


Figure 9 Intensity change (in percent) as a function of z-distance (from  $-1.5$  to  $1.5$  mm) of the collimator mirror for the nine field points.

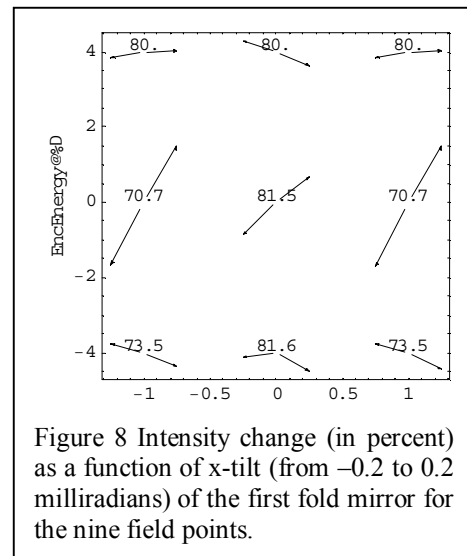


Figure 8 Intensity change (in percent) as a function of x-tilt (from  $-0.2$  to  $0.2$  milliradians) of the first fold mirror for the nine field points.

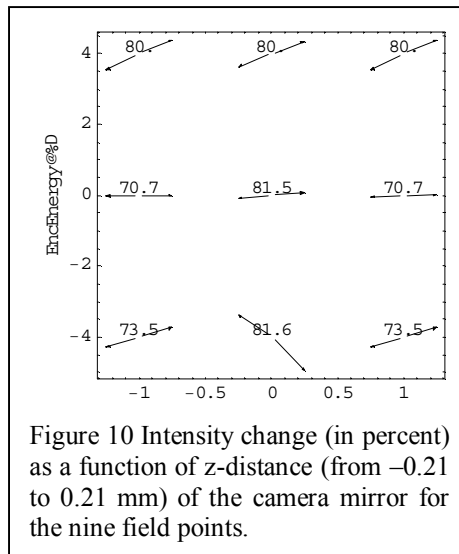
## 1.7 Collimator distance, or z-position

A collimator decenter error in the z-direction affects all fields of the image. All fields save the top center undergo the same change. The top center undergoes a change opposite the rest of the fields. In other words, the top center becomes fainter if every other field gets brighter (see Figure 9). This error can be determined by the intensity of the top left, top center, and top right fields. If the top center field is much brighter or fainter than both the top left and top right fields, then the error is due to a z-decenter of the collimator. Alignment is reached when the intensity difference between top

center and top right or left is minimized, and when the difference between center and bottom center is minimized.

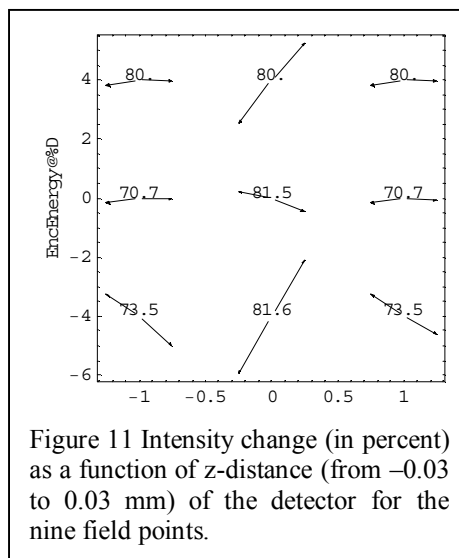
### 1.8 Camera distance, or z-position

A camera decenter error in the z-direction affects the top and bottom fields of the image. All changing fields save the bottom center undergo the same change. The bottom center undergoes a change opposite the rest of the fields. In other words, the bottom center becomes fainter if the top row and the bottom sides become brighter (see Figure 10). This error can be determined by the intensity of the center and bottom center fields. If the bottom center field is much brighter or fainter than the center field, then the error is due to a z-decenter of the camera mirror. Alignment is reached when the difference between center and bottom center field is minimized.



### 1.9 Detector distance, or z-position

A displacement in detector position mostly affects the top center and the bottom row of the image. If the detector is too close to the lens, the top and bottom center fields become fainter, while the bottom left and bottom right fields become brighter (see Figure 11). The detector is in the correct position when the top three fields have the same intensity, and the center and bottom center fields have the same intensity. Alignment is reached when the difference between top center and top left/right is minimized, and when the difference between center and bottom center is minimized.



## 2 Alignment Test

This section describes a simulated alignment. ZEMAX created twenty Monte Carlo camera models with random error parameters. These parameters have a gaussian distribution with a standard deviation of twice the alignment tolerance. The tolerance is defined so that if all parameters have an error equal to the tolerance value, the Strehl ratio of the field point with the highest encircled energy will degrade by no more than five percent. The model camera with the greatest wavefront error was selected from this group of twenty. This procedure was then used to align that model camera. The alignment worked quite well: the intensity for every field was no farther than 0.2% from the expected value (see Figure 12).

