SAM

The Main Module Alignment Manual

SAM-AD-02-2313

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1.- Introduction:

There are three stages in the alignment procedure to couple the SOAR Adaptive Optics Module to the lateral port of the Optical ISB for SOAR. In the following list, steps ii) and iii) are done in the Laboratory while step i) (Opt-ISB M4 alignment) must be done at the telescope site with the Opt-ISB dismounted from the Nasmyth rotator and installed on the Handling Cart.

i) Opt-ISB M4 Alignment.
ii) SAM Bench Alignment, Science Path.
iii) SAM Bench Alignment, WFS Path.

Within the SAM bench alignment, the most demanding work is the science path in particular the alignment of the two Off-Axis parabolic mirrors OAP1 and OAP2, where OAP1 acts as collimator and OAP2 as camera.

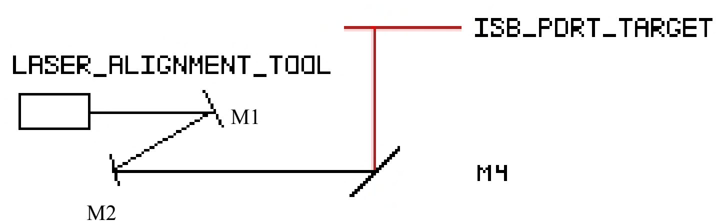
2.- Tools (drawings/pictures in Appendix on Tools and Analysis):

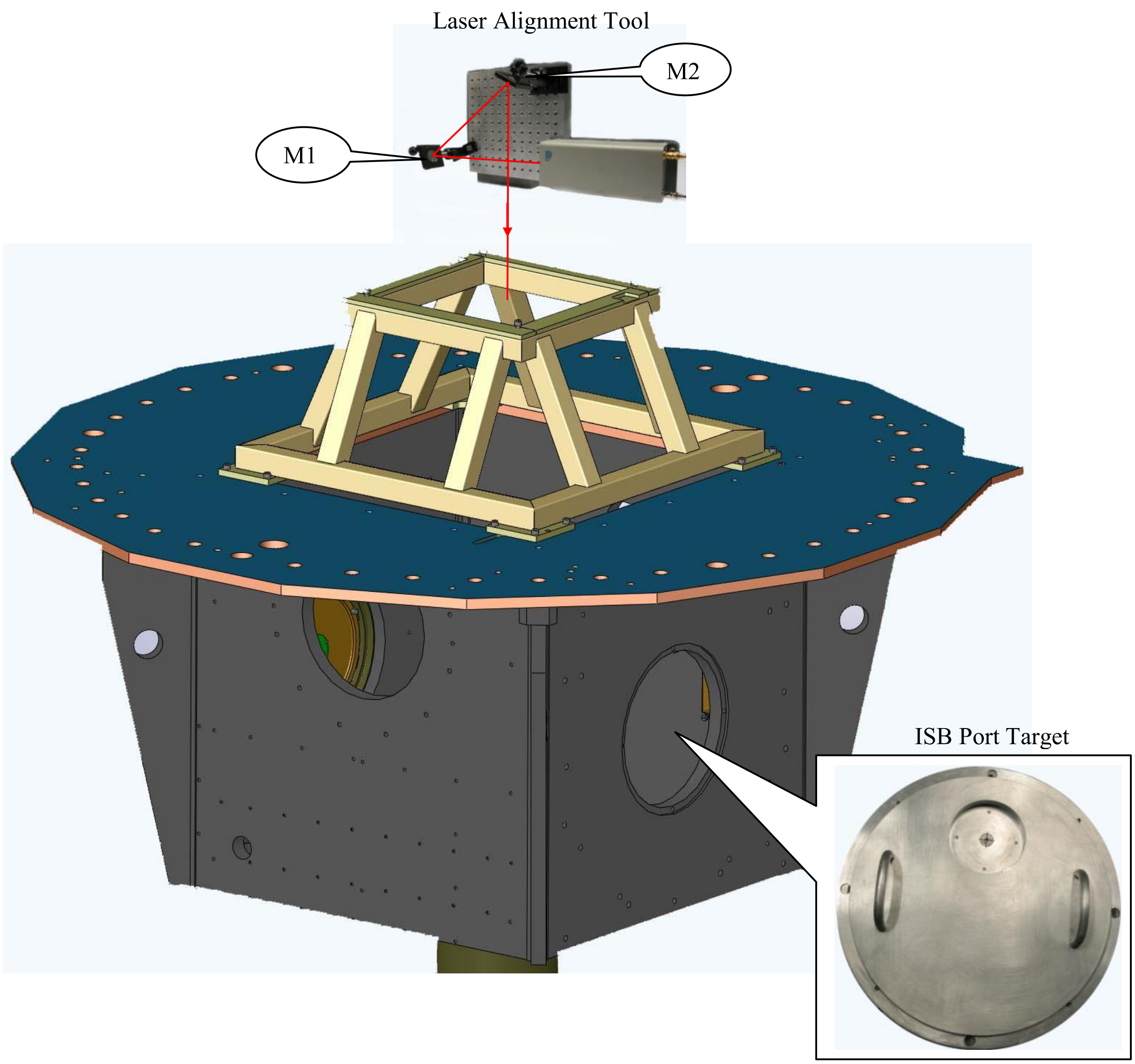
- Laser_Alignment_Tool.
- Alignment_x-hair_Targets, for all optical components.
- ISB_Direct_Port_Target
- ISB_SAM_Port_Target.
- SOAR_FocalPlane_Target.
- OAP1_Dummy_Target.
- Shear-Plate Interferometer.
- Flat_Mirror_Φ100mm_λ/20
- DM_Dummy_Support
- DM_DummyFlat_Masks_ Φ 70 and Φ 50.2mm
- DM_Pupil_Mask_ Φ 50.2mm.
- Height_Target.
- Flat_Mirrors_ Φ 25mm, Φ 40mm, λ /10.
- WF-Sensing_Device (Wavescope).
- Single-mode_Fiber_patch-cable, as laser (or other) point source.
- The SAMI focal plane Target.

3.- Opt-ISB M4 Alignment (Opt-ISB on handling cart):

The Laser_Alignment_Tool shown in Fig1, is mounted on its frame and attached to the ISB-to-Nasmyth connecting surface. The laser beam is directed to and centered on the ISB_Direct_Port_Target tool and then auto-collimated from it by adjusting the laser tool's M1 and M2 tip-tilt knobs, thus defining the ISB Optical Axis (the direct port centering and auto-collimating target tool already exists) . The ISB_SAM_Port_Target (schematically shown in Fig1), is installed on the SAM ISB lateral port. M4 is moved to its nominal SAM position and adjusted in Tip-Tilt rotations and X displacement (positioning linear stage), until the laser beam is centered on the target and auto-collimated from it. M4 tip-tilt adjustments are clamped and X encoder value defined as SAM position in the ISB (Labview) control software.

Fig 1





4.- SAM Opto-mechanical Integration:

Driven mainly by the optical layout and the mechanical stability (flexure and thermal) requirements, the SAM Optical Bench/Housing (1) evolved to a structure which is neither

an optical table nor a closed box, but rather a parallelepiped shaped frame structure with light-weight removable light-tight covers (2). Removing the covers allows access to the optical path for integration alignment and future maintenance.
The supports and/or cells of the optical components, will be mounted onto predetermined nominal positions in this frame. Table1 lists the optical components their type of holder and their adjustment degrees of freedom and ranges. The number of adjustments per component has been minimized to the strictly necessary for alignment.

Table 1

Optical Component	Holder	Adjustment Degrees Of Freedom	Min.Adjustment Ranges +/- (mm), (º)	Max.Adjustment Tolerances +/- (um), (")
SOAR Focal Plane Target	Slide fit disk	Z, θz	2 , 180	10 , 1º
OAP1	Stand	X-Y, θx-θy-θ-z	1-1 , 0.2-0.2-5	50-50 , 10-10-1º
DM	Stand	θx-θy	1-1	10-10
Science Path:				
Dichroic (in transmission)	Stand	θx-θy	1-1	5-5
OAP2	Stand	X-Y, θx-θy-θz	1-1 , 0.2-0.2-5	50-50 , 10-10-1º
V.I.Fold	Cell, 3 point axial	θx-θy	1-1	5-5
CCD Fold	Cell, 3 point axial	θx-θy	1-1	5-5
WFS Path:				
Dichroic (in reflection)	Stand	θx-θy	1-1	5-5
WFS camera triplet	Stand	X-Y(shim)	2-1	20-20
WFS Fold	Cell, 3 point axial	X θx-θy	2 , 1-1	50 , 5-5
WFS Module LGS:				
L1 (F/# adjustment lens)	Stand (brr type)	X-Y-Z	1-1-1	50-50-10
WFS Field Stop	Stand	Z	2	10
S-H reference light	Stand	X-Y-Z	1-1-1	50-50-50
L2	Stand (brr type)	X-Y-Z	1-1-1	50-50-10
λ/4	Stand	θz	180	1º
Glan-Taylor	Stand	θz	180	1º
Pockels Cell	Stand	X-Y , θx- θy- θz	1-1 , 1-1-90	200-200,20-20-1º
Glan-Taylor	Stand	θz	180	1º
L3a	Stand (brr type)	X-Y-Z	1-1-1	20-20-10
L3b	Stand (brr type)	X-Y-Z	1-1-2	20-20-10
Baffling Field-Stop	Stand (brr type)	X-Y-Z	1-1-2	50-50-50
L4	Stand (brr type)	X-Y-Z	1-1-1	20-20-10
LLA	Plate to bracket	X-Y-Z , θz	0.5-0.5-0.5 , 3	10-10-10 , 200
CCD (to LLA plate offline)	Plate to bracket	X-Y-Z	0.5-0.5-0.5	2-2-5
Module Base Plate/Rail	Tbb on Z Stage	pinned		
WFS Module NGS:				
WFS Field stop	Stand	Z	2	10
S-H reference light	Stand	X-Y-Z	1-1-1	50-50-50
L1	Stand (brr type)	X-Y-Z	1-1-1	20-20-10
L2	Stand (brr type)	X-Y	1-1	20-20
LLA	Plate to bracket	X-Y-Z , θ z	0.5-0.5-0.5 , 1	10-10-10 , 200
CCD (to LLA plate offline)	Plate to bracket	X-Y-Z	0.5-0.5-0.5	2-2-5
Module Base Plate/Rail	Tbb on Z Stage	X-Y(shim) , θy	1-1 , 0.5	20-20 , 10

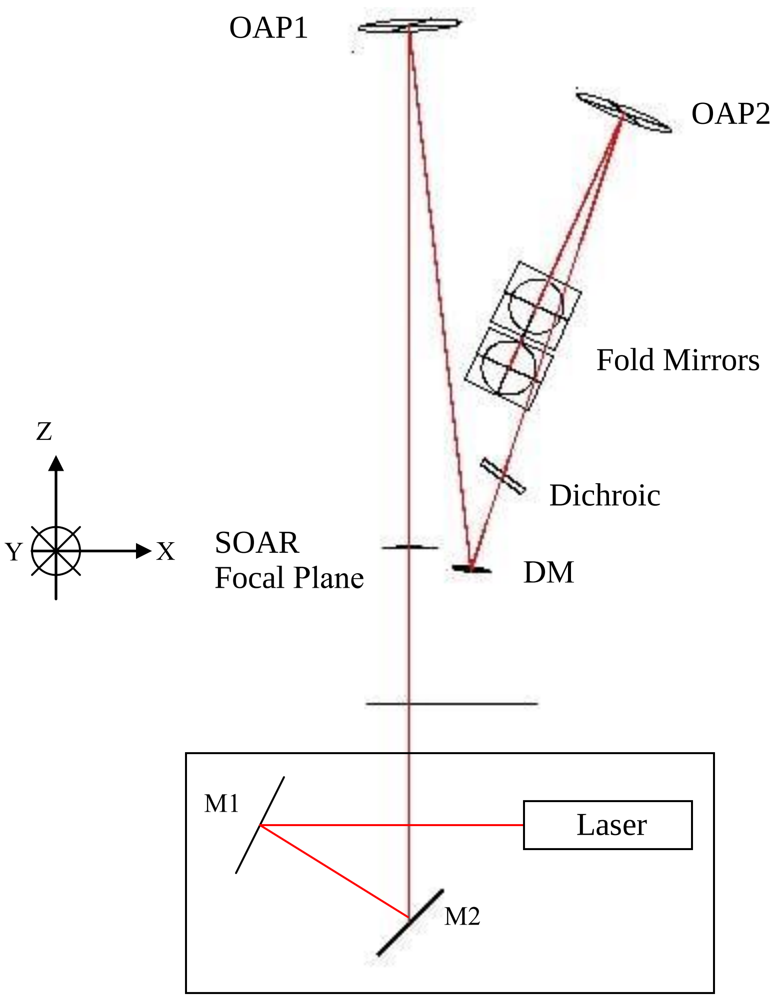
Brr: Barrel and retaining ring. Tbb: To be bolted

5.- SAM Science Path Alignment:

5.1.- Optical Axis definition and Laser Alignment check:

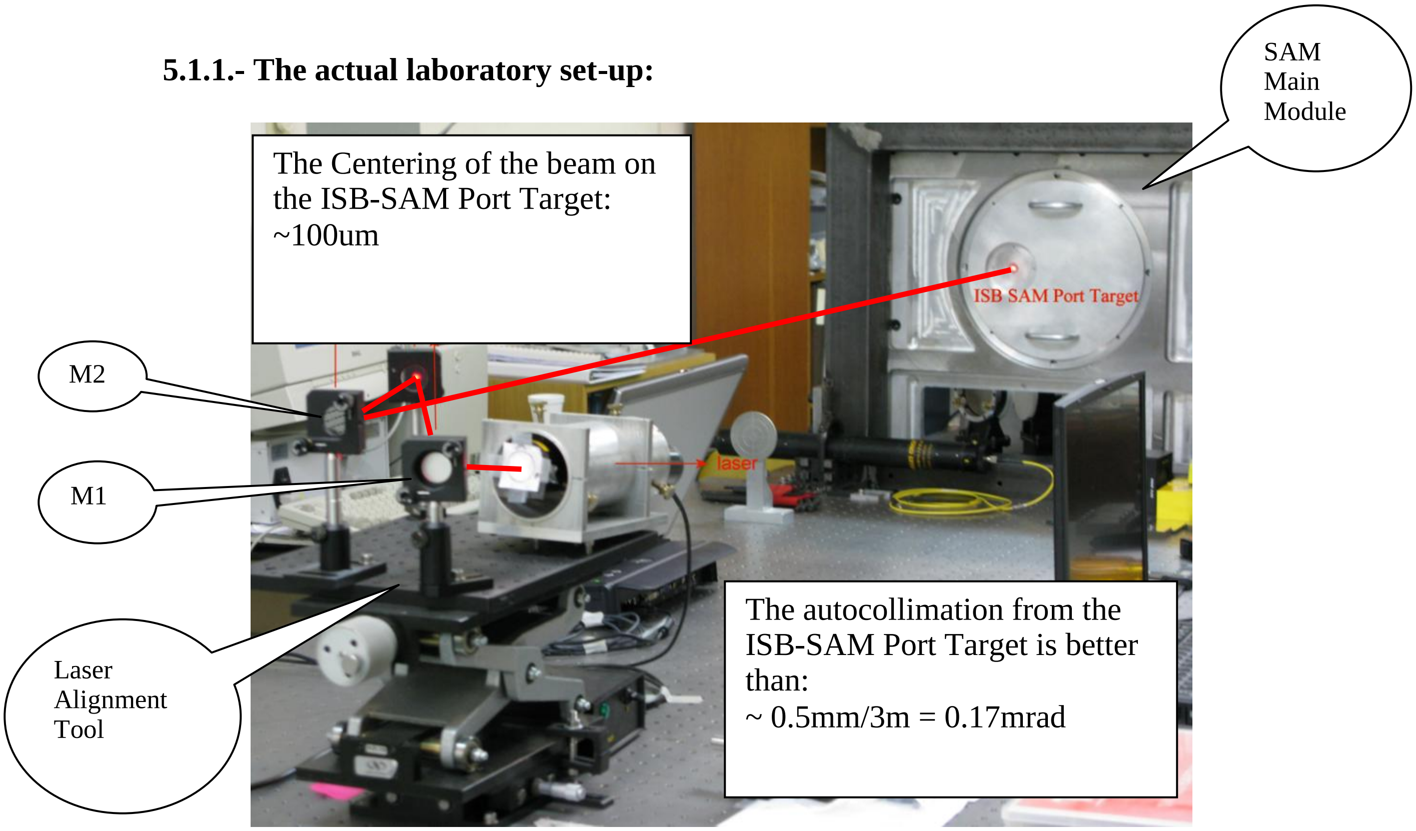
Mount the Laser_Alignment_Tool on a breadboard attached to the SAM mounting flange at a convenient distance from SAM (~1m; the total lever arm is ~1.5-2m considering the folded beam inside the alignment tool). Install the ISB_SAM_Port_Target on the SAM mounting flange (note the hole in this flange is identical to the hole in the ISB SAM port) auto-collimate the laser beam from the mounting surface keeping the beam on the (67.5mm de-centered) SAM port cross-hair. Install the SOAR_FocalPlane_Target in the hole in the tt-guider frame plate. Adjust the laser tool in X-Y and Tip-Tilt until the laser beam is centered on this target (it should be almost there already). The optical axis has thus been defined as the beam perpendicular to the SAM mounting Flange and centered in the SOAR Focal Plane position in SAM. Once assembled the SAM bench should end up close to built-to-print, then the Optical axis as defined above should also be the line connecting the center cross of the SOAR_Focal Plane_Target and the center cross of the OAP1_Dummy_Target. A hands-on decision will be taken at the time of alignment as to which is more convenient to use in practice as the Optical Axis. The accuracy of the Laser Alignment Tool in auto-collimation as measured in the Optics Lab is better than 0.2mm/1800mm =0.1 mRad or <20Arcsec and the error in direct cross-hair centering is ~0.25mm/824mm= 0.3 mRad so ~1Arcmin. The laser is to be kept in place during all the alignment for sanity checks.

