Alignment of the Optics
Spartan IR Camera for the SOAR Telescope

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17 July 2003	
13 October 2005	Realigned after focus test
4 April 2006	Installed 4 eye
7 January 2008	Realigned after cleaning
23 May 2008	Realigned after focusing

Abstract

The requirements for alignment of the optics, the procedure for alignment, and inspection reports are described here.

1 Preliminaries

Figure 1 defines directions on the cryo-optical box, which holds the optics, and Figure 2 is a schematic of the optics.

The global coordinate system is used in the mechanical design. In the global coordinate system, the origin is where the optical axis intersects the front surface of the window. The x-coordinate increases toward the right wall in Figure 1. The y-coordinate increases toward the back wall; the z-axis, toward the top plate.

Alignment of the optics is done with mechanical metrology: the optics are placed and bolted accurately. There are two reasons for choosing this method. Optical alignment of an off-axis aspheric mirror requires adjusting 5 parameters, which are three translations of the vertex and two rotations of the axis. A sphere requires the position of the surface in one dimension and two rotations of the axis. We found that minimizing the image size does not determine which parameter to adjust. The second reason is that the optics are bolted down. Adjusting mechanisms, which risk loosening and long times for thermal equilibrium, are avoided.

Axsys Technologies fabricated the aluminum mirrors with precisely located pads and pin holes. Since the pads and holes were used to locate the optic during interferometric testing (and machining and polishing), the offset between them and the mirror surface is known precisely. Alignment means to position the pads and pin holes of each optic in the COB.

An optic mounts on an assembly, and the assembly mounts in the cryo-optical box (COB). Pins and pads locate the assembly in the COB. Two shims mount between the assembly and the top and bottom plates of the COB. See Figure 3 for the shim for the fold mirrors and the filter wheels. One shim attaches to the top of the optic and is pinned to the top plate of the COB. Another shim serves the same function for the bottom.

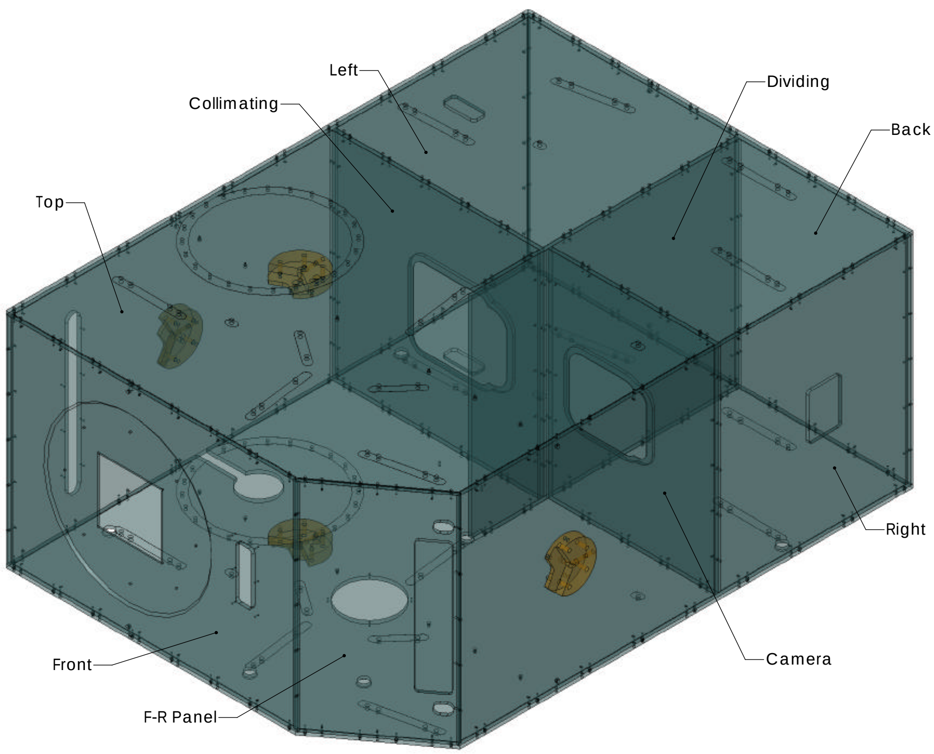


Figure 1: The cryo-optical box. Each optic attaches to both the top and bottom plates. The walls keep the top and bottom rigid.

Alignment involves three steps. The first step is to measure the holes and pads on the COB. The second step is to grind the bosses on the shims to adjust the z-position. The third step is to position the shims on each assembly to adjust the x and y positions.

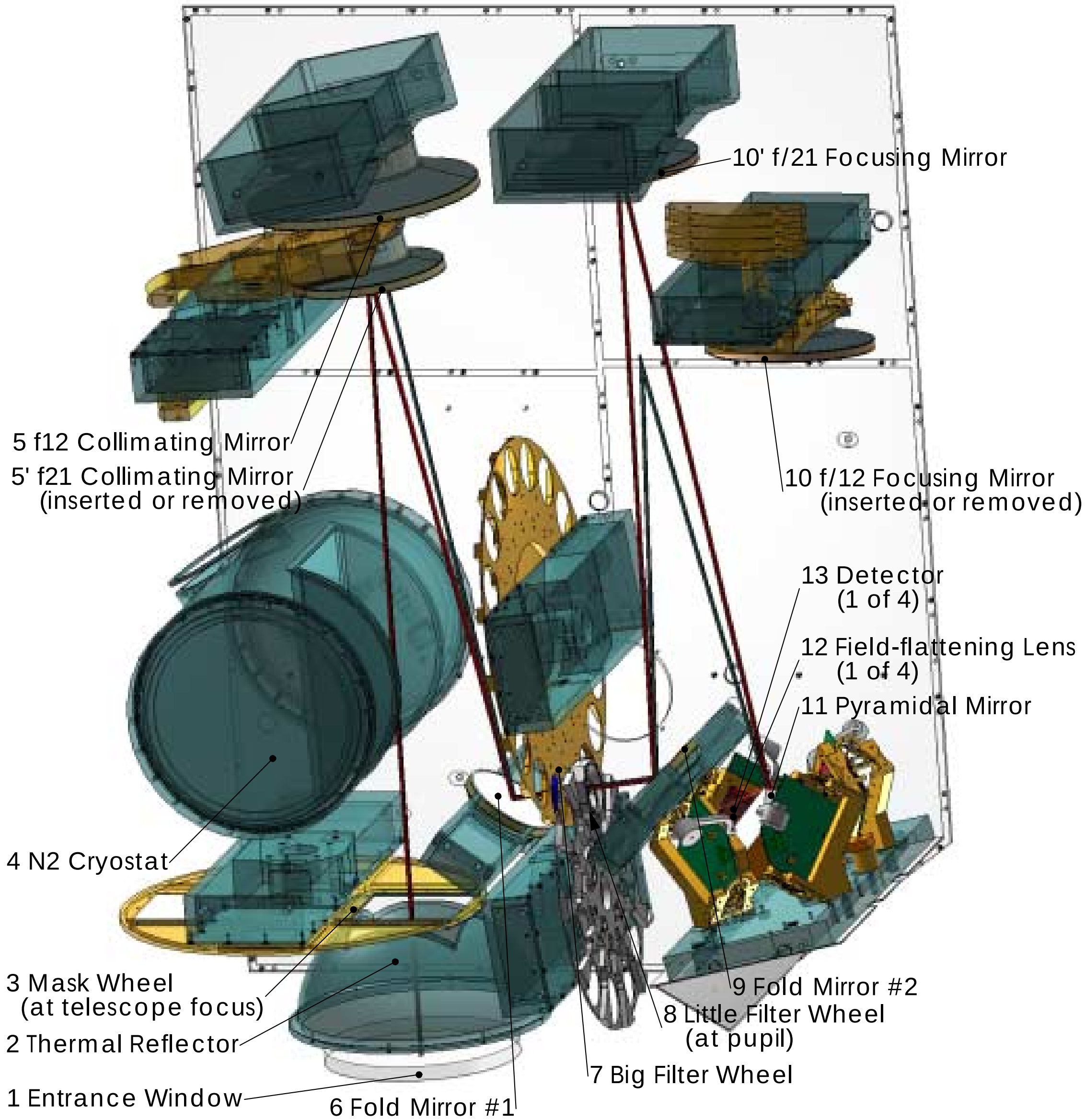


Figure 2: Optical schematic. These parts require alignment: the mask assembly (3), the two collimators (5 and 5'), the filter-fold assembly (6–9), the two camera mirrors (10 and 10'), and the detector assembly (11-13).

A faux COB with pins that mimic the pins in the real COB (Figure 3) holds the shim. A fine-pitched “nudger” shifts the assembly with respect to the shims, and then the shim is fastened with bolts.

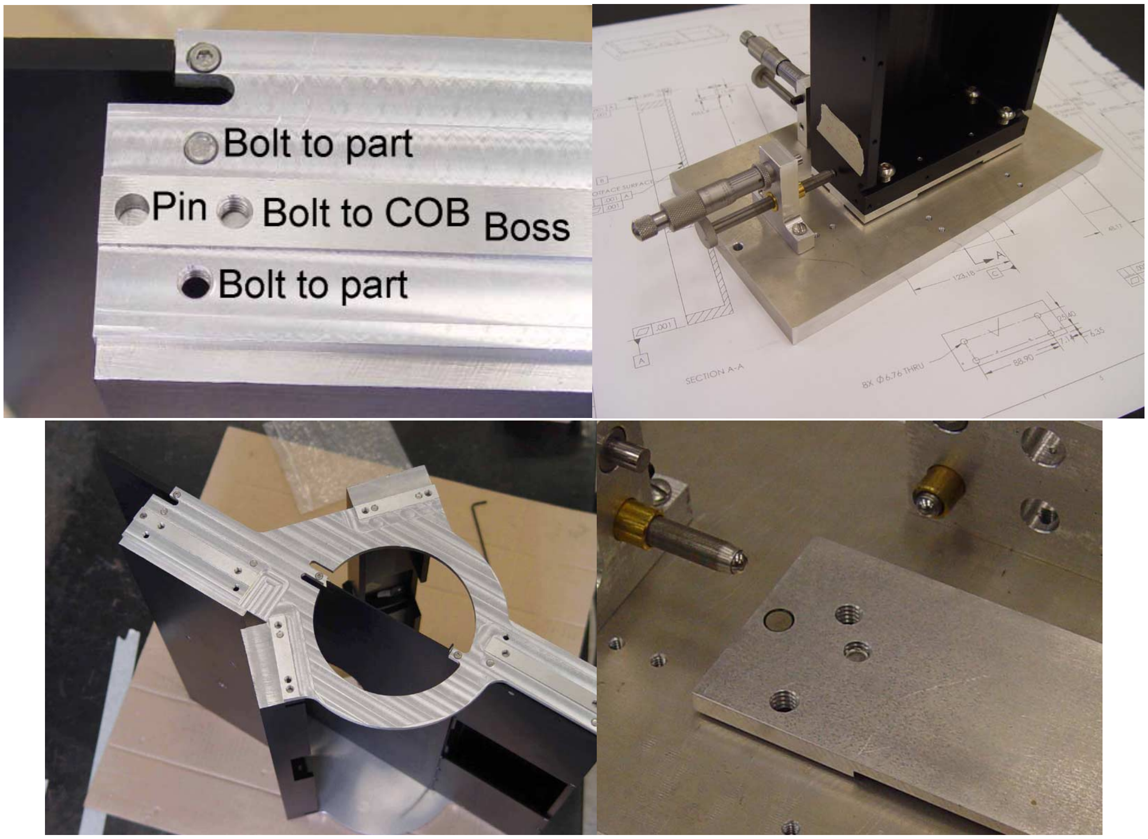


Figure 3: Bottom left panel: the bottom shim for the fold-filter assembly. (The shim is shiny.) Top left: detail showing the region of shim near the large filter wheel. Right panels: faux COB for positioning the assembly.

1.1 Metrology of the mirrors

Our method of alignment by metrology requires that the relation between the surface of the mirror and mounting pads be known accurately.

We estimate that the tilt between the surface of the mirror and mounting pads is sufficiently accurate. The pads are pinned to a master plate during turning on the lathe and during polishing and testing with an interferometer. During polishing, a tilt of “a few waves" is ignored. A tilt of 3 waves over the diameter of the smallest mirror (100 mm) is 0.019 mrad. This is a factor of 5 smaller than the tightest tolerance of tilt in Table 2.

We estimate that the location of the pads in the direction perpendicular to the axis of the mirror is sufficiently accurate. The position is fixed by pins. Assembly requires "pushing on the mirror in the direction away from the axis.[1]" We interpret that to mean there is some looseness, and we assume that assembly is reproducible to 0.006 mm, which is half of the fit of the pins.

We estimate that the accuracy of the focal position is 0.01 mm. The mirror is tested with a computer-generated hologram (CGH), which is mounted on a steel rail. The temperature of the room can change by 1 C, which moves the CGH and mirror radius by 1.4×10^{-5}, the relative expansion between aluminum and steel. The change in radius is 0.016–0.024 mm for the four mirrors.

