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ABSTRACT:

The LBT (Large Binocular Telescope), located at about 3200m on Mount Graham (Tucson, Arizona) is an innovative project undertaken by institutions from Europe and USA. LINC-NIRVANA is an instrument which provides MCAO (Multi-Conjugate Adaptive Optics) and interferometry, combining the light from the two 8.4m telescopes coherently. This configuration offers 23m-baseline optical resolution and the sensitivity of a 12m mirror, with a 2 arc-minute diffraction limited field of view.

The integration, alignment and testing of such a big instrument requires a well-organized choreography and AIV planning which has been developed in a hierarchical way. The instrument is divided in largely independent systems, and all of them consist of various subsystems. Every subsystem integration ends with a verification test and an acceptance procedure. When a certain number of systems are finished and accepted, the instrument AIV phase starts. This hierarchical approach allows testing at early stages with simple setups. The philosophy is to have internally aligned subsystems to be integrated in the instrument optical path, and extrapolate to finally align the instrument to the Gregorian bent foci of the telescope. The alignment plan was successfully executed in Heidelberg at MPIA facilities, and now the instrument is being re-integrated at the LBT over a series of 11 campaigns along the year 2016. After its commissioning, the instrument will offer MCAO sensing with the LBT telescope. The interferometric mode will be implemented in a future update of the instrument.

This paper focuses on the alignment done in the clean room at the LBT facilities for the collimator, camera, and High-layer Wavefront Sensor (HWS) during March and April 2016. It also summarizes the previous work done in preparation for shipping and arrival of the instrument to the telescope. Results are presented for every step, and a final section outlines the future work to be done in next runs until its final commissioning.

1. INTRODUCTION

LINC-NIRVANA (LN) aims to achieve multi-conjugate adaptive optics (MCAO) using only Natural Guide Stars (NGS), using a pair of wavefront sensors (WFS) on each aperture of the telescope. The incoming light from the M3 mirror is split by an annular mirror in two sections, the central 2 arc-minutes (′) and

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the outer ring from 2´ to 6´, feeding the High-layer Wavefront Sensor (HWS) and the Ground-layer Wavefront Sensor (GWS) respectively. Both sensors use the pyramid-WFS concept, but the GWS is designed to sense the turbulence at about 100m height, whereas the HWS observes at 7.1km above the telescope. Apart from the optical design itself, they also differ in the solutions adopted for FoV derotation: GWS is equipped with a bearing to rotate the whole optical assembly, while the HWS uses a K-mirror.

The instrument contains over 250 lenses and mirrors, 2 deformable mirrors each with 379 actuators, more than 130 motors, and also makes use of the two adaptive secondary mirrors of the LBT via the GWS´s. All this complexity aims to achieve ELT-like performance, allowing astronomers to produce superb data for their research. Figure 1 sketches the LINC-NIRVANA instrument.

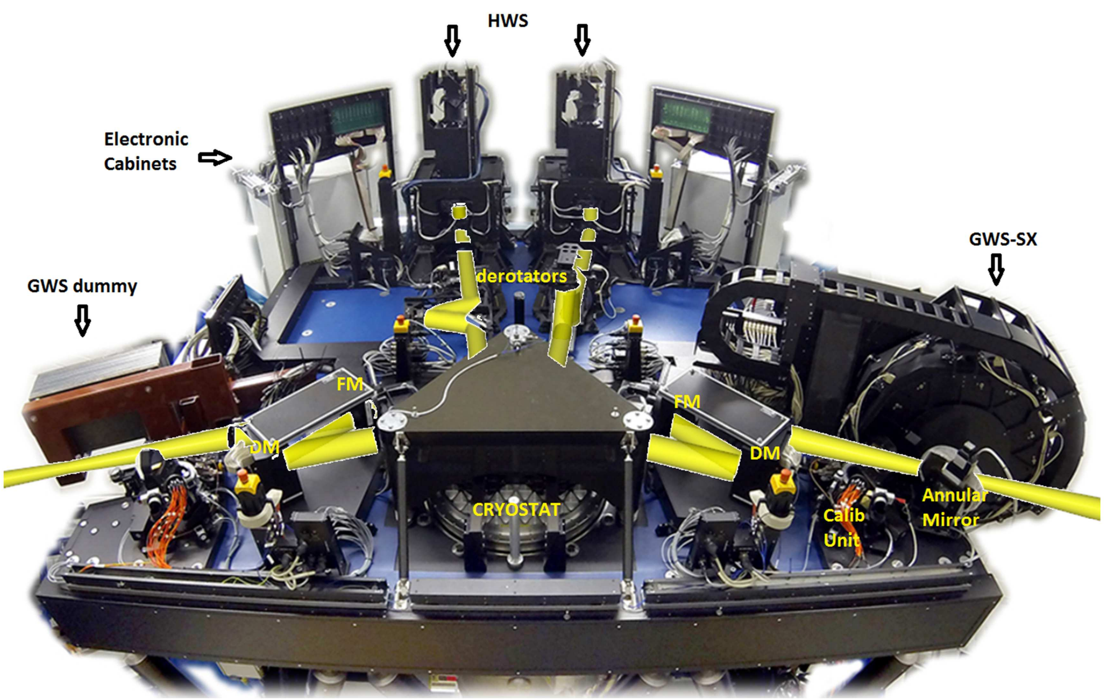

Fig 1: LINC-NIRVANA optical bench. Light comes from both sides through the annular mirrors