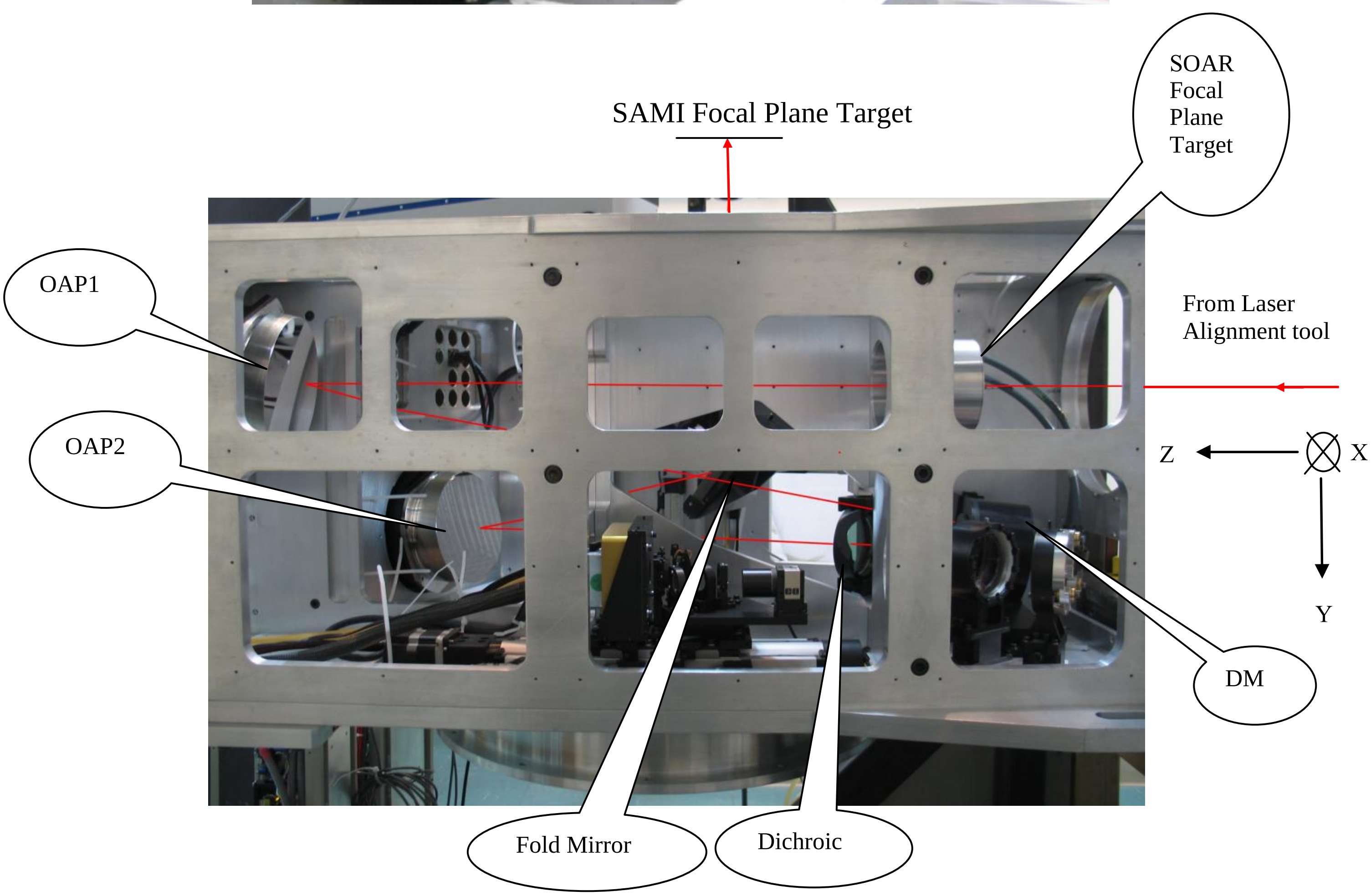
Fig 2



Laser Alignment Tool

5.1.1.- The actual laboratory set-up:





5.2.- OAP1 Alignment:

5.2.1.- Introduction:

For both Off-Axis Parabolas, we define a Local Coordinate System on the center of the Off-Axis mirror surface characterized by a Radial axis X, which lies along the off-axis distance, and a Tangential axis Y, which is perpendicular to the Radial axis and passes through the center of the mirror. The Axial supports conceptually consist of three pads placed at 120Deg around a circle close to the perimeter of the mirror. By placing one of these supports on the Radial axis (say external edge), the other two supports end up on a line parallel to the Tangential axis. The OAPs design as well as their holder design is such that we have uncoupled X-Y displacements and Θ_x , Θ_y and Θ_z rotations on this coordinate system (where Z is the optical axis defined above). The OAPs will be mounted on their supports close to their nominal mid-range adjustment positions with nominal clocking marks coinciding.

5.2.2.- Method:

The measurement method will be double pass by auto-collimation. But the beam used for measuring will come from a point on the focal plane 21mm off-center. When the misalignment of the OAP1 focal point respect to the Fiber point source is >~1mm, the aberration measured on a 21mm off-axis beam is nearly the same as the values for the center field. And when the misalignments become <1mm, then the calculated (Zemax simulation) values for a point-source at that field position, must be attained for perfect alignment. The dominant aberration is Astigmatism and the sensitivity of the method is:

Sensitivity = 10.26λ/Deg (waves of Astigmatism per Degree of OAP1 tilt).

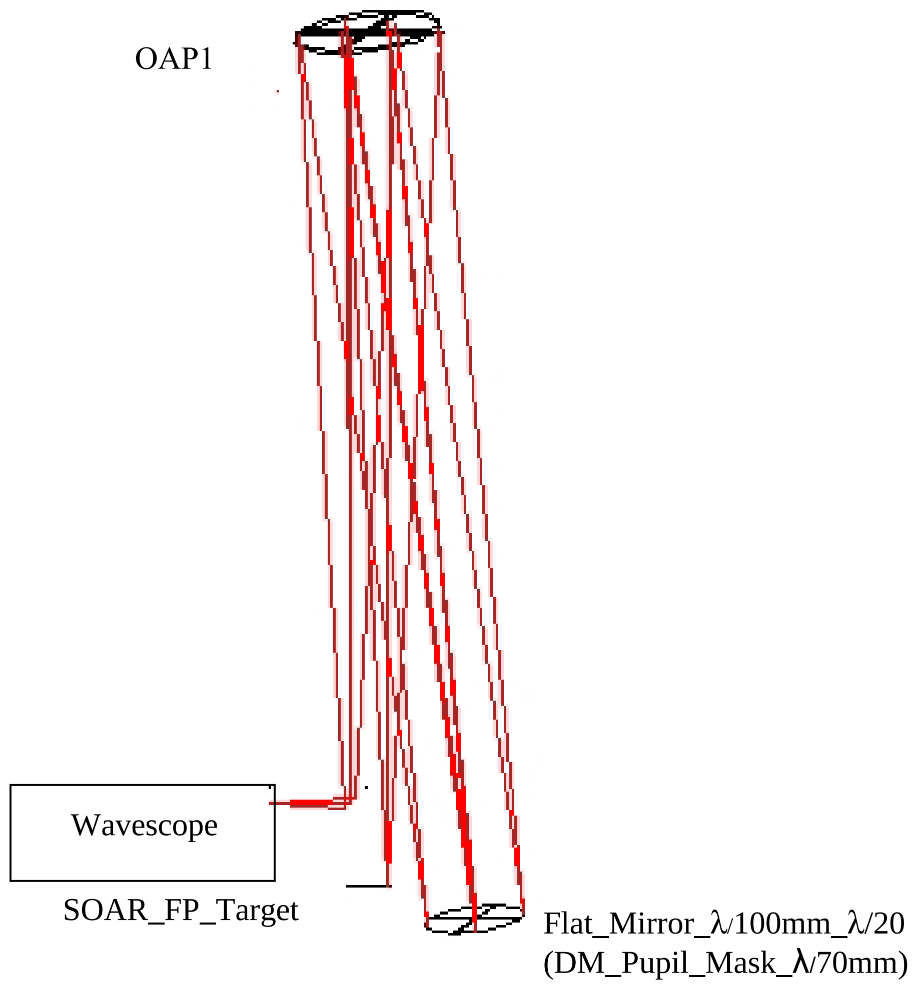
5.2.3.- Procedure:

Connect the laser-fed single-mode Fiber in the FC connector at the center of the SOAR FP_Target, and shine the light onto OAP1.
Install the Flat_Mirror_Θ100mm_ λ /20 for auto-collimation at the position of the DM or close by, called DM_Dummy. Place the DM_Pupil_Mask_Θ70mm on it (mostly for centering, no mask at all will have higher sensitivity but some rays will be vignetted).
Place the Shear-Plate interferometer in the parallel beam exiting OAP1 and adjust focus by moving SOAR FP_Target in Z.
Adjust DM_Dummy in Tip-Tilt until the beam is reflected back into the Fiber. The Center Field beam is now auto-collimated.
Insert the same, or a second Fiber, in the Outer-Radial-21mm off-axis FC connector in the SOAR_FP_Target and shine the laser light on. The return beam will arrive towards the edge of the field opposite to the out-going beam, where it can readily be fed into the WF-Sensing_Device (wavescope) by means of the fold Flat_Mirror_Θ25mm .

This set-up, shown in Fig 3, has three important advantages:

1) It's tool-oriented (we have all we need).
2) It has double sensitivity respect to any single pass method.
3) The WFS is setup once and needs no adjustment during the alignment process.

Take a first measurement with Wavescope, if Astigmatism is >~0.2λ(the baseline for this field point), adjust the OAP1 in tilt by the calculated amounts Θ_x and Θ_y, auto-collimate again by adjusting the DM Dummy Tip-Tilt, and measure the off-axis beam again with Wavescope. Repeat the procedure if necessary.



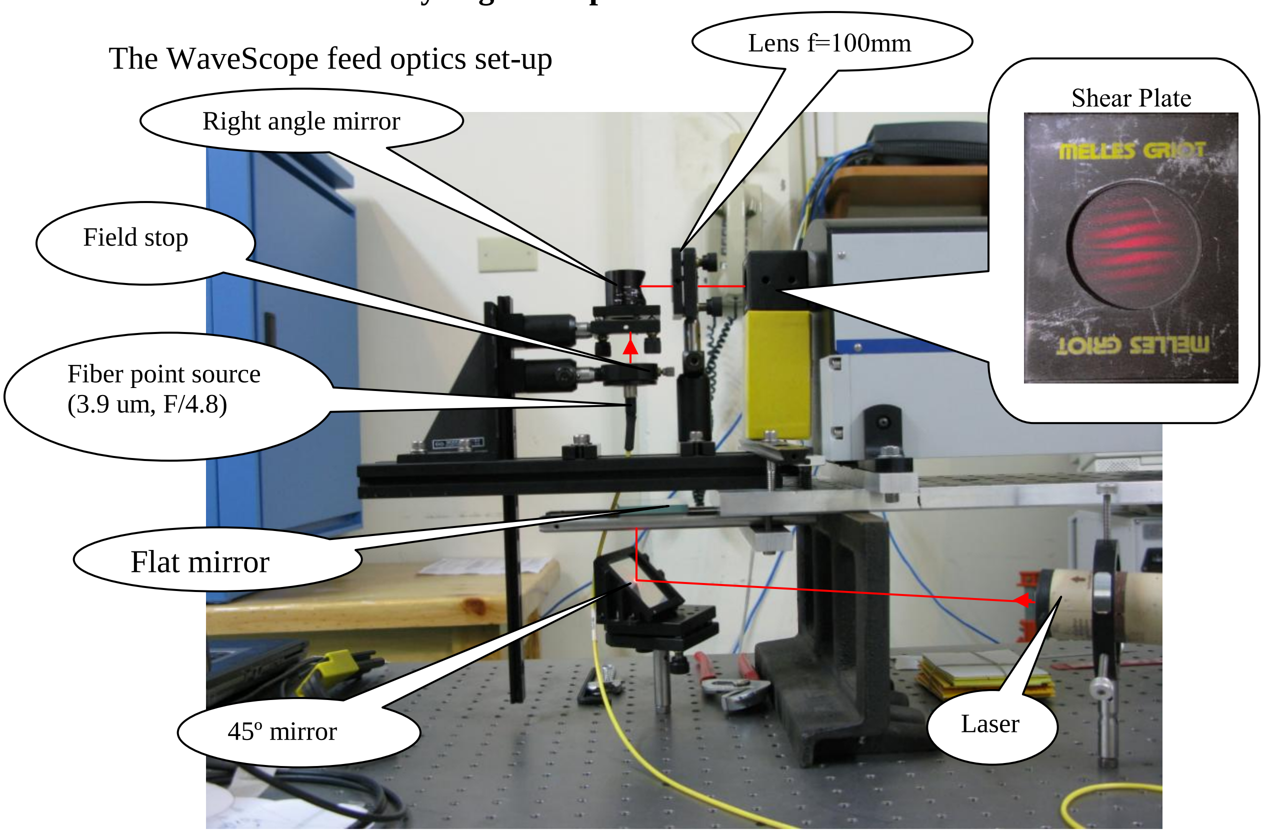
This process will end up with the OAP1's focal point centered on the SOAR_FP_Target center field. Now it must be checked if the collimated beam exiting OAP1, is arriving centered on DM.
Check first with the Optical Axis-marking laser beam on the DM_Pupil_Mask cross-hair. If the beam isn't centered (having checked the DM support position), OAP1 may need clocking adjustment. Rotation of OAP1 about the Optical Axis is desirable because it will not move the parabola's focal point, therefore maintaining alignment.
If misalignment of the beam on DM still persists in the Y(vertical) direction on DM Local coordinates, the OAP1 off-axis distance must be wrong. Here we present some ways of correcting:

a) Displace and Tilt OAP1. This method isn't recommended here because of its low sensitivity (see Appendix on Tools and analysis, OAP1 Alignment Diagram).
b) Correct the dy decentering error by a parallel displacement of the Defined Optical Axis in the OAP1 X direction by dx=dy (mm). This method has the disadvantage that now the SAM Mounting Flange Bolt Circle (as well as other holes and bolt circles) is no longer centered on the SOAR telescope Optical Axis (to which the defined optical axis is collinear). Thus the target center-crosses must be redefined and the SAM should then be displaced as a whole at the interface to the ISB. Nevertheless, the latter is already considered in the mounting flange mechanics.
c) Shim the DM base plate. This method doesn't require redoing adjustments to the preceding components nor redefining the optical axis. The only consequence it has, is that maybe the Dichroic base and the WFS triplet base have to be shimmed as well. But this is the Y adjustment foreseen for these components anyway.

The strategy should be defined at the time of the integration, a possible compromise could be: if dy>1mm shim DM or translate optical axis, if dy<1mm leave it as it is given that the real concentricity of actuators w/r to the mirror is not expected to be better than 0.5mm.

5.2.4.- OAP1 laboratory alignment procedure:

The WaveScope feed optics set-up

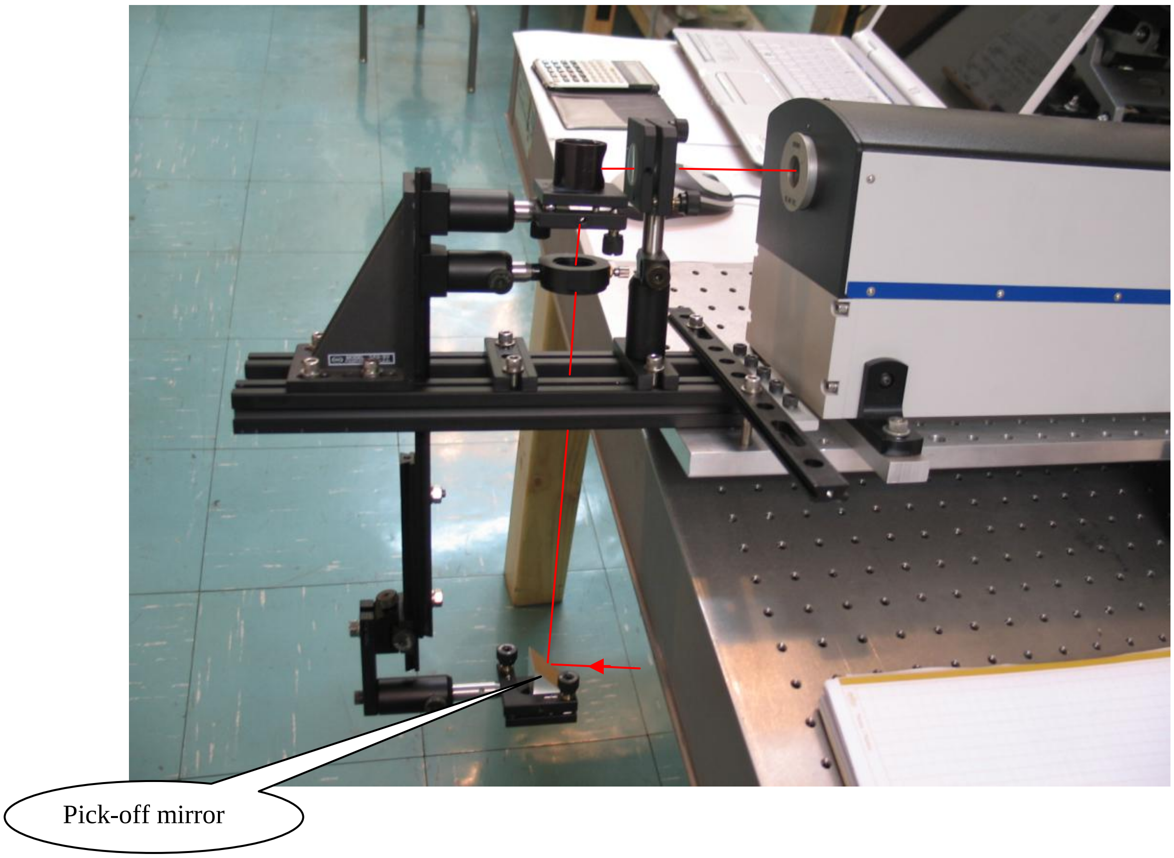


Adjustment Check list:
- Laser autocollimation using the flat mirror parallel to Wave Scope base plate
- Centering laser into field stop

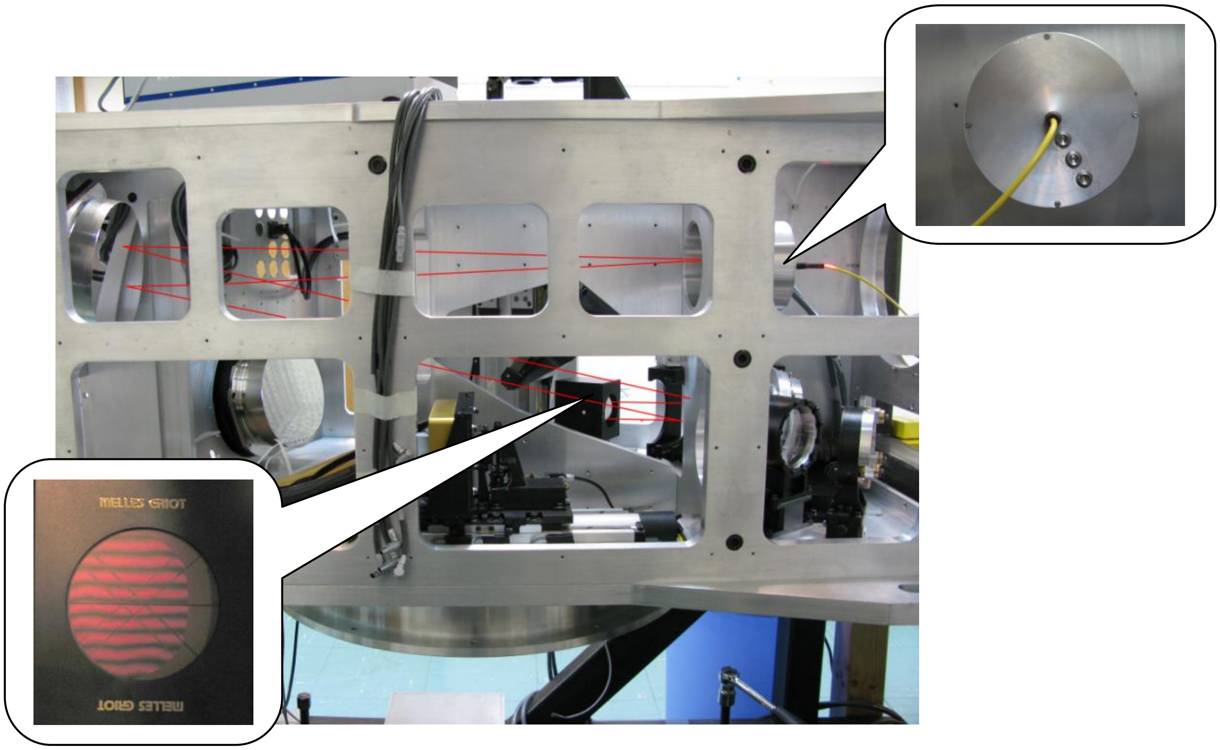
- Autocollimation at field stop.
- Autocollimation from right angle prism mount.
- Centering of the outcoming beam from right angle prism onto u-lens array.
- Autocollimation from collimator lens mount.
-Mount f=100mmm collimator lens…(falta)
- Insert fiber point source in to field stop mount

