



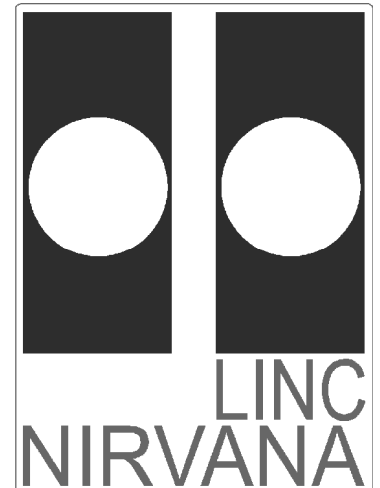
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Pupil Re-imager alignment procedure

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Issue	Date	Section/ Parag. Affected	Reason/Initiation/Documents/Remarks
0.1	22 December 2009	All	New alignment procedure for the GWS Pupile Re-Imager
1.0	12 February 2010	Section 2: added Section 4: added Section 5: modified Section 6.3: modified	Modifications after P. Bizemberger comments as an approver. Calculation checked: - test-camera replacement repeatability limit (< 0.58 mm to < 0.55 mm) - flat mirror alignment (0.001° to 0.003°)

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for the laser placed on the “Parabola side” of the Objective and a standard deviation of 0.022mm in centering and 0.006 degrees in tilt for the laser placed on the “CCD side” of the Objective. On the right an example of back-reflected spots configuration is shown. 6

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1 Scope

The scope of this document is to describe the alignment procedure for the GWS Pupil Re-Imager.

2 Applicable Documents

No.	Title	Number & Issue
AD1.	GWS Error Budget	LN-INAFP-DES-GEN-001

3 Acronyms and abbreviations

FoV	Field of View
FP15	LBT F/15 Focal Plane
GWS	Ground layer Wavefront Sensor
LBT	Large Binocular Telescope
PR-I	Pupil Re-Imager
SE	Star Enlarger
TT	Tip-Tilt

4 Goal of the Pupil Re-Imager alignment

After the components procurement and subsequent tests, a revised version of the Error Budget of the entire GWS has been presented in a memo (AD1). From that document, the required Pupil Re-Imager optical quality shall lead to a maximum RMS blur of 25 μ m over the four pupils re-imaged on the CCD.

The possible deterioration on the optical quality due to alignment indeterminations depends on the combination of defocus, tilt and de-center of the Parabolic mirror with respect to the Prime Focus Corrector.

The final blur on the pupils, due to PR-I optical quality, can be verified also without the rest of the GWS. If you feed the PR-I with a wide collimated beam, resembling one of the directions of the rays that will enter the PR-I itself, these rays should focus on a diffraction-limited spot on the focal plane, if the PR-I is perfectly aligned. The tolerance on that spot RMS radius is exactly the same as for the RMS blur of the pupils, as it can be easily verifiable geometrically.

The alignment concept is to illuminate the PR-I with a wide collimated beam and to align the Parabolic Mirror with respect to the Prime Focus Corrector in order to optimize the optical quality along the field of view of interest. One should notice that the FoV of the PR-I as a stand alone camera is not the 2' to 6' FoV of the GWS. The PR-I FoV, indeed, is depending on the SE exit F/# (187.5) and the divergence angle of the pyramids (0.56573 $^{\circ}$), and it corresponds to a 0.88 $^{\circ}$ FoV.

Hereafter, we will consider a procedure in which a collimated beam is focused by the PR-I; the goal of the procedure will be to have a RMS spot radius lower than 25 μ m in a FoV which is 0.88 $^{\circ}$ in diameter.

5 Alignment tolerances

We already said that the Pupil Re-Imager optical quality shall lead to a RMS spot radius lower than $25\mu\text{m}$ over the complete FoV of the PR-I intended as a stand-alone camera.

We explored several ways to check separately defocus, tip-tilt and de-centering of the Parabolic Mirror with respect to the Prime Focus Corrector, to define the best-achievable combination of tolerances for the three of them in order to be sure we can reach the goal we set at the beginning.

We fixed the focus tolerance at 0.5mm, which is achievable with mechanical positioning of the Parabola.

The alignment procedure explained in the following should allow us to reach a final alignment better than 0.1mm in de-centering and 0.02° in tip-tilt.

6 Procedure

The procedure is divided into 6 main Phases, described in the following sections. The overall idea is to illuminate the PR-I with a collimated beam and to align the Parabola to the Objective (Prime Focus Corrector) by checking the optical quality over the FoV and the amount of coma on a defocused image of the reference spot on axis.

This fact poses a problem: we need to have a reference spot, within a certain precision, close to the center of the field, being the aberrations field dependent. This means that there must be a preliminary procedure that has the purpose to align the reference beam arriving on the parabola (which means the 2 flat mirrors which are folding the light towards the Parabola, as it will be clearer in the following, and as it can be seen from Fig. 7 where the optical setup that will be used is shown).

From Zemax computation we have taken as a maximum off axis error $\pm 0.3^\circ$, which is compatible with having a RMS spot radius lower than $25\mu\text{m}$ over the complete FoV (0.88° , at the edges of the four pupils re-imaged on the final CCD), once all the other source of error are added and the CCD focus is optimized, as it can be seen in Fig. 1 and Fig. 2.

The off axis of the reference incoming beam is produced by several sources of error, which are dependent on the particular procedure adopted for the alignment, and will be shown in the following sections. This is why, to arrive to this procedure, we have first double-checked each error source, when possible with optical test on the bench, otherwise with Zemax computation, in a way to have a total budget in agreement with the maximum acceptable off-axis of the reference beam of $\pm 0.3^\circ$.

To better understand the various sources of error, we have to outline the concept of the alignment, that will be developed in 6 different Phases, and by the means of an optical setup which foresees the usage of an additional flat folding mirror (with the aim of folding the light toward the PR-I), of an optical fiber (acting as reference source) and of an off-axis parabolic mirror (collimating the beam).