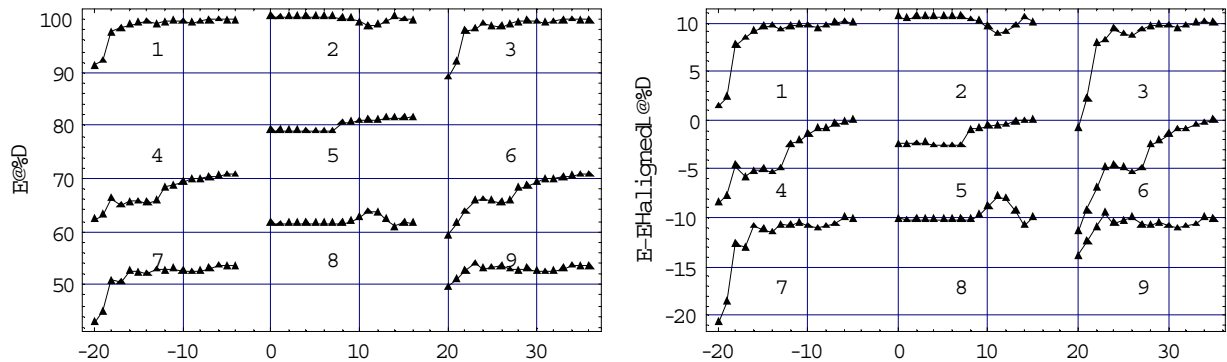


Figure 12 Encircled energy vs. alignment step (left) for the nine field points. The data are offset in the vertical direction by 20%, 0%, and -20% from top to bottom.  $I_n$ , encircled energy relative to that for perfect alignment vs. alignment step (right) for the nine field points. The data are offset in the vertical direction by 10%, 0%, and -10%.

Initially there were two glaring problems. First  $I_1 < I_2$  and  $I_2 < I_3$ , where  $I_n$  is the intensity of field  $n$  relative to that with perfect alignment. (The alignment fields are numbered in Figure 12.) Second,  $I_7 < I_9$ .

We chose to correct the second problem first because few misalignments can cause it whereas many errors can cause the first problem. The first correction made was to the x-position of the collimator mirror, although any of the parameters that correct for left/right differences could have been chosen. This position was corrected by making small changes in the x-position of the mirror, then measuring the encircled energy of the nine field points. When the differences between the intensities left and right of the image were minimized, the error was corrected. This correction made little improvement. The RMS of  $I_n$  improved by 1.4% (last column of Table 2). The next correction, the tilt of the lens about the y-axis, was very significant. It was misaligned by more than twice the tolerance. Next, several parameters (Table 2) were corrected to fix the left-right differences, but the improvements proved to be minor.

After the first set of corrections, the most serious errors were that  $I_5 < I_8$  and  $I_5 - I_4$  was much larger than expected. The next major correction was the x-tilt of the first fold mirror, which was out of alignment by twice the tolerance. This correction was chosen not only to equalize  $I_5$  and  $I_8$ , but also to fix  $I_4$  and  $I_6$ . That change accounts for the large intensity increase between steps seven and eight. The next correction was adjusting the distance between the collimator mirror and the following elements. This adjustment was chosen because  $I_2$  was high, and a change in collimator distance will correct that error. The remaining steps were minor corrections that equalized  $I_1$ ,  $I_2$ , and  $I_3$  as well as  $I_5$  and  $I_8$ . They were chosen based on the error they best corrected. The following table gives more details.

Table 2 Log for the simulated alignment.

Step	Change Made	Reason for Change	$I_1-I_3$	$I_4-I_6$	$I_7-I_9$	$I_2-I_3$	$I_5-I_8$	RMS $I_n$
Start	None		2.2	2.9	-6.9	11.5	-2.5	7.7
1	X Position of Collimator	Correct L/R differences	0.2	1.5	-6.1	8.3	-2.2	6.3
2	Y Tilt of Lens	Correct L/R differences	-0.3	2.4	-1.8	2.7	-2.3	3.2
3	Y Tilt of Collimator	Correct center L/R	0.2	-1.0	-2.6	2.4	-2.2	3.0
4	X Position of Lens	Correct bottom L/R	-0.2	-0.5	-0.3	1.3	-2.5	2.6
5	X Position of Camera	Correct center L/R	0.7	-0.2	-0.9	1.7	-2.5	2.6
6	Y Tilt of Camera	Correct center L/R	0.0	0.0	0.0	1.4	-2.5	2.5
7	X Tilt of Fold 1	Correct 5 8	0.0	0.0	0.0	0.7	-0.9	1.3
8	Z Position of Collimator	Correct 8 to 1 disparity	0.0	0.0	0.0	0.4	-1.1	1.1
9	X Tilt of Camera	Correct 2 3	0.0	0.0	0.0	-0.1	-1.7	1.0
10	Y Position of Collimator	Correct 5 8	0.0	0.0	0.0	-0.6	-2.7	1.1
11	Z Position of Camera	Correct 8 to 1 disparity	0.0	0.1	0.0	-0.6	-2.5	1.0
12	X Tilt of Collimator	Correct 5 8 & 2 3	0.0	0.1	0.0	-0.3	-0.9	0.5
13	X Tilt of Lens	Correct 5 8 & 2 3	0.0	0.1	0.0	0.4	0.7	0.3
14	Y Position of Camera	Correct 5 8 & 2 3	0.0	0.0	0.0	0.1	-0.1	0.0