-Collimated beam using shear-plate interferometer
-Autocollimation from u-lens array position using direct laser

WaveScope set-up for OAP1 alignment

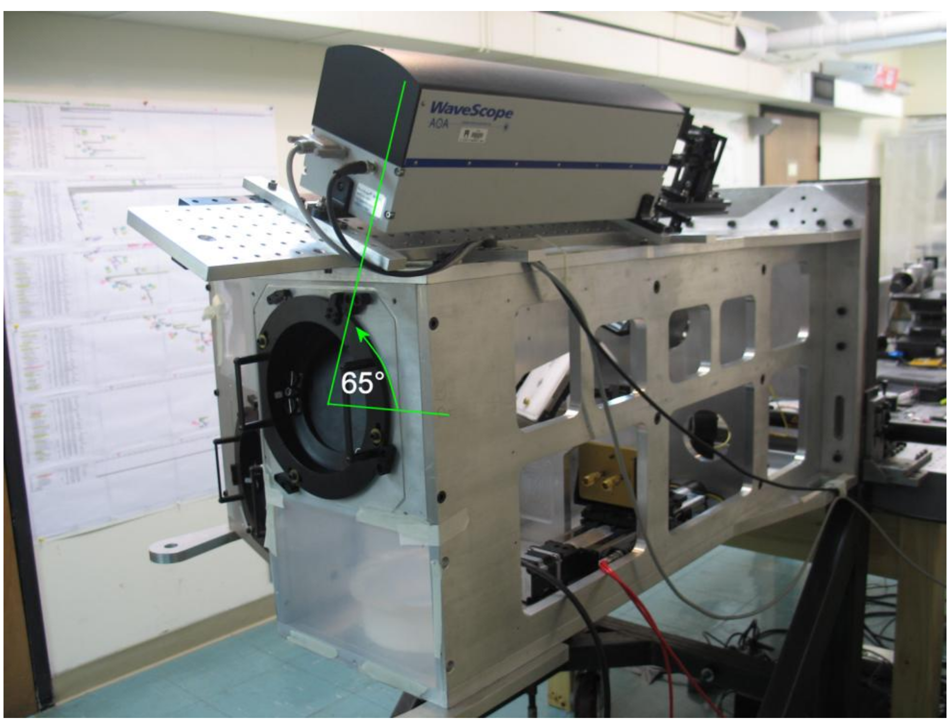


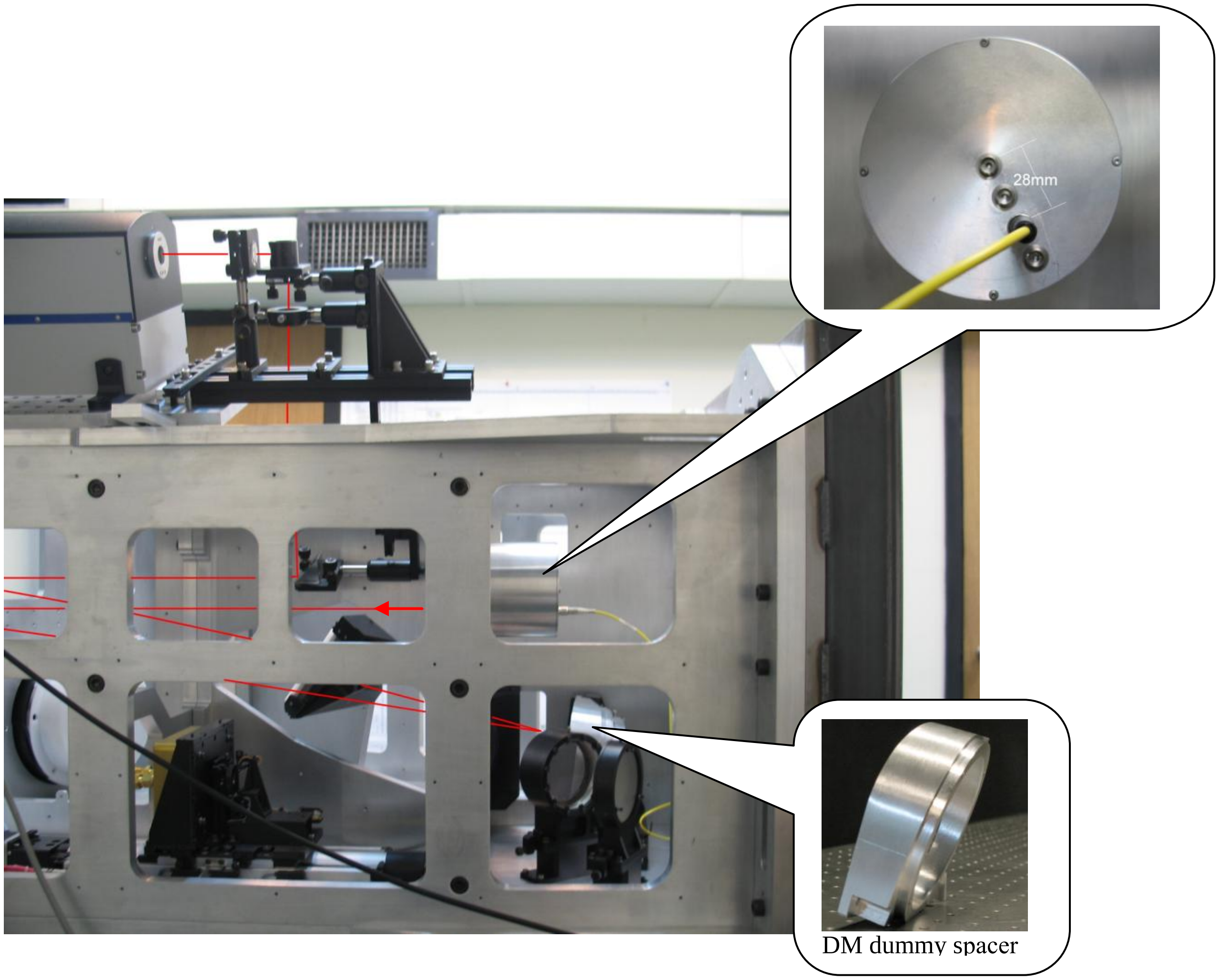
Focusing OAP1 on the SOAR focal plane target:



50mm
shear plate
placed in
collimated
path

Measuring OAP1 in autocollimation

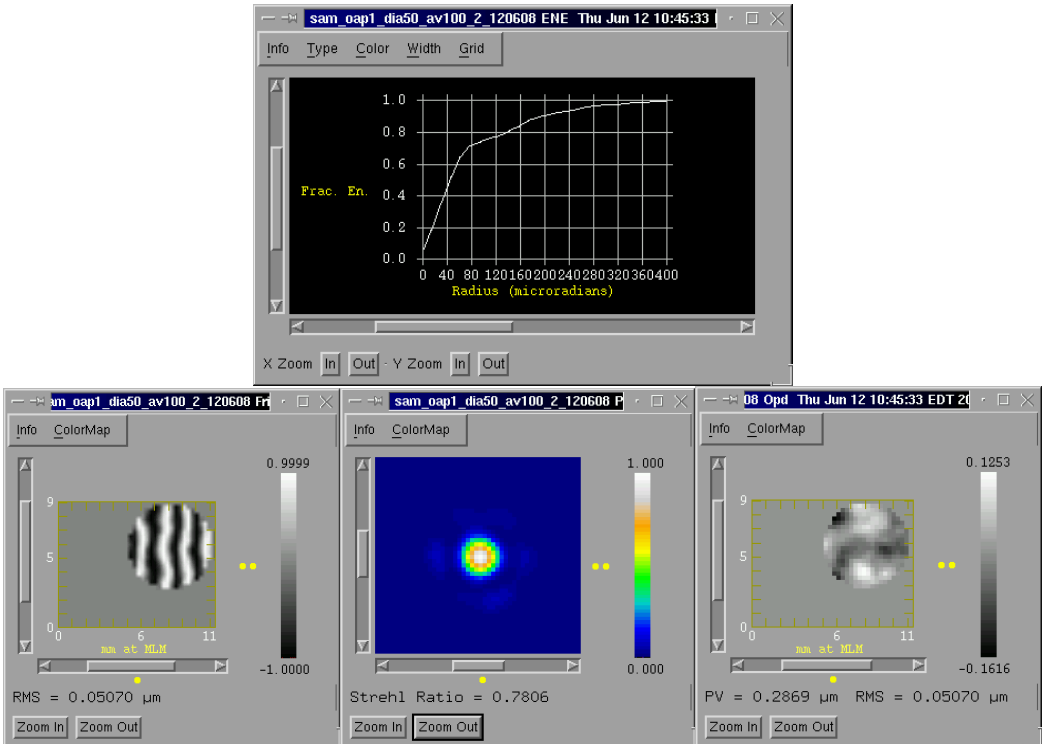




- …w/laser line and laser fiber + shear plate interferometer. Iterated tilt-focus-centering until good interferogram (starting tilt was done by centering beam on DM dummy, kept there by oap1 clocking).
- ….fiber 28mm off-axis

-
- ….
- Center and autocollimate direct laser beam in to interface plate target
- Remove interface plate target
- Center laser beam in focal plane target by x-y displacement of laser table
- Autocollimate laser beam by tip-tilt DM dummy through focal plane target pinhole(young diffraction circular rings)
- Check wavescope reference tip-tilt alignment (x<1mrad and y<1mrad)
- Check wavescope test tip-tilt, adjust test to same tip-tilt as reference
- Wavescope calibration . Save reference file, define pupil of test beam, follow wavescope software guide. SAM OAP1 DM pupil size for alignment 71.6mm. Radius 180 pixels in Wavescope.
- Adjust tilt x and tilt y to 0 tilting OAP1

The aligned OAP1 (best compromise).
Wave Scope results from 28mm off-axis from DM dummy



Zernike Coefficients

Index	Coefs(µm)	Equation
1	-0.002926	# rcos(t) (X Tilt)
2	-0.003379	# rsin(t) (Y Tilt)
3	-0.000000	# $2r^2-1$ (Focus)
4	-0.063813	# r^2cos(2t) (0 Astigmatism)
5	0.002256	# r^2sin(2t) (45 Astigmatism)
6	0.005037	# $(3r^2-2)$rcos(t) (X Coma)
7	-0.016895	# $(3r^2-2)$rsin(t) (Y Coma)
8	-0.019576	# $6r^4-6r^2+1$ (Spherical)
9	-0.044655	# r^3cos(3t)
10	-0.000445	# r^3sin(3t)
11	0.069065	# $(4r^2-3)$r^2cos(2t)
12	-0.013237	# $(4r^2-3)$r^2sin(2t)
13	-0.005697	# $(10r^4-12r^2+3)$rcos(t)
14	0.026736	# $(10r^4-12r^2+3)$rsin(t)
15	0.006845	# $20r^6-30r^4+12r^2-1$
16	0.056156	# r^4cos(4t)
17	-0.011927	# r^4sin(4t)
18	0.001910	# $(5r^2-4)$r^3cos(3t)
19	-0.033843	# $(5r^2-4)$r^3sin(3t)
20	-0.034049	# $(15r^4-20r^2+6)$r^2cos(2t)
21	0.016384	# $(15r^4-20r^2+6)$r^2sin(2t)
22	-0.002815	# $(35r^6-60r^4+30r^2-4)$rcos(t)
23	-0.003662	# $(35r^6-60r^4+30r^2-4)$rsin(t)
24	-0.003933	# $70r^8-140r^6+90r^4-20r^2+1$
25	-0.028745	# r^5cos(5t)
26	0.014708	# r^5sin(5t)
27	-0.002987	# $(6r^2-5)$r^4cos(4t)
28	0.006872	# $(6r^2-5)$r^4sin(4t)
29	0.011474	# $(21r^4-30r^2+10)$r^3cos(3t)
30	0.021439	# $(21r^4-30r^2+10)$r^3sin(3t)
31	0.003393	# $(56r^6-105r^4+60r^2-10)$r^2cos(2t)
32	-0.004498	# $(56r^6-105r^4+60r^2-10)$r^2sin(2t)
33	0.004753	# $(126r^8-280r^6+210r^4-$

The OAP1 mirror mount aligned position

OAP1 positioning values measured with a depthmeter:

Hard points position	**#1**	**#2**	**#3**
Spacing in mm	2.480	2.643	2.541
New hard points position	**#1-2**	**#2-3**	**#3-1**
Spacing in mm	2.627	2.473	2.436
Clocking	63.9º		
Decenter from fiducial marks	2.1mm towards#1(opposite #2-3)		

5.3.- OAP2 Alignment:

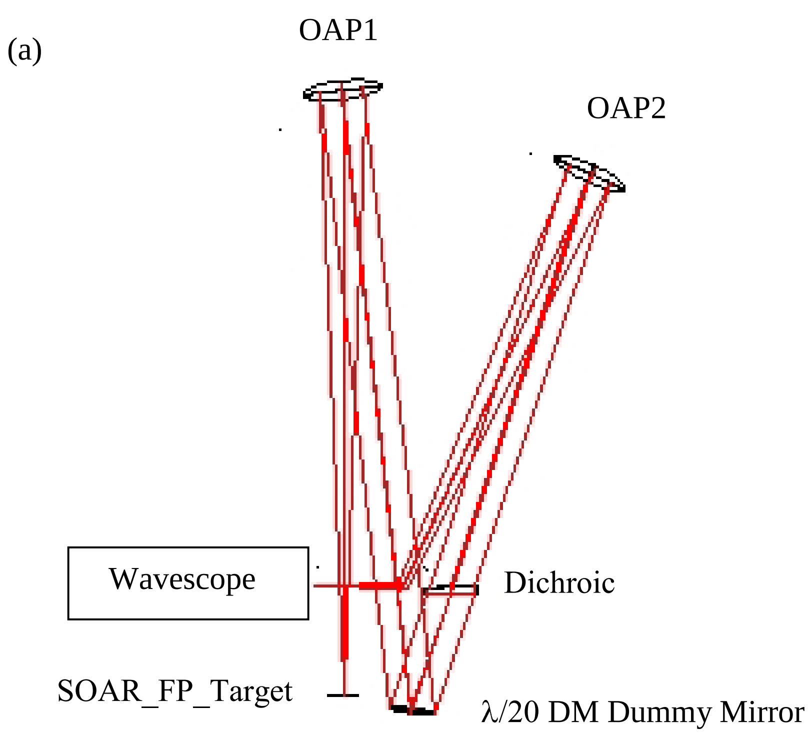
5.3.1.-Procedure:

Having aligned OAP1, we use the Center Field point source in the SOAR_FP_Target to produce a high quality collimated beam reflected off the DM_dummy and feeding OAP2 with it. The alignment of OAP2 will consist in getting the parabola's virtual axis parallel to this collimated beam and passing through the Dichroic Simulator. To within the tolerances imposed by the manufacturer and our own built-to-print accuracy, we do not really care where the image ends up (to<0.5mm), because we have detector X-Y freedom. Wavefront sensing of the beam exiting OAP2 is again the way to measure the quality of the alignment. OAP2 will be adjusted in Tilt about the Local X and Y axes until the aberrations (only Astigmatism for the on-axis beam), are zero.

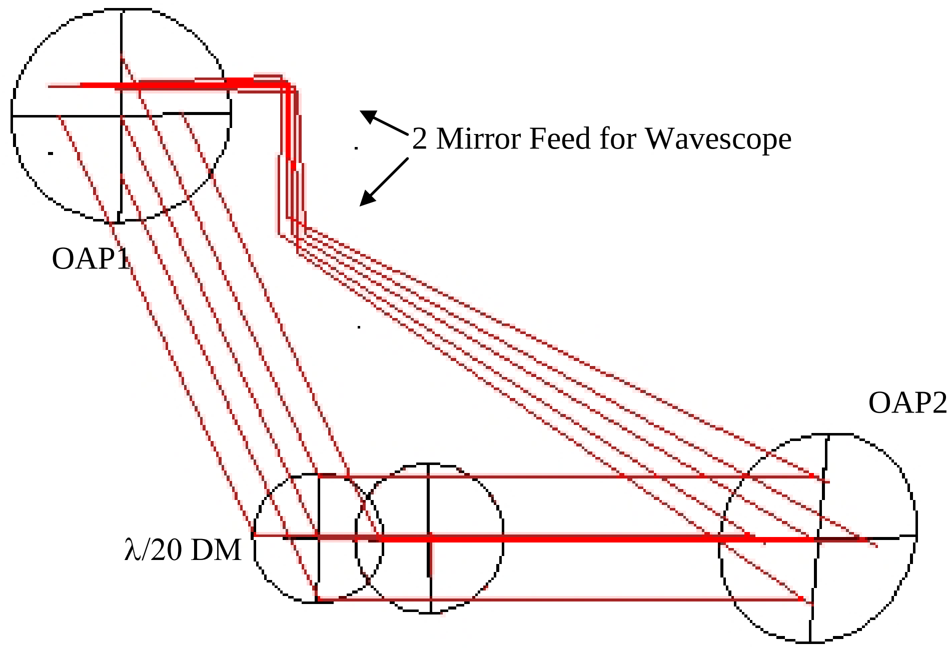
The practical difficulty in this setup is that tilting OAP2 moves the image. This forces adjustment of Wavescope. The convenient way to overcome this problem is to feed the OAP2 beam into the wfs devise by two adjustable mirrors. The setup is shown in Fig 4, where (a) is top view and (b) is looking along the optical axis. In this two mirror system setup, the first mirror will be the normal SAM CCD-Fold and the second a λ/10 λ25mm common mirror. The sensitivity of the single pass measurement is:

Sensitivity = 5.14λDeg (waves of Astigmatism per Degree of OAP2 tilt)

If the SAM image ends up too far from nominal position (>~0.5mm), adjust OAP2 by clocking Θ_z and using the decenter X-Tilt Θ_y method (5.2.3.a) above with Pivot on DM, until the image is in position. Now IQ (astigmatism) must be corrected by tilting DM back by the same angle.



(b)



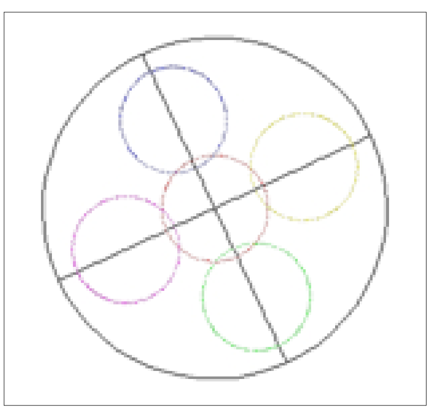
5.3.2.- Expected Results:

The OAP1 (a) and OAP2 (b) beam footprints for perfectly aligned parabolas with a pupil mask of Φ 50.2mm at the DM, are shown in Fig 5 and the IQ should be that of the SAM Optical Design (3).