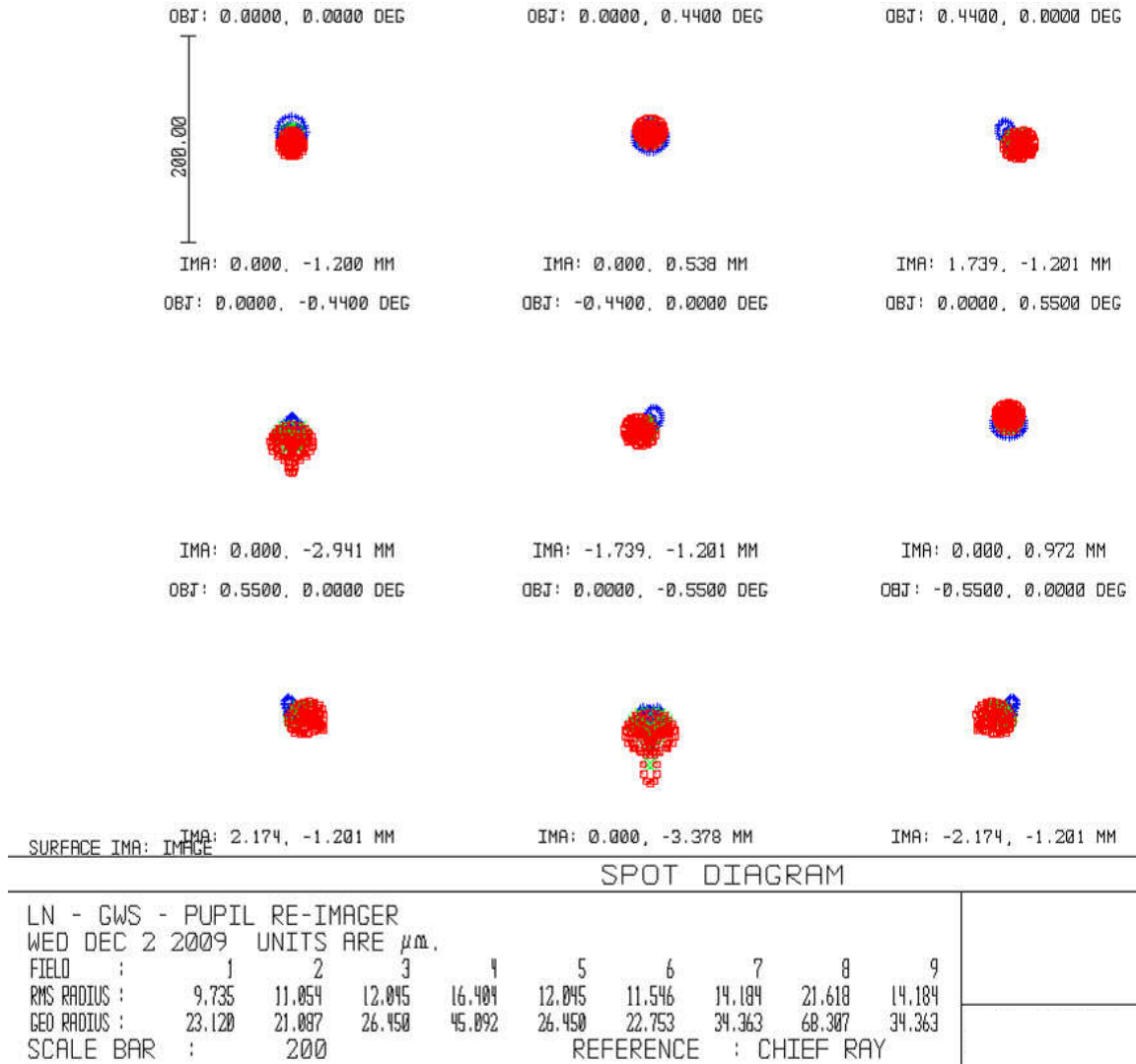


Fig. 1: RMS spot radius in the entire FoV, with 0.5mm of defocus and an alignment obtained with a 0.3° off-axis of the reference incoming beam. The CCD focus has been optimized minimizing the RMS spot radius on the whole FoV. Field 1 represents the on-axis beam, fields from 2 to 5 represent the edges of the four pupils that will be re-imaged by the PR-I on the final CCD, while fields from 6 to 9 are the four corners of the CCD (so, they are already outside the utilized FoV). Other error sources introduced during the Phase 4 and Phase 5 of the alignment procedure are not considered in this spot diagram. These sources introduce an RMS blur contribution smaller than the ones already considered. A complete error budget will be summarized in Table 3.

