Optical Alignment of the VLTI

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ABSTRACT

When completed the VLTI project will be composed by four 8.2m Unit Telescopes (UT) and four 1.8m Auxiliary Telescopes (AT) with their respective Coudé trains and relay optics, two test siderostats, 6 (up to 8) Delay lines and 8 Beam compressors with their corresponding feeding mirrors. There will be more than 200 optical components, mirrors and lenses, with diameters ranging from 5 mm to 8200 mm. Their surface shapes range from flat to off-axis ellipsoid, including also spherical, on and off-axis hyperbolae and parabolas as well as cylindrical surfaces. Depending on the interferometer configuration, the different possible optical path lengths are of the order of 100 to 300 meters. We describe briefly the principles chosen as well as the types of criteria and method used for the alignment. The method can certainly be applied to other optical systems. The explanations given are understandable to the non-optician, this text is not intended to be an alignment procedure.
Keywords: VLTI, Optical Alignment.

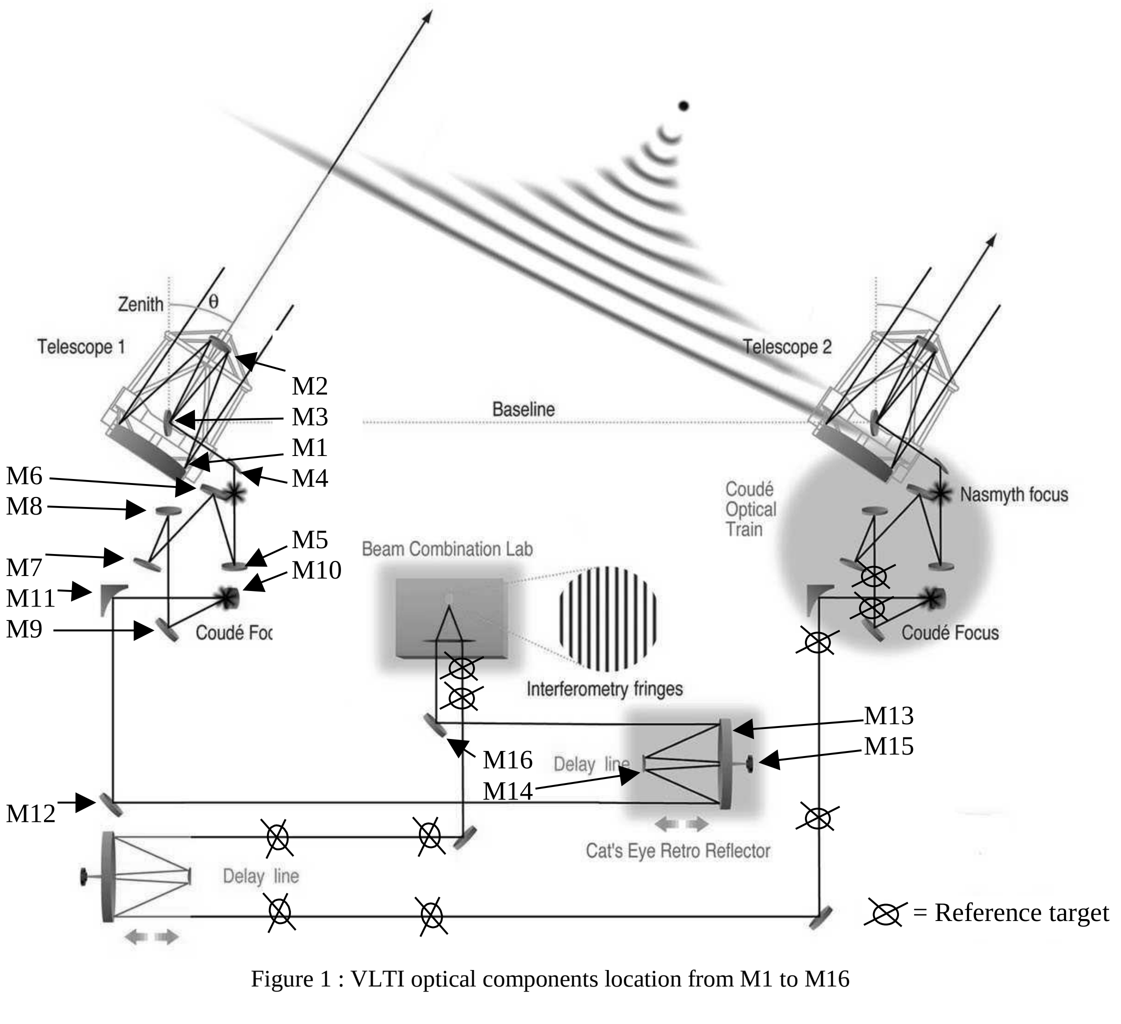

Figure 1 : VLTI optical components location from M1 to M16

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1. WHAT DOES OPTICAL ALIGNMENT MEAN ?

Aligning the VLTI optics could be defined as making sure that the light falling on the primary mirror of each of the telescopes gets to the entrance of the instruments in the interferometric laboratory. This can easily be done by proper sequential tilt adjustments, using a laser for example, of the 20 mirrors of each optical path. Unfortunately this definition is a bit too simplistic as the optical alignment, apart from just "getting light at the other end" also includes specifications to be met and budget errors to be respected. We can cite for example :

- the final optical quality of the system at center field and in the field as well as the optical quality at given intermediate positions or for individual systems (cat eye, beam compressor, Coudé train …).
- polarization difference between separate optical paths.
- vignetting.
- pupil, pupil images and images positions at several places along the optical path.
- pupil, pupil images and images motions and rotations (during telescope rotation, cat eye displacement on the delay line etc …).
- stability of the adjustments.
- parallelism and distance between input and output beams for cat eyes, beam compressors.

Table 1 summarizes the mirrors in the path from a UT down to the entrance of the instruments. The case of the AT is very similar. The siderostats case is somewhat different and not developed here. An important feature of the VLTI to take into account when defining the alignment method is the large number of possible optical configurations. There is for example the choice between 30 stations for the AT, 6 delay lines and 8 beam compressors for any beam coming from the AT, UT or siderostat giving a total of more than 3500 possible configurations for the light to arrive on the detector. When changing configurations, some elements are moved (AT / Siderostats / M9 / M12 / M16) but not realigned. This feature adds supplementary constraints on the mechanics quality but also on the way the alignment is done.

Table 1 : Mirrors list in the UT case,Cvx=Convex, Ccv=Concave, Parab=Paraboloid, Hyperb=hyperboloid, Ellip=Ellipsoid, Alt=altitude, Az=Azimuth,

VLTI name	Component "official" name	Location	Shape	degrees of freedom	Size (mm)	Movements
M1	UT M1	UT tube	Ccv Hyperb.	5	Ø 8200	Move with UT alt / az axes
M2	UT M2		Cvx Hyperb.	5	Ø 1200	
M3	UT M3		Flat	3	870 x 1240	
M4	Coudé M4	UT structure	Flat	3	140 x 200	Move with UT az axis
M5	Coudé M5		Off-axis Ccv Ellip.	6	Ø 630	
M6	Coudé M6		Flat	3	Ø 495	
M7	Coudé M7		Off-axis Ccv Ellip.	6	Ø 375	
M8	Coudé M8		Flat (deformable)	5	Ø 140	
M9	Relay Optics M9	Coudé Laboratory	Flat (dichroic)	3	250 x 370	No motion
M10	Relay Optics M10		Cvx Spher.	5	Ø 50	
M11	Relay Optics M11		Off-axis Parab.	6	Ø 220	
M12	M12	Interferometric Tunnel	Flat	3	230 x 650	
M13	Cat eye M1		Hyperbola	5	Ø 570	Move with cat eye on Delay line
M14	Cat eye M2		Hyperbola	5	Ø 120	
M15	Cat eye M3		Spher. (variable R)	5	Ø 15	
M16	M16		Flat	3	230 x 650	No motion
M17	Beam Compressor M1	Interferometric Laboratory	Off-axis Parab.	6	Ø 105	
M18	Beam Compressor M2		Spherical	5	Ø 5	
M19	Beam Compressor M3		Off-axis Parab.	6	Ø 70	
M20	Switch-yard mirror		Flat	3	Ø 100	

2. ALIGNMENT PRINCIPLES USED

2.1. Defining subsystems separations

The approach chosen consists in dividing the VLTI into optical subsystems considering the following criteria :

- each subsystem can be aligned independently from the others (meaning existence of sufficient criteria and degrees of freedom for the alignment, physical access for installing alignment tools…etc).
- each subsystem is defined by an entrance axis and an output axis. These axes are usually mostly mechanical axes on which the optical axis has to be aligned.
- a flat mirror separates each subsystem.

There are several advantages to this approach. First, a given subsystem can be aligned separately from the others. A sequential approach could have been done also, but would have assumed that the alignment can only be done once all the elements exist. This was not a reasonable solution in term of schedule. Second, the alignment can be checked separately for each subsystem (in case the system gets misaligned, the exact component that needs readjustment can be found).

The principle is that each subsystem can be aligned separately, and that the "junction" between subsystems is done by a proper alignment of the intermediate flat mirror. This operation can be done exactly, if and only if the output axis of a subsystem intersects the input axis of the following subsystem (i.e. axes in the same plane and not parallel). This seems to add a constraint to the alignment, but in fact there are only 3 incidence planes in the VLTI. We will call them plane A, B and C and their respective definition is given below:

- plane A: plane defined by the altitude and azimuth axes of the telescope (vertical plane rotating with telescope azimuth).
- plane B : the horizontal plane of coordinate W=-1250 mm in the (U,V,W) coordinate system of the VLTI.
- plane C : the horizontal plane of coordinate W=-1490 mm.

Table 2 details the subsystem separations chosen, their input and output axes, and the flat mirrors located at the intersection of the axis of the subsystems.

Table 2 : Subsystem division of the VLTI chosen for the alignment

Input Axis and incidence plane		**Subsystem**	**Output Axis and incidence plane**		**Link to next subsystem (flat mirrors)**
Center field pointing axis	A	Tel at Nasmyth M1/M2/M3	Tel. Altitude axis	A	M4
Vertical line passing through Folded Nasmyth focus	A	Coudé M5/M6/M7/M8	Tel. Azimuth axis	A	M9
Line passing through center of M9 and M10	A / B	Relay optics : M10/M11	Light duct axis	B	M12
Line passing through mechanical center of cat eye entrance and parallel to DL rails	B	Cat eye : M13/M14/M15	Line passing through mechanical center of cat eye output and parallel to DL rails	C	M16
Defined by reference supports	C	Beam Compressor M17/M18/M19	// to input axis	C	M20

2.2. Materializing axes

Once the subsystems and their axes are defined, it is necessary to materialize the axis in order to be able to align optical tools on them (wavefront analyzer, sighting telescopes (ST), lasers etc…).

Coming back to school level geometrical considerations, we remember than an axis is a line, and that a line can be defined by different manners. For two of them there are ways to materialize the line (see Figure 2):

- Method A: by two distant points (two reticules for example) on which a sighting telescope can be aligned
- Method B. by a point and a direction (a flat glass with an engraved reticule), the point is given by the reticule and the direction by the normal to the glass plate (pointed in autocollimation with a sighting telescope).

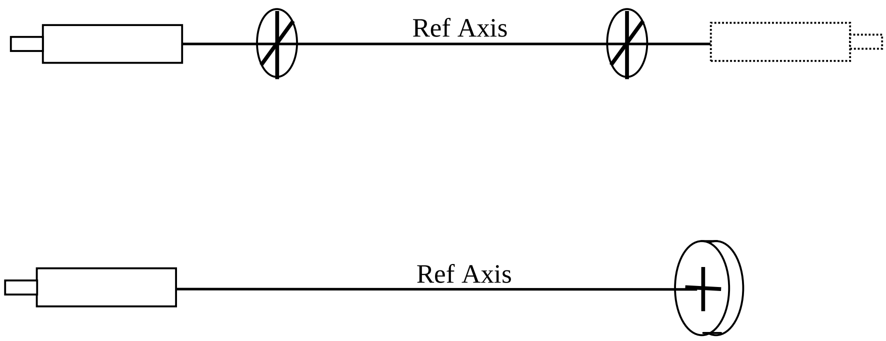

Figure 2 : : two methods to materialize the subsystem axes

We choose the first solution (method A), which consists in materializing the reference axes by two removable open target reticules. The advantages of this method are :

- the stability in time (compared with keeping the orientation of the small glass plate of method B). This stability is in fact the consequence of the large distances found in the VLTI. For example to get the two reticules to define a line with an angular error of less than 1", the lateral stability of the reticules needed is 5 microns if the reticules are 1 m away, but only 0.4 mm if they are 80 meters away.
- the reversibility of the pointing (the sighting telescope can be aligned pointing towards either side of the axis.
- the relaxed needed accuracy for the mechanics of the reticule holders which depends basically on the distance between the two targets (from 4 meters to 80 meters in the VLTI).

2.3. Defining the degrees of freedom of the mirrors

It is important to analyze and define the need of degrees of freedom and adjustments for each mirror. Column 5 of Figure 1 shows the 91 degrees of freedom necessary and also available for the exact alignment of the VLTI optics. It does not show the degrees of freedom needed for the rough alignment usually necessary to avoid vignetting by the optical components. A flat mirror, for example, needs only 2 tilts and 1 translation fine movements for an exact alignment. To make sure however that the mirror is centered (within 0.5 mm for example) 2 supplementary rough translation movements can be necessary.

3. THE ALIGNMENT METHOD

3.1. Introduction

The method used can be summarized by the following steps :

1. installation of alignment reference support (reticule holders).
2. rough positioning of the optics (mounts alignment).
3. internal alignment of the subsystems (fine alignment of the optics).

4. alignment of the flat mirrors separating the subsystems

3.2. Installation of the alignment reference support

The references (pairs of reticule) are installed on all the reference axes using permanent reference supports. These supports are simply metallic plates with holes. The target themselves are removable since the light beam shall not be obstructed during observations. They can be inserted in any of the holes of the reference plates according to the alignment needs. The accuracy of repositioning required is usually of the order or 0.05 mm (depending on the available maximum distance between the two targets). The different alignment reference supports are represented by a cross on Figure 1, they are :

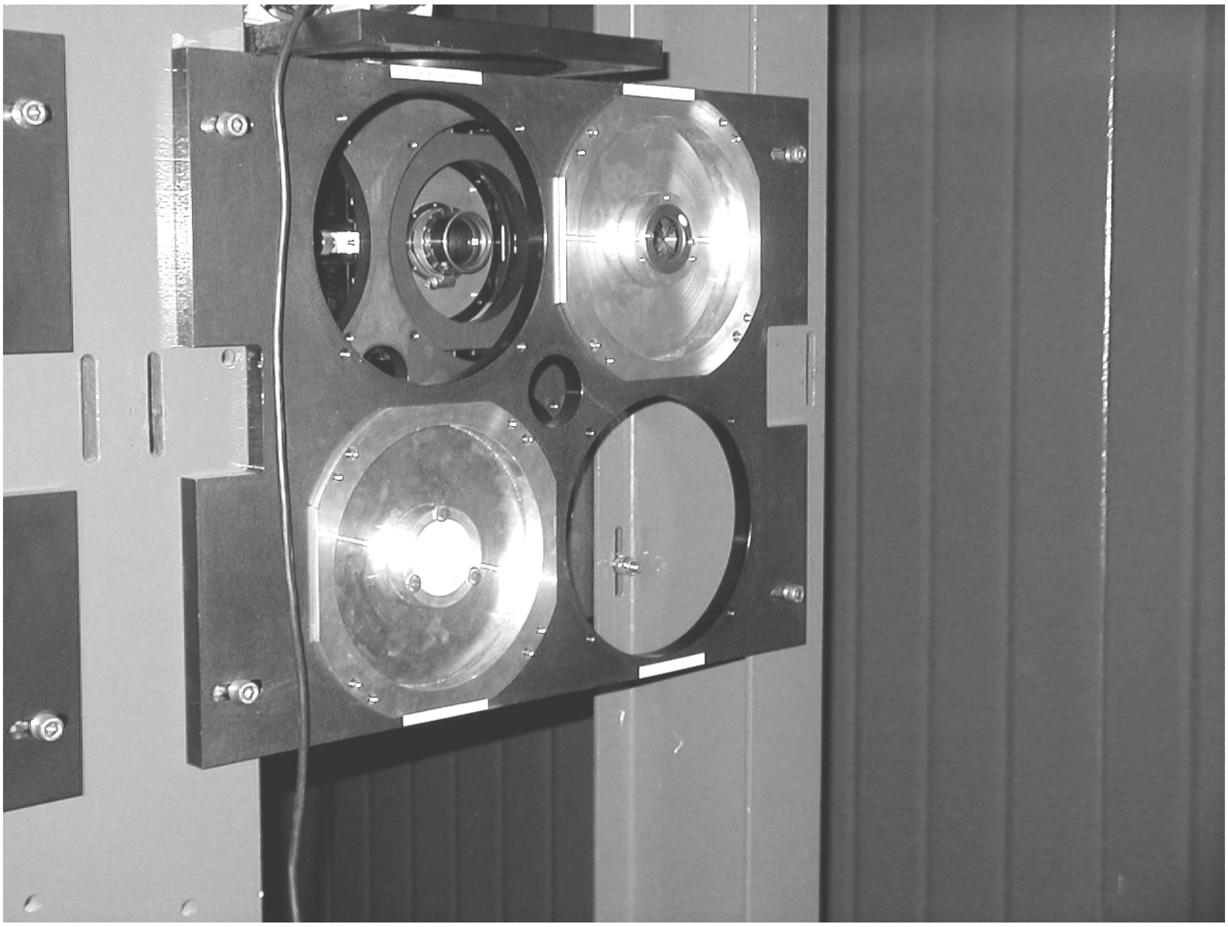

Figure 3 : Alignment reference plate of the delay line cat-eye.

- The references on telescope altitude axis : direct references are not possible anymore because they would obstruct the light going to both Nasmyth foci. These references existed at the very early stage of the UT's when the alignment of M1, M2 and M3 was done. This alignment aimed at making the optical axis of M1/M2/M3 coincident with the altitude axis of the telescope and the rotation axis of the adapter/rotator. We therefore use to materialize the axis of the telescope the line (folded by M3) defined by the center of M2 (at the center of which a temporary light source can be installed) and the center of the adapter (which defines the center of the field of the telescope). This axis defines directly and exactly the chief ray of the on-axis beam.
- The references on telescope azimuth axis : two targets are fixed to the rotating body of the telescope below M8. The telescope is rotated and the target adjusted in centering until their centers do not move anymore. These targets are in the plane A and define the output axis of the Coudé optics and the input axis of the relay optics.

- The references for the light ducts (link between the Coudé laboratory and the delay-line tunnel) : the targets are installed at each end of the light ducts and aligned with a theodolite in the B plane. The references in the light duct is very important for the case of the AT's because the telescopes can be moved to different stations along a given light duct and in all the cases the light has to come through the same path to the M12.
- The references for the delay lines (input and output) : the delay lines rails have been installed and aligned using two reference points given by a theodolite. The actual DL references are however defined and installed once the DL rails are aligned and the cat eye installed. The procedure is to move back and forth the cat eye and align a sighting telescope until the center of the cat eye aperture keeps centered in the sighting telescope. The references are aligned by looking through the adjusted sighting telescope. The reference for the input beams are in the plane B while the references for the output beam are in the plane C . One of the alignment reference plate is shown on Figure 3 (with targets installed), the four holes correspond to the input and output beams of the two channel of the cat-eye.
- The references in the interferometric laboratory : they define the axis for the input and output beams of the 8 beam compressors (plates with 16 holes) and the instrument. They were installed with a theodolite in the plane C. Figure 4 shows the VLTI laboratory alignment reference supports.

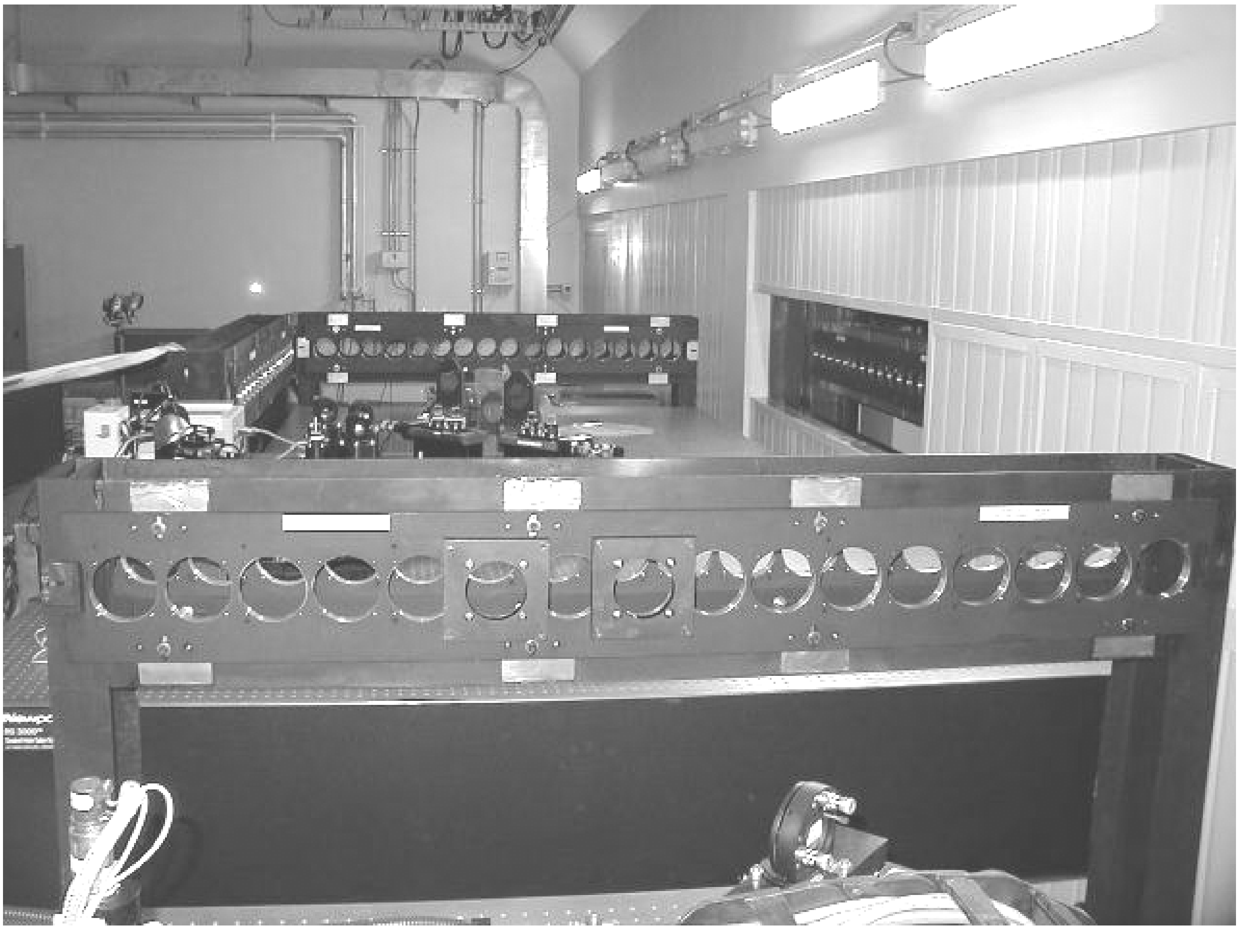

Figure 4 : VLTI laboratory alignment reference support

3.3. Positioning of the optics

Within a subsystem, the optics are generally placed mechanically with their center in a common plane. This is done usually by rough adjustments of the mounts after having set the fine adjustments of the optics to the middle of their range.

For the Coudé optics (M5 to M8), this plane is the plane A and the positioning is done with a theodolite. The relay optics (M9 to M11) are in the plane B and the positioning is also done with a theodolite. The positioning of M12, M16 and M20 in translation and tilt are, as a consequence of the method used, entirely defined by the references targets of the preceding and following subsystems. The alignment of these mirrors is therefore straightforward.

The M13, M14 and M15 are the cat-eye mirrors. They were aligned and shimmed by FOKKER, the manufacturer of the cat-eye, to comply with severe specifications of beam quality and parallelism, their positions are fixed within the cat-eye. The positioning of these mirrors therefore reduces to the positioning of the whole cat eye with respect to the rails of the delay lines. The M17, M18 and M19 optics are the mirrors of the beam compressors and are mounted on an optical table. Since this system is relatively small, all the positioning of the optics is easily done mechanically with respect to the table (which was itself accurately aligned with a theodolite in position and orientation with respect to the reference coordinate system of the VLTI).

3.4. Internal alignment of the subsystems

We will not describe in this document the internal procedure of each subsystem. We can however for most of the subsystems summarize the alignment actions as follows :

- align a laser on the input axis of the subsystem and tilt sequentially the mirrors to propagate the beam down to the output axis.
- measure and correct first order optics beam characteristics (magnification for afocal subsystem, position of the image and pupil image, focal length of the subsystem).
- measure and correct third order optics beam characteristics (wavefront quality).

These actions have to be iterated a few times until all the specifications are met. Usually a laser point source is used to simulate the star, such laser is available at the Nasmyth folded focus (after M4) .

3.5. Alignment of the flat mirrors

This step can be done even if the corresponding subsystems are not in lace or aligned since it only requires the presence of the targets materialising the two reference axes. This alignment operation is simple.

4. RESULTING WAVEFRONT QUALITY

The wavefront quality was measured for each subsystem using interferometers and Shack-Hartmann sensors, they are summarized in the Table 3. The measurements in the last column correspond to measurements of static alignment with Active Optics working (M1-M2-M3 in the loop) but without Adaptive Optics (MACAO system, not yet installed, that will include M1 to M8 in its correction loop).

Table 3 : specified and measured wavefront error budget (tilt excluded)

Subsystem	Mirrors	specifications (nm rms)	real measurements (nm rms)
Telescope	M1-M3	135	40 - 100
Coudé train	M4-M8	125	60 -100
Relay optics	M9-M11	35	35
M12	M12	20	5 - 10
Cat eye	M13-M15	40	35
M16	M16	20	5 - 10
Beam Compressor	M17-M19	40	20 - 35
Switch-yard mirror	M20	10	5 - 7
Total	M1-M20	198	90 - 155

In the last column, we give the range of values measured over all the existing units of each subsystems. The “real measurements” total value range is a computed value corresponding to the best and worst configuration cases of the subsystems.

5. FINAL IMAGE QUALITY AND ALIGNMENT CHECKS

The optical quality of the VLTI train could be determined by measuring directly the image FWHM on the VINCI instrument. This action was performed for UT1/2/3 and 4 and all the telescopes showed similar optical and alignment qualities.

5.1. Measurements with a laser source

The laser point source available at the Nasmyth folded focus (between M4 and M5) was used to perform these check measurements on all four UTs. The image FWHM was measured on the Vinci instrument. The optical path therefore includes the mirrors from M5 to M20, the Vinci internal optics as well as the air turbulence effect on this 100 to 200 meters optical path length. The final image FWHM measured with the laser point source turned out to be of the order of 0.04” to 0.07” (equivalent angular size on sky).

5.2. Measurements on stars

This measurement was done on UT1 and UT3 during a night with good external seeing (0.4” FWHM measured by Paranal seeing monitor). After centering the star at the Nasmyth focus, M4 was inserted to send the light to the interferometric laboratory. After 22 reflection (M1 to M20 plus two more mirrors in Vinci) and 200 meters of optical path, the pointing error measured was smaller than 2” on sky (typically 1”) and the image quality measured (including external seeing, alignment errors and internal turbulence in the interferometric tunnel) was around 0.4” FWHM (on sky).

6. CONCLUSIONS

A simple but systematic approach was used to define the optical alignment method of the VLTI. This method was applied successfully to the optical alignment of the four telescopes of the VLT and following optics down to the interferometric laboratory, leading to excellent results in terms of image and pupil alignment as well as wavefront quality.