Tips & tricks for aligning an image derotator


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ABSTRACT

One possible key reference element in optical alignment is represented by the rotational stage, a mechanical bearing, or any similar suitable device having enough accuracy and precision so that optical tolerances are reasonably relaxed wrt imperfections in the rotational movement. This allows a safe, reliable, easy to reproduce, determination of both rays parallel to the axis or to their centering within almost any plane. An image derotator, that in its simplest form is made up by three flat mirrors arranged in a so called K-mirror layout, moving together on a precision rotating stage, seems to be the most safe, strong, and self built-in alignment tool. Moreover you can use the mechanical part as well as the optical one. Care has to be given when internally and externally aligning has to be accomplished within a certain degree of precision. To further make the situation more complex, the technical overall requirements can be tight enough that the distribution of the error budget among the various components (imperfect mechanical rotation, imperfect internal alignment, flexures during rotations) is not due to a single item. In this case, in fact, a number of tips and tricks can be useful to find out which is the best approach to follow. The specific case of the two K-mirrors on board LINC-NIRVANA is here illustrated in a few lessons.

Keywords: K-mirror, optical derotator, NIRVANA, Adaptive optics, LBT, pyramid sensor

1. INTRODUCTION

The optical derotator consists of three mirrors, M1, M2 and M3 assembled together in a stiff and stable and rotating stage which defines the internal optical axis. The derotator is also called K-Mirror (KM) and its name originates from the “k” optical configuration of the mirrors in the instrumental design. The main feature of an optical derotator is the ability to rotate the incoming wavefront of an angle that is a double angle wrt the three mirrors orientation. The KM is a fundamental component of altazimutal mount telescopes such as LBT which is characterized by a rotation of the focal plane during the tracking. To maintain the telescope FoV fixed on a detector, two solution are allowed: 1) rotating the detector with the same angular velocity of the FoV; 2) using a rotating K-mirror to produce a contra-rotation of the FoV.

Both solutions are used for the Linc-NIRVANA wave front sensors of LBT[1]. The Ground Layer Wave front Sensor (GWS) rotates around its optical axis to follow the rotation of LBT focal plane whereas the Mid High Wave Front Sensor (MHWS) is fixed to the carbon fiber bench and requires an optical derotator for a 200mm beam to compensate the sky rotation.

Two KMs are assembled, characterized and internally aligned in the INAF and MPIA laboratories of Padua and Heidelberg, respectively. The KM design solution has been identified in a three separate mirrors configuration instead of a monolithic glass fused prism because of dimension, weight, costs and technological limitations. Three glass mirrors and adjustable mounts are assembled on a structure fixed to a commercial rotating stage. All the opto-mechanics is than assembled on a base-plate equipped with tip-tilt and decentering adjustment systems for the external alignment.

A reliable KM internal alignment procedure is described in this article in relation with the requested accuracy and mechanical limitation such as flexures, bearing wobble and run-out and other requirements.

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2. REQUIREMENTS

2.1 Decentering

KMs have to rotate during a scientific exposure to introduce a contro-rotation of the field of view of the MHWS wave front sensor. The first important KM requirement is the decentering of the beam transmitted. It produces a rigid shift of the reference natural guide stars on the Mid High Wave Front-Sensor (MHWS) focal plane, forcing the Star Enlargers (SEs) of the MHWS to be re-centered via software continuously making everything more complex [2].

This rigid stars shift on the MHWS focal plane is measured as a tilt signal on each reference star. This common mode can be retrieved and used as a feedback to perform the SEs adjustment via software.

A reasonable decentering which doesn’t requires SEs repositioning is 1/10 of SE FoV corresponding to 0.11 arcsec, or to 88μm on the MHWS entrance focal plane (optically it is the FP20 focal plane).

Assuming the same contribution for the KM and the FP20, quadratic summed, the KM acceptable chief ray decentering would become 62μm. Considering that this requirement on the decentering should include bearing wobble, alignment results, thermal effects and flexures, a 62μm requirement seems to be too strict to be fulfilled. A SEs optional re-centering during an exposure is required to be implemented. A realistically achievable decentering requirement could be 100μm (this value represents the decentering KM specification). Since the KM is placed in between the two FP20 optics groups, the decentering of the chief ray slightly affects also the pupil position on CCD, since the beam reaches the SE entrance focal plane with a little tilt. This effect, for a beam decentering however lower than 300μm, is negligible, resulting in a shift of less than 1/20 of sub-aperture in the 1x1 binning mode.