In this paper we describe the integration of the instrument going from the telescope focus to the CCD camera used on top of the HWS, the so-called "warm-optics". The "warm optics" group includes the collimator, beam-splitter, derotator, FP-20 camera up to the HWS, plus the alignment of eight star enlargers on each high-layer sensor and the fiber plate in the calibration unit. The calibration units are smart setups for alignment, calibration and analysis of the FoV. A rotary fold mirror allows injecting the beams from 24 different fibers strategically placed at different positions of the FoV.

The "cold optics" inside the cryostat is a Cassegrain optical design operating at 60K at wavelengths from 1 to 2.4 microns, see [2] for further details.

2. PREVIOUS WORK

2.1 Integration and verification at MPIA in Heidelberg

The AIV process of the instrument took about 2.5 years, roughly from early 2013 until July 2015. The whole process could be split in three main areas: the warm-optics (including the HWS sensors), the GWS sensors, and the cold-optics which includes everything related to the optics inside the cryostat and the science detector. Of course, many other tasks related to software, electronics, mechanics, cryogenics… etc were running in parallel. Besides, a number of tasks were performed to bring auxiliary hardware, for example the scaffolding giving access to the optical bench (about 3m high) or the tent, which allows working in darkness in one side while the lights in the clean room are on.

The warm-optics alignment starts from the pupil plane and spreads over the rest of the instrument. This approach is needed in order to achieve good superposition of images in the focal plane in interferometric mode. The alignment plan was defined and executed, as explained in detail in [1]. The cold-optics work package aims for the alignment of the optics inside the cryostat and the characterization of the science detector. This involves frequent interaction with cryogenics and electronics specialists, since the science detector must be treated with special care. A detailed description of the process is given in [2].

The GWS alignment and verification was carried out mainly by the INAF colleagues in Padova, Italy. The sensor for the SX side was delivered to the MPIA in October 2013, while the sensor for the DX side was sent directly to the LBT telescope in the framework of a “Pathfinder” experiment, described in [5]. Biggest highlight was achieved in November 2013, when the GWS achieved turbulence correction working in closed loop with the LBT secondary mirror, therefore validating the experiment.

Before shipment to LBT, two major tests were performed at MPIA facilities. The flexure test puts the instrument between 0 and 70 degrees of inclination, simulating its movement when mounted on the telescope platform. No major issues came up, apart from the expected deviation of the pupil images on the HWS. The lifting test is needed to check whether the traverse can properly hold the instrument and be balanced. This is fundamental since the instrument will be lifted in this way from the lowest level of the telescope building up to the platform, going through a very narrow hatch. Therefore a good balance is mandatory.

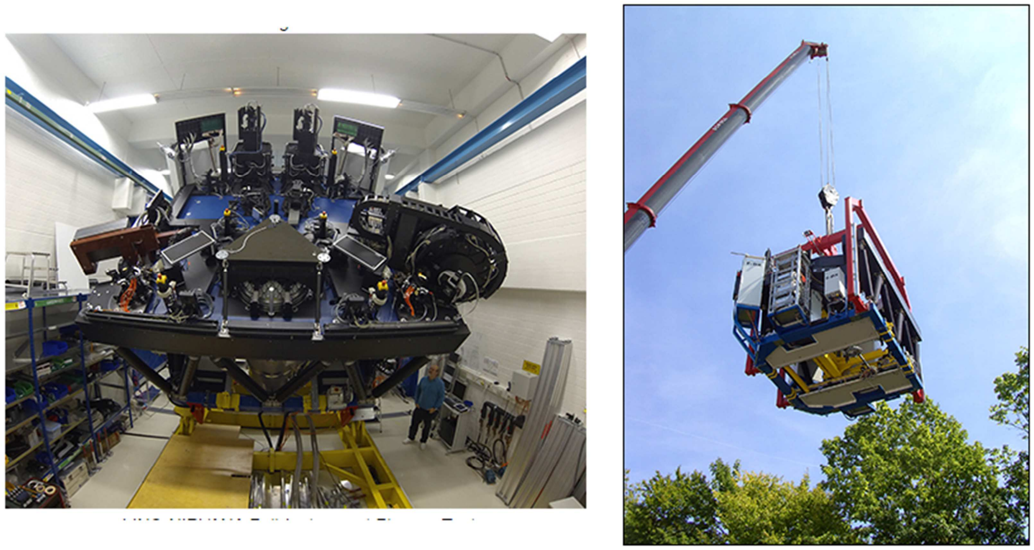

Fig 2: Left: Before PAE, “flexure-test” was performed. Right: “flight-test” before packing

2.2 Packing and shipment to LBT

After successful passage of the Preliminary Acceptance Europe (PAE), the team started to disassemble the instrument, preparing for shipment to Arizona. Nine large containers plus one oversized box for the optical bench were needed. In total, more than 80 boxes weighing about 37 tonnes traveled by from Heidelberg to Rotterdam and then across the Atlantic and though the Panama Canal to Los Angeles. From there, a fleet of trucks transported the boxes to the LBT (Figure 3). The whole trip took about 7 weeks, finishing in October 2015.