Table 1: Parameters from ref. 5 of the powered mirrors measured with a CMM. Positive x means the vertex is shifted toward the mirror center. Positive z means there is too much material. (x, y, z) is a right handed system. Positive dr means the radius of curvature is too large.

Mirror	dx	dy	dz	dr
f/12 Coll	0.072 ± 0.004	0.037 ± 0.001	0.012 ± 0.0002	-0.18 ± 0.04
f/12 Cam	0.099 ± 0.005	0.004 ± 0.001	-0.069 ± 0.0002	0.04 ± 0.05
f/21 Coll	0.063 ± 0.008	-0.053 ± 0.001	0.023 ± 0.0004	0.04 ± 0.07
f/21 Cam	-0.115 ± 0.009	0.147 ± 0.002	-0.074 ± 0.0003	-0.06 ± 0.12

Measurements[2] of the mirrors with a CMM at Coordinate Measurement Specialists in Wixom, MI show that the errors do not affect the image quality although they are larger than our estimate. We did not account for these errors in the alignment, since the largest errors, the offset between the vertex and the mirror pads, will be subsumed in a final adjustment of focus.

[1] Mark Warren, 5 Nov. 2003, Axsys Technologies, private communication.
[2] Baker, D., Hanold, B., & Loh, E., 2005, Test of Focus, Spartan IR Camera

2 Measurements of the cryo-optical box

The measurements of the COB[3] are summarized here.

A coordinate measuring machine (CMM) (DEA Diamond 01.02) was used for all measurements. Its greatest error over the 1020×660×460-mm volume is 0.006 mm. Over short distances, the error is smaller.

2.1 Pin locations

Pin holes locate the optics, and the table in Figure 4 lists their positions with respect to reference holes A and B. The nominal locations of the pin holes are given in the global coordinate system.

2.2 Deviation of the bottom plate from a plane

Since the top and bottom plates of the COB are thin (6 mm) and flexible, the walls fix the form of the plates. Three points, “frontL” and “frontR” in the front wall and “insideFar” in dividing wall, define the reference plane. All of the optics are centered on this plane.

The deviation of the bottom plate from the reference plane is shown in Figure 6. The standard deviation is 0.063 mm. To first order, the back of the COB is twisted, and the standard deviation is 0.037 mm with the twist removed.

2.3 Shift between the top and bottom plates

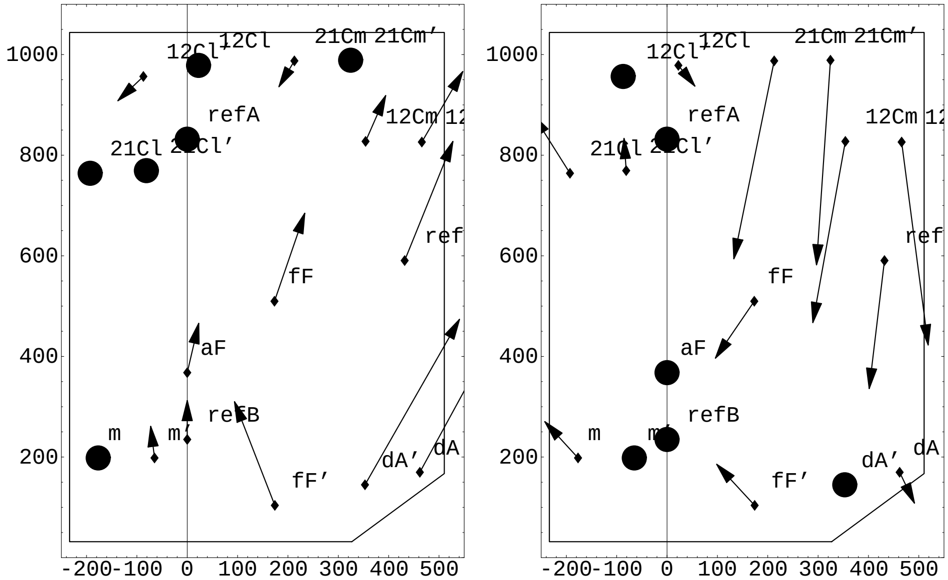
To determine the shift, the hole on the bottom plate is projected perpendicular to the reference plane of §2.2 to the top plate, which is 40 mm distant.

The location of reference hole A in the top is $(0.038, 0.079)$ mm from the hole in the bottom (Figure 4).

2.4 Height of the walls

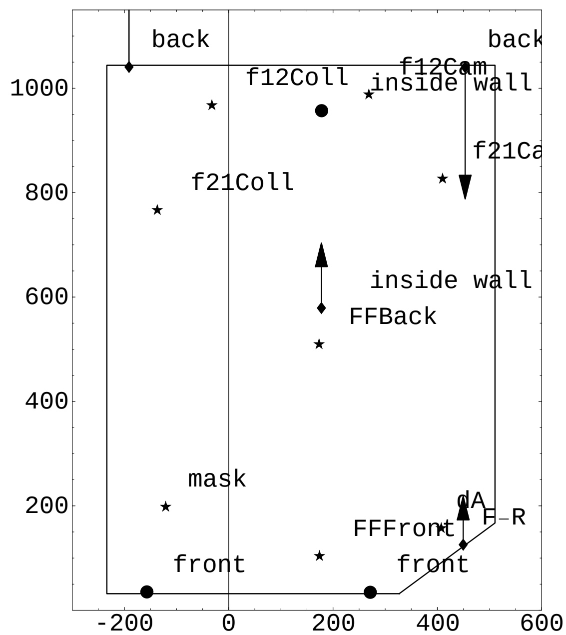
The walls define the separation between the top and bottom plates. Measurements are in Figure 7. The walls are generally 0.010 mm lower in the middle. The walls were fabricated to be 419.10 mm in height, but the actual mean is 419.141 mm. We adopt 419.141 mm to be the target separation between the top and bottom plates.

[3] Samet, Biel, & Loh, 2003,Metrology of the Cryo-optical Box



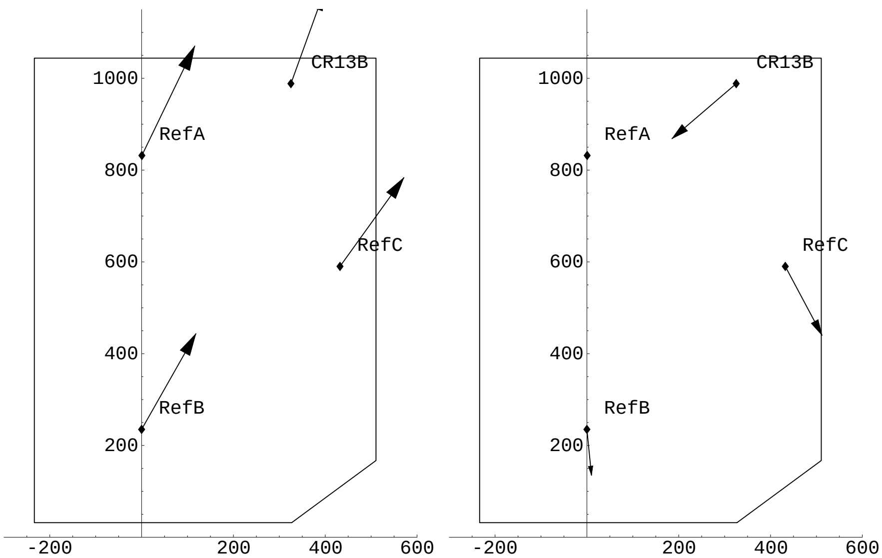
Pin		Nominal Location		Error Bot		Error Top	
		x	**y**	**x**	**y**	**x**	**y**
Detector Assy - Right	dA-R	461.954	169.731	-0.023	0.041	-0.003	-0.006
Detector Assy - Left	dA-L	352.998	144.853	-0.019	0.033	0.003	-0.003
Fold-Filter - Back	fF-B	173.236	509.686	-0.006	0.017	0.008	-0.011
Fold-Filter - Front	fF-F	174.002	103.915	0.008	0.021	0.008	0.008
Mask - Left	m-L	-176.768	198.222	0.002	0.003	0.007	0.007
Mask - Right	m-R	-65.008	198.222	0.001	0.006	0.001	0.003
f/12 Collimator - Right	12Cl-R	22.485	978.487	0.002	0.002	-0.003	-0.004
f/12 Collimator - Left	12Cl-L	-87.090	956.492	0.005	-0.005	0.001	0.000
f/12 Camera - Left	12Cm-L	354.156	827.397	-0.004	0.009	0.006	-0.036
f/12 Camera - Right	12Cm-R	465.909	826.129	-0.008	0.014	-0.005	-0.040
f/21 Collimator - Left	21Cl-L	-192.759	764.050	0.002	-0.002	0.007	0.012
f/21 Collimator - Right	21Cl-R	-81.123	769.314	0.001	0.004	0.000	0.006
f/21 Camera - Left	21Cm-L	212.779	987.489	0.003	-0.005	0.008	-0.039
f/21 Camera - Right	21Cm-R	324.539	988.757	0.003	-0.001	0.003	-0.041
aFrame	aF	0.000	367.774	-0.002	0.010	-0.003	-0.001
refC		431.800	590.550	-0.010	0.024	0.003	-0.025
refB		0.000	234.950	0	0.008	0	-0.001
refA		0.000	831.850	0	0	0	0
Top with respect to bottom						0.038	0.079
Standard deviation excluding refA-refC				0.009	0.014	0.005	0.019

Figure 4: Errors (magnified by 10,000) of the pin holes in the bottom (left panel) and top (right panel) plates. Points with errors less than 0.005 mm are shown as dots. The points are shifted so that refA has zero error and rotated so that refB has minimal error.



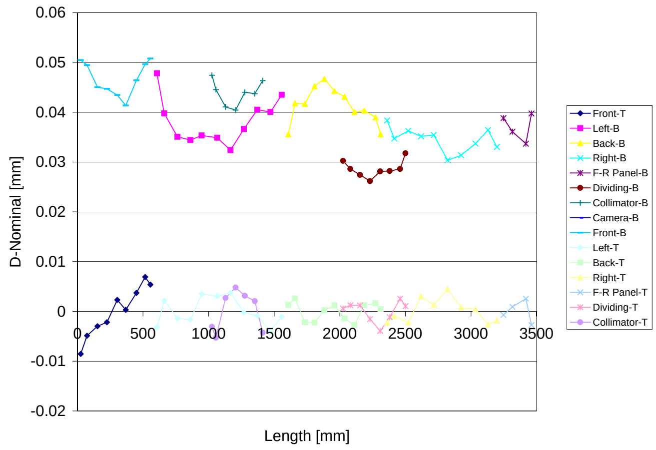
Location	x [mm]	y [mm]	zBot [mm]
backL	-191	1041	0.079
backR	453	1040	-0.126
insideFar	178	957	0.000
insideNear	178	579	0.062
front-right	450	126	0.046
frontR	271	34	0.000
frontL	-157	35	0.000

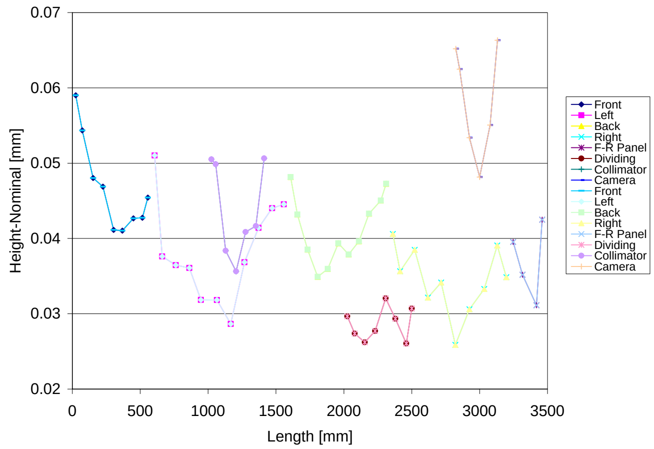
Figure 5: Deviation, magnified by 2000, of the bottom edge of the walls from a plane. An down arrow indicates the wall is low (shifted away from the top). The right edge of the back wall is low (shifted away from the top) by 0.13 mm. The asterisks show the location of the optics, the mask, f/21 collimator, f/12 collimator, the filter-fold mirror assembly (FFFront and FFBack), f/21 camera mirror, f/12 camera mirror, and detector assembly (dA).



Name	top-bot
CR13B	(-0.014, -0.012)
refA	(0.000, 0.000)
refB	(0.001, -0.010)
refC	(0.008, -0.015)

Figure 6: Shift (left), magnified by 3000, of the pins in the top plate with respect to those in the bottom. Shift (right), magnified by 10,000, after offsetting by the shift of refA $(0.038, 0.079)$. Residuals (in Table) are calculated after offsetting.