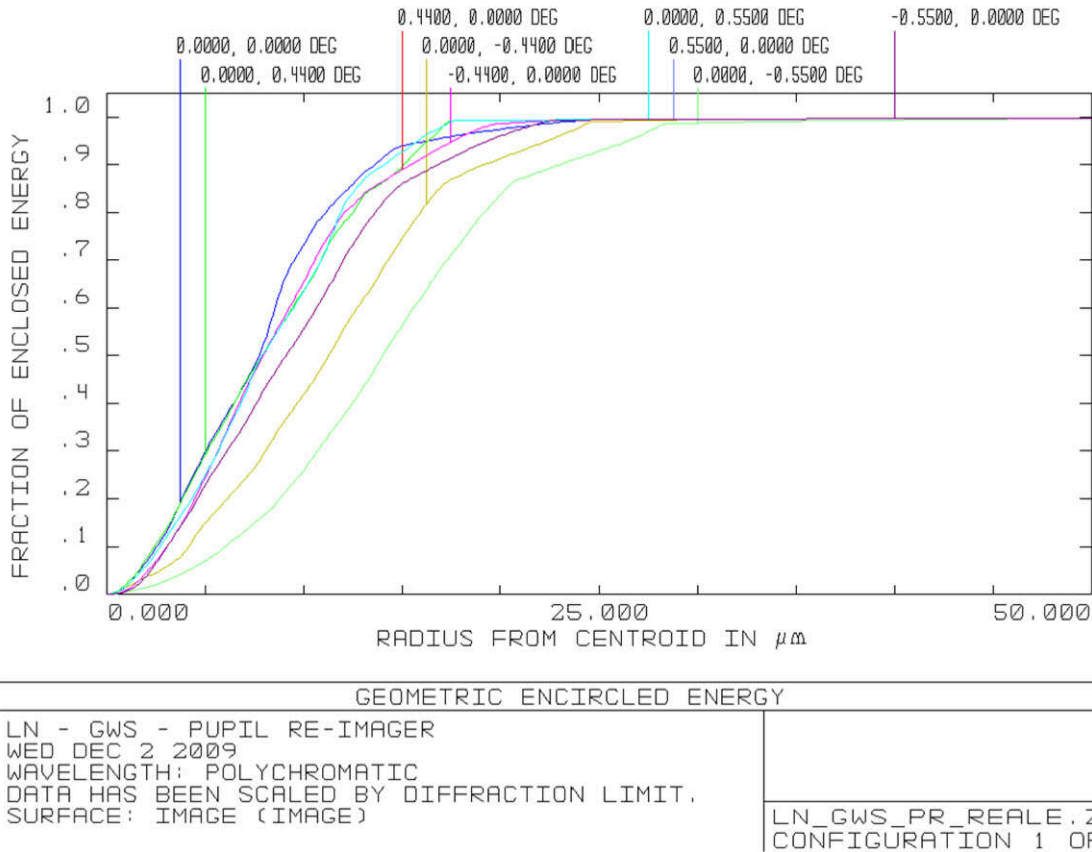


Fig. 2 Geometric encircled energy in the entire FoV, with 0.5mm of defocus and an alignment obtained with a 0.3° off-axis of the reference incoming beam. The CCD focus has been optimized minimizing the RMS spot radius on the whole FoV. Field 1 represents the on-axis beam, fields from 2 to 5 represent the edges of the four pupils that will be re-imaged by the PR-I on the final CCD, while fields from 6 to 9 are the four corners of the CCD (so, they are already outside the utilized FoV). Other error sources introduced during the Phase 4 and Phase 5 of the alignment procedure are not considered in this spot diagram. These sources introduce an RMS blur contribution smaller than the ones already considered. A complete error budget will be summarized in Table 3.

This optical setup is shown in Fig. 7 and Fig. 8, and it is made in this way:

- an optical fiber (mounted on a X-Y-Z stage for alignment purposes) is used as reference light for the alignment (we can feed it both with laser light and with visible light);
- an off-axis parabolic mirror, mounted on a custom tip-tilt mount, collimates the beam coming from the optical fiber, directing it toward the PR-I;
- an additional flat folding mirror, positioned below the PR-I, sends the collimated beam inside the PR-I itself; this folding mirror has TT adjustments (performed using actuators with differential micrometers, with a resolution of $0.1\mu\text{m}$), in order to move the reference created by the fiber along the whole PR-I field of view;
- a test camera, with a very high spatial sampling ($2.2\mu\text{m}$ of pixel size) is used instead of the final CCD EEV50, in order to have the highest possible resolution for the evaluation of the images affected by the coma during the alignment procedure.

The different phases of the alignment are outlined in the following sections, and they reflect what we just mentioned above: the real alignment of the PR-I Parabola is performed in Phase 4 and Phase 5, in Phase 3 there is the alignment of the two flat mirrors, which must precede the fine-alignment of the Parabola and must be preceded by a pre-alignment, at least in the sense of direction of the beam, of the Parabolic mirror itself. In a certain sense, in the first two Phases of

pre-alignment of the Parabola, we do not care about the optical quality onto the focal plane and we care instead of the beam direction, treating the Parabola like it is a flat mirror.

6.1 PHASE 1: On axis reference definition on the test camera

This phase has the purpose to align and center the test camera to the Objective optical axis materialized by a laser beam and, in particular, to define on the CCD the Objective optical axis projection. The main steps are the following:

- A. Materialize the optical axis of the Objective with a laser source positioned on the optical bench (see Fig. 3, left side):
 - dismount the parabola from the PR-I;
 - mount on a dedicated flange a test camera, chosen in a way to have a better spatial sampling than the final one; we will use a commercial camera having $2.2\mu\text{m}$ pixel size; the detector has the possibility to be centered and focused using the 3 motorized stages of the PR-I (located in the detector area);
 - mount a laser on the optical bench with centering and tip-tilt capabilities, which has the purpose to materialize the optical axis of the Objective, from the side of the removed PR-I parabola;
 - by observing the back reflected spots, align the laser with the PR-I in a way to materialize the Objective optical axis. This operation can be achieved with a precision of 0.027mm in centering and 0.008 degrees in tilt, since we have tested on the bench the system, as described in Fig. 4. This error will cause a shift of the focused spot on the test camera of $6\mu\text{m}$.
- B. Center the test camera with the Objective optical axis, materialized by the laser, and focus it; record the position of the spot on the CCD (see Fig. 3, right side). The precision is of the order of the pixel size of $2.2\mu\text{m}$.

The error of de-center and tilt of the laser, summed (in worst case) with the error in recording the spot position, will cause an indetermination of the definition of the Objective optical axis projection of $8.2\mu\text{m}$.