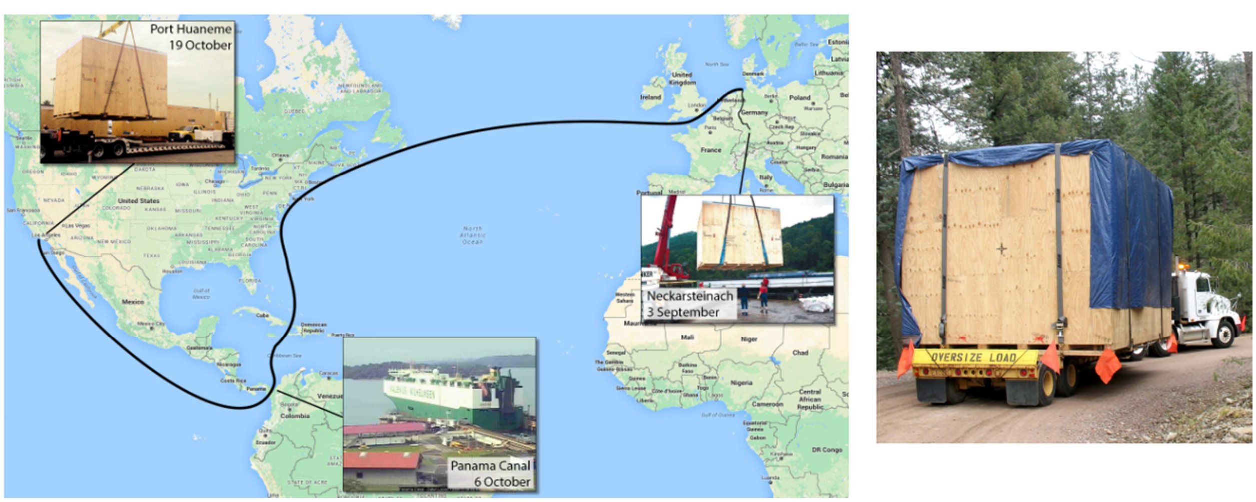

Fig 3: Left: LINC´s trip from Rotterdam to Los Angeles. Right: The instrument on its way up to the telescope

2.3 Previous runs at LBT

A total of 11 runs will be needed for the installation of LINC-NIRVANA in the telescope platform. “I-1” goal was the dismantling of the “Pathfinder” experiment. This GWS sensor was taken off the telescope and some parts needed to be replaced. “I-2” was devoted to the receipt of the instrument at the telescope and a “dry-run”, consisting on a first installation of the optical bench (without optical components) on the telescope platform (Figure 4). Everything ran smoothly, and no further modifications are needed for this step.

During “I-3”, GWS were internally aligned and the electronics & computing environment prepared. The GWS will not get light from the annular mirrors until the “I-9” run. Detailed information about the alignment is given in [4]. And during “I-4” the cryostat was assembled, cold optics integrated and the science detector was tested. The cryostat was then stored until run “I-10”.

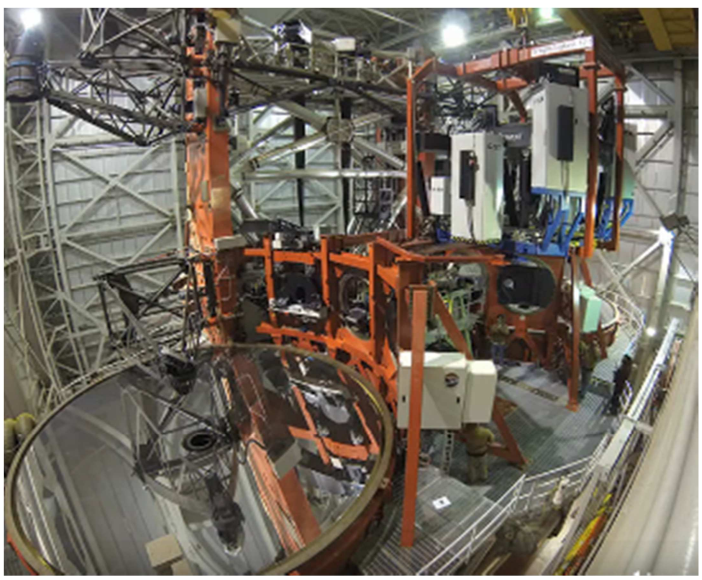

Fig 4: Frame from a video showing LINC-NIRVANA landing on the telescope (http://www.lbto.org/videos.html)

3. WARM-OPTICS ALIGNMENT

All the alignment is constrained by the fact that both GWS sensors can not be adjusted in any angle or direction. Thus, they define the focus positions on both sides, and there we have to place the FISBA interferometers which will be used for the alignment. These interferometers are extremely useful, since they are portable and can be attached to a variety of objectives. We will use the 5mm collimated beam that is provides by default, and an f/12.5 objective to recreate the diverging beam from the focus. These positions are symmetric and measured with respect to a reference rail and a reference pin. With the distances from the CAD model to these two items we can uniquely allocate the focus position on the bench. All posterior alignment should keep the symmetry between both sides.