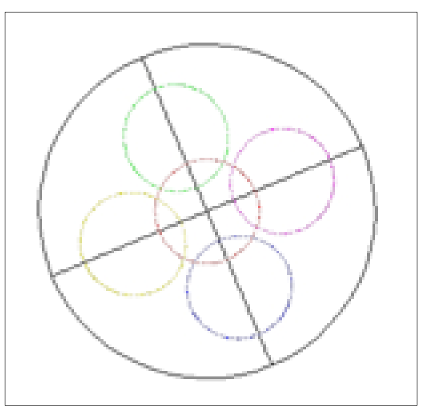
Warning Note: It may be useful to insist that the center of the SAM-ISB interface flange hole, the center of the Guider/Focal Plane plate hole and the center of the Nominal OAP1 Dummy support or hole, are important Reference Points that will be used throughout the lifetime of the instrument. The Optical Axis should be collinear to the last two points and x-displaced 67.5mm from the first, therefore they should be fabricated built-to-print with an accuracy <0.1mm the same as the requirement imposed on the Off-Axis-Distance of the OAPs. It is also desirable that the center of the Nominal_OAP2_Dummy support or hole, be fabricated in the same way.

Fig 5

(a)

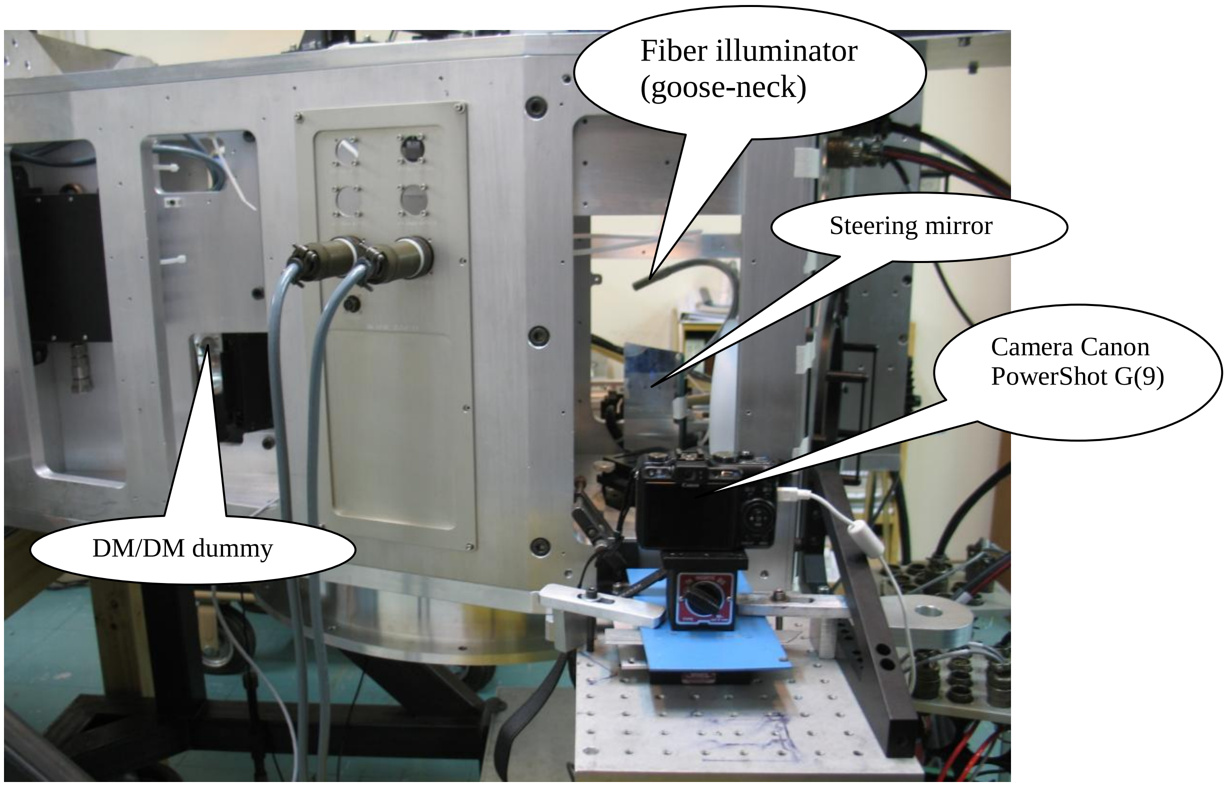


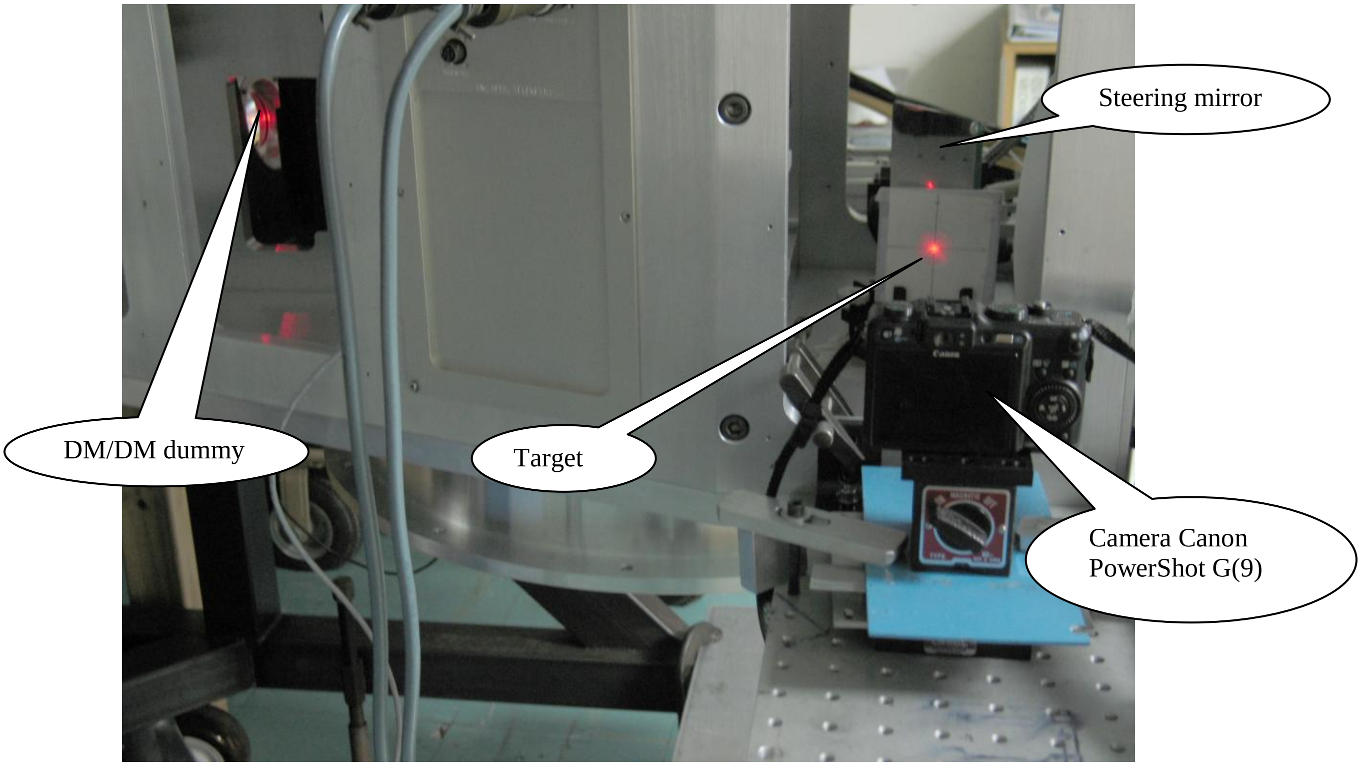
(b)



5.3.3- OAP2 laboratory alignment procedure :

DM dummy to DM adjustments:

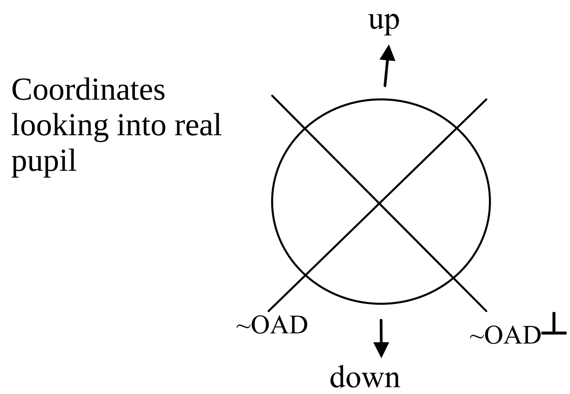




Adjustments check list:

- DM flat voltages in nominal position
- Fiber Illuminator as shown in fig. turn it on. Cover OAP1 on
- Manual focusing on the DM surface and 12x Magnification
- Take a picture w/remote capture or set a 2 sec. delay.
- Remove OAP1 cover and diffuser
- Turn on laser bam (Optical Axis)
- Put the diffuser x-hair target (set-up fig) on the laser beam. Manually focus the camera on target w/laser beam in center. Take a picture
- Turn DM voltages off and remove DM
- Mount DM dummy
- Check laser beam position on target. Take snapshot
- Put back cover and diffuser paper on OAP1. Turn on fiber illuminator(goose-neck). Focus camera on DM dummy surface and take a snap-shot.
- Two arrays of measurements…
  1. pupil DM dummy relative displacement w/r pupil DM
  2. DM dummy and DM beams on target give relative tilt measurement

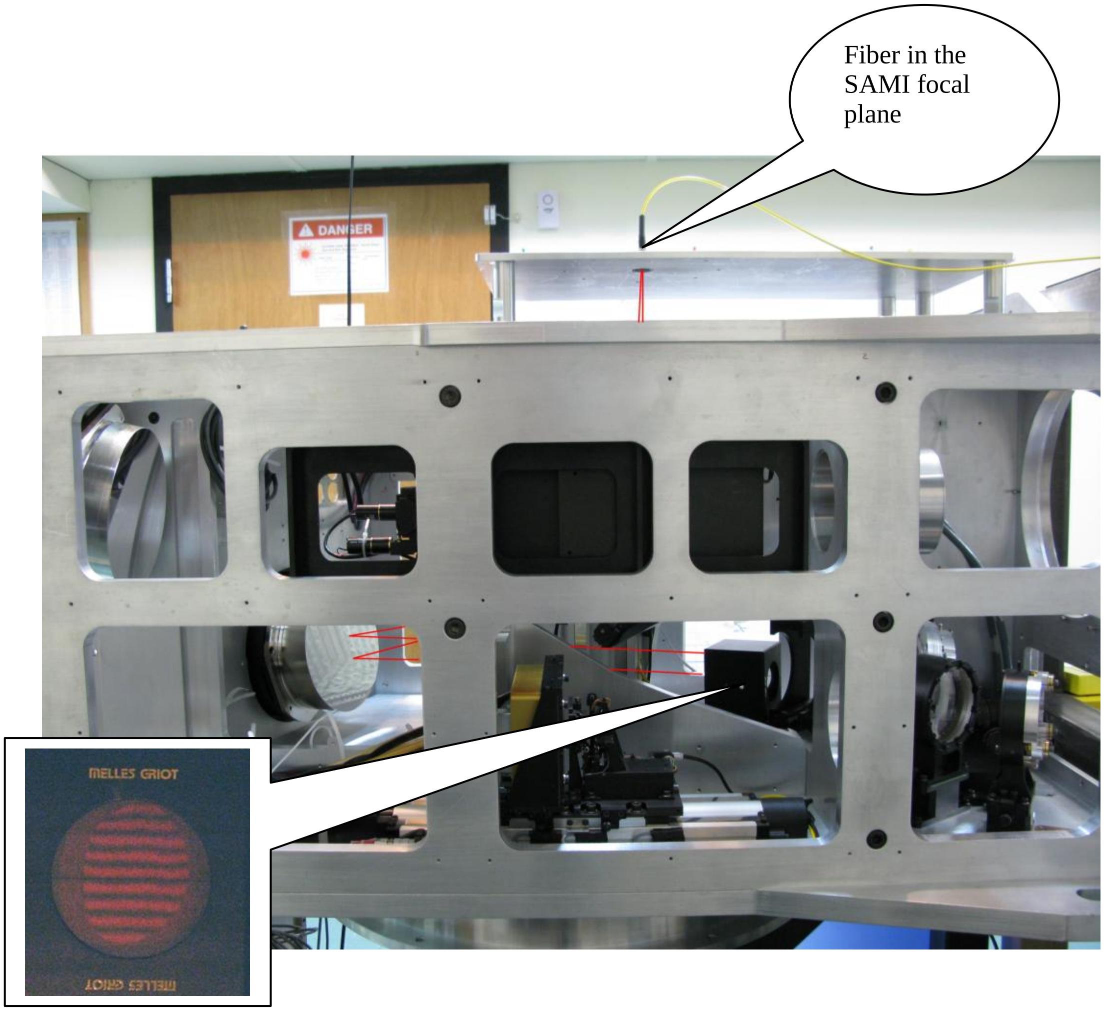
Results:



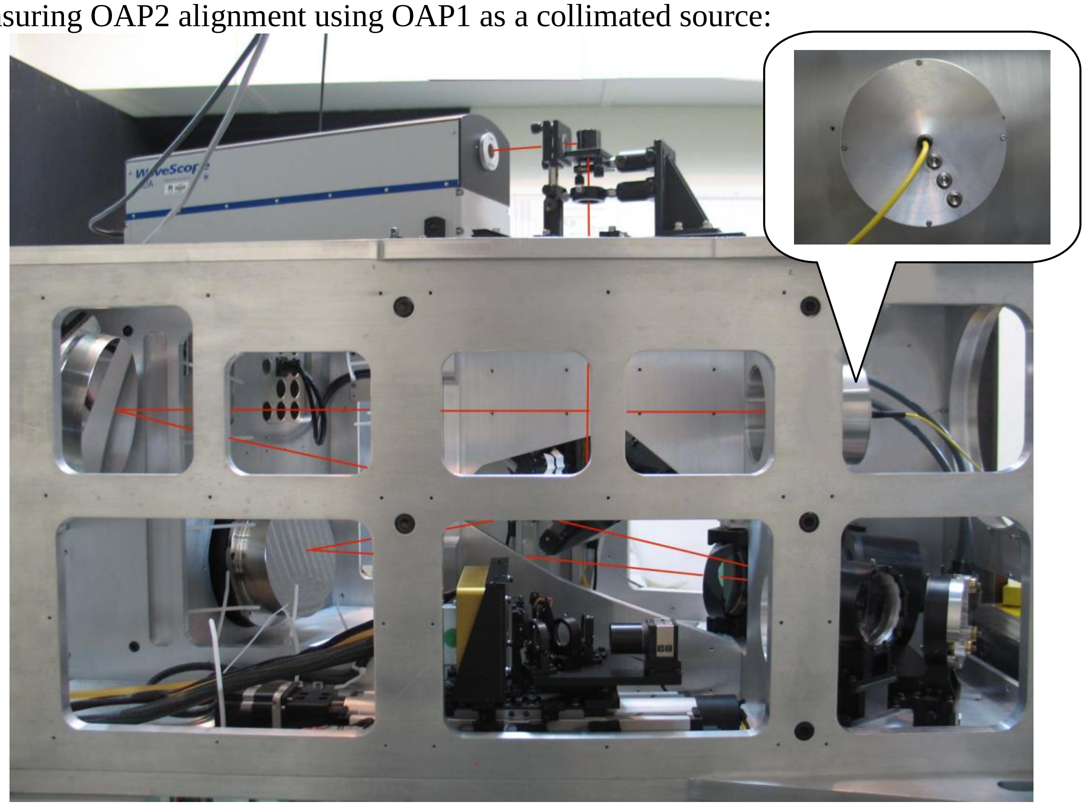
<u>Displacement</u>
DM dummy is displaced 0.06mm down in the OAD direction 0.13 down in the OAD⊥ direction w/r to DM

<u>Tilt</u>
DM dummy beam displacement w/r to the DM beam at the target position is 0.26mm and the distance from DM to x-hair target is 760mm, thus the angular error between beams is 0.18mrad. So DM dummy to DM angular mismatch =0.09mr

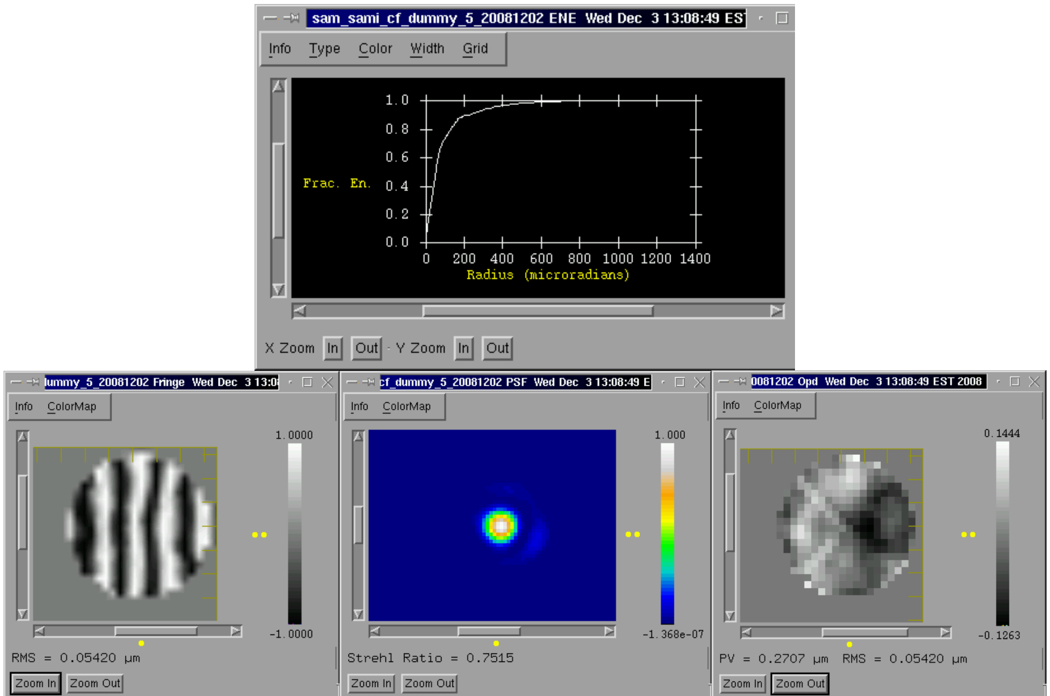
Checking OAP2 focus:



Measuring OAP2 alignment using OAP1 as a collimated source:



The aligned OAP2(best compromise).
Wave Scope results on axis and through the DM dummy