2.2 Telecentricity

The telecentricity angle of the beam at the level of the MHWS entrance focal plane is the second important KM requirement. A deviation from the telecentricity angle produces a rigid shift of the 4 pupils on the CCD.

Considering a reasonably acceptable rigid pupil shift of a 1/10 of sub-aperture of the MHWS, the corresponding tilt is a function of the sub-aperture dimension on the CCD and varies accordingly to the binning mode required for each sensor conjugation height.

A 0km conjugation height determine the 1x1 binning and in this condition a single sub-aperture, corresponding to 24μm, leads to 56arcsec of tilt.
A 7.1km conjugation height as for line-NIRVANA mode, a 2x2 binning would still allow the minimum required pupil sampling. The acceptable tilt introduced in front of the FP20 focal plane becomes 112arcsec. The first consideration would apply perfectly if the KM were the last optical system before the MHWS entrance focal plane. In the real case in which the KM should be placed in between the FP20 optics, the deflection of the chief ray would affect the pupil position lightly less than what said before, and a non-negligible rigid shift of the stars on the focal plane would occur too e.g. a 50arcsec deflection of the beam at the KM level, would cause a 150μm star shift on the SE entrance focal plane. Quadratically combining this effect with the shift due to chief ray decentering, the overall shift to be taken into account corresponds to 1/5 of the SE FoV.

2.3 Strehl ratio

The required Strehl Ratio (SR) is 90% for the KM and FP20 camera system. For this reason the KM Strehl Ratio will be kept as high as possible, in order to match this combined requirement and leave a not so strict requirement in terms of SR to the FP20 camera. It is decided to fix the minimum of KM Strehl Ratio to 95%, supposing an analogous value for the FP20 camera. An inverse sensitivity analysis on Zemax has been performed in order to evaluate the requirements on the flatness. It has been defined the maximum surface RMS (in waves) which is required to guarantee a SR better than 95%. Moreover, the large incidence angle on M1 and M2 is of about 55deg and determines a less stringent requirement on the surface flatness if compared to M2, whose angle of incidence is 20deg. The mirror flatness is estimated over the optically clear area and the Strehl is estimated at the wavelength of 1μm, on the mirror area interested by the footprint of a single beam. The reference wavelength is 800 nm, and the results are the following:

- RMS M1: 25 nm (λ/32)
- RMS M2: 14 nm (λ/57)
- RMS M3: 24 nm (λ/33)

To fulfil the requirements it is necessary to hold the mirrors in the correct way in order to avoid any thermal and gravitational stress.

2.4 Internal optical path

The optical path in the FP20 beam, (where the KM is placed is determined by design and therefore the distance between the three mirrors of the KM, nominally 640mm) must be adjusted. The distance between the vertexes of M1 and M3 results to be, by design, 218.89mm. The additional optical path introduced by the KM in the FP20 beam corresponds to the difference between 2 values: 640 - 218.89 = 421.11±1mm. This value is important because (even if KM has no optical power), the KM will be inserted in a position inside the FP20 camera in which the beam is focussing, so a non-conformance to the expected additional optical path is translate in a de-focus on the MHWS. The tolerance in the additional optical path comes from the MHWS position adjustment range, which is 2mm. All these considerations lead to the requirement on the additional optical path of 421.11±1mm.
3. DESIGN

3.1 Stiff structure

The mechanical KM design is a 120kg structure which aims to create a stiff solution stable enough to avoid any flexure during the bearing rotation and during Linc-NIRVANA bench inclination [3]. This is a tricky requirement to maintain high measurement repeatability, to limit variable errors and to have a stable and aligned KM during time and for different rotation angles. This is an essential topic before starting the internal alignment because any flexure can introduce or multiply the KM degrees of freedom making every error source detection really hard. A drift was measured in the mirror mount before modification. This flexure of about 3 – 15 arcsec was identified in a long period starting from 15' to several hours, causing a non repeatability of measurement. The second mirror mount generation which is already described doesn’t show flexures on short neither long period.

3.2 Mirror adjustment

The three mirrors mounts require a micrometric tip-tilt adjustment with a resolution of 1-2 arcsec and at the same time a holding mount to prevent thermal and mechanical stress to fulfill the mirror surface quality which is strictly bounded to the MHWS strehl ratio. Each mirror is glued to three invar pads. Each pad is circular and manufactured in order to touch the glass in three points. Glue keep in touch glass and pad as shown in Figure 4. The M1, M2 and M3 mounts have adjustment screws to adjust mirror orientation. They are very similar, so the description for just one unit will be given. There are three couples of screws placed at 120° on each mirror mount. One screw is used to lock the adjacent one. For fine adjustments is sufficient to tighten the adjustment/locking screws. A plate is rigidly connected to the K-Mirror frame and a second one is placed above thanks to the described push-pull screws. The pulling screw enter into tapped hole on one plate and is screwed to the other one. The upper plate can be adjusted in tip-tilt. An air variable thickness is between the two plates and this mutual distance could be adjusted to correct the optical path if necessary. The upper plate is connected to the mirror thanks to the three pads and bars interface. The slack between every mechanical part ensures the possibility to adjust the mirror orientation, while the flexible bars prevent any mirror damage and stress. The adjustments along one direction, as far as practicable, have a good unidirectional repeatability but in case of reversal motion the hysteresis of actuators and the elasticity of the mount could give the wrong sensation that the actuation has no effect on the base-plate position. M2 unit exploits the same concept of push-pull screws, which allows the translation of the mirror along the direction orthogonal to its reflecting surface. Thus it is designed to allow angular adjustment and it is used to adjust the KM optical path.
4. SETUP

A laser beam is expanded using a beam expander. A variable diaphragm, integral with the laser head and the beam expander, selects the inner area of the beam.

The whole source is mounted on a linear and vertical stage in order to regulate the translation of the beam. A folding mirror on a tip-tilt mount reflects the beam towards the KM and is used to adjust the angle in order to get the laser beam parallel wrt the mechanical rotation axis of the bearing.

To materialize the mechanical rotation axis of the KM are used:

- translation in the x-y plane under the laser holder
- tip-tilt mirror mount of the folding mirror

No neutral density filters are placed between the source and the rest of the opto-mechanics in order to avoid refraction. Anyway a filter can be used in front of the detector. A reference flat mirror (diam=1inch), with tip-tilt capabilities, is fixed to the rotating bearing of the KM through a dedicated crescent flange and a magnetic repositionable plate.

The same mount is used to hold the CCD test camera during the decentering alignment procedure. The light reflected by the flat mirror comes back to the beam splitter and is reflected towards a 1inch plano-convex lens (focal length 750 mm) and a CCD (pixelsize=5.2μm), placed in the focal plane of the lens. The lens and the CCD are mounted on x/y stages to simplify the setup alignment.
Figure 6: optical bench setup used for KM alignment. The laser beam (right) hit the folding mirror, reaches the beam splitter and then the KM. When the beam is back reflected by the reference mirror it passes through the beam-splitter and reaches the CCD1 test camera. Once the axis is materialized the KM is a internally aligned looking at CCD2 (decentering) and CCD3 (inclination) test camera.

The beam which passes through the bearing is reflected by M1, M2 and M3. All mirrors are equipped with tip-tilt mounts for the tip-tilt adjustment. M2 must use also its screws to adjust his vertical position which is an important requirement for the KM optical path. A CCD test camera is placed close to M3 to measure the decentering caused by a tip-tilt misalignment of M1. A second CCD camera is placed in the focal plane of a 1m focal length lens to measure the exit beam tip-tilt.

The goal of the alignment procedure is to properly orient mirrors M1 and M3 so that a laser beam materializing the axis of rotation is transmitted through the KM with decentering and tilt complying with the specifications. To achieve this it’s necessary to align the laser to the bearing rotation axis and then align mirrors to the laser beam. Finally the optical properties of the KM can be used to disentangle the contribute given by source misalignment and the contribute given by internal mirrors misalignments.

5. INTERNAL ALIGNMENT

In this section is described the alignment procedure of a three mirror optical derotator. The opto-mechanics used to test and characterize the KM include an expanded laser beam, lenses, CCD test cameras, micrometric linear translations and a corner cube.

The most confident approach is to materialize the rotation stage mechanical axis thanks to a laser beam and then aligning the mirrors. All alignment procedure phases require a rotation of the bearing of 0 - 180 deg to compute the spot trajectory on the CCD test cameras. It is reminded that the main characteristic of an optical derotator is the image rotation of a double angle wrt the bearing rotation. This geometrical properties is always used during the alignment.

At the end of the alignment, the procedure is tuned to increase the performance in the KM operation range which is required to perform on NIRVANA bench. Its operative range is defined by a 15 degrees range rotation, corresponding to 30 degrees rotation of the FoV whereas the entire scanning range is 90 degrees.

A laser beam passes through the KM and hit a CCD. The generated trajectory is the result of the laser source and/or mirrors misalignments. To understand better the mechanism is useful to think about two ideal situations. A perfectly aligned KM but a misaligned laser source and a misaligned KM but a laser source perfectly aligned wrt the rotation axis. In the first example the laser behaves as a generic off-axis rays source which is derotated by the KM and draws a circle of about 360 degrees rotation during a 180 deg KM rotation.

In the second example KM mirrors are misaligned and only a 180deg trajectory is visible on the CCD during a 180 deg KM rotation. When both effects are contemporary present, the resulting trajectory is a spiral: the larger the distance between the starting point (-90°) and the ending point (+90°) of the spiral, the larger will be the KM misalignment.
Figure 7: wobble measured for both KMs during a 180° rotation. The axis materialization contains an error of about 15arcsec. The units on both graphics must be divided by two because of a geometric factor due to reflection.

Tip-tilt and decentering source alignment is necessary to tune the KM performance by observing the out-coming KM beam. This preliminary considerations are fundamental since the KM is not ideal and the bearing wobble introduces a non negligible uncertainty on the axis materialization.

5.1 Entrance axis inclination

To materialize the mechanical rotation axis of the K-mirror a flat mirror is implemented as a reference inside the k-mirror bearing and equipped with tip-tilt regulations.

The laser station is assembled on micrometric regulation for decentering XY adjustment. A beam expander and a variable diaphragm allow, respectively, to adjust collimation and to select a small central portion of the beam to minimize aberrations. The beam is folded by a tip-tilt reference mirror into the KM axis direction.

The beam splitter separates the light into the corner cube and ref. mirror direction. The beam coming from the ref. mirror and the c. cube are re-combined and reflected into the lens direction and CCD test camera.

The c. cube has the property to reflect back the incident beam into the same direction. It produces a spot which defines the laser beam angle which is adjusted by the folding mirror.

The reference mirror produces a spot which is a reference to understand the ref. mirror position inside the KM wrt the bearing rotation axis. Two separate spots are visible on the CCD test camera.

One is fixed and stationary, during KM rotation, since it comes from the c. cube.

The other one produces a semicircle trajectory whose radius is proportional to the reference mirror inclination. The first phase is to minimize the semi-circle in order to place the reference mirror surface perpendicular to the rotation axis.

In this configuration each mirror angular rotation is equivalent and the back reflected beam appears stationary on the detector. Bearing manufacturing imperfections cause non negligible deviation (bearing wobble or precession) producing a circular trajectory of about 15arcsec PtV for both KMs.

The alignment to the reference mirror to define the bearing rotation axis has an uncertainty of 15arcsec.
Once the ref. mirror is aligned is necessary to make the incident laser beam perpendicular. The folding mirror in front of the laser is adjusted in order to superimpose the two spot on the CCD. The sensibility of the tip-tilt adjustment allows to position the spot inside the wobble points but the real accuracy doesn’t exceed 15arcsec.

5.2 Entrance axis decentering

To materialize the rotation axis it is necessary to adjust the laser XY decenter. The reference flat mirror is removed and replaced by a CCD test camera. The spot generates a trajectory on the CCD having a semi-circular shape whose radius is minimized thanks to the XY micrometric translating stages under the laser station. The micrometric adjustment accuracy is of about 10 microns but the 15 arcsec angle error decreases the decentering accuracy to a value of about 50-100μm since the pivot-point to adjust the angle is 1m far from CCD test camera.

5.3 M1 alignment

The alignment of the three mirrors M1, M2 and M3 is iterative. It must be take into account that the optical path adjustment performed by M2, requires to restart the mirrors alignment procedure. The first step is to align M1 observing the decenter trajectory on CCD2. To do that, a CCD is placed very close to M3 and the bearing is rotated of 180°. If M1 is aligned, the beam reflected by M2 reaches the surface of M3 in a point defined by the intersection of the mirror surface and the rotation axis. A misalignment of M1 leads the spot above or below this point. The spot produces a spiral or a semi-circle on the CCD and the radius must be minimized using the tip-tilt correction of M1.

5.4 M3 alignment

During M3 alignment phase is observed on CCD3 tip-tilt of KM out-coming beam. It is necessary to place a CCD on the focal plane of a lens. KM is rotated and M3 tip-tilt is adjusted minimizing again the radius of the spiral or semi-circle drawn by the spot. When the trajectory becomes a circle instead of a point it means that KM is de-rotating the incoming beam and it will be necessary to tune a residual tip-tilt and decentering of the laser source in the 90° KM operation range. This correction is of the same order of the 15 arcseconds and 50 – 100 μm uncertainty estimated for entrance axis inclination and displacement respectively.

At the end of the alignment it is necessary to adjust the optical path between M1 and M3. This phase has been developed thanks to a laser distantiometer with an accuracy of about 1mm. It as been placed on the KM materialized axis and its inclination and decentering has been adjusted. It has been measured the optical path inside and outside the KM using a reference white screen. The difference between the two values gives the correct additional optical path.
Internal optical path distance is adjusted with a piston movement of M2 inside the K-mirror. M1 and M3 alignment and tuning have to be repeated iteratively, to achieve the best performance.

6. RESULTS

The Alignment procedure has been followed as described and its first evidence has been the non negligible bearing wobble. During the axis materialization is observed a non expected wobble due to the assembling between the bearing and base plate and between the bearing and the mirrors mount.

To minimize the wobble around 15arcsec it has been necessary to hold the bearing using three screw pints for each side. This effect must be considered like an angular error generated in the path between the folding mirror and the reference mirror inside the bearing. The axis error angle at 1meter distance introduces a displacement error of about 50 - 100μm which is close to the decentering requirement.

The alignment is performed after a KM rotation angle of about 180° but the tuning is done in half range concerning the Linc-NIRVANA bench operation range. The laser was tilted looking at CCD3 in order to move the spot in the center of the circle in order to correct/compensate the uncertainty given by the bearing wobble. The source is then decentered in XY direction to minimize the circle which is visible in CCD2. It must be taken into account that a single Linc-NIRVANA exposure requires a KM rotation of about 15° instead of 90° as shown in the graphics below and therefore the performance is even better than specifications.

Figure 9: Tip-tilt and decentering of the out-coming KM beam for both KMs. The performances are within the specifications of 50arcsec and 100μm respectively and are referred to a 90° KM rotation. The alignment is tuned in the operation KM range of 90° by shifting and decentering the laser source of an amount that is comparable wrt the axis materialization uncertainty. It must be taken into account that a single Linc-NIRVANA exposure requires a KM rotation of about 15° instead of 90° as shown in the graphics and therefore the performance is even better than specifications.
7. CONCLUSIONS

The alignment of a three mirror optical derotator is a tricky procedure since a lot of unexpected mechanical degrees of freedom could affect the system especially when alignment accuracy is forced to very tight requirements. The surface RMS accuracy determines the mirror mounts and an experienced mechanical manufacturing can save time, cost and tests.

Take care when bearing wobble is certified to be “small” by the manufacturer since it is true when the rotating stage is placed on a high accuracy flat surface (RMS $\approx 10\mu m$) or when it stands unscrewed. Once the bearing is screwed in three points or more, performance decreases because of the presence of internal mechanical stress.

The actual best solution has been identified in a three points screwing of the KM bearing to the base-plate and in three points screwing to the mirrors mount.

The rotation of a three heavy mirrors assembly requires a stiff mechanical design to prevent any gravitational flexure on short and long period. If a flexure of few arcsec occurs in KM optical path for a certain rotation angle, it behaves as a sort of internal KM misalignment that decrease the instrument performance and measurements repeatability is not achievable anymore.

Base plate flexure is also responsible of KM optical performance.

The internal alignment is easy and painless and it could be finished in 1 day if the parameter characterization revealed that flexure, thermal effect, gravitational load and wobble are small if compared wrt the required alignment precision.

Lighter mirrors such as carbon fiber ones can help to limit the weight and consequently to improve the stiffness of a more rigid design structure and base-plate.

REFERENCES