Wall	Mean	Stdev	P-V	-Nom	-Mean
Front	419.147	0.006	0.018	0.047	0.006
Left	419.138	0.007	0.022	0.038	-0.003
Back	419.141	0.004	0.013	0.041	0.000
Right	419.134	0.004	0.015	0.034	-0.007
F-R panel	419.137	0.005	0.011	0.037	-0.004
Dividing	419.129	0.002	0.006	0.029	-0.012
Camera	419.158	0.007	0.018	0.058	0.017
Collimator	419.144	0.006	0.015	0.044	0.003
Nominal	419.100				
Mean	419.141				

Figure 7: Top and bottom edges (top panel) and height (middle panel) of the walls. Each wall is positioned where it connects to the previous one. Table at bottom contains the heights of the walls.

3 Requirements for positioning the optics

Image quality drives most of the requirements for positional tolerance[4][5]. See Table 2. Alignment errors with approximately 40 degrees of freedom are allowed to degrade the Strehl ratio by 4% at $\lambda 1.6\,\mu$m, which translates to 0.005 wave for each degree of freedom.

The coordinate system is fixed to each optical element. It is defined by the unit vectors $\mathbf{a} \times \mathbf{z}$, $\mathbf{z}$, and $\mathbf{a}$, where $\mathbf{z}$ points from the bottom of the COB to the top and $\mathbf{a}$ is the axis of symmetry of an optic.

Table 2: Requirements for positioning the optical elements. The requirement for focus determines $\mathbf{a}'$.

Element	Positional [mm]				Angular [mrad]		
	z	a×z	a	a'	z	a´z	a
Mask	1.00	1.00	0.30	0.04	2.50	2.50	NA
f/21 collimator	0.22	0.63	0.12	0.04	0.40	0.23	4.80
f/11 collimator	0.14	0.55	1.00	0.04	0.49	0.24	3.70
Collimators, to align Lyot stops					0.10	0.10	
Fold mirror 1	NA	NA	0.50		0.19	0.14	NA
Filter wheels	NA	NA	NA		NA	NA	NA
Lyot stop	0.07	0.07	NA		NA	NA	NA
f/21 camera mirror	0.19	0.52	0.24	0.07	0.40	0.19	3.80
f/11 camera mirror	0.24	0.36	2.60	0.03	0.30	0.23	2.70
Fold mirror 2	NA	NA	0.10		0.37	0.23	NA
Lens	0.23	0.37	0.22		8.90	1.34	NA
Detector	0.20	0.85		0.03	0.64	0.64	NA

Besides image quality, other considerations impose further requirements.

To prevent loss of light of no more than 0.25% in the f/12 and f/21 Lyot stops, the tilt of the collimators must be better than 0.1 mrad, and the Lyot stops must be located better than 0.07 mm.

Focus In order that the Strehl not degrade by more than 1%, the focus must true to 0.12 mm for the f/12 channel and 0.33 mm for the f/21 channel at $\lambda 1500$ nm.[6] For optic i, a shift in the a-direction of $d\mathbf{a}_i$ contributes $d\mathbf{a}_i(f_0/f_i)^2$ to the path length at the 0-th optic, where f_i is the focal length of the i-th optic. Since the fold mirrors are flat, this only affects the mask, collimating mirrors, camera mirrors, and detectors. Thus if the mask is allowed the entire focus error, it may shift 0.18 mm. Each of the 5 optics in the wide-field or high-res configurations is allowed $5^{-1/2}$ of the total.

Focus coincidence for wide-field and high-res channels With the tightened the requirements on $d\mathbf{a}$, the focus for the two channels will be coincident.

[4] Davis, M., & Loh, E., 2001, Optical Design, Spartan IR Camera

[5] Loh, E., 2003, Requirements for the 2-detector Assembly, Spartan IR Camera

[6] This is estimated by considering the central intensity of a diffraction image as a function of position along the optic axis (Born & Wolf, *Principles of Optics*, 4th ed., Pergamon: New York, p. 441.)

Focus across mask To preserve focus across the field, the a-axis must tilt by less than 2.5 mrad.

4 Thickness of the shims

Shims compensate the errors in the COB (Table 3) and the assemblies that hold the optics. After the COB was assembled and measured, the shims were ground to compensate the errors perpendicular to the top and bottom plates. The shim identification and deviation from the nominal thickness, d_{Top} for the top shims and d_{Bot} for the bottom shims, are shown in the Table. To compensate for errors parallel to the top and bottom plates, the optics were positioned on the shims, which is discussed in section 5.

Table 3: Thickness of the shims. Deviation from nominal thickness (6.370 mm) is d_{Bot} for the bottom shims and d_{Top} for the top shims. The location of the optics is checked to be coincident with the reference plane: the location calculated from the bottom, l_{Bot}, should be zero. The location calculated from the top (l_{Top}, not shown) agrees with l_{Bot}. The height of the posts were measured.

Optic (Note)	**dPlane**	**dWall**	**Post**		**Rotation**	**dSpeci**	**Shim**	**Bottom**		**Top**		**lBot**
				dPost	**Stage**			**#**	**dBot**	**#**	**dTop**	
Detector Assy (1)	0.046	-0.004	detAssy	-0.003	02060-099	0.126	DA	11	-0.171	12	0.169	-0.126
Big FW	0.062	-0.012	Cradle3	0.003	02060-097		FF-Back	13	-0.064	14	0.048	0.000
Small FW	0.000	0.007	Cradle1	-0.023	000		FF-Front		0.011		0.018	0.000
Fold1	0.031	-0.003	Fold1	0.029			FF-Left		-0.046		0.014	0.000
Fold2	0.031	-0.003	Fold2	-0.005			FF-Right		-0.028		0.031	0.000
Mask (2)	0.013	0.001	Cradle2	-0.012	02060-098		Mask	1	-0.007	2	0.020	0.000
f/12 Collimator	0.029	-0.008	12Coll	-0.020			f12Coll	7	-0.018	8	0.031	0.000
f/12 Camera	-0.086	-0.001	Cradle4	0.005	02060-099		f12Cam	3	0.083	4	-0.089	0.000
f/21 Collimator	0.058	0.000	Cradle5	-0.020	02060-100		f21Coll	5	-0.047	6	0.068	0.000
f/21 Camera	-0.067	-0.005	21Cam	0.034			f21Cam	9	0.050	10	-0.089	0.000

dPlane	deviation at the optic of the bottom of the COB from a plane
dWall	deviation of the height of wall at optic
dPost	deviation of post for optic
dBot	thickness of bottom shim - 6.370 mm = -dPlane-dPost/2-dSpecial
dTop	thickness of top shim - 6.370 mm = (dPlane+dWall)-dPost/2+dSpecial
lBot	position of optic calculated from bottom of COB = dPlane+dBot+dPost/2. (Normally 0.)
lTop	position of optic calculated from top of COB = dPlane+dWall-dTop-dPost/2. (Normally 0.)
Note 1	Optic is shifted down because rotation stage shifts up.
Note 2	Surfaces that mount to shims are non-coplanar by the largest mount for Cradle2

Twist of the Bottom of the COB The bottom of the COB was machined flat when it was bolted inside-out on the walls, but it acquires non-flatness after reassembly with the outside out. The deviation of the bottom plate from a plane, d_{Plane}, is interpolated from the measurements of the bottom (§2.2) at the walls that fix the bottom.

Height of Walls The walls fix the offset of the top and bottom plates. The deviation d_{Wall} from nominal at the optic is interpolated from the measurements of §2.4.

Height of Posts Several types of holders—cradles with rotation stages for the mask and filter wheels, cradles with rotation stages and arms for the f/21 collimator and f/12 camera mirrors, posts for the f/12 collimator, f/21 camera, and fold mirrors, and an assembly for the detector— support the optics, and these are all called posts here.

The heights of the posts were measured individually, and later with all of them placed vertically on the bed of the coordinate-measuring machine as a sanity check. The earlier measurements define the height as the separation of the two planes that are defined by four points on the top and four points on the bottom. In the sanity check, the height is defined to be the distance between many points on the top and many on the bottom. The ends of the posts are not flat, which was discovered in the sanity check, and this makes the sanity check more reliable than the earlier measurements. The deviation d_{Post} from the nominal of 406.400 mm is taken from the sanity check.

Special cases Most of the posts allow the optic to be moved to center it vertically, but the three for the f/12 collimating mirror, f/21 camera mirror, and the 2-eyed detector assembly do not. For the two mirrors, the required tolerances (0.14 and 0.19 mm, respectively) are looser than machining tolerances experienced on such parts. Therefore the mirrors are assumed to be centered in the posts. The 2-eyed detector assembly, which is mounted on a rotation stage, should be moved by d_{Special} from the center of the post.

For the 4-eyed detector assembly, positioning the legs that hold the detectors compensates for the error on the COB.

The bottom shim (between the bottom of the COB and the bottom of the post) must compensate for the non-flatness of the bottom of the COB and half of the height of the post. Its thickness is

$$t_{\text{Bot}} = 6.350 + 0.020 - d_{\text{Plane}} - d_{\text{Post}}/2 - d_{\text{Special}}.$$

The nominal thickness of the shim is 6.350 [0.25 in]. Because the walls are oversized by 0.041, the shims are thicker by half. The term $d_{Special}$ is the thickness deviation of the rotation stage for the detector assembly; it is 0 for all others. The top shim (between the top of the COB and the top of the post) must compensate for the non-flatness of the top of the COB and half of the height of the post. Its thickness is

$$t_{\mathrm{Top}} = 6.350 + 0.020 + (d_{\mathrm{Plane}} + d_{\mathrm{Wall}}) - d_{\mathrm{Post}}/2 + d_{\mathrm{Special}}.$$

The term in parenthesis is the non-flatness of the top of the COB.

5 Installing the optics

The positional error of the vertex of an optic is $\mathbf{p}_\mathrm{m} - \mathbf{p}_\mathrm{t}$, where $\mathbf{p}_\mathrm{t}$ is the target position and $\mathbf{p}_\mathrm{m}$ is the measured position. The rotational error of an optic is expressed as $\mathbf{a}_\mathrm{t} \times \mathbf{a}_\mathrm{m}$, where $\mathbf{a}_\mathrm{t}$ is the target axis of the optic and $\mathbf{a}_\mathrm{m}$ is the measured axis. The direction of $\mathbf{a}_\mathrm{t} \times \mathbf{a}_\mathrm{m}$ is the axis of the error, and its length is the rotation angle.

The coordinate system that is fixed to each optical element is defined by the unit vectors $\mathbf{a} \times \mathbf{z}$, $\mathbf{z}$, and $\mathbf{a}$, where $\mathbf{z}$ points from the bottom of the COB to the top and $\mathbf{a}$ is the axis of rotation of the optic.

Tightening the bolts must be done in a way that the part does not shift. (1) Tighten all of the bolts finger tight. (2) Tighten a bolt with an Allen wrench by rolling it between the thumb and fingers. Tighten all of the bolts in the same way in sequence. Tighten opposite bolts in pairs. For example, with 4 bolts numbered 1–4 in clockwise order, tighten them in the order 1, 3, 2, and 4. (3) Tighten the bolts to 1/10 of the final torque in the same sequence. (4) Tighten the bolts to 1/3 of the final torque in the same sequence. (5)Tighten the bolts to the final torque in the same sequence.

For fine movements, we use fine-pitch (320 μm/turn, 80 turn/in) nudgers (Figure 11). A rubber band maintains a constant force between the nudgers and the part. After moving the shim and before measuring the pin holes on the shim, the bolts are tightened slightly beyond finger tight, to prevent the shim from moving accidentally after the measurement. With the nudgers and rubber band, moving to a precision of 10 μm is routine.

5.1 Mask wheel

Alignment requirements and errors are in Table 4. Table 6 is the alignment instructions. Table 5 is the inspection report.

Aligning the mask wheel means to position two shims with respect to the mask wheel.

Table 4: Alignment requirements and errors for the mask wheel

parameter	*component*	*tol*	*meas*		*driver*
position	z	1.0	0.045	mm	Shift of image <2% of field
pm-pt	**a×z**	1.0	0.011	mm	Same
	a	0.04	0.005	mm	Focus
tilt	z	6.4	0.18	mrad	Focus across field
at×am	**at×z**	6.4	0.04	mrad	Focus across field
rotation about axis		8.7	0.22	mrad	Shift of image <2% of field

The faux COB and attached nudgers are used to move the shims (steps 4 and 5 of Table 6). See Figure 9 for the faux COB on the wide-field collimator post. Centering the mask wheel on the rotation stage (step 7) is done with the centering tool (left panel of Figure 8). To find the rotational address of the reference optic, we use a height gauge (right panel of Figure 8).

Table 5: Inspection report for the mask wheel

Inspection of Mask Wheel

Coordinate definition 05 Nov 2007

RS
x-y plane = load plane of the rotation stage
Origin = intersection of x-y plane & rotation axis
y-axis is parallel to the right side of the cradle

Cradle
back of cradle, defined by tops of 1-2-3 blocks
intersection of y-axis and bottom of cradle.
intersection of back and right sides of cradle.