3.1 Installation of the Large Reference Mirror (LRM)

The optics feeding the HWS´s is a collimator-camera design, with the pupil in the interface between cold and warm optics. At this point, the light is split by a dichroic, and the visible light continues to the HWS while the infrared goes to the science detector in the cryostat. The LRM mirror replaces the cryostat during this phase of alignment (Figure 5), allowing us to get the beam back to the interferometer and therefore measuring collimation and wavefront quality. Since we need to get the red light from the interferometer back, the coated dichroics need to be replaced by substrates. This way, the beam goes through the substrate, and is reflected in the LRM back to the interferometer. The small shift produced by the dichroic is of course reproduced by the substrates.

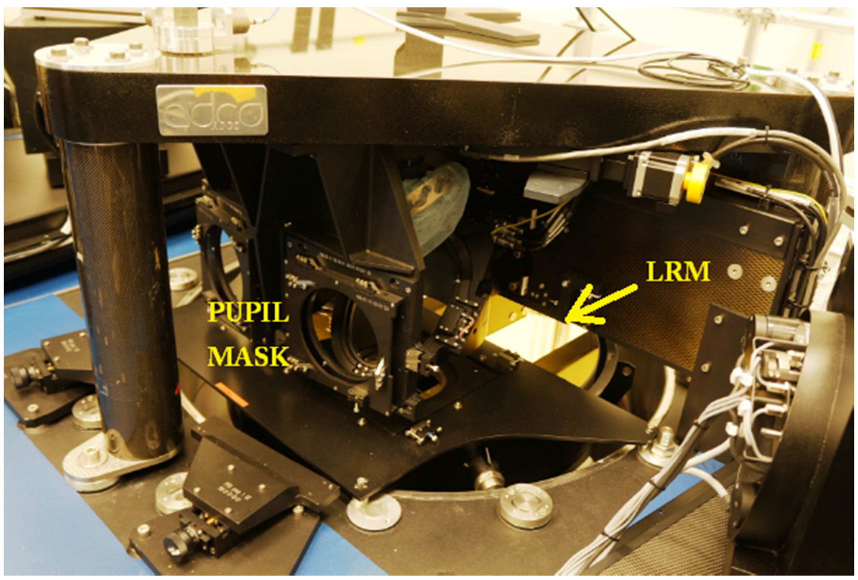

Fig 5. The LRM replacing the cryostat on the optical bench

3.2 Deformable Mirror (DM) Influence function calibration

The Xinetics DM´s contain 379 actuators each, and a flat pattern must be defined in order to get reliable wavefront measurements at every following step. Roughly speaking, the method consists on measuring the deviation provoked by every actuator when it is push-pulled, and with these data we can predict the voltage needed on the actuators to compensate a given wavefront shape. The interferometer is previously calibrated against a reference mirror and then set to illuminate the DM in a double-pass configuration (Figure 6). When the process of measuring every actuator was done, we achieved 30nm RMS wavefront error on both sides. This process can be heavily affected by temperature, so different flat patterns for different temperatures might be a solution.

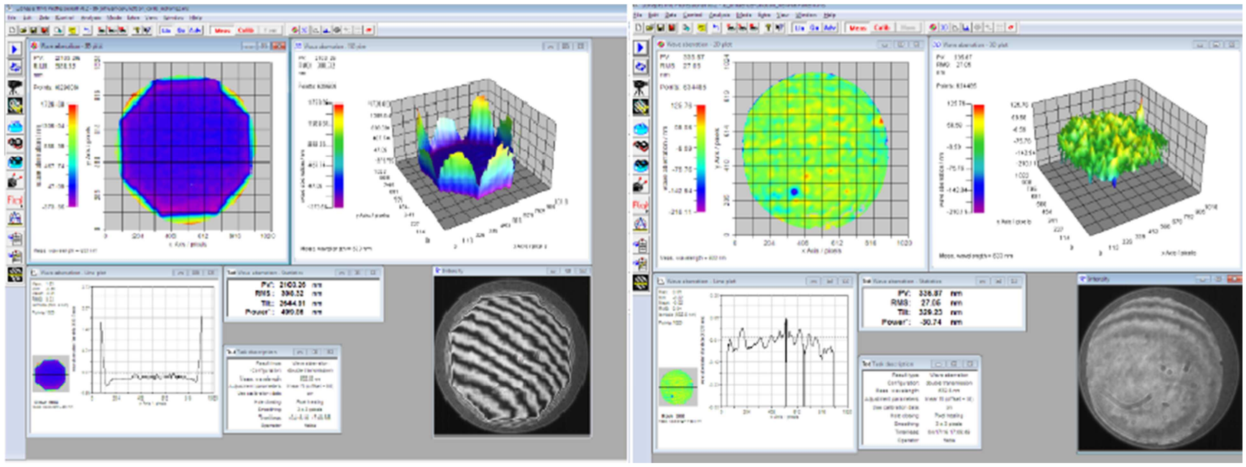

Fig6. Left: Pushing the outermost actuators helps during the alignment process. Right: WFE of 27nm when flattened

3.3 Verification of Piston Mirror (PM) position

The PM is a monolithic mirror receiving light from both sides and reflecting it towards the dichroics. It has a piezo-controller to eliminate the optical path difference when working in interferometric mode.