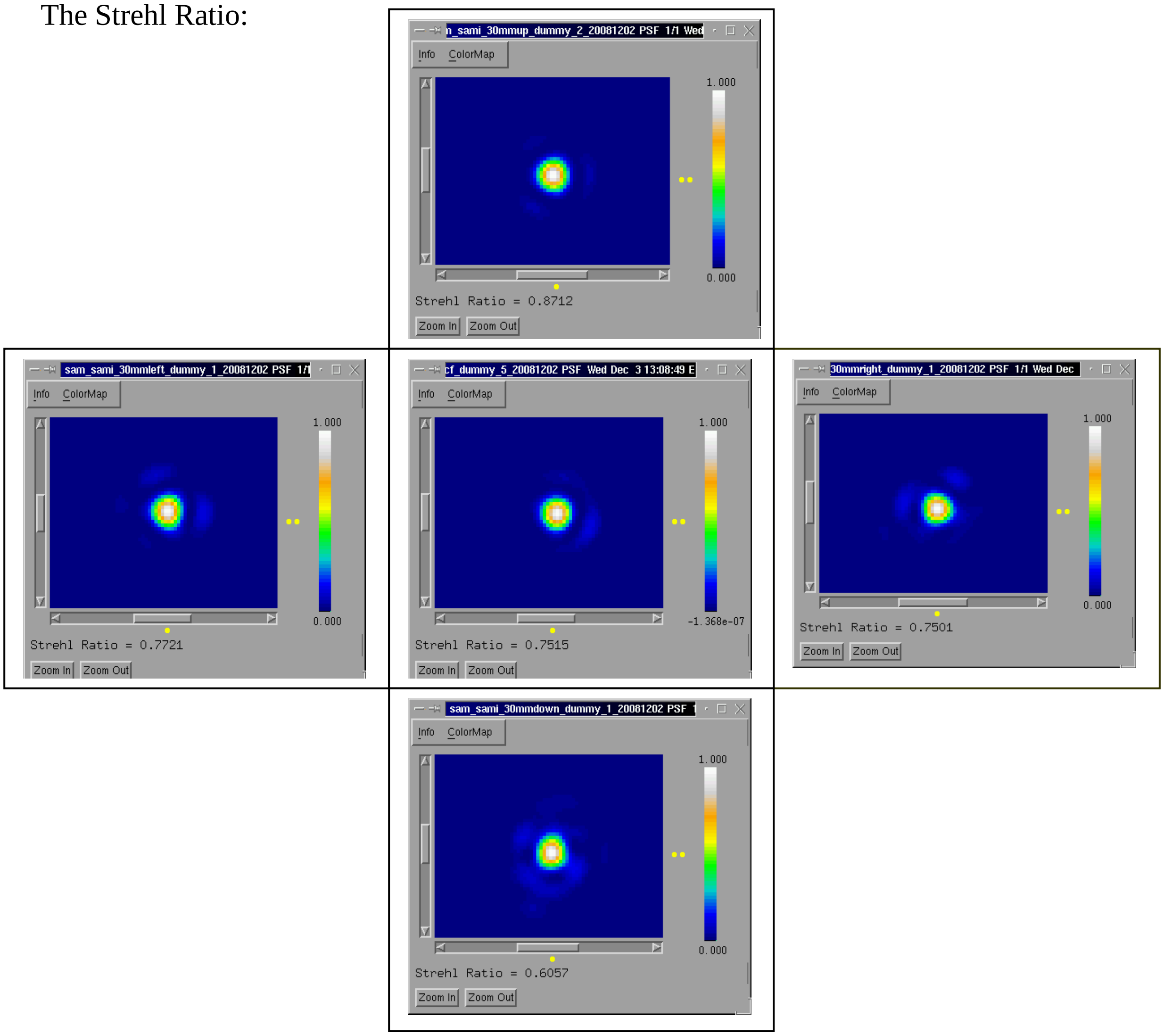
Zernike Coefficients

Index	Coefs(µm)	Equation
1	-0.057912	# rcos(t) (X Tilt)
2	0.014319	# rsin(t) (Y Tilt)
3	-0.000000	# 2r^2-1 (Focus)
4	-0.044578	# r^2cos(2t) (0 Astigmatism)
5	0.017062	# r^2sin(2t) (45 Astigmatism)
6	0.072158	# (3r^2-2)rcos(t) (X Coma)
7	-0.018103	# (3r^2-2)rsin(t) (Y Coma)
8	-0.028836	# 6r^4-6r^2+1 (Spherical)
9	0.001857	# r^3cos(3t)
10	-0.032878	# r^3sin(3t)
11	0.012569	# (4r^2-3)r^2cos(2t)
12	-0.004868	# (4r^2-3)r^2sin(2t)
13	-0.012873	# (10r^4-12r^2+3)rcos(t)
14	-0.001137	# (10r^4-12r^2+3)rsin(t)
15	0.014816	# 20r^6-30r^4+12r^2-1
16	-0.023622	# r^4cos(4t)
17	-0.023834	# r^4sin(4t)
18	-0.007202	# (5r^2-4)r^3cos(3t)
19	0.015885	# (5r^2-4)r^3sin(3t)
20	-0.013870	# (15r^4-20r^2+6)r^2cos(2t)
21	0.002945	# (15r^4-20r^2+6)r^2sin(2t)
22	0.003686	# (35r^6-60r^4+30r^2-4)rcos(t)
23	0.015993	# (35r^6-60r^4+30r^2-4)rsin(t)
24	0.019361	# 70r^8-140r^6+90r^4-20r^2+1
25	0.004174	# r^5cos(5t)
26	0.017914	# r^5sin(5t)
27	-0.013120	# (6r^2-5)r^4cos(4t)
28	-0.004480	# (6r^2-5)r^4sin(4t)
29	-0.002373	# (21r^4-30r^2+10)r^3cos(3t)
30	-0.007040	# (21r^4-30r^2+10)r^3sin(3t)
31	0.019672	# (56r^6-105r^4+60r^2-10)r^2cos(2t)
32	0.012721	# (56r^6-105r^4+60r^2-10)r^2sin(2t)
33	-0.010636	# (126r^8-280r^6+210r^4-60r^2+5)rcos(t)
34	-0.010114	# (126r^8-280r^6+210r^4-60r^2+5)rsin(t)

WaveScope over the field:

The Image Quality over the 3'x 3' square SAMI Focal Plane (Radius=30mm). The OPD was measured with the AOA Wavescope Shack-Hartmann (20081202).

The Strehl Ratio:



Note: There is a residual misalignment astigmatism mainly in the up-down direction, probably due to OAP1 off-axis distance not well adjusted because it is at the end of its adjustment range (tb fixed during anodization). Trefoil on all off-axis images as shown by the corresponding field Zernike coefficients below, hopefully due to the OAP's mounts, should be corrected by the new mounts design (already fabricated).

The Zernike Coefficients:

```
# sam_sami_30mmup_dummy_2_20081202 Frame 1/1
# Wed Dec  3 19:19:10 EST 2008
# Zygo Zernike Coefficients
# Obscuration Ratio = 0.0000
#Index Coefs(microns) Equation
   1   -0.029413  # rcos(t) (X Tilt)
   2    0.010327  # rsin(t) (Y Tilt)
   3   -0.000000  # 2r^2-1 (Focus)
   4    0.016373  # r^2cos(2t) (0 Astigmatism)
   5    0.039714  # r^2sin(2t) (45 Astigmatism)
   6    0.021865  # (3r^2-2)rcos(t) (X Coma)
   7   -0.011666  # (3r^2-2)rsin(t) (Y Coma)
   8   -0.006646  # 6r^4-6r^2+1 (Spherical)
   9    0.061729  # r^3cos(3t)
  10   -0.011668  # r^3sin(3t)
  11    0.030087  # (4r^2-3)r^2cos(2t)
  12    0.001626  # (4r^2-3)r^2sin(2t)
  13    0.023974  # (10r^4-12r^2+3)rcos(t)
  14    0.001768  # (10r^4-12r^2+3)rsin(t)
  15    0.010829  # 20r^6-30r^4+12r^2-1
  16   -0.027789  # r^4cos(4t)
  17   -0.012545  # r^4sin(4t)
  18   -0.006379  # (5r^2-4)r^3cos(3t)
  19   -0.001617  # (5r^2-4)r^3sin(3t)
```

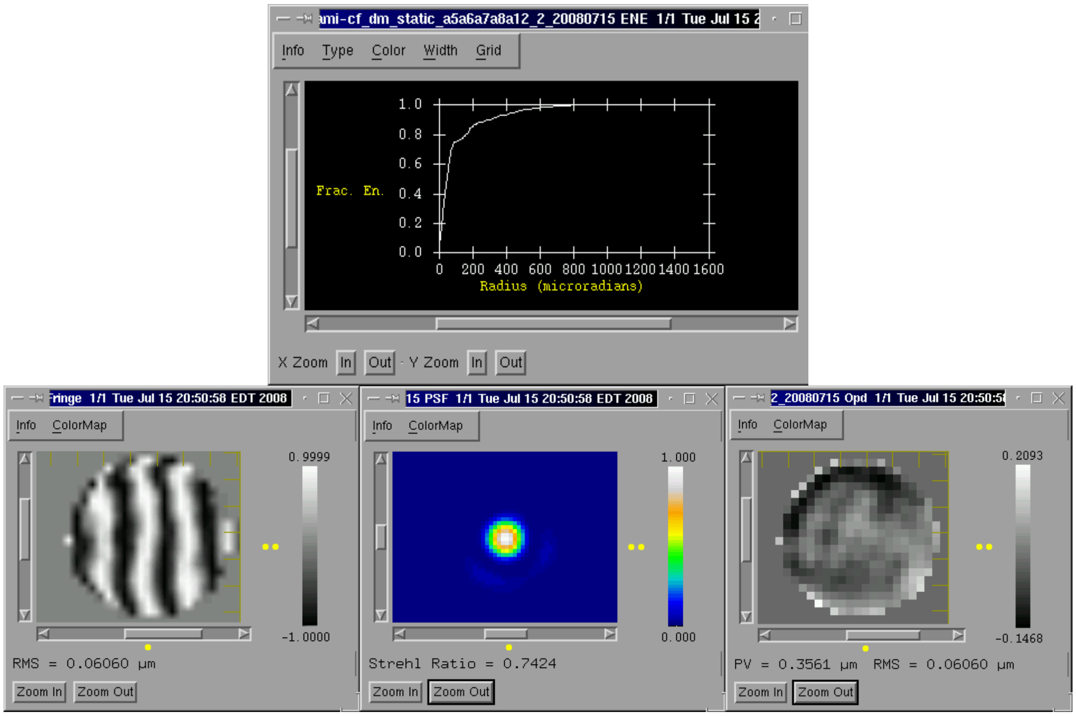
```
# sam_sami_30mmleft_dummy_1_20081202 Fr
# Wed Dec  3 21:17:26 EST 2008
# Zygo Zernike Coefficients
# Obscuration Ratio = 0.0000
#Index Coefs(microns) Equation
   1   -0.026763  # rcos(t) (X Tilt)
   2   -0.001066  # rsin(t) (Y Tilt)
   3   -0.000000  # 2r^2-1 (Focus)
   4   -0.040088  # r^2cos(2t) (0 Astig
   5   -0.031465  # r^2sin(2t) (45 Asti
   6    0.047070  # (3r^2-2)rcos(t) (X
   7    0.022035  # (3r^2-2)rsin(t) (Y
   8    0.021950  # 6r^4-6r^2+1 (Spheri
   9    0.068757  # r^3cos(3t)
  10   -0.050912  # r^3sin(3t)
  11    0.005598  # (4r^2-3)r^2cos(2t)
  12    0.007513  # (4r^2-3)r^2sin(2t)
  13   -0.029031  # (10r^4-12r^2+3)rcos
  14   -0.017124  # (10r^4-12r^2+3)rsir
  15    0.003179  # 20r^6-30r^4+12r^2-1
  16    0.009340  # r^4cos(4t)
  17    0.005365  # r^4sin(4t)
  18   -0.032595  # (5r^2-4)r^3cos(3t)
  19    0.040007  # (5r^2-4)r^3sin(3t)
```

```
   3   -0.000000  # 2r^2-1 (F
   4   -0.044578  # r^2cos(2t
   5    0.017062  # r^2sin(2t
   6    0.072158  # (3r^2-2)r
   7   -0.018103  # (3r^2-2)r
   8   -0.028836  # 6r^4-6r^2
   9    0.001857  # r^3cos(3t
  10   -0.032878  # r^3sin(3t
  11    0.012569  # (4r^2-3)r
  12   -0.004868  # (4r^2-3)r
  13   -0.012873  # (10r^4-12
  14   -0.001137  # (10r^4-12
  15    0.014816  # 20r^6-30r
  16   -0.023622  # r^4cos(4t
  17   -0.023834  # r^4sin(4t
  18   -0.007202  # (5r^2-4)r
  19    0.015885  # (5r^2-4)r
```

```
ght_dummy_1_20081202 Frame 1/1
3:32 EST 2008
efficients
io = 0.0000
ons) Equation
                  # rcos(t) (X Tilt)
                  # rsin(t) (Y Tilt)
   3    0.000000  # 2r^2-1 (Focus)
   4    0.034575  # r^2cos(2t) (0 Astigmatism)
   5   -0.078270  # r^2sin(2t) (45 Astigmatism)
   6   -0.029999  # (3r^2-2)rcos(t) (X Coma)
   7    0.024882  # (3r^2-2)rsin(t) (Y Coma)
   8   -0.024628  # 6r^4-6r^2+1 (Spherical)
   9   -0.065455  # r^3cos(3t)
  10    0.022925  # r^3sin(3t)
  11   -0.022706  # (4r^2-3)r^2cos(2t)
  12    0.037000  # (4r^2-3)r^2sin(2t)
  13    0.015238  # (10r^4-12r^2+3)rcos(t)
  14   -0.021072  # (10r^4-12r^2+3)rsin(t)
  15    0.012921  # 20r^6-30r^4+12r^2-1
  16   -0.040941  # r^4cos(4t)
  17    0.003440  # r^4sin(4t)
  18    0.027531  # (5r^2-4)r^3cos(3t)
  19   -0.011783  # (5r^2-4)r^3sin(3t)
```

```
#Index Coefs(microns) Equation
   1    0.012414  # rcos(t) (X Tilt)
   2    0.020540  # rsin(t) (Y Tilt)
   3   -0.000000  # 2r^2-1 (Focus)
   4    0.035566  # r^2cos(2t) (0 Astigmatism)
   5   -0.110915  # r^2sin(2t) (45 Astigmatism)
   6   -0.019421  # (3r^2-2)rcos(t) (X Coma)
   7   -0.062536  # (3r^2-2)rsin(t) (Y Coma)
   8   -0.012112  # 6r^4-6r^2+1 (Spherical)
   9    0.003200  # r^3cos(3t)
  10    0.049883  # r^3sin(3t)
  11    0.039615  # (4r^2-3)r^2cos(2t)
  12    0.041449  # (4r^2-3)r^2sin(2t)
  13    0.029388  # (10r^4-12r^2+3)rcos(t)
  14    0.041345  # (10r^4-12r^2+3)rsin(t)
  15    0.012346  # 20r^6-30r^4+12r^2-1
  16    0.002209  # r^4cos(4t)
  17    0.043625  # r^4sin(4t)
  18   -0.002691  # (5r^2-4)r^3cos(3t)
  19   -0.043947  # (5r^2-4)r^3sin(3t)
```

Wave Scope results at SAMI focus on axis through the real DM with flat voltages.



Zernike Coefficients

Index	Coefs(μm)	Equation
1	0.034846	# rcos(t) (X Tilt)
2	-0.065632	# rsin(t) (Y Tilt)
3	-0.000000	# 2r^2-1 (Focus)
4	0.013738	# r^2cos(2t) (0 Astigmatism)
5	-0.021930	# r^2sin(2t) (45 Astigmatism)
6	0.007035	# (3r^2-2)rcos(t) (X Coma)
7	-0.038893	# (3r^2-2)rsin(t) (Y Coma)
8	0.057045	# 6r^4-6r^2+1 (Spherical)
9	0.031966	# r^3cos(3t)
10	-0.005928	# r^3sin(3t)
11	-0.042139	# (4r^2-3)r^2cos(2t)
12	0.017740	# (4r^2-3)r^2sin(2t)
13	-0.019931	# (10r^4-12r^2+3)rcos(t)
14	0.057668	# (10r^4-12r^2+3)rsin(t)
15	0.030102	# 20r^6-30r^4+12r^2-1
16	-0.010458	# r^4cos(4t)
17	-0.008400	# r^4sin(4t)
18	0.007266	# (5r^2-4)r^3cos(3t)
19	0.011711	# (5r^2-4)r^3sin(3t)
20	-0.010153	# (15r^4-20r^2+6)r^2cos(2t)
21	-0.004572	# (15r^4-20r^2+6)r^2sin(2t)
22	-0.043504	# (35r^6-60r^4+30r^2-4)rcos(t)
23	0.040746	# (35r^6-60r^4+30r^2-4)rsin(t)
24	0.030219	# 70r^8-140r^6+90r^4-20r^2+1
25	0.008330	# r^5cos(5t)
26	0.017362	# r^5sin(5t)
27	-0.018441	# (6r^2-5)r^4cos(4t)
28	-0.005738	# (6r^2-5)r^4sin(4t)
29	0.010117	# (21r^4-30r^2+10)r^3cos(3t)
30	-0.001676	# (21r^4-30r^2+10)r^3sin(3t)
31	0.016033	# (56r^6-105r^4+60r^2-10)r^2cos(2t)
32	-0.016638	# (56r^6-105r^4+60r^2-10)r^2sin(2t)
33	0.013022	# (126r^8-280r^6+210r^4-60r^2+5)rcos(t)
34	-0.004453	# (126r^8-280r^6+210r^4-60r^2+5)rsin(t)
35	-0.007937	# 252r^10-630r^8+560r^6-210r^4+30r^2-1

The OAP1 mirror mount aligned position

OAP2 positioning values measured with a depthmeter:

Hard points position	**#1**	**#2**	**#3**
Spacing in mm	2.571	2.607	2.439
New hard points position	**#1-2**	**#2-3**	**#3-1**
Spacing in mm	2.591	2.497	2.405
Clocking	66.6º		
Decenter from fiducial marks	2.35 mm towards#3(opssite#1-2)		

6.- SAM WFS Path Alignment.

6.1.- Introduction:

The WFS path comprises three arrays of optical components: the first is the SAM-common-path which includes the SOAR focal plane, OAP1 and DM; second is the WFS-non-common path which includes the Dichroic, the WFS triplet camera and the WFS fold mirror; the third is the WFS Module (one for LGS and one for NGS) whose optical aberrations are "nulled" out by the S-H Reference.

6.2.- WFS Optical Axis Definition:

For the WFS path alignment, the visible reflecting Dichroic must be installed. Because of our Dichroic-mounting design, the reflective surfaces of all three dichroics, should end up in the same position.
At this stage, the SAM optical path is aligned up to the Dichroic. With the WFS Triplet lens removed, adjust the Dichroic in tip-tilt until the reflected beam is centered on the WFS Fold Mirror x-hair (X-Y error<0.5mm). Using the Dichroic and the WFS Fold as a two mirror system, align the beam exiting the WFS Fold to have the proper height (Y) and be collinear to the Line-of-Sight of the WFS Module Linear Stage when moving it from the NGS position to the farthest (7km) LGS position as in Fig 6. This line will be the Defined WFS Optical Axis and onto it will the WFS Modules be mounted.
This WFS Optical Axis definition is done in the following way:

i) There are two Module_BasePlate/Rails, one for LGS and one for NGS. The LGS Base Plate/Rail has no adjustments respect to the WFS Linear Stage on the contrary, it has position defining pins or hard-stops for reproducible mounting/dismounting. The NGS BasePlate/ Rail on the other hand has X displacement and □ y Tilt adjustments that will be clamped after alignment also to act as position defining hard-stops for reproducible mounting/dismounting.
ii) On the WFS Module Linear Stage, mount the LGS Module BasePlate/Rail (or a dummy of it) with only the S-H Bracket and the Field-Stop (or field-stop x-hair) installed in their nominal positions.

iii) Adjusting Tip-Tilt of Dichroic and WFS Fold, get the laser beam to be centered in the Field_Stop to <0.2mm and autocollimated to the S-H Bracket to <1' by placing a mirror against the machined referenced back side of the S-H Bracket, for all positions of Linear Stage along its 300mm range.