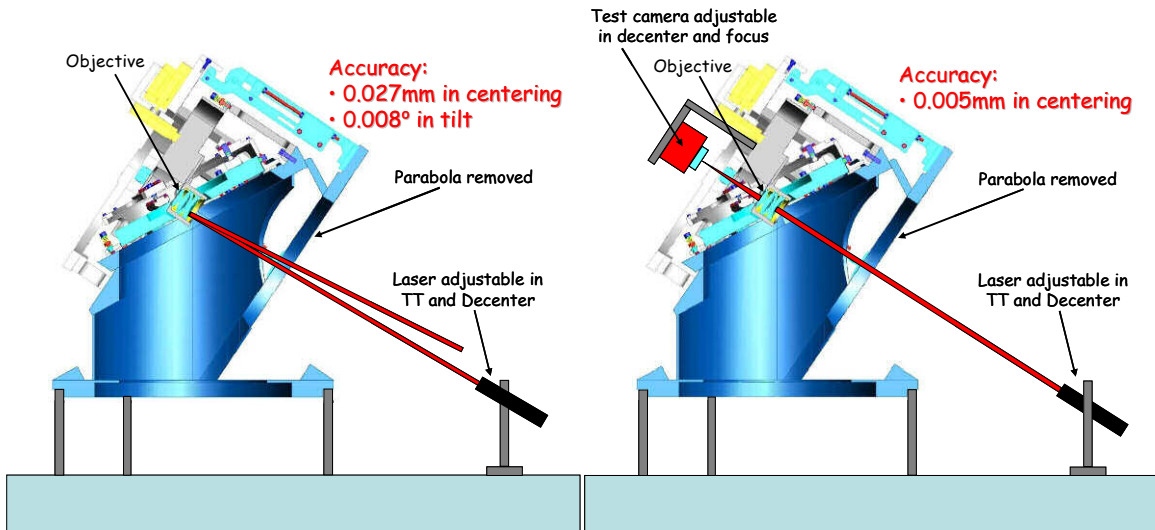


Fig. 3 - Left Side: Phase 1-A, aligning the laser to the Objective (also called “prime focus corrector”) Right Side: Phase 1-B, aligning the test camera to the Objective and recording the spot position on the CCD.

This translates in an error of 0.0012° in the alignment of the flat mirror and, thus, in a tilt of the incoming beam used for the parabolic mirror alignment, of 0.0025° .

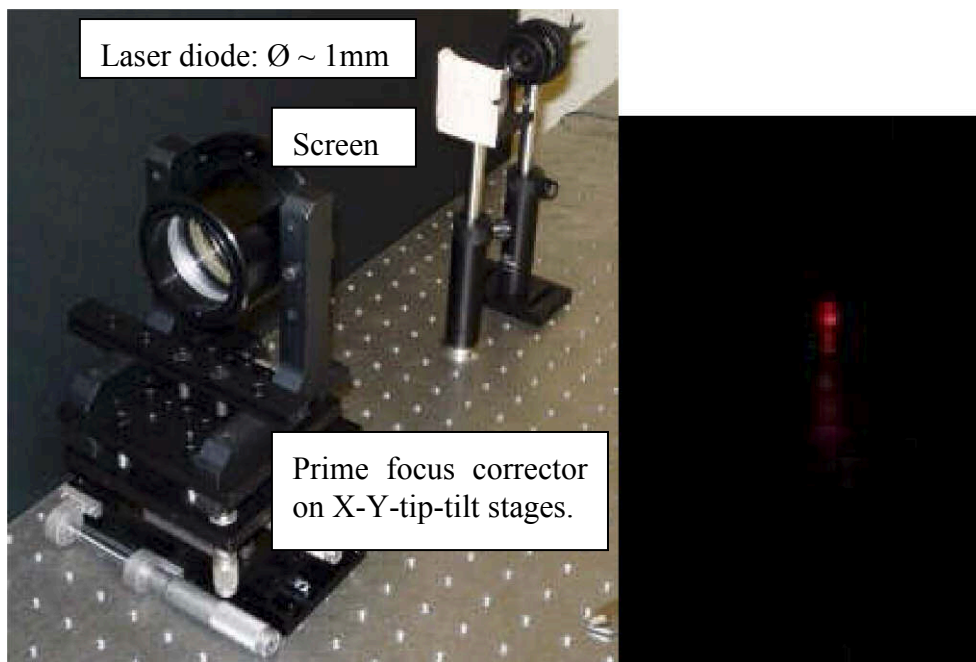


Fig. 4 On the left, the on-bench test setup to check the sensibility in materializing the Objective optical axis with a laser beam. A $\sim 1\text{mm}$ in diameter laser beam passes through an holed screen and is reflected by the 8 faces of the 4 lenses of the corrector. The back reflected spots appear on the screen and are used to align the laser beam with the Objective. The procedure has been repeated 10 times in order to obtain a statistical error. This operation can be achieved with a standard deviation of 0.027mm in centering and 0.008 degrees in tilt for the laser placed on the “Parabola side” of the Objective and a standard deviation of 0.022mm in centering and 0.006 degrees in tilt for the laser placed on the “CCD side” of the Objective. On the right an example of back-reflected spots configuration is shown.

6.2 PHASE 2: Alignment on axis between the Objective and the parabola

This Phase has the purpose to make a rough pre-alignment of the Parabola to the Objective, in order to accomplish, during Phase 3, the alignment of the 2 flat mirrors.

We call it “rough pre-alignment” since, at this stage, having only one observable described in the following, it is impossible to distinguish between the decenter and the tilt of the Parabola.

A. Align a laser source, positioned instead of the test camera, to the Objective:

- mount the parabola on the PR-I;
- position the parabola mechanically at its nominal focal place, the mechanical precision is enough to fulfill the tolerance of 0.5mm in focus;
- dismount the test camera (this operation has to be performed with the possibility to re-mount the test camera with a certain repeatability, equivalent to 0.55mm);
- mount, through a dedicated flange, a laser on the stages of the removed test camera, shining the light toward the Objective; the laser has centering (motorized) and tip-tilt adjustments;
- by observing the back reflected spots (masking the parabola with a black screen, see Fig. 5 left side), align the laser with the Objective in a way to materialize the Objective optical axis. This operation can be achieved with a precision of 0.022mm in centering and 0.006 degrees in tilt, since we have tested on the bench the system, as described in Fig. 4;