Before dealing with the PM, both FISBA interferometers are mounted at nominal position, delivering a 5mm collimated beam. They are set to the correct height using a reference target, and aligned in tilt using the same target far from it. Then by moving in azimuth, we move the spots until they hit the reference mask (which represents the cryostat windows). Finally, the structure from which the PM is hanging (the so-called Coffee Table, CoTa) must be rotated until both spots return to the interferometers maybe not exactly but at least symmetrically. This is essential for the final alignment of the instrument to the telescope.

3.4 Alignment of Deformable Mirror (DM) in tilt

A laser source (or the FISBA interferometer itself) is placed far from the DM and aligned in tilt so the beam travels parallel to the bench. This is guaranteed using a target close and far from the source. Then it is pointed towards the DM, which is shimmed until tilt deviation is corrected. Laser-cut shims of 0.1 and 0.2 mm are used.

3.5 Align Deformable Mirror (DM) and Fold Mirror (FM) to transmit parallel beam

In order to define the collimator axis, which is deflected by DM and FM, we need to define first the direct beam, as it would be without those mirrors, and shift the beam afterwards. For that we use an autocollimation telescope (hereafter ACT) and point it towards the PM (through the mount of the DM, which is removed for this step). Tune in tip-tilt until the beam comes back to the ACT (i.e. the beam hits perpendicular to the LRM). Now making use of a reference mirror big enough to get direct and folded beam, we keep that axis and set a second ACT at the folded beam position perpendicular to the reference mirror. If both ACT´s are perpendicular to the same mirror, we can say they are parallel.

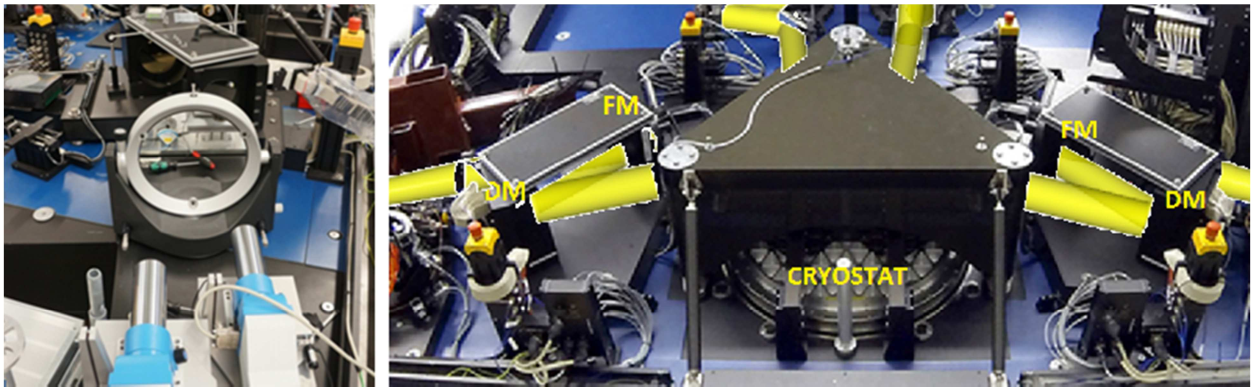

Fig 7. Left: the two ACT´s facing the reference mirror. Right: FM and DM parallel to each other

Now we put back the DM, so only the folded beam goes through. Since the DM is fixed, the FM is tuned in tip tilt until the folded-beam-ACT display shows the same value as the direct-beam display (usually set to zero). This means they are parallel.

3.6 Define collimator axis

Once FM and DM mirrors are parallel, the breadboard carrying both mirrors can be rotated to modify the distance between the two beams, keeping them parallel. Now the ACT´s can be taken off the bench and use the FISBA at the nominal folded beam position. This position is defined by the reference-sphere nest of the calibration unit (CU), so it needs to be installed beforehand. Rotate the FM&DM breadboard until the axis hits the pupil mask at the correct position and also goes through the GWS focus. Now the collimator axis is defined, and the position is kept by using a spherical objective and aligning the reference sphere to zero fringes.

3.7 Mount and align collimator optics

The collimator optics consists of two lenses, where the first one only comprises the beam to properly fill the DM, and the second one makes the beam actually collimated. We refer to [3] for further details.