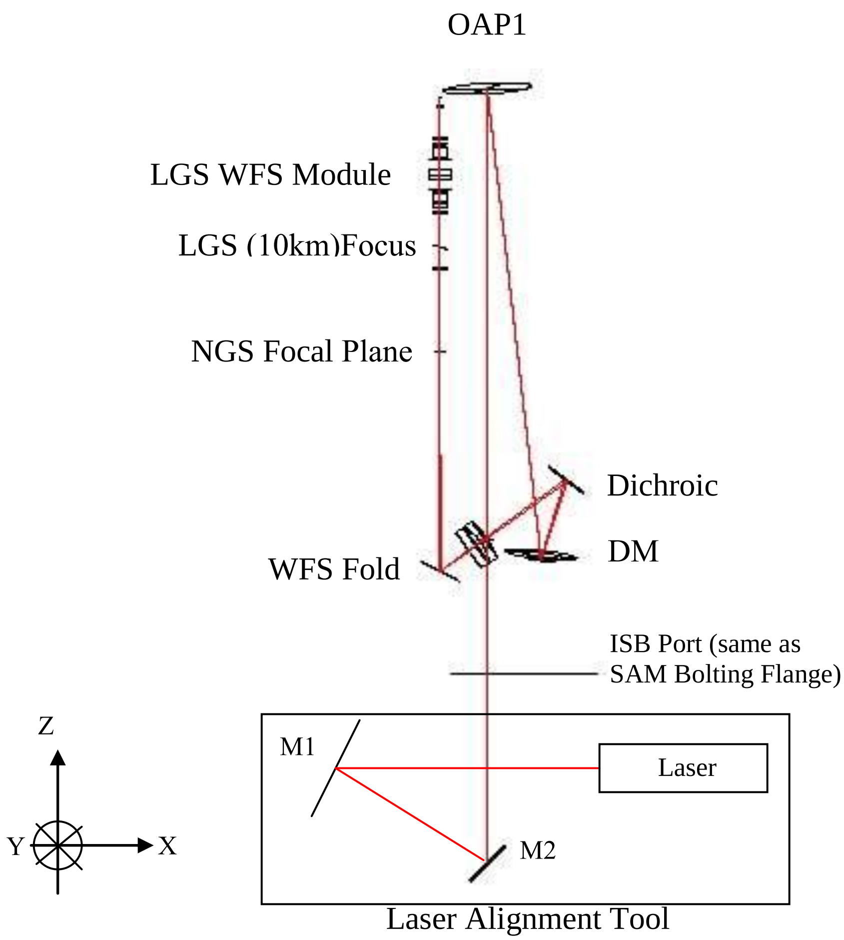
iv) Dismount the LGS Module BasePlate/Rail (or a dummy of it) from the Linear Stage and mount the NGS Module BasePlate/Rail (or a dummy of it) with Field-Stop (or field-stop x-hair) and S-H Bracket installed. Adjust X and □ y on the BasePlate/Rail w/r to the Linear Stage, until the beam is centered in the Field-Stop to <0.2mm and autocollimated to <1' as before. Move the NGS Module along the 300mm range of the Linear Stage and check that centering and autocollimation stays as specified. Clamping the adjustments now transform them into position defining hard-stops.

v) Mount the WFS Camera Triplet onto the WFS Optical Axis centering it with the X-Y (shimming) adjustments. Also check beam height and auto-collimation from lens vertex to keep Triplet Tilt <0.09º (tolerance). Finally re-check the WFS Optical Axis beyond the WFS Fold. If slightly displaced, repeat steps ii) through iv) iterating small adjustments on Dichroic, WFS Fold and Triplet.

vi) Mount the SOAR_FocalPlane_Target with the Single-mode_Fiber_patch-cable in the center, mount the DM_DummyPupil_Mask_□ 50.2mm and shine the laser through the system. Check centration at the triplet with the Height_Target, check that the image is centered in the Field-Stop for the NGS Module and then for the LGS Module when moving it along the 300mm range of the Linear Stage with the Single-mode_Fiber_patch-cable inserted at 7, 10 and 14Km LGS positions along the SAM input Optical Axis. If necessary, give small adjustments to Dichroic and WFS Fold (triplet will stay within decenter tolerance).

vii) Clamp the Dichroic, Triplet and WFS Fold mirror adjustments, they should not be touched here after. All the Optical Elements for both the LGS and the NGS Modules must be mounted and aligned onto the Optical Axis defined above, by using the adjustments defined for each component.

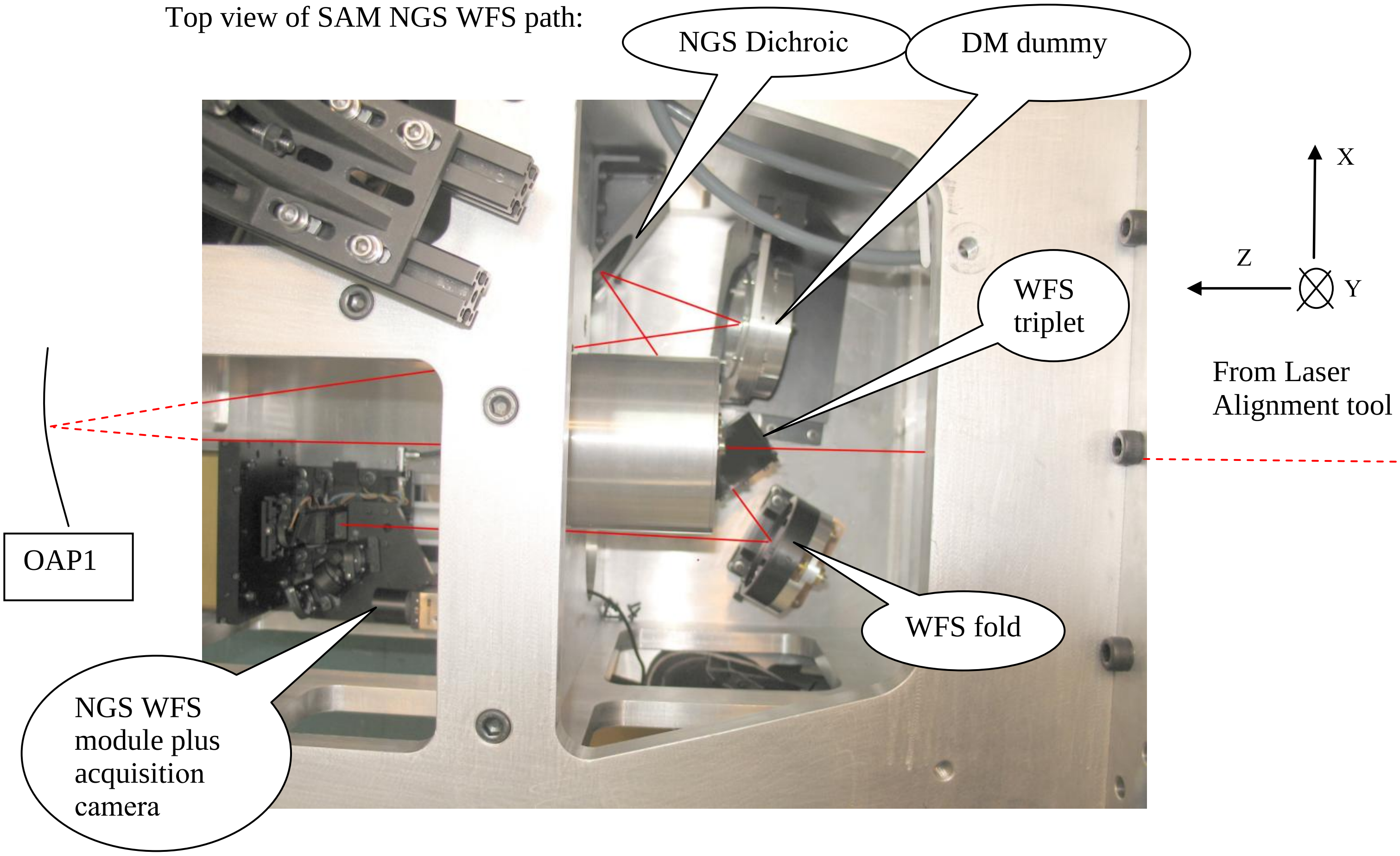
Fig 6



Note: the laser beam does not need focusing because in traversing the optical system, the beam spot will not exceed FWHM of ~3mm at any position along the path.

62.1.- The WFS Optical Axis Definition as done:

Top view of SAM NGS WFS path:



Alignment procedure in SAM Bench

6.3.- WFS path IQ measurements:

Previous to this alignment process and as part of the WFS Triplet acceptance testing, build a set-up at finite conjugates (e.g equivalent to 10km LGS), including Dichroic in reflection, WFS Triplet and WFS Fold. As the object point-source use the Single-mode_ fiber_patch-cable, feed the image to Wavescope and measure a Zernike coefficient array of aberrations.
In Zernike space, subtract the theoretical aberrations for this setup as given by Zemax from the above measurement. The result is the As-Built_WFS_Non-common-path_Zern.

Place the Wavescope at the NGS Focal Plane in Fig 6, insert the Single-mode_fiber_ patch-cable in the center field of the SOAR_FocalPlane_Target. Feed the fiber with laser light and measure the NGS WFS path aberration. From this Zernike file subtract the As-Built_WFS_Non-common-path_Zern. This gives the As-Built_SAM-common-path_ Zern.
During OAP2 alignment, Wavescope was installed at the SAM focal plane as shown in Fig 4. Once aligned, the last measurement is the SAM Science path aberration. From this Zernike file, subtract the As-Built_SAM-common-path_Zern. The result is the As-Built_ SAM-Non-common-path_Zern.

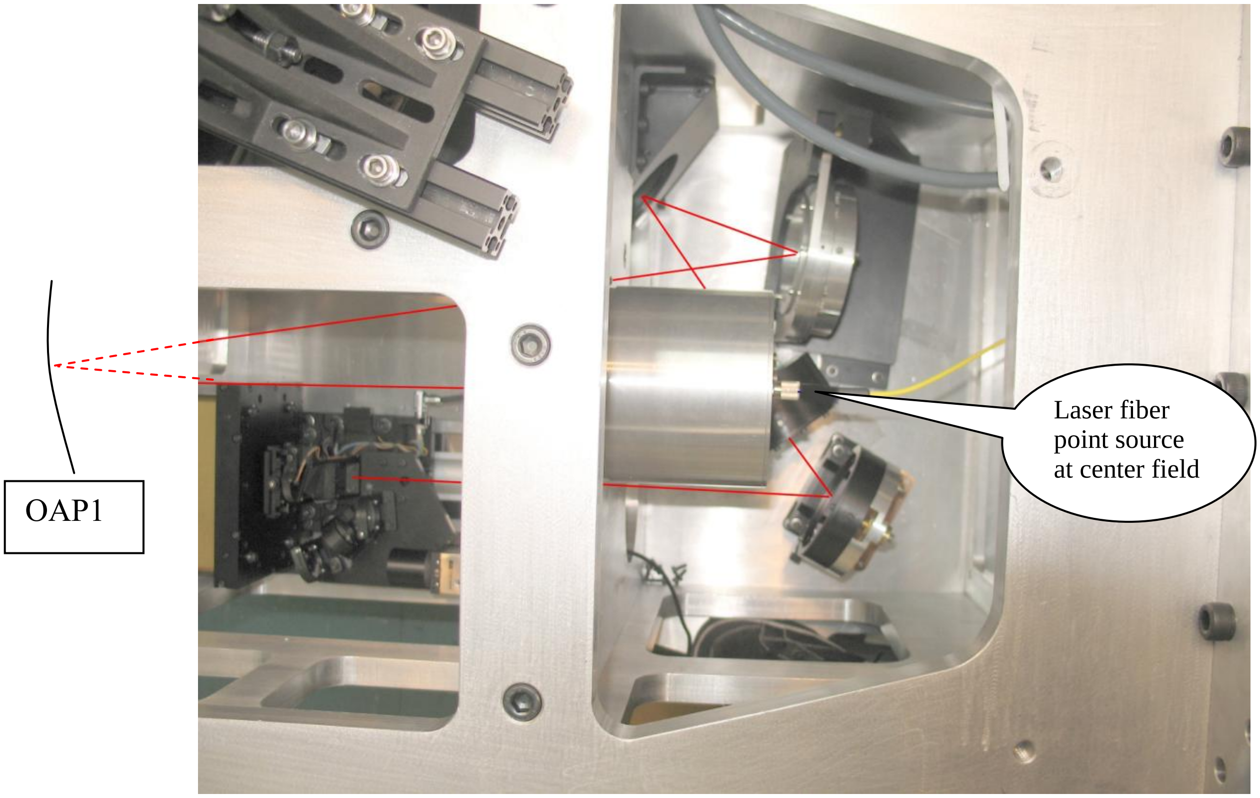
Compare the values of the As-Built_WFS_Non-common-path_Zern and the As-Built_ SAM-Non-common-path_Zern with the measurement Error Zernike file of Wavescope + experimental setup (tbd). If the non-common path errors are bigger than the error file, then they must be added as an offset to the S-H_NGS_Reference_file.

Place a standard Post+x-yFCconnector centered on the SAM Optical Axis defined in 5.1. and at the nominal Z position for an LGS at altitude 10km. Feed the fiber with He-Ne laser light and measure the 10kmLGS WFS path aberration (repeat for 7Km and 14Km). From this Zernike file subtract the As-Built_WFS_Non-common-path_Zern and the As-Built_ SAM-common-path_Zern. The result is the 10kmLGS_WFS-path_Residuals, namely Coma and Spherical aberration that should be equal to the values given by the Zemax model of SAM.
If this is so, then in general, the theoretical LGS_WFS-path_Residuals obtained with Zemax for any given LGS altitude, plus the As-Built_WFS_Non-common-path_Zern, plus the As-Built_SAM-Non-common-path_Zern should be added as an offset to the corresponding S-H_LGS_Reference file.

Having corrected in this way the Reference files both for NGS and LGS, the SAM WFS will now be measuring only the Common Path aberrations of a star, be it natural or laser.

Discussion: Although this procedure may be considered redundant, it is an exercise that should be done because it gives the as-built optical quantitative characterization for each subsystem of the instrument, which can then be compared to the design values. This is a one-time job and the proper time to do it is during integration and alignment.
In practice the offsets can be obtained in closed loop by optimizing the average science image quality, but this lacks the quantitative detail needed for instrument characterization (even if only for documentation purpose) specially in the LGS mode.

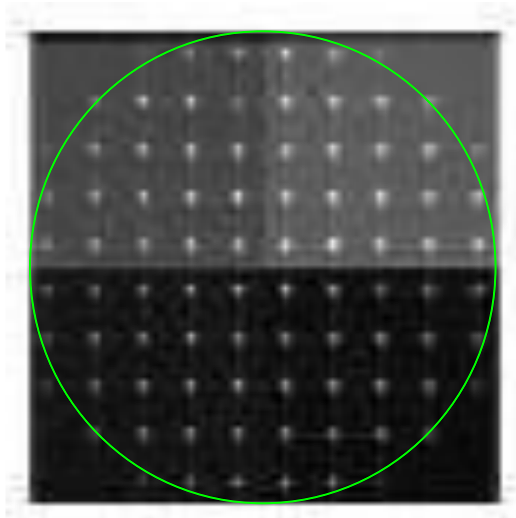
6.3.1.- The NGS WFS path IQ measurements as done:



IQ measurement procedure

Pupil size on LLA =1.97+/- 0.1mm. Measured in lab set-up with Peak microscope

Note: LLA in focus when lens let boundaries are thin clear lines.



The Zernike List of Coefficients at the WFS Camera focus:

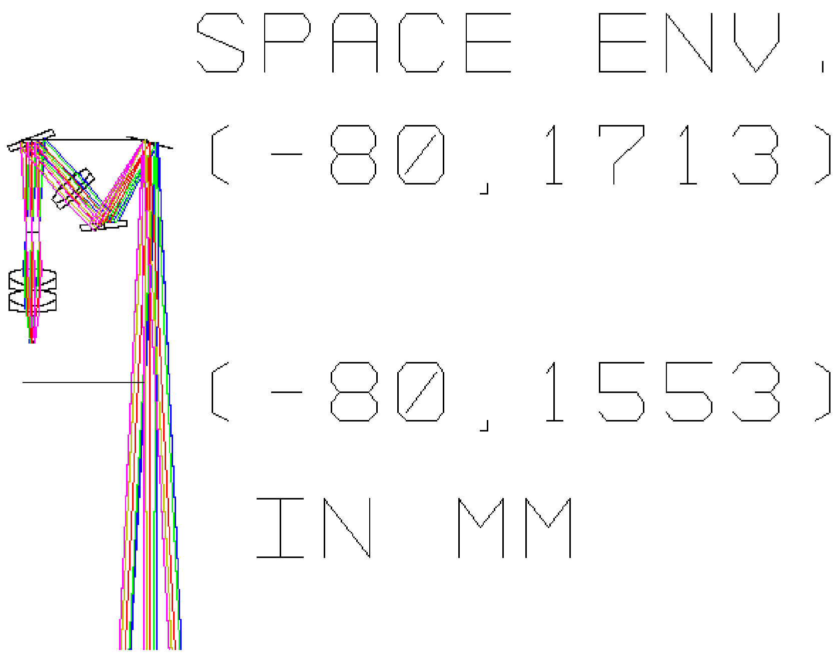
sam_WFS-path_zer.dummy_20080715.dat

#	Mon	Jun	16	14:14:56	EDT	2008
#	Zygo	Zernike	Coefficients			
#	Obscuration	Ratio	=	0		
#Index	Coefs(microns)	Equation				
2	-0.0060	#	rcos(t)	(X	Tilt)	
3	0.0980	#	rsin(t)	(Y	Tilt)	
4	-0.0460	#	2r^2-1	(Focus)		
5	-0.0560	#	r^2cos(2t)	(0	Astigmatism)	
6	-0.0420	#	r^2sin(2t)	(45	Astigmatism)	
7	-0.0180	#	(3r^2-2)rcos(t)	(X	Coma)	
8	0.0000	#	(3r^2-2)rsin(t)	(Y	Coma)	
9	0.0070	#	6r^4-6r^2+1	(Spherical)		
10	-0.0140	#	r^3cos(3t)			
11	-0.0460	#	r^3sin(3t)			
12	0.0340	#	(4r^2-3)r^2cos(2t)			
13	0.0080	#	(4r^2-3)r^2sin(2t)			
14	-0.0040	#	(10r^4-12r^2+3)rcos(t)			
15	0.0010	#	(10r^4-12r^2+3)rsin(t)			
16	-0.0080	#	20r^6-30r^4+12r^2-1			
17	-0.0150	#	r^4cos(4t)			
18	-0.0020	#	r^4sin(4t)			
19	0.0130	#	(5r^2-4)r^3cos(3t)			
20	-0.0020	#	(5r^2-4)r^3sin(3t)			
21	-0.0010	#	(15r^4-20r^2+6)r^2cos(2t)			
22	0.0020	#	(15r^4-20r^2+6)r^2sin(2t)			
23	0.0010	#	(35r^6-60r^4+30r^2-4)rcos(t)			
24	-0.0100	#	(35r^6-60r^4+30r^2-4)rsin(t)			
25	-0.0050	#	70r^8-140r^6+90r^4-20r^2+1			
26	-0.0070	#	r^5cos(5t)			
27	0.0070	#	r^5sin(5t)			