Features		**Coord**	**x**	**y**	**z**	**i**	**j**	**k**	**flatness**
			mm	**mm**	**mm**	**×1000 or (×1)**			**mm**
PL1	Right side of cradle	Cradle	-0.002	202.752	39.563	(1)	0.00	0.04	0.031
PL2	Bottom of cradle	Cradle	-61.733	-0.008	38.784	0.11	(-1)	-0.02	0.009
PL3	Load plane of the rotation stage	Cradle	-54.865	203.626	61.505	-0.39	-0.13	(1)	0.015
L1	Rotation axis of the stage	RS	0.000	0.000	0.000	0.00	0.00	(1)	
		Cradle	-55.057	203.199					
P1	Pin1 @shim	RS	49.305	-209.582	-36.912	-0.08	(1)	-0.24	
P2	Pin2 @shim	RS	-62.449	-209.591	-36.929	-0.08	(1)	-0.24	
P3	Pin3 @shim	RS	49.342	207.986	-36.971				
P4	Pin4 @shim	RS	-62.429	207.989	-37.034				
S1	Position of reference optic wrt reverse limit		15564	µstep	(MW is rotated 0.22 mrad.)				
D	Distance edge large opening to shim 1		154.97						

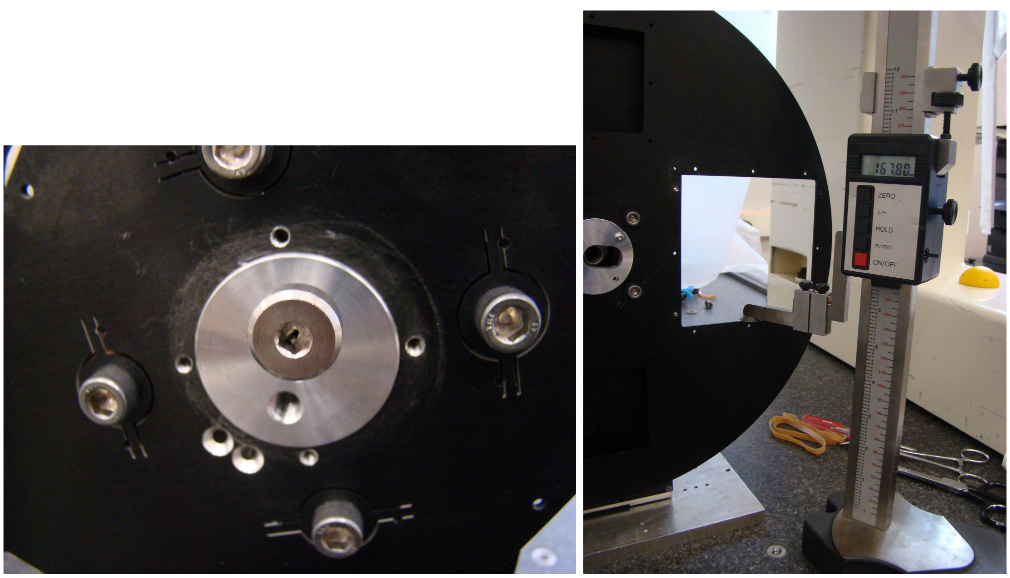


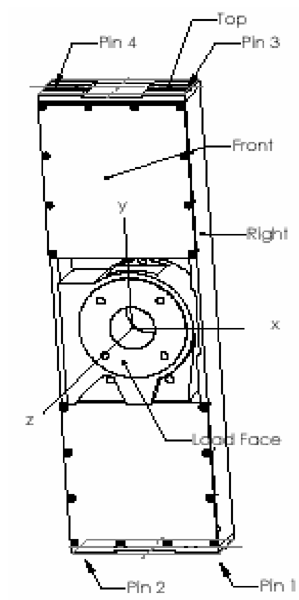
Figure 8: Left: Use of the cen-o-matic to center the mask wheel on the rotation stage. Right: Use of a height gauge to find the reference position of the mask wheel.

Table 6: Alignment instructions for the mask wheel

Mask Wheel		Created 15 Dec 2003	**Inspection**	
Components		Revised 10 Jun 2004	05 Nov 07	
	Mask wheel	Installed 16 Jul 2004		
	Antibacklash spring	Fix RS correction 01 Mar 2005		
02060-098	Rotation stage	Mod for refab'd RS 07 Jul 2005		
Shim 2	Shim for top of COB	Corrections reversed 31 Jul 2005		
Shim 1	Shim for bottom of COB	Reference to surface of MW 25 Aug 2005		
Cradle2	Cradle **(Do not install pin into pinhole 4.)**	New method 19 Aug 2007		

Orientation

Back of cradle is on the table. Bottom is facing out.



Instructions		**err**	**p/f**
1	Place the cradle with the back down on three 2-in blocks and clamp down.		
2	Bolt the rotation stage onto the cradle using pins for alignment. The center of rotation should be		
	55.0±0.1 from PL1 and	0.055	P
	-203.2±0.1 from PL2.	-0.006	P
3	Measure features to define the coordinate system:		
	x-y plane = load plane of the rotation stage		
	Origin = intersection of x-y plane & rotation axis		
	y-axis is parallel to the right side of the cradle		
4	Attach bottom shim and faux COB. Use the faux COB to move bottom shim so that Pin1 is at		
	dx1 = x - 49.294 = 0.000±0.100	0.011	P
	z = -36.908±0.019	-0.004	P
	and Pin 2 with respect to pin 1 is at		
	dz = 0.003±0.064	-0.017	P
5	Use the faux COB to move top shim so that Pin3 is at		
	x = 49.332 + dx1 ±0.030	0.010	P
	z = -36.984±0.019	0.013	P
6	Rotate the RS in the reverse direction so that it is near the reverse limit.		
7	Use the hole-a-centric to make the mask concentric with the rotation stage. Bolt the mask wheel onto the rotation stage.		
8	Attach the front covers		
9	Rotate RS forward so that a large opening is in the light path (at positive x) and its center is at y=0±0.1 This is the reference position.		
9'	or alternatively the distance between the edge of the large opening and the shim is d = 154.9±0.1	0.030	P

Inspection features

PL1	Right side of cradle	P1	Pin1 @shim
PL2	Bottom of cradle	P2	Pin2 @shim
PL3	Load plane of the rotation stage	P3	Pin3 @shim
L1	Rotation axis of the stage	P4	Pin4 @shim
D	Distance edge large opening to shim 1	S1	Position of reference wrt reverse limit

5.2 Post for the wide-field collimator

The requirements and measured errors are in Table 7. Table 9 is the instruction sheet for alignment, and Table 8 is the inspection report. The positioning of the optic meets the requirement (Table 7), even though pin 3 is slightly off (Table 9). (The requirements for the individual parts are written with the assumption that the errors add in quadrature, but the error in location of the optic is calculated from the actual errors.)

Table 7: Alignment errors and requirements for the wide-field collimator post

parameter	*component*	*tol*	*meas*		*driver*
position	z	0.14	0.001	mm	Image quality
pm-pt	**a**×**z**	0.55	0.006	mm	Image quality
	a	0.04	-0.017	mm	Focus
tilt	z	0.49	-0.04	mrad	Image quality
at×**am**	**a**×**z**	0.24	0.07	mrad	Image quality
rotation about optic center		3.7	-0.02	mrad	Image quality

Table 8: Inspection report of the post for the wide-field collimating mirror. The pins and features P1–P4, were measured with and without the clamps used the hold the part. “Rotation” is the average rotation derived from pairs of pins. “Twist” is the difference between the rotations derived from two pairs of pins.

Inspection of Wide-field Collimator Post 5/15/2008

Coordinate definition

x-y plane = plane of the pads A, B, & C
Origin = intersection of x-y plane & axis of Pin B
y-axis is goes through axis of pin A

Features		**x**	**y**	**z**	**i**	**j**	**k**	**flatness**
		mm	**mm**	**mm**	**×1000 (×1)**			**mm**
PL1	Right side of post	27.810	71.443	1.765	(1)	0.03	-0.01	0.011
PL2	Bottom surface of Shim 7	-47.518	-137.522	20.180	0.06	(-1)	0.04	0.002
PL3	Front plane	-28.387	71.817	0.000	0.00	0.00	(1)	0.002
PL4	Top surface of Shim 8	-47.188	281.561	19.441	-0.01	(1)	0.90	0.010
P1	Shim 7 & Pin1	8.223	-137.519	-20.846				
P2	Shim 7 & Pin2	-103.545	-137.525	-20.835				
P3	Shim 8 & Pin3	8.261	281.560	-20.880				
P4	Shim 8 & Pin4	-103.491	281.562	-20.933				

Derived features	**Meas**	**Nom**	**M-N**	**Paran**	**Req**	**P/F**
Length of post with shims	419.083	419.153	-0.070			
Bottom surface of Shim 7	-137.522	-137.517	-0.005	dy	0.028	P
Top surface of Shim 8	281.561	281.566	-0.005	dy	0.028	P

Clamped-unclamped	**qx**	**qy**	**qz**
		microrad	
Rotation	40±5	-140±18	-3±5
Twist	105±5	-396±18	-7±5

Aligning the wide-field collimator post means to position two shims with respect to the pads and holes for dowel pins for the mirror (Figure 9).

First, we define the coordinate system with the pads and pin holes for the mirror, which is step 2 in Table 8. Next in step 3, we measure the holes for dowel pins in the bottom shim and use nudgers to move it.

During alignment, the part is clamped to the bed of the coordinate-measuring machine, and during inspection, the part is not clamped. Over constrained clamping can easily twist the part by milliradians, as we discovered. With clamping at three points, the twist (last row in Table 8) is consistent with 0.

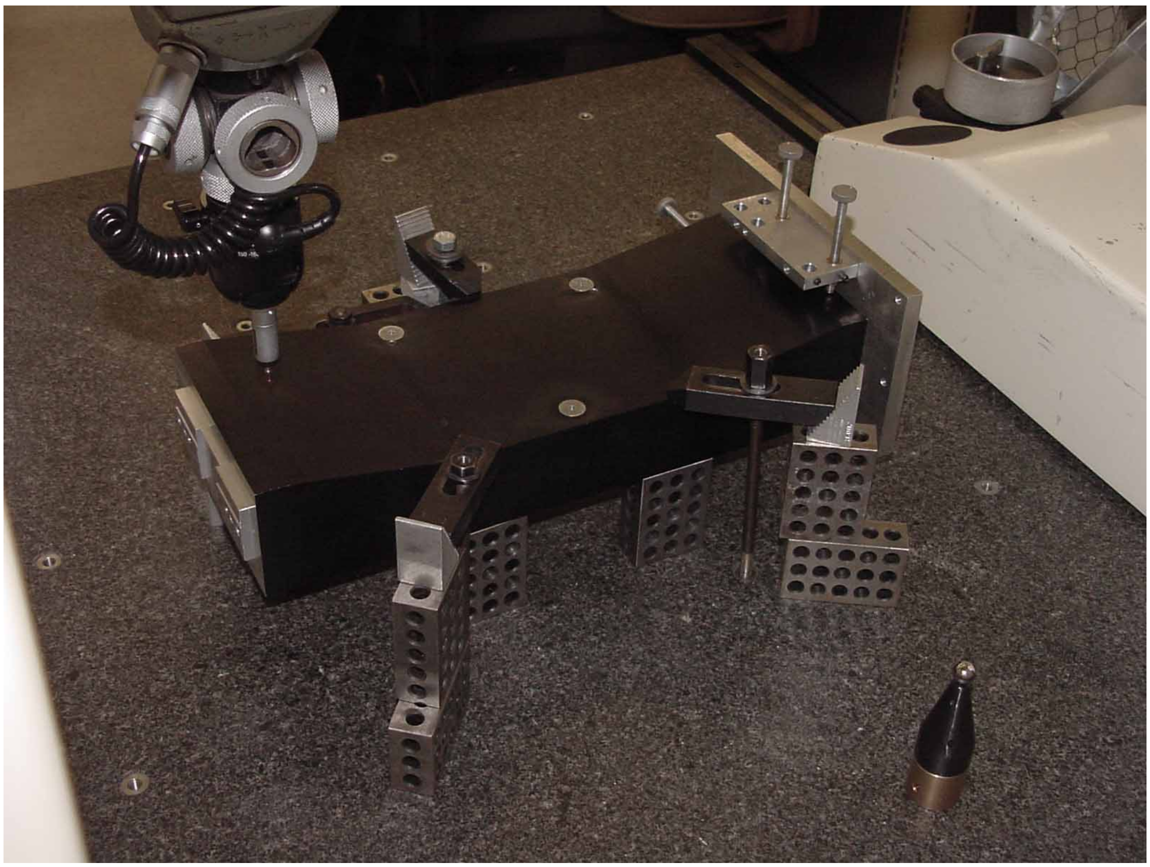


Figure 9: Alignment of the shims (one is visible on the left) on the wide-field collimator post with the pads (three shiny circles) and pins (too small to be seen) for the mirror. Three nudgers are attached to the faux COB to move the shim on the right.

Table 9: Alignment instructions and inspection notes for the post for the wide-field collimating mirror

Wide-field Collimator Post

Revised per ImageTest --21 Mar 2005

Move away from mask by 1.0mm --06 May 2008

Inspection 15 May 08

Note: Use pins on the bottom & pin 3 on top when installing in COB

Components

wide-field collimator post

Shim 8	Shim for top
Shim 7	Shim for bottom

Orientation

Back of post is on the table. Bottom is facing out.

Instructions

1 Place the post with the back down on three 2-in blocks and clamp down.

2 Measure features to define the coordinate system:
x-y plane = plane of the pads A, B, & C
Origin = intersection of x-y plane & axis of Pin B
y-axis is goes through axis of pin A

3 Attach bottom shim and faux COB. Use the faux COB to move bottom shim so that Pin1 is at

	Inspection	
x = 8.213±0.055	0.010	P
z = -20.846±0.027	-0.001	P

and Pin 2 with respect to pin 1 is at

	Inspection	
dz = 0.007±0.014	0.004	P

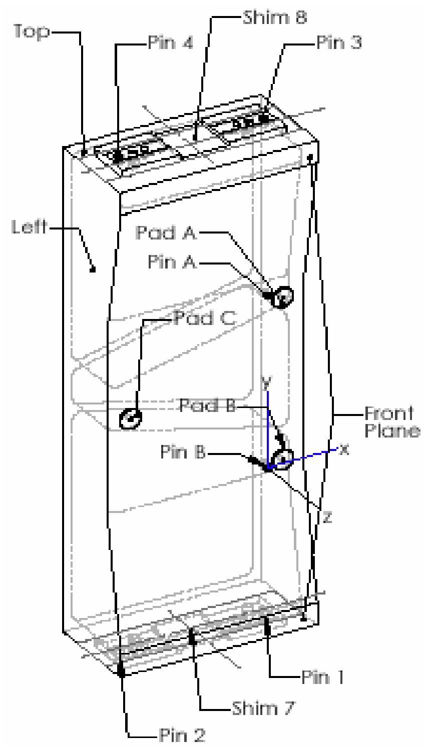
4 Use the faux COB to move top shim so that Pin3 is at

	Inspection	
x = 8.260±0.049	0.001	P
z = -20.911±0.027	0.030	F

and Pin 4 with repect to Pin 3 is at

	Inspection	
dz = -0.003±0.055	-0.050	P

5 Report inspection features



Inspection features

PL1	Right side of post	P1	Pin1 @ shim
PL2	Bottom surface of Shim 7	P2	Pin2 @ shim
PL3	Front plane	P3	Pin3 @ shim
PL4	Top surface of Shim 8	P4	Pin4 @ shim

5.3 Wide-field camera assembly

The requirements and measured errors are in Table 10. Table 12 is the instruction sheet for alignment, and Table 11 is the inspection report.

Table 10: Requirements and errors for the mirror arm of the wide-field camera assembly.

parameter	*component*	*req*	*meas*	
position	z	0.24	-0.17	mm
pm-pt	$\mathbf{a}\times\mathbf{z}$	0.36	-0.017	mm
	a	0.03	-0.030	mm
axis tilt	z	0.30	0.38	mrad
$\mathbf{at}\times\mathbf{am}$	$\mathbf{a}\times\mathbf{z}$	0.23	-0.09	mrad
rotation about optic center		2.7	0.01	mrad

Aligning the wide-field camera mechanism means to position two shims with respect to the pads and holes for dowel pins for the mirror. Two pins locate the rotation stage in the cradle, and the “cen-o-matic” centers the mirror arm on the rotation stage. The remaining degrees of freedom are the x and z position of pin 1, which is set in step 10 in Table 12, rotation of the bottom shim (step 10), the x and z positions of pin 3 (step 11), and the rotation angle of the mirror arm (step 8). The faux COB and attached nudgers are used to move the shims.

If the shims are not unbolted, the rotation stage may be removed and reinstalled without the use of a coordinate-measuring machine. A height gauge may be used to set the rotation angle of the mirror arm. In that case, use step 8’ in Table 12.

The pin holes for the mirror are oversized by 0.035 and 0.045 mm, whereas the specification for fabrication is $^{+0.010}_{-0.000}$. A full step on the rotation stage is a rotation of 0.35 mrad and a shift of the pins on the mirror arm of 0.05 mm.

Table 11: Inspection report of the wide-field camera mirror assembly

Inspection of Wide-field Camera Assembly 02 Jan 2007

C coordinate definition
x-y plane = plane of back of cradle. (Measure tops of 1-2-3 blocks.)
y-axis = intersection of left of cradle & x-y plane
Point on the bottom of cradle is on the x-z plane.
AB coordinate definition
y-axis runs from Pin B toward Pin A parallel to the intersection of PL4 and PL1.
x-y plane = plane of mirror pads

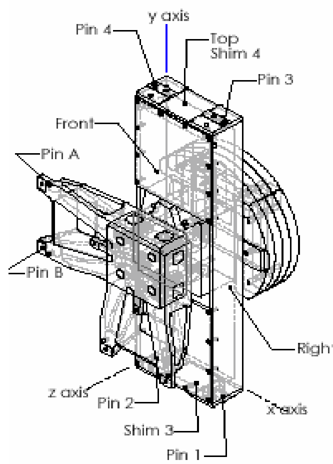
Features		**Coord**	**x**	**y**	**z**	**i**	**j**	**k**	**flatns**
			mm	**mm**	**mm**	**×1000 (×1)**			**µm**
PL1	Left side of cradle	AB	84.823	61.939	-63.964	(1)	0.00	0.19	7
PL2	Bottom of surface of Shim 3	AB	144.808	-157.629	-79.030	0.13	(-1)	0.61	9
PL3	Top of surface of shim 4	AB	144.106	261.477	-79.731	-0.21	(1)	0.26	9
PL4	Pads of the arm	AB	17.138	51.997	0.000	0.00	0.00	(1)	1
P1	Pin 1 @ shim	AB	200.877	-157.623	-79.963	-0.13	(1)	-0.61	
P2	Pin 2 @ shim	AB	89.127	-157.637	-79.950	-0.13	(1)	-0.61	
P3	Pin 3 @ shim	AB	200.915	261.489	-79.952	0.21	(-1)	-0.26	
P4	Pin 4 @ shim	AB	89.167	261.466	-79.888	0.21	(-1)	-0.26	
D	Distance top of arm to bottom shim				266.76				
			x	**y**	**z**				
PinA		C	-84.713	255.208					
		AB	0.110	104.032	0.000				
PinB		C	-84.823	151.176					
S1	Rev limit to "In"		155	microstep					
	Rev limit to forward limit		46266	microstep					

Table 12: Alignment instructions and inspection notes for the wide-field camera mirror assembly

Wide-field Camera Assembly		Inspection	
Wide-field Camera Assembly	Created 01 Mar 2004	**Inspection**	
Components	Mod 11 Jun 2004	02 Jan 07	
Cradle4	Mod b/c pins in COB shifted 12 Jul 2005		
Rotation stage 02060-099	Fix 2 small errors 29 Jul 2005	**err**	**p/f**
Shim 4 Shim for top	Mod instruction for ABS 07 Apr 2006		
Shim 3 Shim for bottom	Changed RS; fixed sign dz 27 Jun 2006		
Mirror arm	Make f/12&f/21 focus coincident 07 Dec 2006		
(Counterweights to be added after alignment.)	Pin RS 27 Sep 2007		
	Move toward detector by 0.03 19 Dec 2007		

Note Use pins on the bottom & only pin 3 on top when installing assembly in COB.

Instructions



Instructions	err	p/f
1 Back of cradle is on the table with bottom out.		
2 Bolt RS into the cradle using the pins.		
3 Install the mirror arm using the cent-o-matic.		
4 Install antibacklash spring & bumpers so that spring is engaged slightly when mirror is in the beam & forward limit engages before hard stop. The spring should touch the arm for 70±10 step before reaching the In position, and the reverse limit must be no more than 30 step from the In position.	16	P
5 Verify that		
a. Find home and test home work.		
b. The antibacklash springs are engaged at both the In and Out positions.		
c. The forward limit engages before hard stop.		
6 Place the cradle with the back down on three 2-in blocks and clamp down.		
7 Measure features to define coordinate system:		
x-y plane = plane of back of cradle. (Measure tops of 1-2-3 blocks.)		
y-axis = intersection of left of cradle & x-y plane		
Point on the bottom of cradle is on the x-z plane.		
8 Rotate the RS to a multiple of 4 steps so that		
dx = 0.00±0.14 for pins A and B. Pin B should be at	0.110	P
y = 151.20±0.12	-0.026	P
8' Alternately, rotate so that the distance between the top of the arm and bottom shim is		
D = 266.80±0.13	-0.04	P
9 Measure the plane PL4 defined by the three pads of the arm.		
10 Attach bottom shim and faux COB. Use the faux COB to move bottom shim so that the		
x = 200.86±0.12	0.018	P
z = -79.954±0.025, and Pin 2 with respect to Pin 1 is at	-0.009	P
dz = 0.005±0.017	0.008	P
Here and in step 11, project parallel to PL4 to the y-coord of pin B.		
11 Move top shim so that the projected location of Pin3 with respect to pin B is		
x = 200.899±0.108	0.016	P
z = -79.979±0.025	0.027	P
and Pin4 with respect to pin 3 is at		
dz = -0.004		

Inspection features

PL1	Left side of cradle	D	Distance top of arm to bottom shim
PL2	Bottom of surface of Shim 3	PB	Pin B
PL3	Top of surface of shim 4	P1	Pin 1 @ shim
PL4	Pads of the arm	P2	Pin 2 @ shim
PA	Pin A	P3	Pin 3 @ shim
		P4	Pin 4 @ shim

5.4 Filter-fold assembly

Table 13: Measured errors and required tolerances for the filter-fold assembly

parameter	*component*	*tol*	*meas*	*tol*	*meas*	
		LFW		BFW		
position	z	0.2	-0.05		0.01	mm
	$\mathbf{a}\times\mathbf{z}$	0.2	-0.01		-0.04	mm
	a	3.2	-0.12		-0.15	mm
		Fold 1		Fold2		
position	a	0.14	0.02	0.5	0.00	mm
tilt	z	0.19	0.19	0.4	-0.04	mrad
	$\mathbf{a}\times\mathbf{z}$	0.14	0.19	0.2	-0.31	mrad

Alignment means to locate the cradles for the two rotation stages and the two posts for the fold mirrors on the top and bottom shims. The requirements and measured errors are in Table 13. For fold mirror 1, that the light beam is coincident with the Lyot stop sets the requirement for positioning in the direction of the optic axis. All requirements are met, except for the tilts of the fold mirrors, which are slightly out of tolerance. Table 15 is the instruction sheet for alignment, and Table 14 is the inspection report.

An alignment jig and attached nudgers are used to move the mirror posts and cradles for the rotation stages.

First, the parts are positioned on the bottom shim (Steps 1–7 in Table 15). The bottom shim is bolted to the alignment jig, which locates the shim with holes for two pins. The coordinate system "B", defined by the pins and plane of bottom shim, is used. At this point, the positioning of the parts are not completely fixed, since they are not yet bolted to the top shim. To eliminate the freedom at the top shim, positions are projected onto the bottom shim. For example, the location of the post of the fold mirror #1 in the direction of its axis changes from the bottom shim to the top, because the top is not bolted down, and the location at the bottom shim is used in step 6. Three nudgers are used to move each optic.

Next, parts are positioned on the top shim (Steps 8–13 in Table 16). The top shim is bolted to the alignment jig (Figure 10). The coordinate system "T", defined by the pins and plane of top shim, is used. Measurements in the T coordinate system are more reliable, since both the top and bottom of the part have been bolted to the shims. In step 11, the bottom shim is positioned with respect to the top shim by moving the two cradles for rotation stages. Three nudgers are used, two for positioning the cradle for the little filter wheel in the x and y-directions and one for positioning the cradle for the big filter wheel in the x-direction. Next the posts for the fold mirrors are moved with respect to the top shim (steps 12 and 13).

We had some difficulties with positioning the bottom shim in step 11 and the posts for the fold mirrors in steps 12 and 13, because we had forgotten to keep the parts in contact with the nudgers when we tightened the bolts.

To find the rotational position of the reference filter (steps 16 and 17), we used a height gauge to measure the distance between the bottom of the shim and the opening for the filter cell.

Table 14: Inspection report for the filter-fold assembly.

Filter-Fold Inspection 07 Nov 07

Coordinate system & bolting

T Pins and plane of top shim define this. Top shim bolted to alignment jig.

B' Pins and plane of bottom shim define this. Top shim bolted to alignment jig.

		coord	position			1000 **at**×**am**		flatness
			x	y	z	t×z	z	
PL1	Back of cradle of Fold 1	B'	-60.509	143.533	-0.006	-0.75	0.03	0.007
		T	60.395	143.301	0.019	0.19	0.19	0.010
PL2	Back of cradle of Fold 2	B'	137.274	146.407	0.009	1.15	0.02	0.011
		T	-136.914	146.073	-0.028	-0.31	-0.04	0.005
PL3	Outside surface of Shim 13	T	-31.057	187.341	419.138			0.051
PL4	Outside surface of Shim 14	T	-505.644	181.983	0.027			0.086
P9	LF BFW @ filter center	B'	18.891	170.094	209.569			
P10	LF LFW @ filter center	B'	29.908	171.444	209.569			
P1	Pin 1 @ plane of Shim 13	T	0.055	-0.052	419.190			
P2	Pin 2 @ plane of Shim 13	T	-51.068	402.427	419.074			
P3	Pin 3 @ plane of Shim 14	T	0.000	0.000	0.000			
P4	Pin 4 @ plane of Shim 14	T	-51.146	402.475	0.000			
P5	Rotation axis of BFW @ PL5	B'	19.068	340.094	209.455	0.25	-1.0	
P6	Rotation axis of LFW @ PL6	B'	29.834	62.444	209.499	-0.14	-0.7	
P7	Center BFW @240° wrt rot. axis		0.000	0.000	0.000			
P8	Center LFW @240° wrt rot. axis		0.000	0.000	0.000			
S1	Steps to filter position 0 of BFW		15908	µstep				
S2	Steps to filter position 0 of LFW		17926	µstep				
	Position of BF cell 0 wrt AJ		236.52					
	Position of LF cell 0 wrt AJ		236.46					

Table 15: Alignment instructions and inspection notes for the filter-fold assembly. Part 1.

Filter-fold Assembly

Correct ang F1 10 Aug 2004
Correct Fold 28 Jul 2004
Use correct mirror config 28 Jul 2005
Method using pins 18 Aug 2007
Better spec on mirror tilt 24 Oct 2007

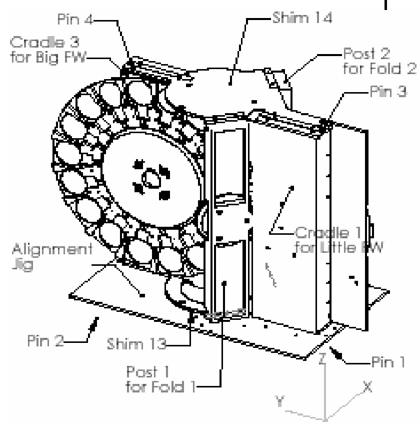
Inspection
07 Nov 07
err **p/f**

Principle of adjustment

The top and bottom shims support each post, and posts support the shims. To adjust a post, loosen the bolts attaching it to the shims, but keep the other posts fastened.

Components

Big filter wheel
Cradle3 w/ antibacklash spring for big FW
Rotation stage 02060-097 for big FW
Little filter wheel
Cradle1 w/ antibacklash spring for little FW
Rotation stage 000 for little FW
Shim 14 Shim for top
Shim 13 Shim for bottom
Wall
Fold-post 1
Fold-post 2
Fold mirror 1
Fold mirror 2

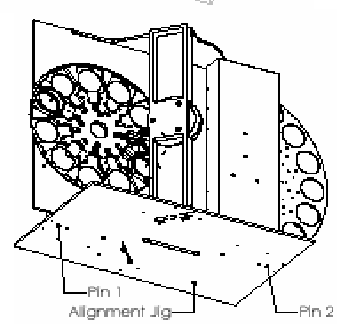


Preparation

1 Measure filter wheels and fold posts.
2 Assemble all but fold mirrors & filter wheels. Bolt finger tight. Do not install covers on cradles.

Instructions

1 Clamp alignment jig (AJ) on table with 1-2-3 blocks for access underneath.
2 Define a coordinate system B such that
a. The x-y plane is on the top of the alignment jig.
b. The origin is at pin 1 at the top of the alignment jig
c. Pin 2 is at
x = 51.136±0.008



3 Using pins for alignment, bolt assembly on alignment jig.

	err	p/f
4 Bolt RS000 into cradle 1 using pins. Move the cradle so that the rotation axis at the load face is at		
x = 29.78±0.46	0.051	P
y = 62.45±0.10	-0.006	P
Make certain the filter wheel clears the wall.		
5 Bolt RS097 into cradle 3 using pins. Move the cradle so that the rotation axis at the load face is at		
x = 19.04±0.64	0.024	P
y = 340.05±0.10	0.045	P
Make certain the filter wheel clears the wall.		
6 Move Post 1 so that the plane of its back, projected to the bottom shim, is at		
d1 = (x+61.347)*-0.68217+(y-144.330)*-0.73119=0±0.07	0.011	P
(i*-0.73119) - (j*-0.68217) = 0±0.00019	0.0000	P
Recall (x-x0)*normal=0 defines a plane		
7 Move Post 2 so that the plane of its back, projected to the bottom shim, is at		
d2 = (x-138.653)*0.65612+(y-147.638)*-0.75465=0±0.07	0.024	P
(i*-0.75465) - (j*0.65612) = 0±0.00037	0.0000	P

Table 16: Alignment instructions and inspection notes for the filter-fold assembly. Part 2.

8	Remove assembly from alignment jig. Turn alignment jig over. Define coordinate system T centered on pin 3 with the x-y plane on the top of the alignment jig and for pin 4		
	x = -51.148±0.008	0.002	P
9	Turn assembly over & attach top shim to alignment jig. Now position posts on shim 14.		
10	Measure plane of alignment jig.		
11	Move RS cradles to position pin 1 at		
	x = 0.046±0.011	0.010	P
	y = -0.061±0.011	0.009	P
	and pin 2 at		
	x = -51.091±0.008	0.022	F
12	Move Post 1 so that the plane of its back, projected to the top shim, is at		
	(x-61.393)*0.68217 + (y-144.269)*-0.73119 = d1±0.04	0.016	P
	(i*-0.73119) - (j*-0.68217) = 0±0.00019	0.00019	F
	k = 0±0.00014	0.00019	F
13	Move Post 2 so that the plane of its back, projected to the top shim, is at		
	(x+138.608)*-0.65612 + (y-147.577)*-0.75465 = d2±0.07	0.000	P
	(i*-0.75465) - (j*0.65612) = 0±0.00037	-0.00004	P
	k = 0±0.00023	-0.00031	F
14	Install covers on the cradle for the big filter wheel.		
15	Install BFW & LFW using the hole-a-centric to make wheels & RS concentric.		
16	Rotate the BFW so that filter position 0 is at y = 0±0.2		
	Alternately, the distance between the AJ & top of the filter cell is 236.51±0.2	0.010	P
17	Rotate the LFW so that filter position 0 is at y = 0±0.1		
	Alternately, the distance between the AJ & top of the filter cell is 236.51±0.1	-0.050	P
18	Install fold mirrors. Take care to keep area dust free.		
19	Report inspection features.		

Inspection Features (Report in either coordinate system.)

PL1	Back of cradle of Fold 1	P1	Pin 1 @ plane of Shim 13
PL2	Back of cradle of Fold 2	P2	Pin 2 @ plane of Shim 13
PL3	Outside surface of Shim 13	P3	Pin 3 @ plane of Shim 14
PL4	Outside surface of Shim 14	P4	Pin 4 @ plane of Shim 14
PL5	Load face for Big Filter Wheel	P5	Rotation axis of BFW @ PL5
PL6	Load face for Little Filter Wheel	P6	Rotation axis of LFW @ PL6
PL7	Plane of mirror surface for Fold 1	S1	Steps to filter position 0 of BFW
PL8	Plane of mirror surface for Fold 2	S2	Steps to filter position 0 of LFW

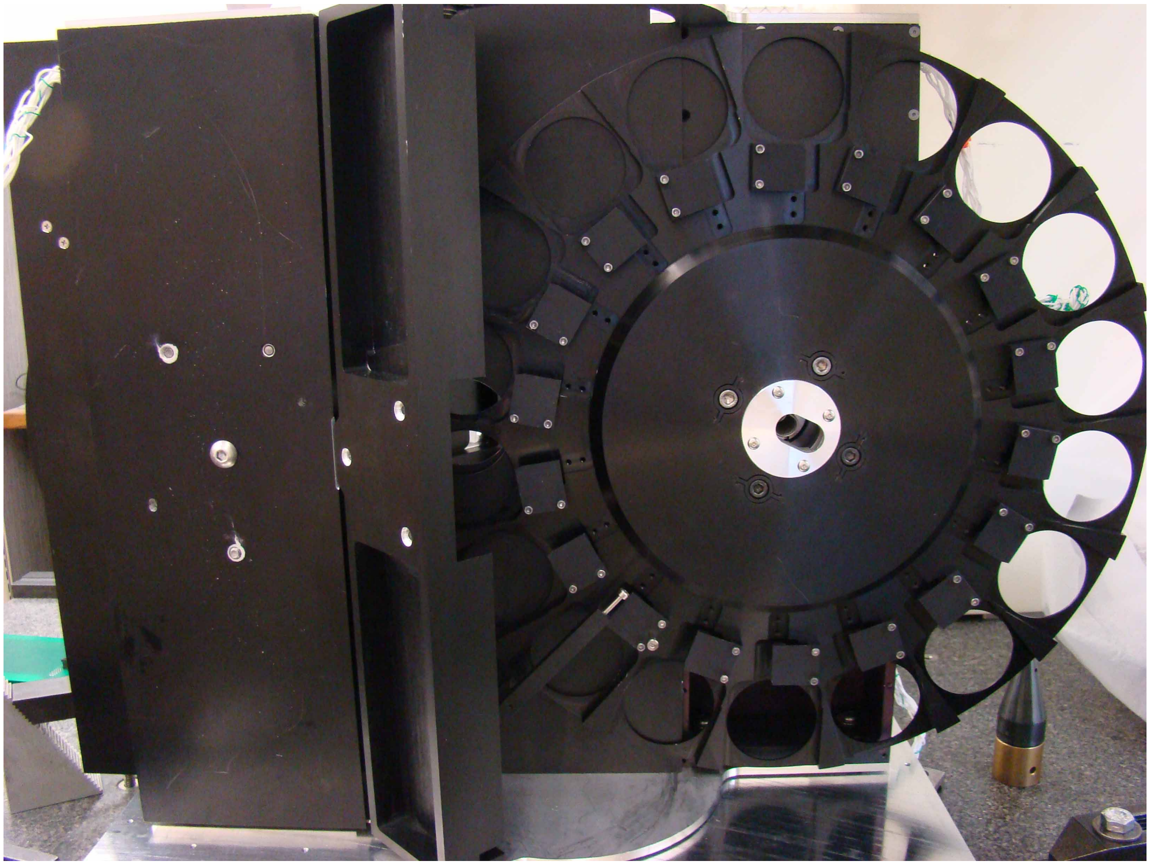


Figure 10: Filter-fold assembly with the top shim (shiny, curved part) bolted on the alignment jig. From left to right are the cradle for the little filter wheel, the post for fold mirror #1, and the big filter wheel.

5.5 Post for high-res camera mirror

The requirements and measured errors are in Table 17. All requirements are met. Table 19 is the instruction sheet for alignment, and Table 18 is the inspection report.

The procedure for alignment is the same as that used for the wide-field collimator post (§5.2).

Table 17: Alignment requirements for the post for the high-res camera mirror.

parameter	*component*	*tol*	*meas*	
position	z	0.24	-0.074	mm
pm-pt	**a**×**z**	0.36	-0.002	mm
	a	0.07	0.004	mm
tilt	z	0.30	-0.04	mrad
at×**am**	**a**×**z**	0.23	0.02	mrad
rotation about optic center		2.70	0.02	mrad

Table 18: Inspection report for the for high-res camera post

Inspection of High-res Camera Post 8/11/2005

Coordinate definition

x-y plane = plane of the pads A, B, & C
Origin = intersection of x-y plane & axis of Pin B
y-axis is goes through axis of pin A

Features		**x**	**y**	**z**	**i**	**j**	**k**	**flatness**
		mm	**mm**	**mm**	**×1000 (×1)**			**mm**
PL1	Right side of post	92.995	47.787	-25.386	(1)	-0.05	0.24	0.004
PL2	Bottom surface of Shim 9	16.554	-157.543	-21.684	0.05	(-1)	-0.17	0.007
PL3	Front plane	18.503	51.647	16.265	-0.08	-0.06	(1)	0.013
PL4	Top surface of Shim 10	17.229	261.606	-21.740	-0.08	(1)	-0.13	0.012
P1	Shim 9 & Pin1	72.339	-157.540	-21.852				
P2	Shim 9 & Pin2	-39.443	-157.545	-21.844				
P3	Shim 10 & Pin3	72.385	261.610	-21.884				
P4	Shim 10 & Pin4	-39.377	261.601	-21.883				

Derived features	**Meas**	**Nom**	**M-N**	**Paran**	**Req**	**P/F**
Length of post with shims	419.149	419.101	0.047			
Bottom surface of Shim 9	-157.540	-157.644	0.104	dy	0.120	P
Top surface of Shim 10	261.606	261.505	0.101	dy	0.120	P

Table 19: Alignment instructions and inspection notes for the for high-res camera post

High-res Camera Post

New 23 Aug 2004
Pins in COB shifted 28 Mar 2005
Corrections for pins garbled 04 Aug 2005

Inspection 11 Aug 05 — **err** / **p/f**

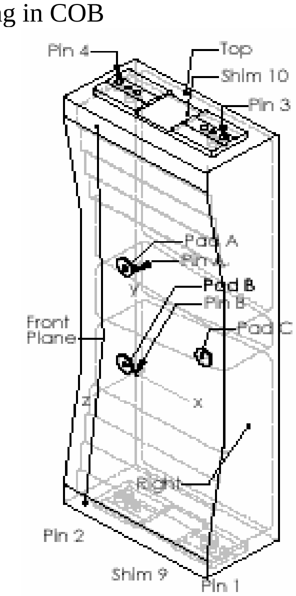
Note: Use pins on the bottom & pin 3 on top when installing in COB

Components

f/21 camera post
Shim 10 Shim for top
Shim 9 Shim for bottom

Orientation

Back of post is on the table. Bottom is facing out.



Instructions

1 Place the post with the back down on three 2-in blocks and clamp down.

2 Measure features to define the coordinate system:
x-y plane = plane of the pads A, B, & C
Origin = intersection of x-y plane & axis of Pin B
y-axis is goes through axis of pin A

3 Attach bottom shim and faux COB. Use the faux COB to move bottom shim so that Pin1 is at

Requirement	err	p/f
x = 72.345±0.014	-0.005	P
z = -21.842±0.072	-0.010	P

and Pin 2 with respect to pin 1 is at

Requirement	err	p/f
dz = 0.004±0.008	0.004	P

4 Use the faux COB to move top shim so that Pin3 is at

Requirement	err	p/f
x = 72.383±0.009	0.002	P
z = -21.882±0.022	-0.002	P

and Pin 4 with repect to Pin 3 is at

Requirement	err	p/f
dz = -0.001±0.033	0.001	P

5 Report inspection features

Inspection features

PL1	Right side of post	P1	Intersection of plane of Shim 9 & Pin1
PL2	Bottom surface of Shim 9	P2	Intersection of plane of Shim 9 & Pin2
PL3	Front plane	P3	Intersection of plane of Shim 10 & Pin3
PL4	Top surface of Shim 10	P4	Intersection of plane of Shim 10 & Pin4

5.6 High-res collimating assembly

The requirements and measured errors are in Table 20. Table 22 is the instruction sheet for alignment, and Table 21 is the inspection report. The optic is 0.11 mm farther from the window than the requirement.

Table 20: Measured errors and required tolerances for the arm of the high-res collimator assembly.

parameter	*component*	*tol*	*meas*	
position	z	0.22	-0.19	mm
pm-pt	$\mathbf{a}\times\mathbf{z}$	0.63	-0.02	mm
	a	0.04	0.11	mm
tilt of axis	z	0.40	0.17	mrad
$\mathbf{at}\times\mathbf{am}$	$\mathbf{a}\times\mathbf{z}$	0.23	-0.04	mrad
rotation about optic center		4.80	-3.1	mrad

Aligning the high-res collimator means to position two shims with respect to the pads and holes for dowel pins for the mirror (Figure 11). Two pins locate the rotation stage in the cradle, and the "cen-o-matic" centers the mirror arm on the rotation stage. The remaining degrees of freedom are the x and z position of pin 1, which is set in step 9 in Table 22, rotation of the bottom shim (step 9), the x and z positions of pin 3 (step 10), and the rotation angle of the mirror arm (step 7).

Fine-pitched nudgers are used in steps 9 and 10 to move the shims. A rubber band maintains a constant force between the nudgers and the cradle.

If the shims are not unbolted, the rotation stage may be removed and reinstalled without the use of a coordinate-measuring machine. A height gauge may be used to set the rotation angle of the mirror arm (Figure 12). In that case, use step 7' in Table 22.

Table 21: Inspection report for the for high-res collimator assembly

Inspection of High-res Collimator Assembly

23 May 2008

C coordinate definition

a. x-y plane = plane of back of cradle. (Measure tops of 1-2-3 blocks.)
b. y-axis is intersection of left of cradle & x-y plane
c. a point on the bottom of cradle is on the x-z plane

AB coordinate definition

Origin shifted to tooling ball B offset by 0.19, distance from base of tooling ball to mirror pad.

		Coord	x	y	z	i	j	k	flatness
PL1	Plane of mirror pads	AB	-16.925	-51.686	-4.737	0.17373	-0.00028	0.98479	0.003
PL2	Left side of cradle	AB	-212.058	-41.061	87.271	-1.00000	0.00000	0.00013	0.017
	Back of cradle	AB	-181.739	-13.764	54.826	0.00000	0.00000	1.00000	0.004
P1	Pin 1 @ Shim 5	AB	-94.719	-261.336	77.989	0.00000	1.00000	0.00035	
P2	Pin 2 @ Shim 5	AB	-206.475	-261.336	77.979	0.00000	1.00000	0.00035	
P3	Pin 3 @ Shim 6	AB	-94.657	157.821	78.081	-0.00003	1.00000	0.00057	
P4	Pin 4 @ Shim 6	AB	-206.417	157.817	78.140	-0.00003	1.00000	0.00057	
						diam			spherty
P5	Tooling ball A	C	212.025	150.977	-55.038	9.358			0.021
		AB	-0.037	-104.027	-0.213				
P6	Tooling ball B	C	212.191	255.005	-55.016	9.361			0.018
		AB	0.129	0.000	-0.190				
PL1	**target**$\times$**meas** with respect to cradle [mrad]					0.28	0.08	-0.05	mrad
PL1	**target**$\times$**meas** with respect to pins [mrad]					0.04	0.17	-0.01	mrad
							zCOB	**a**$\times$**zCOB**	
PL1	**target**$\times$**meas** with respect to pins [mrad]						0.17	-0.04	mrad
S1	In position			40	µsteps				
S0	Reverse limit			-5	µsteps				
S2	Forward limit			NA	µsteps				
D1	Dist shim 5 & top mirror arm			NA					

Table 22: Alignment instructions and inspection notes for the for high-res collimator assembly

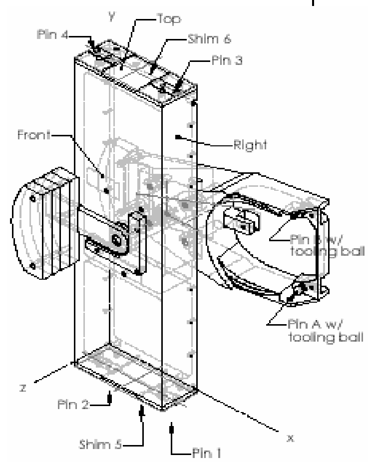
High-res Collimator Assembly

Note: When installing in COB, use both pins on the bottom & only pin 3 on top.

	Inspection
Created 01 Sep 04	23 May 08
Corrected arm direction 08 Sep 04	**err P/F**
Add instruction for bumpers 28 Jul 05	
Mod instruction for ABS 07 Apr 06	
Pin RS 29 Oct 07	
Move toward mask by 0.05 19 Dec 07	
Move toward mask by 0.60 06 May 08	

Components

Cradle5
Rotation stage 02060-100
Shim 6 Shim for top
Shim 5 Shim for bottom
Mirror arm
Antibacklash spring



Orientation

Back of cradle is on the table. Bottom is facing out.

Arm positions

In Mirror intercepts light beam
Out Mirror out; 90° from In.

Instructions

	err	P/F
1 Bolt the RS into the cradle using the pins.		
2 Set the reverse limit slightly behind the In position, and set the antibacklash spring so that is is engaged at both the reverse limit and the In positions. Set the forward limit slightly ahead of the Out position. The spring should touch the arm for 70±10 step before reaching the In position, and the reverse limit must be no more than 30 step from the In position.		
3 Verify that		
a. Find home & test home work.		
b. Antibacklash spring is engaged at the In position.		
c. The arm reaches the Out position.		
d. The forward limit is reached before the hard stop.		
4 Place the cradle with the back down on three 2-in blocks.		
5 Measure features to define the coordinate system:		
a. x-y plane = plane of back of cradle. (Measure tops of 1-2-3 blocks.)		
b. y-axis is intersection of left of cradle & x-y plane		
c. a point on the bottom of cradle is on the x-z plane		
6 Use the cen-o-matic to center arm on the RS. Bolt arm on RS.		
7 Rotate the RS to a multiple of 4 steps so that for balls A and B		
dx = 0.00±0.25	-0.17	P
Tooling ball B should be at		
y = 255.19±0.22	-0.19	P
7' Alternatively, rotate the RS so that the distance between Shim 5 & top of mirror arm is		
D1 = 273.02±0.35		
8 Define this to be the new In position. Verify conditions in step 2.		
9 Use the faux COB to move bottom shim so that Pin1 with respect to ball B is at		
x = -94.73±0.13	0.01	P
z = 77.97±0.04	0.02	P
and the angle between PL1 and the line between pins 1 & 2 is		
da = 174.53±0.34 mrad. (10.000±0.019 deg)	0.17	P
10 Use the faux COB to move top shim so that Pin3 with respect to ball B is at		
x = -94.68±0.10	0.03	P
z = 77.89±0.09	0.19	F

Inspection features

PL1	Plane of mirror pads	P5	Tooling ball A
P1	Intersection of plane of Shim 5 & Pin 1	P6	Tooling ball B
P2	Intersection of plane of Shim 5 & Pin 2	S0	Reverse limit
P3	Intersection of plane of Shim 6 & Pin 3	S1	In position
P4	Intersection of plane of Shim 6 & Pin 4	D1	Dist shim 5 & top mirror arm

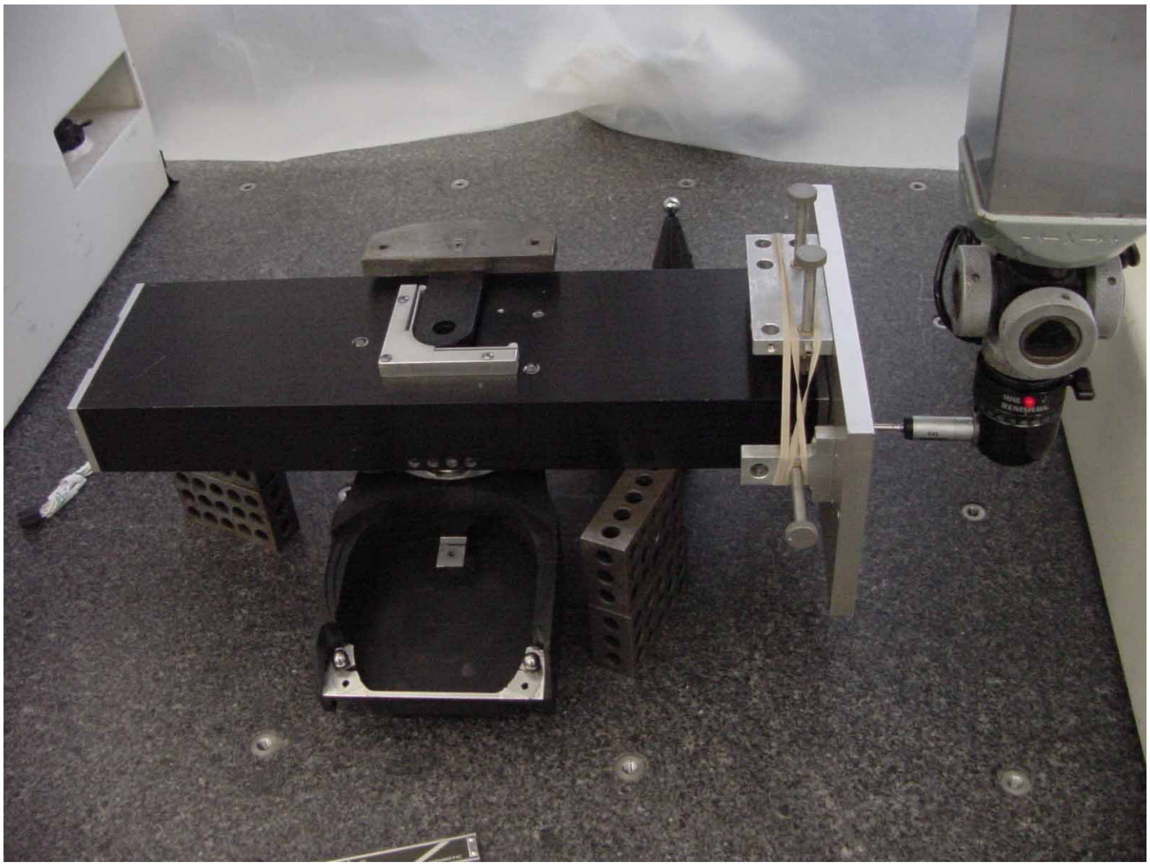


Figure 11: Alignment of the shims (one is visible on the left) on the high-res collimator mechanism with the pads (three shiny regions on the mirror arm) and pins (in which tooling balls are inserted) for the mirror. A nudger is attached to the shim on the right.