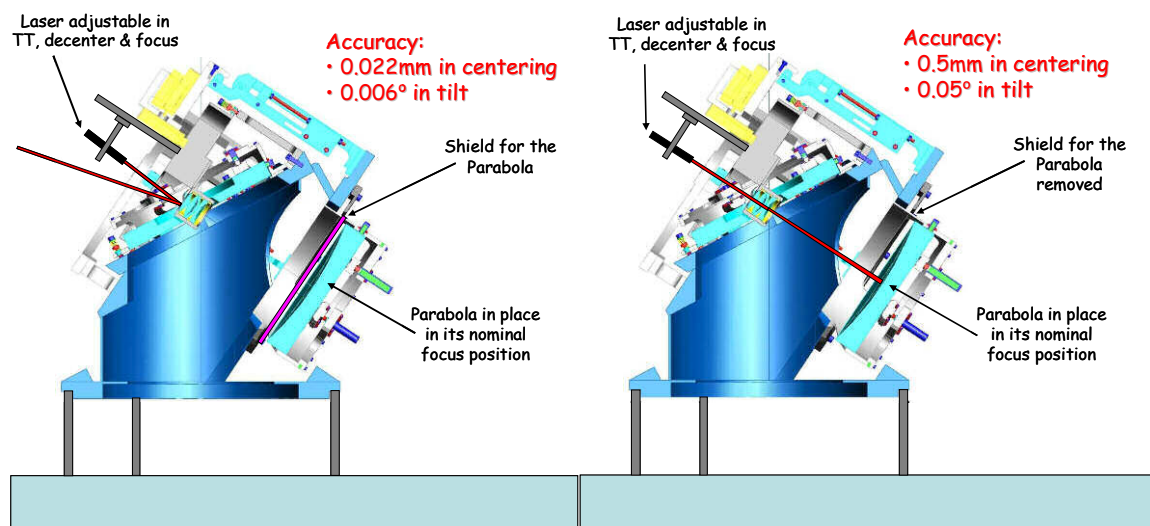


Fig. 5 – Left Side: Phase 2-A, aligning the laser to the Objective from the side of the final CCD camera; Right Side: Phase 2-B, aligning the Parabola to the laser which materialize the Objective optical axis

- B. Remove the black screen from the parabola, and align the parabola with the laser materializing the Objective optical axis (see Fig. 5 right side). Of course, shining a laser on the centre of the Parabola, we can only align the parabola surface normal with the incoming laser beam. Since we have just one observable (the spot coming back from the Parabola towards the Objective) and two degrees of freedom, there will always be a tilt compensating a certain amount of de-center (and vice versa); thus, with this procedure,

we can only say that we are “following the curvature of the parabola”. This operation can be achieved with a precision of 0.6mm in centering and 0.06° in tilt, since we have tested on the bench the system, as described in Fig. 6.

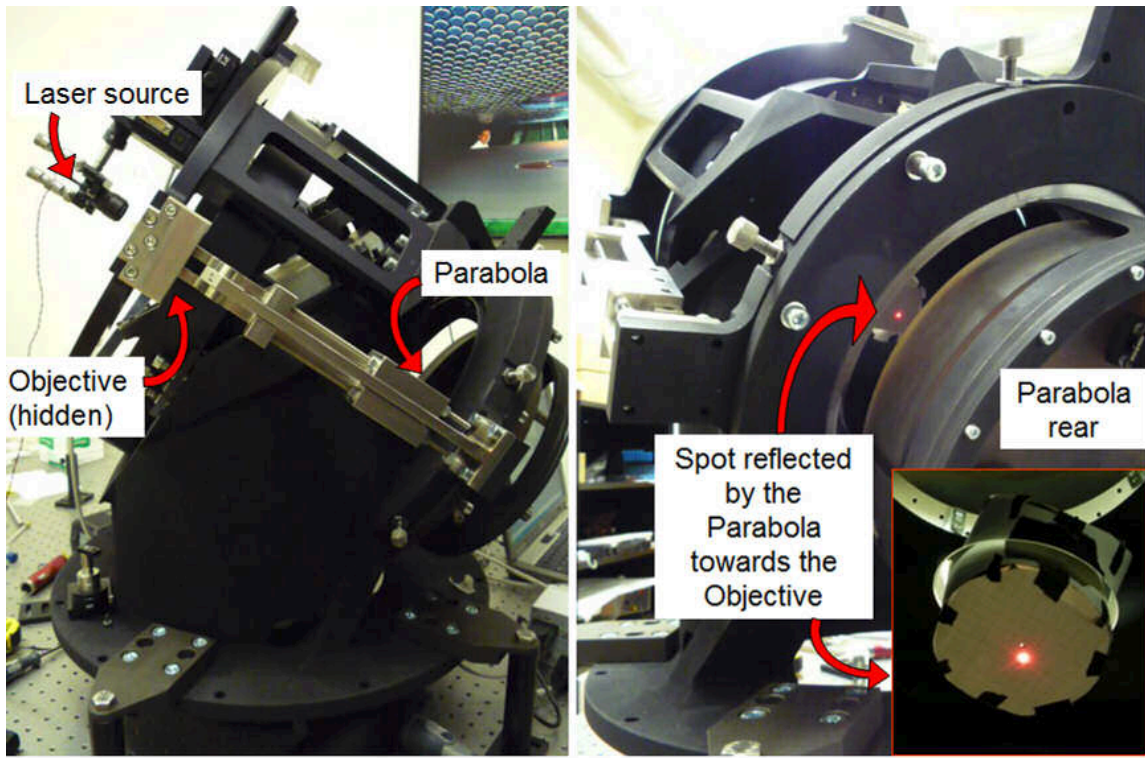


Fig. 6 Alignment of the Parabola surface normal with the incoming laser beam. On the right one can see the spot coming back from the Parabola towards the Objective illuminating a setup screen situated just before the Objective itself.

The total indetermination of the alignment of the Parabola surface normal with respect to the Objective optical axis is the sum of the errors in aligning the Parabola (0.6mm and 0.06°) and the propagation of the errors in materializing the Objective optical axis with the laser beam (0.022mm and 0.006°). They give a total error (in the worst case) of 0.85mm in centering or 0.075° in tilt.

6.3 PHASE 3: Alignment of the two flat mirrors

This Phase has the purpose to feed the PR-I with an extended collimated beam, resembling the on-axis beam coming from the star enlargers. When the beam reaches the Parabola, it has to be parallel to the Objective optical axis. Once this configuration is reached, there will be only one way to align the Parabola minimizing the coma effect and keeping the spot fixed on the recorded position on the CCD (Phase 4 and Phase 5).

There are several ways to change the incoming beam inclination: tilting the PR-I flat folding mirror, tilting the setup flat folding mirror or tilting the PR-I as a whole. The easiest way to do that is moving the setup flat folding mirror, whose custom mount is equipped with micrometric actuators.

- A. Remove the laser from the test camera area.
- B. Re-mount the test camera within the required centering precision of 0.55mm; in this way, the center of the field is, within the known accuracy, where materialized during Phase 1.
- C. Position the PR-I flat mirror at half travel of its tilt adjustment.
- D. Create on the bench the setup described in Fig. 7. Essentially, there are:
 - an optical fiber, creating a reference for the alignment;
 - an Off-Axis Parabolic mirror (OAP), creating an enlarged collimated beam;
 - an additional flat folding mirror, positioned below the PR-I, reflecting the collimated beam inside the PR-I itself; the latter has TT adjustments in order to move the reference created by the fiber along the whole PR-I field of view.

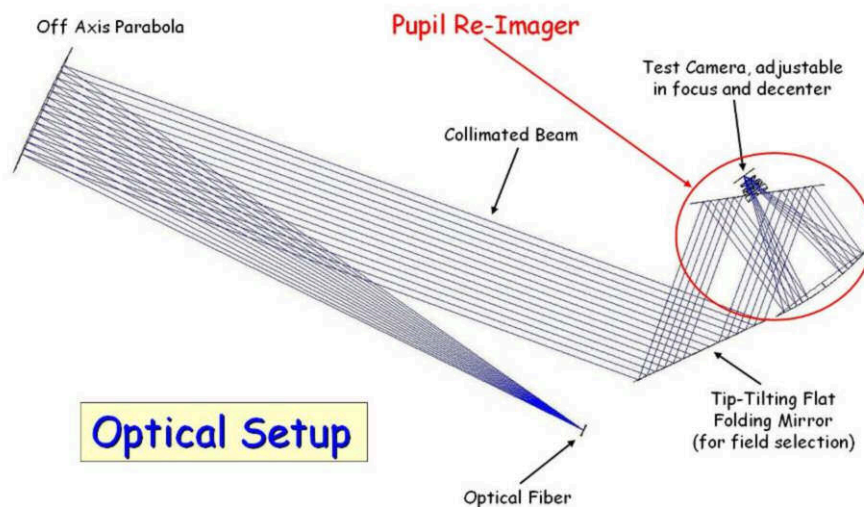


Fig. 7: The optical setup used to align the Pupil Re-Imager. The fiber-OAP alignment procedure is not described in this document. The required precision in the OAP alignment with respect to the fiber is $\pm 3\text{mm}$ in de-center. In this way an eventual coma effect introduced on the spot on Phase 4 and Phase 5 by the OAP is smaller than the minimum coma we want to detect on the CCD.

- E. Move the TT adjustment of the flat folding mirror below the PR-I in a way to superimpose the spot to the reference, recorded on the CCD during Phase 1, within an accuracy of 0.003° (corresponding on a shift of the spot on the CCD of $7\mu\text{m}$, that is to say almost 3 pixels).

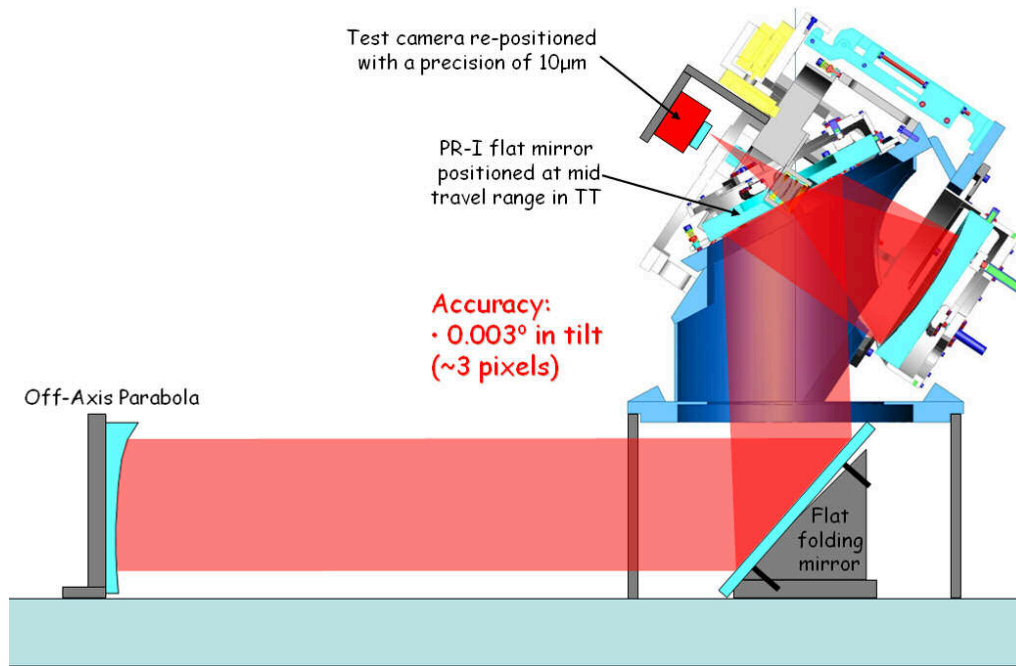


Fig. 8: aligning the additional flat folding mirror placed below the PR-I with the task to fold the light upwards the PR-I itself; this flat mirror is equipped with micrometers for tilt adjustment (reaching the precision of 1µm), and with micrometric rulers to record the mirror position.

Error source	Accuracy	Consequent flat mirror misalignment	Consequent incoming beam tilt
Phase 1: Reference definition on the CCD test camera	0.0082mm	0.0012deg	0.0025deg
Phase 2: Parabola pre-alignment	0.85mm, 0.075deg	0.071deg	0.142deg
Phase 3: CCD re-positioning	< 0.55mm	< 0.07deg	< 0.14deg
Phase 3: Flat mirror alignment	0.003deg	0.003deg	0.006deg
Total off-axis amount			0.3deg

Table 1 Incoming beam off-axis error budget.

6.4 PHASE 4: Alignment of the PR-I

At this point of the procedure the PR-I is fed with a wide collimated beam corresponding to the on-axis beam of the PR-I FoV. There will be only one way to align the Parabola minimizing the coma effect and keeping the spot fixed on the recorded position on the CCD.

The idea is to defocus the test camera in the intra-focal direction. 0.2mm of defocus should be a good compromise to appreciate with the required precision the coma. In fact, 0.2mm of defocus

means a geometrical spot size of $\sim 248\mu\text{m}$ and a central obstruction of $\sim 90\mu\text{m}$, due to the PR-I flat folding mirror, and we should be able to see the distance between the centers of the two spots within $5\mu\text{m}$ (more or less 5% of the smaller spot).

To measure the coma, we are going to determine the position of the central obstruction with respect to the whole defocused reference image. In principle, the coma tends to 0 as the distance between the two centers tends to 0. Once the amount of coma has been determined, in principle we could already know how to tilt and de-center the Parabola to completely remove the coma effect keeping the spot fixed in its position centered with the reference point on the CCD. A look-up table is shown in Table 2.

Coma (μm)	Parabola Dec.(mm)	Parabola Tilt ($^\circ$)
0.0	0.0	0.0
3.1	0.1	0.0083
6.2	0.2	0.0167
9.3	0.3	0.025
12.4	0.4	0.033
15.5	0.5	0.0417
18.6	0.6	0.05
21.7	0.7	0.0583
24.8	0.8	0.067
27.9	0.9	0.075
31.0	1.0	0.083

Table 2 Look-up table to move the Parabola along its curvature, in order to minimize the coma effect, keeping the spot fixed on the CCD.

Since the mechanics of the PR-I do not allow us to perform such a “blind” alignment, we are going to use an optical iterative procedure:

- A. defocus the test camera (0.2mm) in the intra-focal direction (see Fig. 9 left side);
- B. adjust the tilt of the parabola in order to reduce the coma (see Fig. 9 right side). Of course, this operation will cause a movement of the spot on the camera;
- C. position the test camera back in focus (see Fig. 10 left side); we remind that the camera is moved using motorized linear stages with encoders, with a position repeatability of $0.1\mu\text{m}$;
- D. adjust the de-center of the Parabola until taking back the reference spot in the starting position, defined during Phase 1 (see Fig. 10 right side). In this way, we are sure that every movement we are giving to the Parabola is along its curvature;
- E. go back in the intra-focal position and iterate.

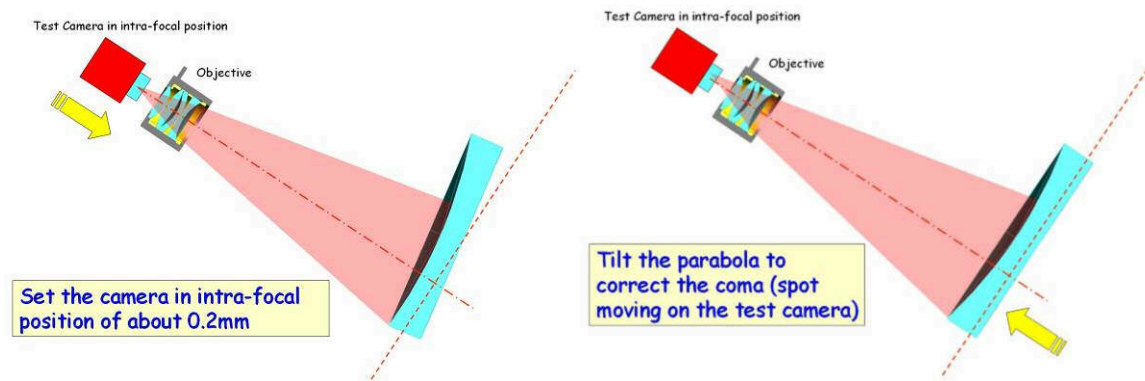


Fig. 9 – Left Side: Phase 4-A, positioning the CCD in intra-focal position of $\sim 0.2\text{mm}$; Right Side: Phase 4-B, tilting the parabola in order to reduce the coma.

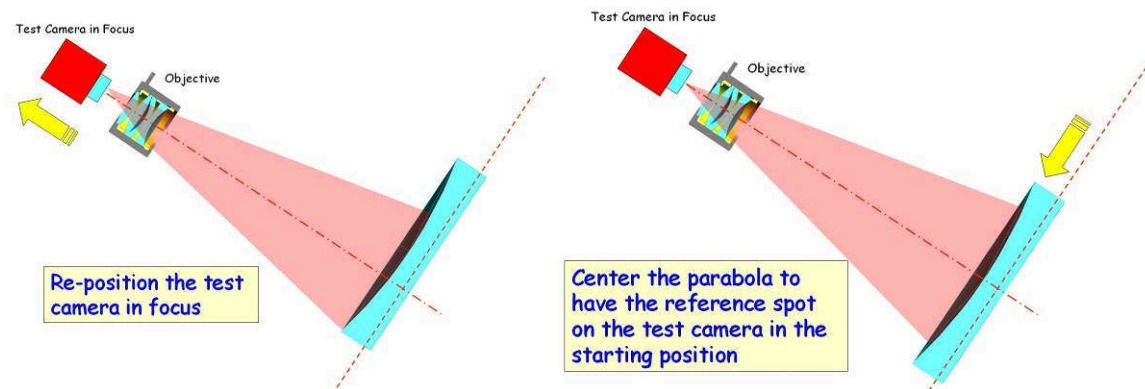


Fig. 10 – Left Side: Phase 4-C, positioning the CCD back to the focal position; Right Side: Phase 4-D, centering the parabola in order to move the spot in the reference position defined during Phase 1.

The precision of the Parabola alignment depends on our sensibility in measuring the coma effect on the defocused spot. We assume to be able to see the distance between the centers of the two spots within $5\mu\text{m}$. So, each Parabola deviation from the aligned configuration, which causes a coma effect smaller than $5\mu\text{m}$, is a source of error we have to take into account.

There are 3 ways to de-center the inner hole respect to the defocused spot of an amount of less than $5\mu\text{m}$, which is our sensibility:

- 1) tilt the Parabola of less than 0.02° ;
- 2) de-center the Parabola of less than 0.1mm ;
- 3) move the Parabola along its curvature of an amount less than 0.17mm in de-centering and, consequently, 0.014° in tilt.

These 3 alignment errors can occur only separately, because otherwise we would detect an amount of coma bigger than $5\mu\text{m}$. Actually, we will have an unknown combination of the three effects, but each of them will consist on an alignment error smaller than the one considered above. From Zemax computations, we found that the three errors, taken separately, cause a very similar amount of RMS blur on the image plane (in the whole FoV). In principle, we could take just one of the three error contributions, since, as already said, they can't occur simultaneously. To be strictly conservative, we decide to consider the worst combination of the first two errors listed above, since we checked that the third would introduce a smaller amount of distortion.

So, we can say that the alignment Parabola-Objective in Phase 4 will have a precision of 0.1mm in de-centering and 0.02° in tilt.

6.5 PHASE 5: Final Focus Adjustment of the PR-I

The de-center and tilt adjustments of the Parabola are not pivoting around its centre; therefore, the alignment procedure described in Phase 4 will most probably change the Parabola focal position.

This effect will be easily detected as a defocus on the CCD or through a mechanical check of the nominal position of the Parabola.

Thus, during this phase, it is required to (see Fig. 11):

1. Check the parabola focus position and, in case, adjust it mechanically at its nominal position
2. Since the previous operation might slightly change the tilt or the decenter of the parabola, re-iterate Phase 4

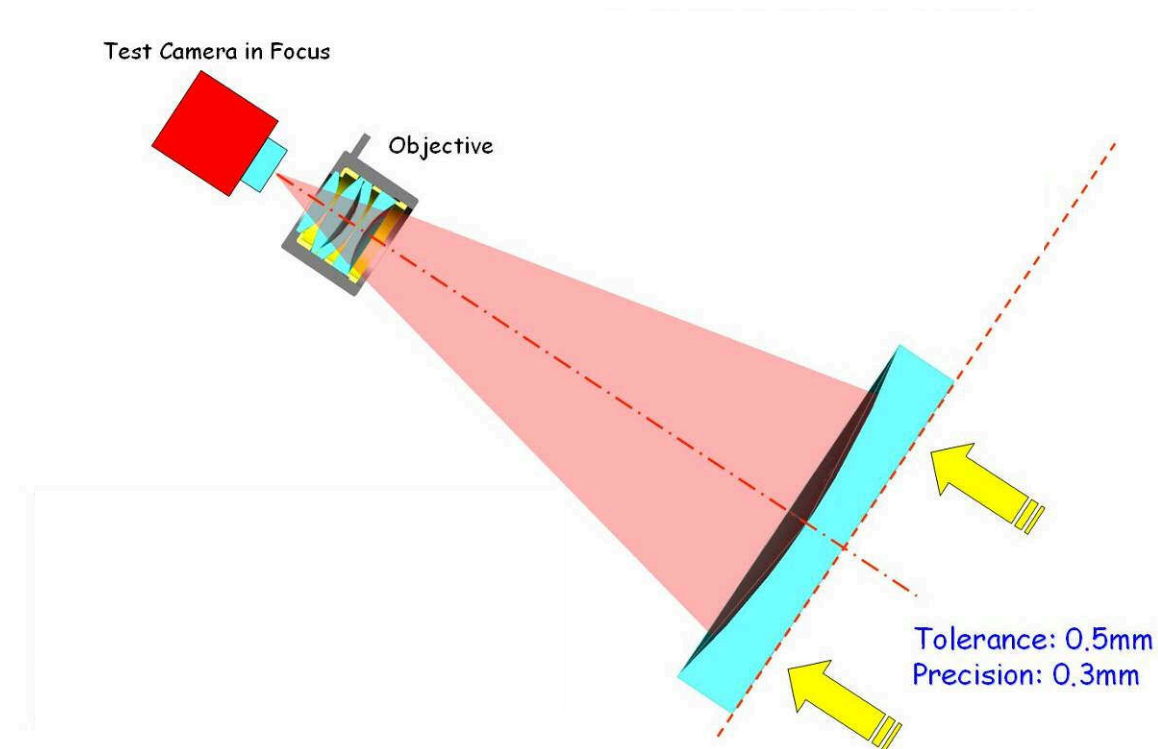


Fig. 11: fine tuning of the Parabola focal position and of the alignment of the PR-I

6.6 PHASE 6: Final PR-I optical quality check

This last phase should be only a check to verify that we did not made any error during the alignment procedure.

By tilting the additional flat folding mirror below the PR-I, we can check the optical quality off axis, at the limit of the PR-I FoV ($\pm 0.44^\circ$). If needed, move the test camera in the intra-focal position and re-iterate Phase 4 step A,B,C,D. We remind that the additional flat folding mirror, positioned below the PR-I, is equipped with actuators which give the possibility to position the

reference spot very precisely in the FoV; these actuators have differential micrometers, allowing to read and record the different positions along the FoV.

The procedure can be considered finished once the achieved optical quality is below 25 μ m of RMS spot radius over the complete FoV.

7 Summary

As it is shown in Table 3, the expected RMS blur due to the alignment procedure described above is well under the required optical quality of 25 μ m over the whole FoV.

Contributions to the spot enlargement	On axis	$\pm 0.44^\circ$ FoV	$\pm 0.55^\circ$ FoV
RMS nominal spot radius	5.8 μ m	7.8 μ m	9.1 μ m
De-focus contribution (0.5mm)	9.1 μ m	11.0 μ m	12.9 μ m
Off axis alignment contribution (0.3 $^\circ$)	7.0 μ m	11.9 μ m	15.6 μ m
Parabola alignment (0.1mm, 0.02 $^\circ$)	9.7 μ m	10.9 μ m	11.9 μ m
Total RMS spot radius	12.6 μm	16.1 μm	19.6 μm

Table 3 Error budget summarizing the various contributions to the total RMS blur, measured as the RMS spot radius, obtained optimizing the focus position of the CCD over the full FoV with polychromatic light