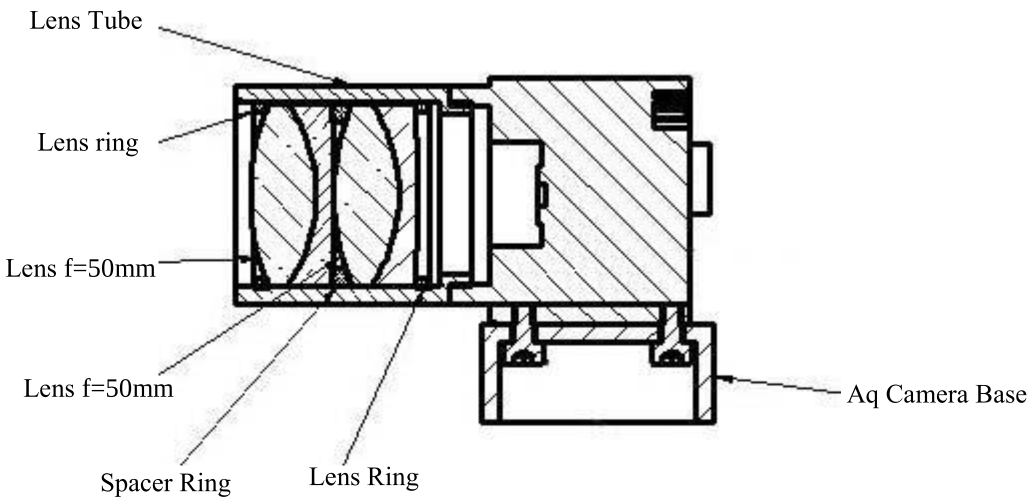
28	-0.0120	#	(6r^2-5)r^4cos(4t)
29	0.0140	#	(6r^2-5)r^4sin(4t)
30	-0.0100	#	(21r^4-30r^2+10)r^3cos(3t)
31	-0.0020	#	(21r^4-30r^2+10)r^3sin(3t)
32	0.0050	#	(56r^6-105r^4+60r^2-10)r^2cos(2t)
33	0.0010	#	(56r^6-105r^4+60r^2-10)r^2sin(2t)
34	0.0090	#	(126r^8-280r^6+210r^4-60r^2+5)rcos(t)
35	-0.0050	#	(126r^8-280r^6+210r^4-60r^2+5)rsin(t)
36	-0.0080	#	252r^10-630r^8+560r^6-210r^4+30r^2-1
37	0.0180	#	r^6cos(6t
38	-0.0040	#	r^6sin(6t)

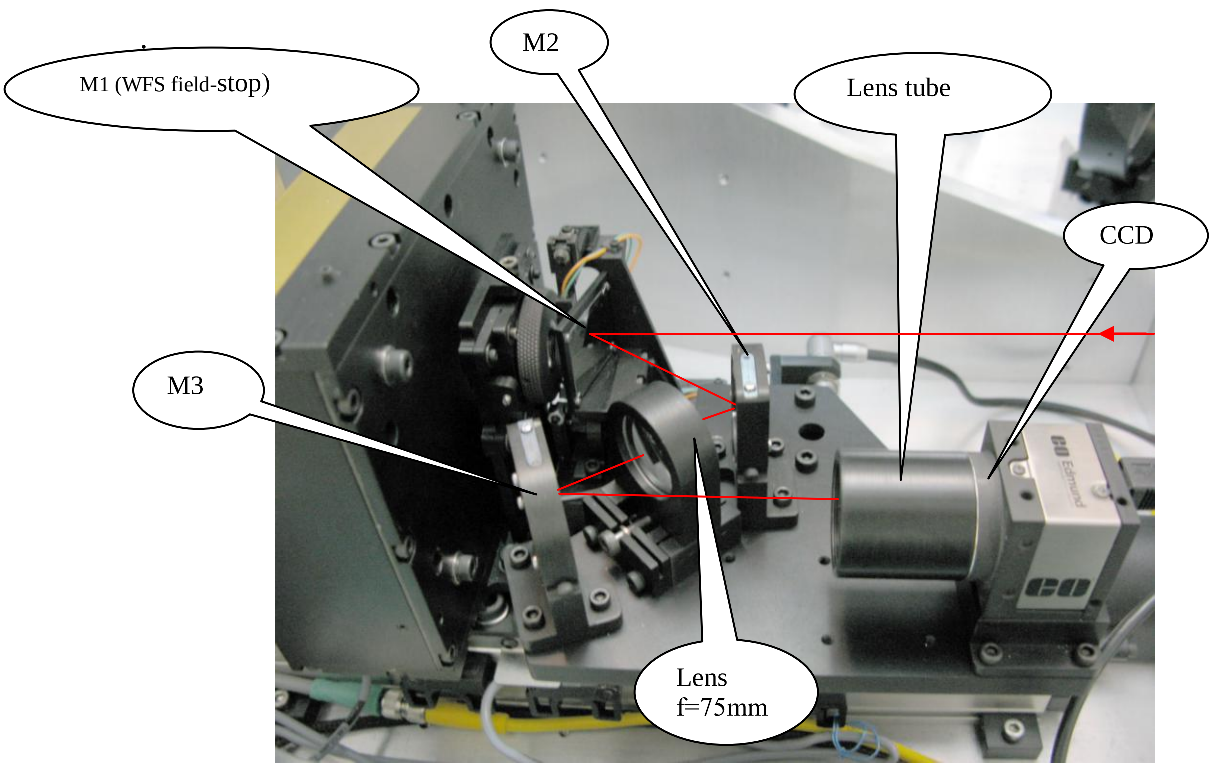
6.4. The NGS Acquisition Camera:

The Acquisition Camera design and its Space Envelope:



The as-built Acquisition Camera

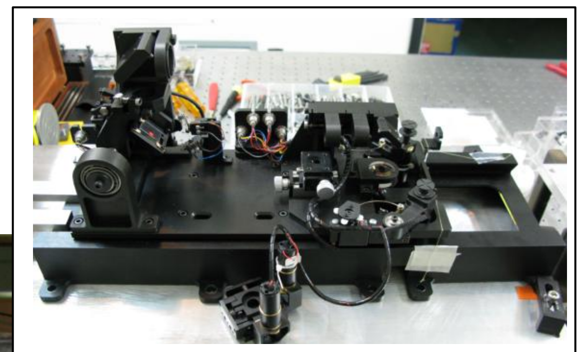




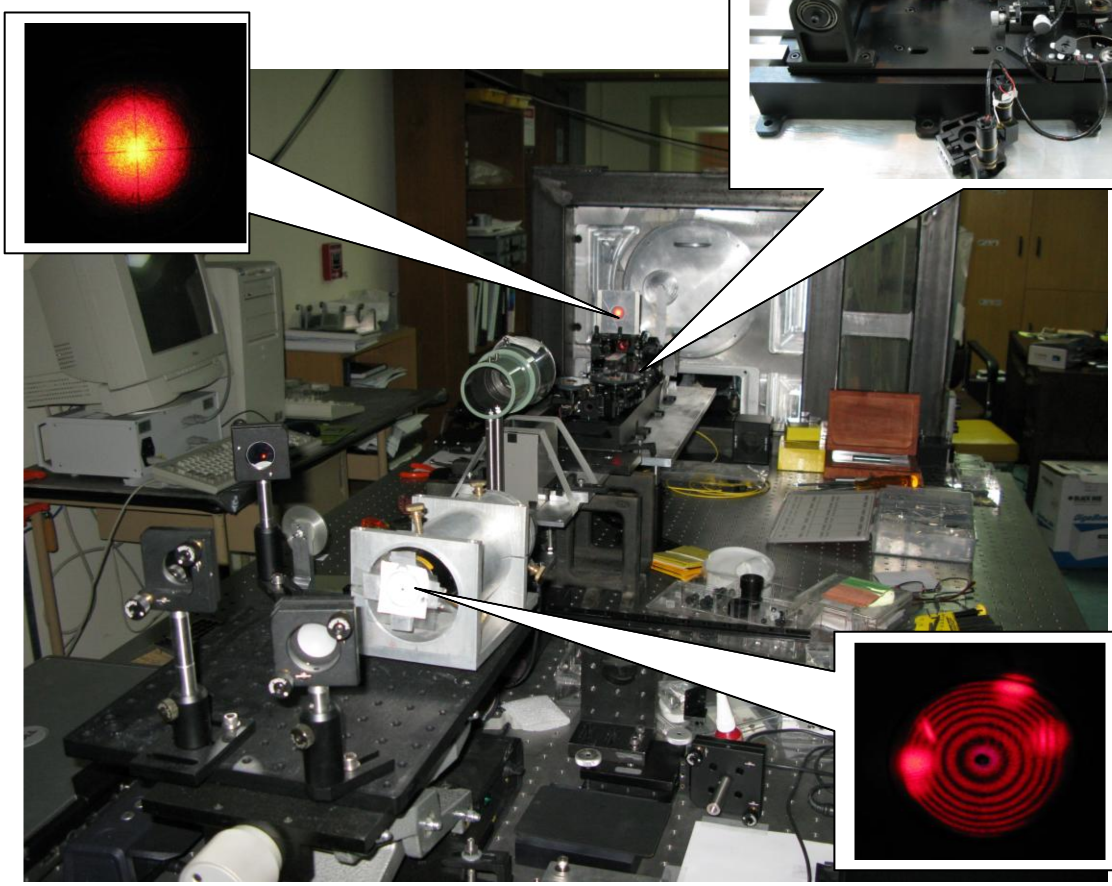
The integration and alignment Procedure:

- Mount f=50mm lenses into the tube at little bit shorter or longer distances than the design tells, in order to adjust and find the best focus.
- Make a F/# = ~16.625 collimator set-up on the optical table. Pupil-stop for TurSim is 6.4565mm, and the available lenses in the optics lab are of 100mm of

focal length, thus the working pupil-stop will be 6mm of diameter. The Beam must be able to pass through M3 mount to reach the camera
- Center the collimated beam on camera. Use camera software as help to find the best center.
- Once the beam is centered. Find the best beam focus on camera adjusting tube lenses distances. In order to adjust lenses distances disassemble the tube and modify lens ring's distance.
- Mount mirrors M2, M3 and the f=75mm lens at mid distances ready to be adjusted for the alignment into the SAM main module.
- Mount acquisitions camera structure into SAM main module as shown in fig.
- Center and adjust beam focus using its Opto-mechanical adjustments…



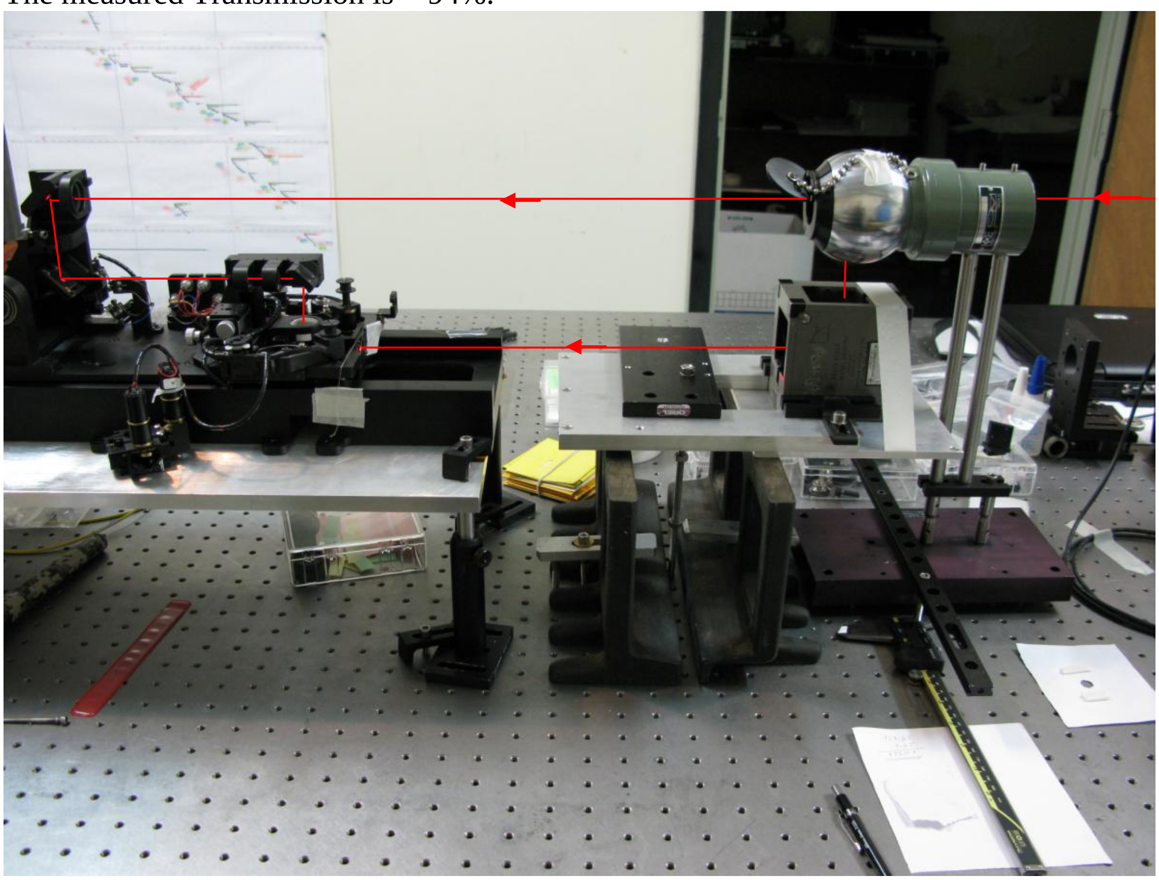
6.5 TurSim



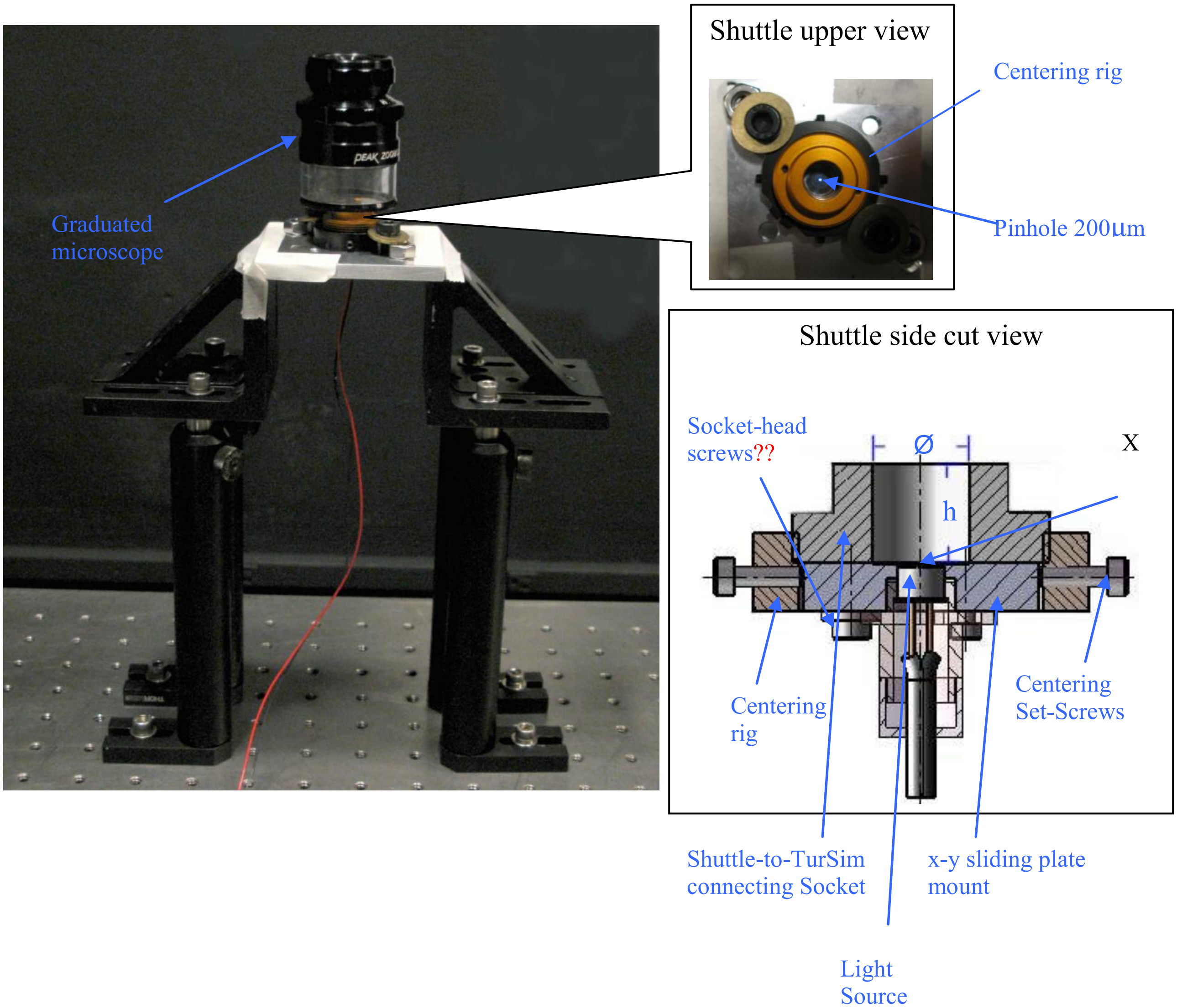
-Assembled the final tursim alignment setup. it uses two high quality pentaprisms (90 deg +/-0.5", from Blanco)

-two parallel laser beams: one is the sam optical axis and the second is at 124.22mm lower (the tursim light source position).
This second beam should enter tursim at the light source position and go through tursim and exit it overlapped to the sam optical axis.
how to do this?
-beam 2, autocollimated form tursim mechanical mount and centered on x-hair at source position (adjust whole tursim mount).
-adjust m1 to center on L1 and autocollimate from l1 vertex. adjust m2 to center on L2 and L3 and autocollimate from L1 and L2 vertices.
-adjust beam injection arm in tip and Az 'till beam1 is autocollimated from a mirror placed instead of L4 (the beam1 is already centered
in L4 by placing beam2 at 124.22mm from it if design correct, check!!...yes OK).
-adjust m3 and m4 to have beam2 centered on L4 and parallel to beam1 (centered into the alignment laser).

First measurement of transmission at 632.8nm throughout the science path.
Without Dichroic:
The measured Transmission is = 94%.



Centering the Light-Sources in the Exchangeable Sockets:



- Pinholes: 200µm

- Connecting Socket Inner Diameter (Ø):
    - Black =10mm
    - Orange =10mm
    - Red =8.4mm???