Lateral alignment is performed using masks and the 5mm beam. Very little correction is needed from the alignment done in Heidelberg. Tip-tilt of the lenses was done in Heidelberg using the back reflection. No further corrections are done at the LBT. In order to measure to collimation, we mount the spherical objective and move both lenses to nominal position. Before measuring, calibration is done using a reference sphere of 200mm radius. The selected criterion is to keep the first lens in nominal position and adjust in focus with the second lens. Collimation is achieved when the software shows a value for the power of the system equal to zero. Figure 8 shows the result for both sides, 35 nm RMS for the SX side and 46nm RMS error for the DX side.

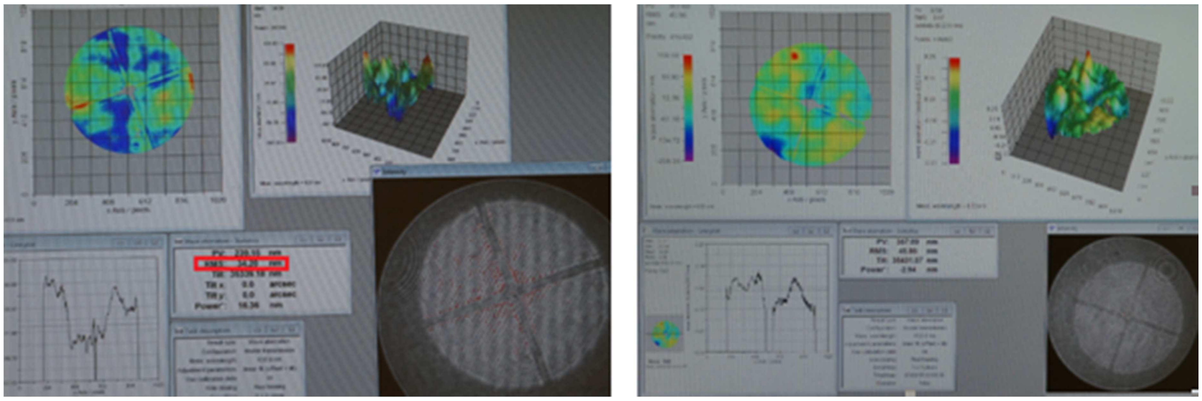

Fig 8. Left: SX-side collimator has error of 35nm RMS. Right: DX side has an error of 45nm RMS

3.8 Alignment of the FP-20 axis

As we did with the collimator optics, first the axis is defined and afterwards the powered optics is integrated in the optical path. Before starting, collimator lenses are removed and the dichroic substrates must be replaced by the coated ones, since we need to reflect the red light towards the HWS.

This is a two-steps process, first the axis is aligned to be parallel to the bench with the dichroic, and later on it is aligned to the bore sight of the HWS. The axis position is kept with a mask in the pupil position with a 5mm hole in the center. This worked without any difference to the procedure described in [1].

3.9 Derotator alignment

The K-mirrors (KM) are located in the FP20 optical path. Once the FP20 axis is aligned, an auxiliary tool is installed to represent the original axis. They are assumed to be internally aligned, so we integrate the KM´s in the optical path as a "black-box" and do the fine alignment until the deviation produced to the original beam is minimized. As described in [1], we measure XY deviations in single-pass and tip-tilt deviations in double-pass. We achieved about 20 arc-seconds in tip-tilt and 50 microns in shift.

3.10 FP-20 optics alignment

In order to align the FP20 optics, a reference sphere is mounted at the bottom of the HWS. The center of this sphere is at the focal plane of the FP20 (with mechanical accuracy), so an incoming converging beam is reflected back. It serves for focusing with the first lens of the FP20 camera. The sphere is surrounded by a flat area, which is used for tip-tilt correction with the 10mm collimated beam. It is important to first check the collimation provided by the collimator group to ensure the input beam to the FP20 is correct. To do that, since the LRM is not reachable any more, an auxiliary reference mirror has to be mounted next to the pupil mask.

Lateral alignment of the lenses is done again using masks. No big corrections are needed. Focus correction is made using the first FP20 lens. Results are 35nm RMS for the SX side and 54 nm RMS for the DX (Figure 9). Even though these numbers include the collimator group, fold mirror, piston mirror and all the FP20 lenses, there is still some margin to improve here, with a better SM flattening.

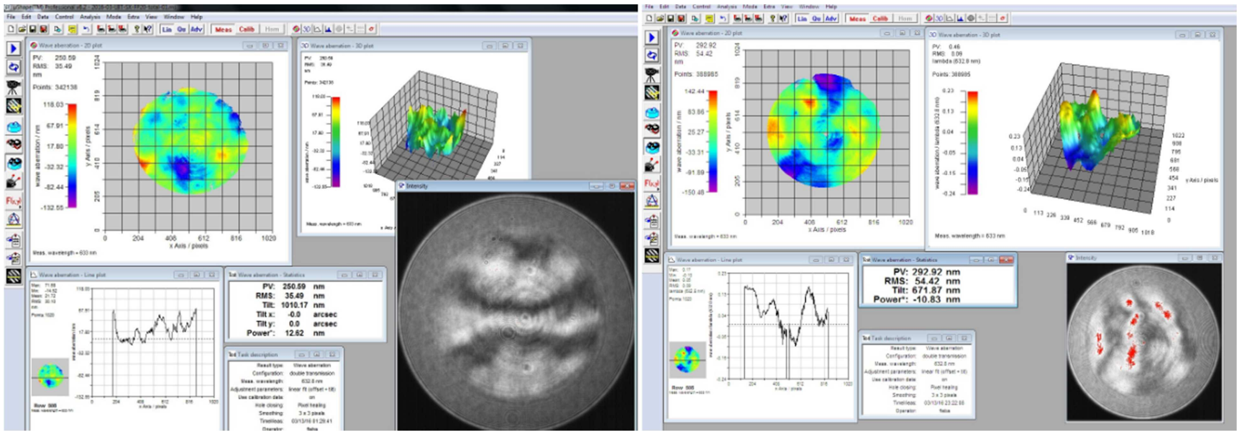

Fig 9. Left: SX side has 36nm RMS error. Right: DX side has 54nm RMS error

After FP20 alignment, the FISBA positions should be kept by aligning the reference sphere to zero fringes. This step concludes the run “I-5” at the LBT.

4. HWS ALIGNMENT

The alignment of the High-layer Wavefront Sensor (HWS) starts with an inspection of the instrument, check of the previous alignment and software preparation. As a result of this stage, all star enlargers (SE´s) will be aligned, and for that the fiber plate in the calibration unit needs to be aligned on-axis and in tip-tilt using the off-axis fibers.

The incoming beam delivered by the FP20 optics is an f/20, flat and telecentric. The light from the reference stars passes through the SE´s and the pupil re-imager, recreating the image of the telescope entrance pupil on a CCD with 80x80, 24micron pitch pixels.

The fiber plate contains 23 fibers evenly distributed over the 2´ field of view (FoV). The fibers are feed with red-light LEDs, having the central one also the possibility of using infrared light (for cold-optics alignment purposes). The alignment of the fiber plate is done in two steps, first on-axis making it coincident with the reference beam defined by the FISBA interferometer, and afterwards the off-axis alignment is performed.

Before starting, performance of the collimator group is checked again, since it may vary with temperature or other factors since last time. At some point the one of the FP20 lenses will be refocused so the FP20 focal plane matches the CCD focal plane when observing the pupil, so it’s important to feed the FP20 camera with a beam correctly collimated.

4.1 CCD lateral adjustment and conjugation to the pupil plane.

Using a mask with a 2mm central hole and without any SE in the optical path, the light goes directly to the CCD. The CCD is moved on its XY plane until the centroid of the on-axis beam falls at the center of the image. When the CCD is conjugated to the pupil plane, the images produced by all SE´s perfectly overlap if the SE´s are co-aligned. Relative misalignment leads to relative displacement of the pupil images on the CCD. To achieve conjugation of the CCD to the pupil plane, four off-axis fibers are used and the CCD is focused until their footprints overlap in the detector.

4.2 Patrol Camera alignment to the reference beam

When the light reaches the bottom of the HWS´s, a beam-splitter redirects about 90% of the light up to the HWS camera, and about 10% hits the Patrol Camera (PCAM). These cameras are manually adjusted in focus to minimize the on-axis spots produced by the reference FISBA beams and their positions are recorded. Positions on both sides are within 10 pixels from those measured in Heidelberg. These positions are the references for the fiber plate on-axis alignment.

4.3 Pre-alignment of the Star Enlargers

Using the reference beam delivered by the interferometer, all SE´s are driven to on-axis position and their images analyzed. The on-axis position is reached when (without pupil mask) the pyramid produces four equally illuminated images of the pupil. These on-axis positions are recorded.

Three features are inspected in this first step: pyramid rotation angle, tip-tilt and focus. The 80x80 detector is subdivided in four 20x20 quadrants, imaging the four pupils. For tip-tilt a holed mask is used, and adjustment is needed until the four spots are at the center of each quadrant. Because the FISBA beam is diffraction limited, the sampling does not allow good measurement of the focus but a first inspection can be done. It is important to notice whether all SE´s follow a general pattern in any of these features, which would point to a problem with the whole sensor.

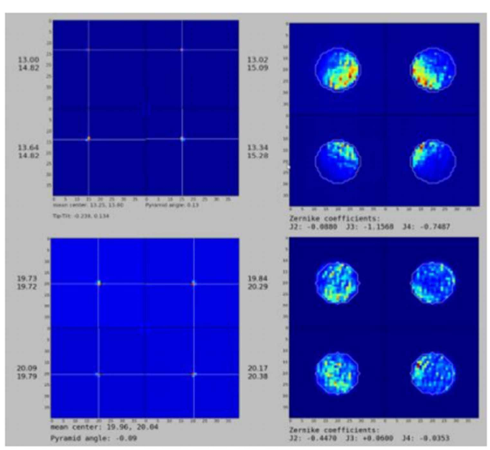

Fig 10. Up: Tip-tilt and defocus before correction. Down: after correction

One SE is selected on each sensor to be the reference. Any SE able to reach the on-axis positions and without clear defects in focus, tip-tilt, vignetting…etc would be valid. The absolute reference fibers are aligned using this SE to uniquely represent the on-axis beam.

4.4 Fiber plate "on-axis" and "tip-tilt" alignment

With the reference SE, catch the light from the FISBA defining the telescope focal plane until it produces the four pupil images. Then switch off the laser, switch on the central fiber LED and move the fiber plate in XYZ with the motorized stages until the central fiber image falls on the same pixel. The mirror in the calibration unit allows injecting the beam into the collimator optics. Now the central fiber mimics the reference beam. Save the CU-mirror position and also the position in pixel coordinates on the PCAM.

For the tip-tilt alignment, the second step is to get (at least) four SE´s at the same plane. That can be achieved by positioning the SE´s at the on-axis position (one at a time) and adjusting in focus. These 4 SE´s will be used to minimize the tip-tilt of the fiber plate by minimizing the focus gradient along each axis. This process may require a few iterations, stating at the on-axis fiber to check common focus offset. The figure below summarizes the process in 4 steps.

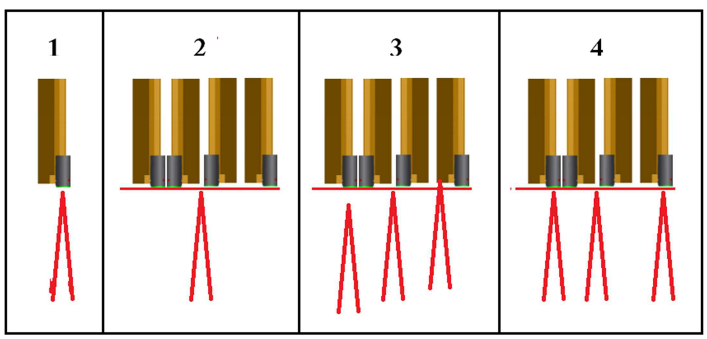

Fig 11. These four steps (strongly) summarizing the fiber plate tip-tilt alignment

4.5 Fine alignment of the Star Enlargers

Now that the fiber-plate is aligned in tip-tilt, the alignment done in (4.3) can be improved. The idea is to somehow optimize every SE to the fibers (or, FoV area) it will be observing. The goal is to have all SE´s below 20nm RMS wavefront error and the four pupil centroids at the coordinates (20,20) with less than 0.1 pixel error. With this, the HWS alignment is considered done.

4.6 Final considerations

The alignment of the HWS sensor is a quite demanding task. It requires a vast number of motors and actuators working properly, as well as many GUI´s and a big amount of patience. Besides, the alignment of the star enlargers is very fragile, so the removal and re-integration of one single unit will affect the alignment of the rest. In the "I-6" campaign, one of the SE´s was removed two times, with the consequent misalignment of the adjacent units.

5. FUTURE WORK

A number of tasks were already done during the "I-6" run, in preparation for incoming campaigns. The annular mirrors (deflecting the 2′ to 6′ FoV to the GWS) were assembled and tested. A few issues regarding limit switches, hardware limits and motor controllers were solved. The so-called "Magic Lantern" (ML), which provides an f/15 beam and serves for the annular mirrors alignment was also tested and set ready for the "I-9" run.

On the mechanical side, some problems with the bearing of the GWS sensor on the DX side were solved. Both GWS sensors were running back and forth during more than four hours without any problem.

The "I-9" run will happen during May 2016 and our colleagues from INAF will deal with the alignment of the annular mirrors to the GWS sensors. As it happens for the "i-6" run, it will strongly depend on the performance of software and electronics, since artifacts like noise or wrong attenuation heavily damage focus measurements.

The "I-10" run will be dedicated to the integration of the cryostat in the optical bench and instrument and instrument verification. Therefore all the read-out electronics and softwares related to the science detector must be ready.

And in the final "I-11" run the instrument will be installed at the telescope. The lift of the instrument to the telescope platform, installation of the helium lines and balancing of the telescope will be few of several milestones.

6. CONCLUSIONS

The instrument is now under re-integration process and will be ready for installation by end of 2016, providing MCAO sensing to the LBT telescope. Having a healthy instrument at the telescope after such a long trip is the result of the excellent job and coordination of the MPIA staff and some private companies which helped with the transport. The warm-optics has been successfully aligned and tested, with similar results to those found in Heidelberg and always in the budget error.

LINC-NIRVANA contains a huge number of subsystems and the alignment of this instrument requires a very clean planning and strict coordination between different specialists. So far, the installation plan has proved to be robust and reliable, and after the sixth run the re-integration process is one month ahead of schedule, even with unexpected issues on the way. When two consecutive campaigns do not overlap in time, a good communication between the teams has been ensured, so the process can continue without major problems. It is of special importance important to report issues using a ticket-system, so everything is tracked. Also, tidy-up of the lab before leaving and updating the inventory are crucial steps that should not be overlooked.

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