Figure 12: Use of a height gauge to set the rotation of the mirror arm for the high-res collimator

5.7 Four eye

The alignment instructions are in Table 24; the inspection is on the right-hand side of the table. The full inspection report is Table 23.

Aligning 4-eye means to position the legs on the spine (Figure 13). Pads and holes for dowel pins, which are machined on the spine, fix the position of the spine in the cryo-optical box (COB). Each detector butts against a frame, which butts against an outer frame. Edges of the outer frame mate with edges on the Henein axles, and other edges on the Henein axle mate with edges on the leg. Therefore the detectors are positioned accurately in the COB.

The setup is show in Figure 14. A nudger and two micrometers attached to the spine are used to move the legs.

Table 23: Inspection report for four-eye

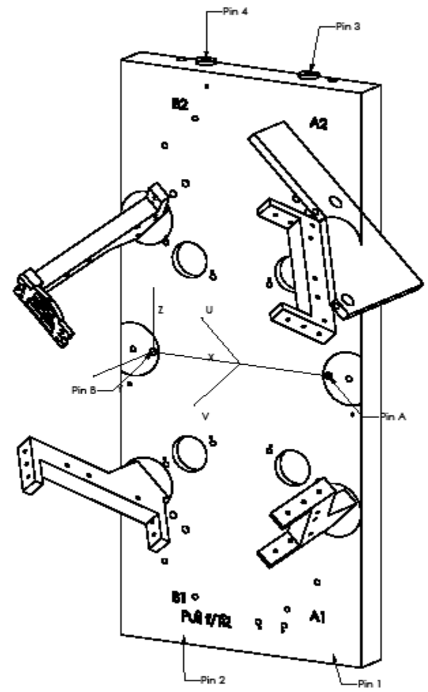
Inspection of 4-Eyed Assembly								20Dec2007
			Position			**Normal**		**flatness**
		x	**y**	**z**	**i**	**j**	**k**	
		mm	**mm**	**mm**	**x1000 (x1)**			**mm**
P1	Pin 1 at boss	120.82	21.01	-211.01				
P2	Pin 2 at boss	9.15	21.08	-206.07				
P3	Pin 3 at boss	120.81	21.01	209.50	0.1	0.08	(-1)	
P4	Pin 4 at boss	9.04	21.00	209.48	0.1	0.08	(-1)	
PLA	Plane of front of spine	67.58	0.00	-0.96	0	(-1)	0	0.012
L1	Right edge of spine	153.97	0.00	0.82	0.06	0	(-1)	
PA	Pin A at Plane A	129.96	0.00	0.00	0	(1)	0	
PB	Pin B at Plane A	0.00	0.00	0.00	0	(1)	0	
		u	**v**	**w**	**u**	**v**	**w**	
PLA1	Plane of leg A1 @ point	-123.61	-12.58	112.68	(-1)	0.28	-1.5	0.023
PLA2	Plane of leg A2 @ point	-12.55	-123.40	112.53	0.29	(-1)	0.1	0.008
PLB1	Plane of leg B1 @ point	12.57	123.29	112.68	0.18	(1)	1.8	0.030
PLB2	Plane of leg B2 @ point	123.64	12.59	112.50	(1)	0.05	-2.1	0.021
PA2	Point on leg A2	-12.55	-123.40	112.53				
PB1	Point on leg B1	12.57	123.29	112.68				
PB2	Point on leg B2	123.64	12.59	112.50				

Table 24: Alignment instructions for the 4-eyed detector assembly

4-Eyed Assembly

1Mx & 1Det, 04 Apr 2006
4 detectors, 30 Nov 2006
Move det 0.3mm toward mask, 23 Mar 2007
Det at nominal posn; mx in A1, 24 Oct 2007
Det at nominal posn, 19 Dec 2007

Note: Leave out pin 4 when installing in COB.



Components

4-eye spine
4-eye legs

A2	Det66	Lens1	Frame2 (upper right in figure)
B2	Det74	Lens2	Frame3 (upper left)
A1	Det24	Lens3	Frame1 (lower right)
B1	Det92	Lens4	Frame4 (lower left)

Coordinate systems

xyz	x-z plane	surface of spine
	origin	Pin B & surface of spine
	x-axis	Line between Pin B and Pin A
	y-axis	Normal to plane of spine
uvw	u-v plane	surface of spine
	origin	Center of Pins A & B on x-axis
	u-axis	135° to x axes

Instructions

		20 Dec 07 err	p/f
1	Attach the spine to the faux COB and clamp the faux COB on the CMM.		
2	Measure features to define the coordinate system.		
3	Use the alignment jig and micrometer for next 4 steps.		
4	Position the leg for A2 so that for the outside plane PLA2		
	normal·u = 0.00000±0.00037	0.00029	P
	| (ptOnPlane-origin)·normal | = 123.39±0.02	0.019	P
	and point PA2 on the plane is at		
	| u | = 12.57±0.10	-0.022	P
5	Position the leg for B2 (Outer, top) so that for the outside plane PLB2		
	normal·v = 0.00000±0.00037	0.00005	P
	| (ptOnPlane-origin)·normal | = 123.40±0.02	0.002	P
	and point PB2 on the plane is at		
	| v | = 12.57±0.10	0.023	P
6	Position the leg for A1 (Inner, bot) so that for the outside plane PLA1		
	normal·v = 0.00000±0.00037	0.00028	P
	| (ptOnPlane-origin)·normal | = 123.42±0.02	0.008	P
	and point PA1 on the plane is at		
	| v | = 12.57±0.10	0.006	P
7	Position the leg for B1 (Outer, bot) so that for the outside plane PLB1		
	normal·u = 0.00000±0.00037	0.00018	P
	| (ptOnPlane-origin)·normal | = 123.50±0.02	0.003	P
	and point PB1 on the plane is at		
	| u | = 12.57±0.10	0.003	P

Inspection Features

P1-4	Pin1-4 at boss	L1	Right edge of spine
PLA1-2, PLB1-2	Plane of legs at point	PA	Pin A at Plane A
PLA	Plane of front of spine	PB	Pin B at Plane A

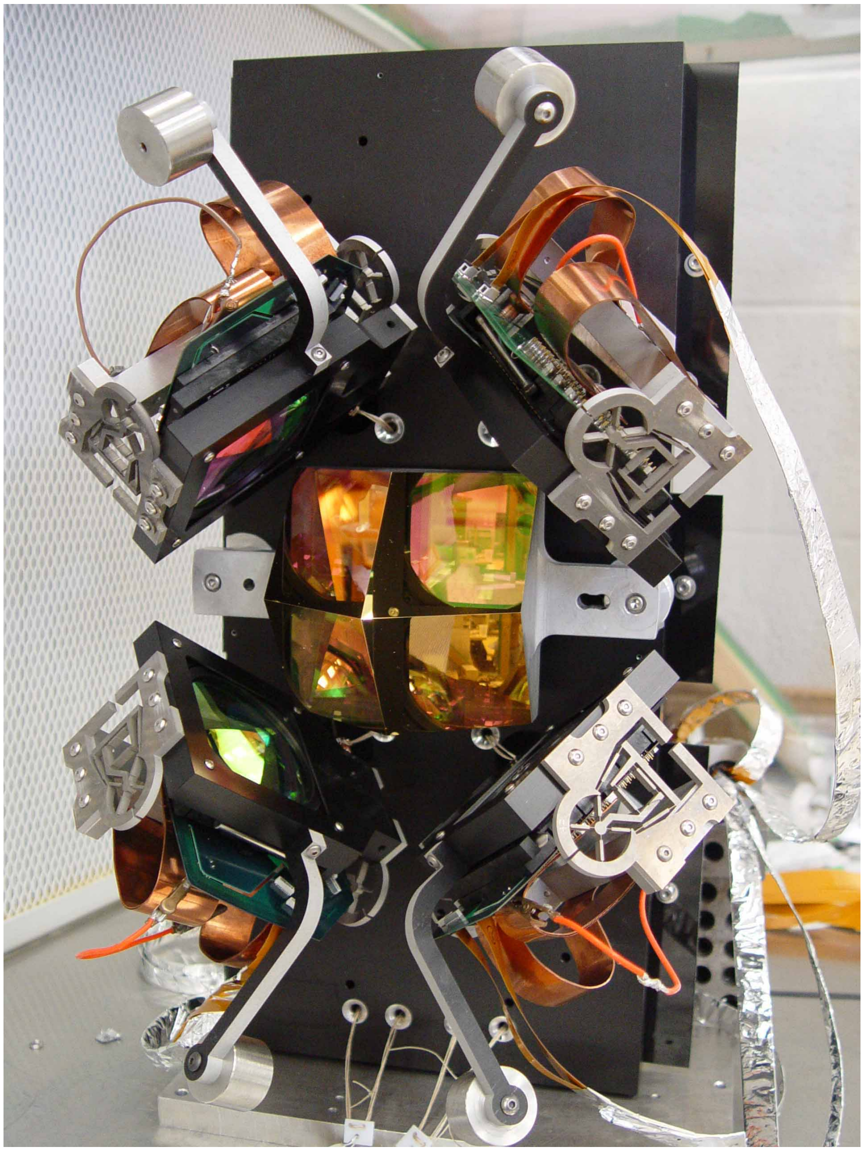


Figure 13: 4-eye detector assembly. Each detector butts against a frame and outer frame, for two of which the field-flattening lenses are visible. Each outer frame mates to two Henein axles, a complicated, shiny object. Each pair of Henein axles mate to a leg, and legs mount to the spine, the black object in the back.

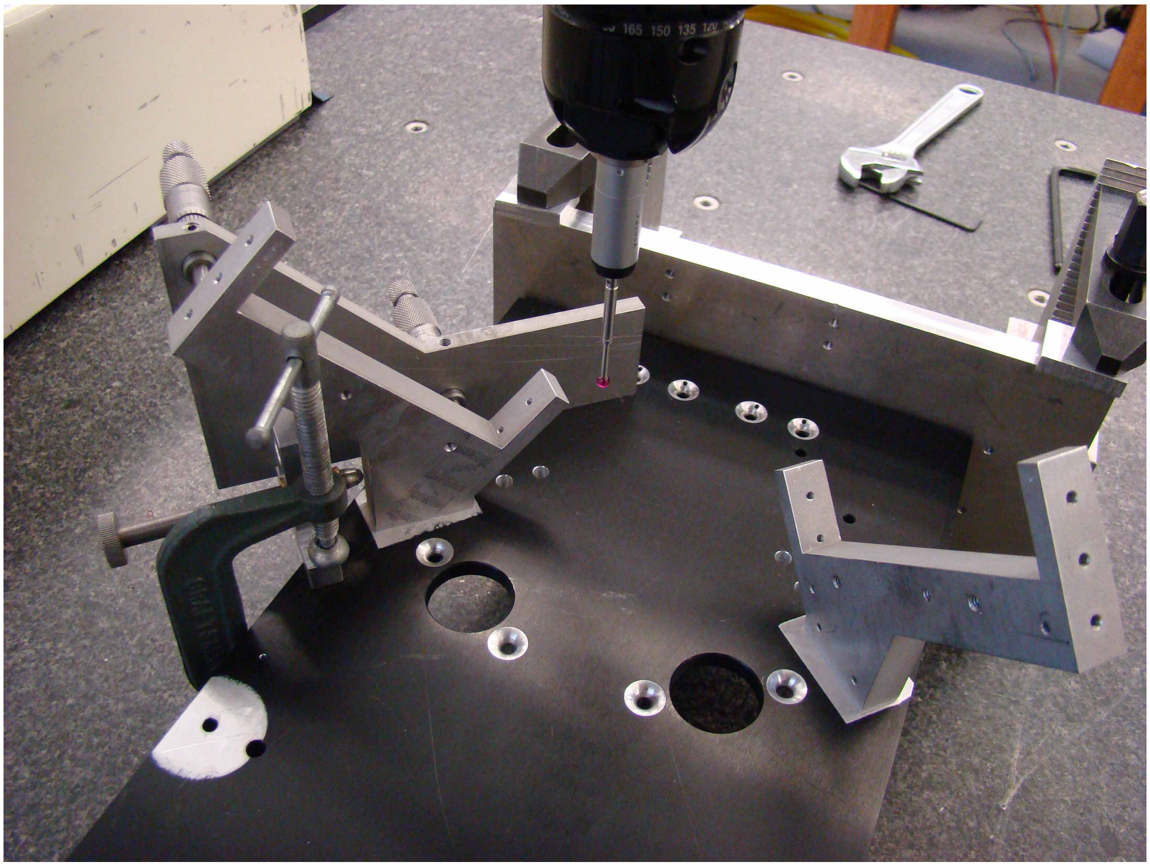


Figure 14: Alignment of 4-eye showing a nudger and two micrometers used to position the leg for detector A1. The spine is bolted on the faux COB, which is clamped to the bed of the coordinate-measuring machine.