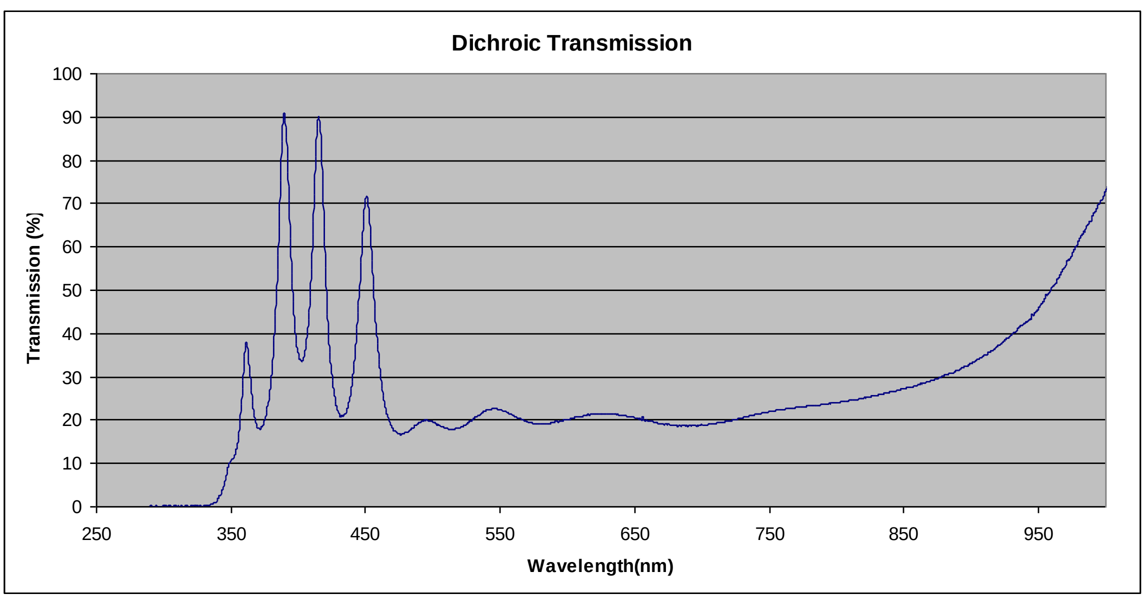
-Depth(h) from connecting socket's top down to pinhole surface:
    - Black: 9.67mm
    - Orange: 9.67mm
    - Red: 9.94mm

Procedure

- First Check if the light-sources are working.
- Screw "socket-head screws" (what is its name?).. and tighten them slightly enough to allow the adjustment of the x-y sliding mount by the centering set-screws.
- Set-up has to give good access to socket-head screws from below. It is needed for tightening them after the pinhole light-source is centered.
- Screw the shuttle into centering rig from the top. ~2 threads only in order to let the centering set-screws have access just to x-y sliding mount and not to the connecting socket
- Switch light-source on.
- Set Graduated microscope on shuttle's top.
- With the graduated microscope Measure the centering of pinhole light source w/r to connection socket. and with help of set-screws adjust the pinhole light source to the center.
- Once it is centered. tighten socket-head screws.

6.6 SAM Transmission Measurements

Dichroic measured with the OO Spectrometer agrees with both requested and delivered specs i.e. 75 - 80% Reflectance and 20 - 25% Transmission
from 500 - 800nm. Measured Dichroic Transmission (see SAM alignment manual) at 632.9nm = 20.7%.
Should be 70/30 it is more like 75/20.

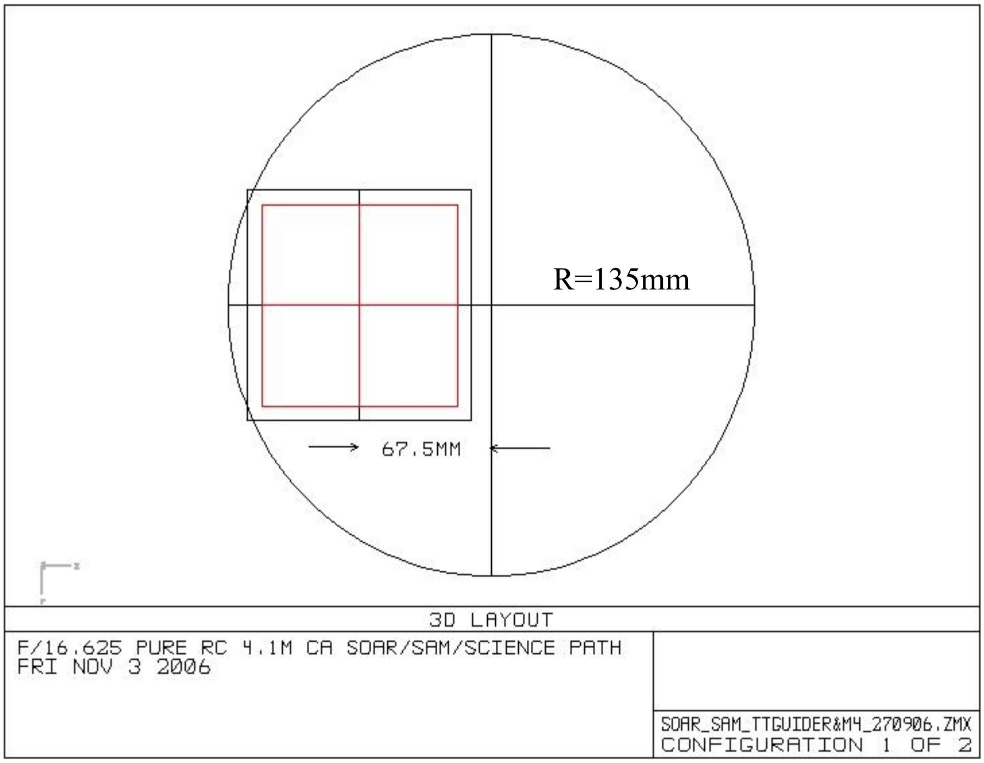


References:

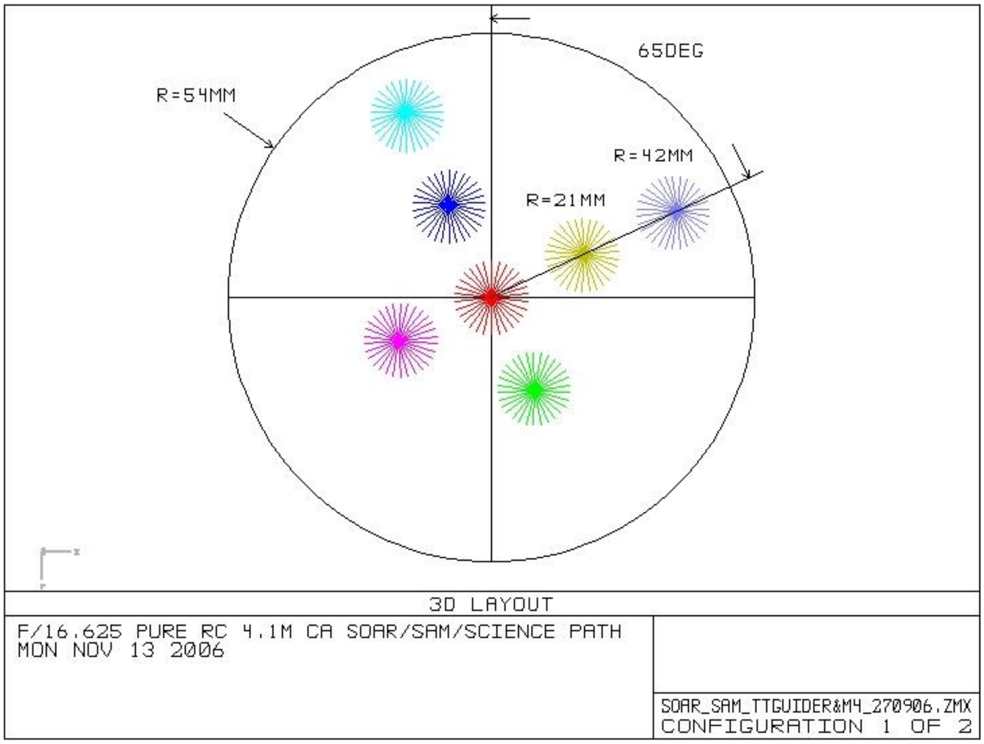
(1)SAM optical alignment, R.Tighe, SDN SAM-AD-02-2207.
(2)SAM Optical Design, SDN SAM-AD-02-2201,A.Tokovinin,S.Thomas,R.Tighe.
(4)Designing a S-H module of the WFS, SDN-AD-02-3203, A.Tokovinin.
(5)SAM WFS design, SDN SAM-AD-02-2209, R.Tighe.
(6)NGS WFS Acquisition Camera, R.Tighe, Zemax file SOAR_sam_NGSwfs_aq.cam_v0_test_290808.zmx
(7)TurSim: concepts, Sandrine Thomas, SDN SAM-AD-02-1204
(8) TurSim for SAM, Optical Design Update, R.Tighe, SDN SAM-AD-02-1204-A

Appendix on Tools and Analysis

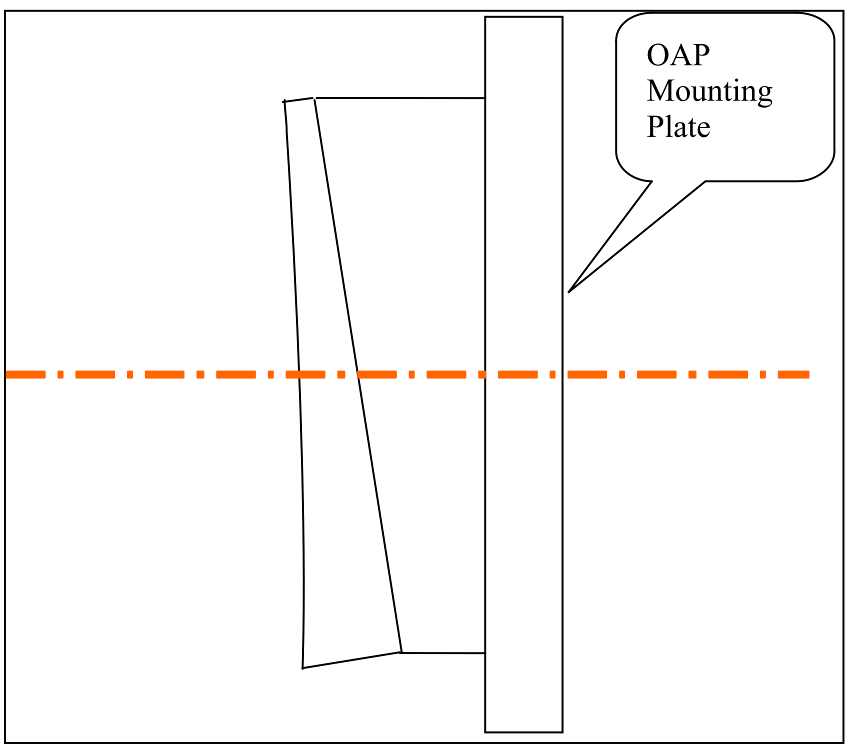
1) ISB_SAM_Port_Target:



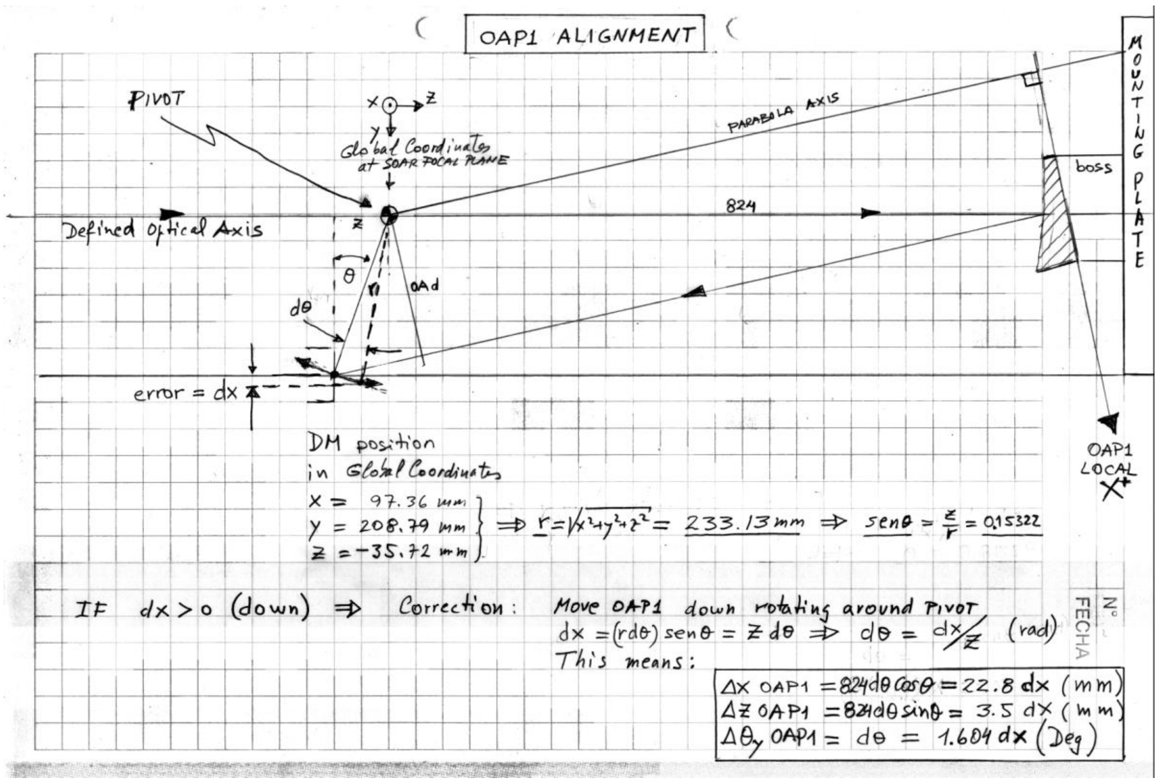
2) SOAR_FocalPlane_Target:



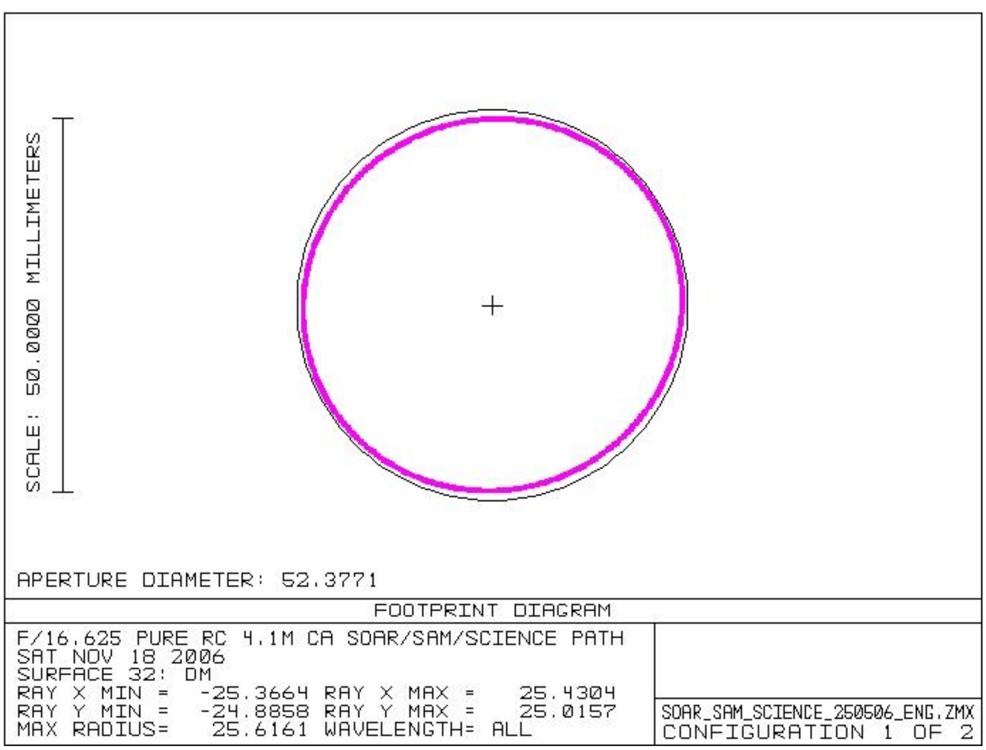
3) Nominal_OAP1_Dummy:



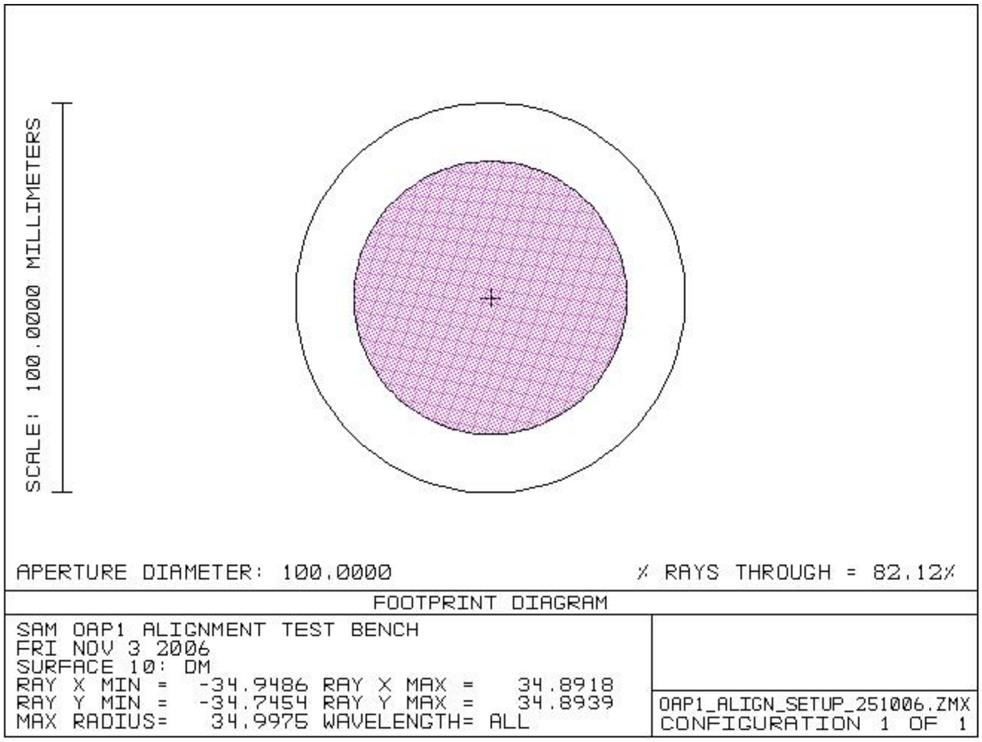
4) OAP1 Alignment Diagram:



5) DM_Pupil_Mask_Φ50.2mm(center field only):
(ellipse of ~50.8x49.9mm)

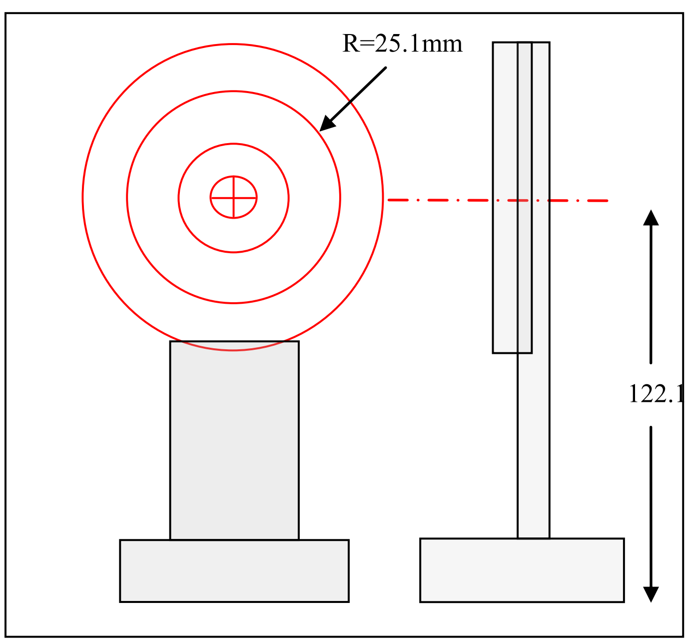


6) DM_Dummy_Pupil_Mask_Φ70mm (to mount on an external Φ100mm mirror):



7) DM_Dummy_Support: Will be designed such that the Flat Dummy DM Mirror can be positioned in two "states" by a gross adjustment, one state is auto-collimation position and the second is DM position simulation. At each one of these states, fine adjustment will be available.

8) Height_Target:



9) The SAMI focal plane Target: