Alignment of the SPHERE-ZIMPOL imaging polarimeter

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ABSTRACT

ZIMPOL is the high contrast imaging polarimeter subsystem of the ESO SPHERE instrument. ZIMPOL is dedicated to detect the very faint reflected and hence polarized visible light from extrasolar planets. ZIMPOL is located behind an extreme AO system (SAXO) and a stellar coronagraph. SPHERE is foreseen to have first light at the VLT early 2013. ZIMPOL is currently integrated in the SPHERE system and in testing phase.

We describe the alignment strategy and the results of the ZIMPOL system and the related alignment of ZIMPOL into SPHERE by the aid of an alignment unit. The field selecting tip/tilt mirror alignment and it's requirement for perpendicularity to the two detectors is described. The test setup of the polarimetric components is described.

SPHERE is an instrument designed and built by a consortium consisting of IPAG, MPIA, LAM, LESIA, Fizeau, INAF, Observatoire de Genève, ETH, NOVA, ONERA and ASTRON in collaboration with ESO.

Keywords: **Keywords:** VLT, high-contrast, imaging, polarimetry, exoplanets, SPHERE, ZIMPOL, alignment

1. INTRODUCTION OF THE SPHERE PROJECT AND ZIMPOL

For the second-generation instrumentation on the VLT of ESO, a unique instrument is developed: SPHERE (Beuzit et al [4]), combining a powerful extreme adaptive optics system (SAXO), various coronagraphs, an infrared differential imaging camera (IRDIS), an infrared integral field spectrograph (IFS) and a visible differential polarimeter (ZIMPOL).

The ZIMPOL focal plane instrument is a technology development from the group of ETH in Zurich (Switzerland) and the NOVA-ASTRON group in Dwingeloo and University of Amsterdam and University Leiden.

SPHERE-ZIMPOL is a high-precision imaging polarimeter working in the visual range. The ZIMPOL instrument principle (Schmid et al[3], Roelfsema et al [2]) is based on differential comparison of the two polarization images by fast modulation with a FLC (Ferro-electric Liquid Crystal), a technique that is also used in solar telescope instruments. Planets with atmosphere are revealed, because their reflected light is polarized, while starlight is not polarized. Also protoplanetary disks and debris disks are candidates to be observed with this polarization technique.

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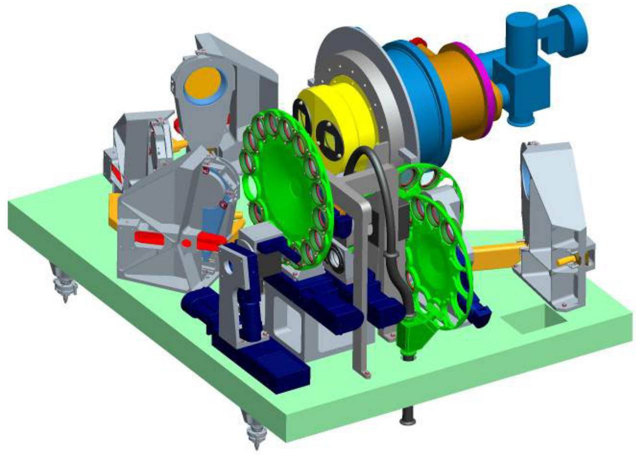


Figure 1 ZIMPOL bench isometric view. The dust-cover is removed. Two of the three spherelinders are visible at the left underneath the bench. The light enters at the left at the polarization compensator plate. The tubing in the middle of the bench leads to the vacuum chamber of the FLC (Ferro Liquid Crystal) the hart of ZIMPOL what switches the polarization of the incoming beam at high frequency (≤1 KHz) and in combination with a synchronized read-out of the detector creates differential polarimetric pictures with contrast up to 10^8. Typical size of the bench: 1000x650 mm, total weight about 200kg .

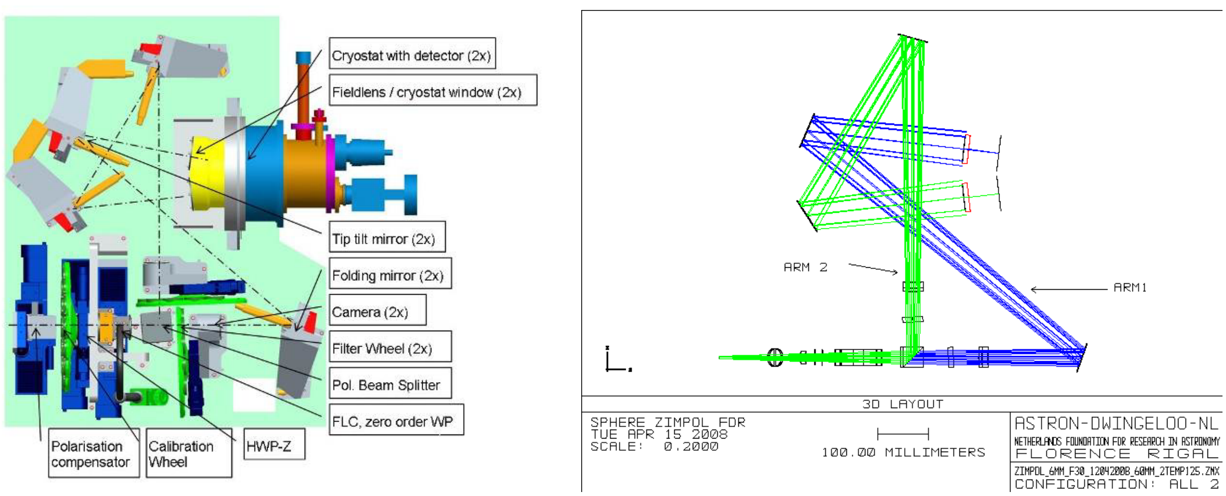


Figure 2 ZIMPOL bench top view and Zimpol optical design. The collimated light enters from the bottom left into ZIMPOL. A coronagraph (not shown) is located on the SPHERE optical bench just in front of the ZIMPOL bench with the pupil plane about 20 mm before the ZIMPOL bench. The Polarizing Beam splitter splits the light into 2 arms. Arm1 transmitted by the Polarizing Beamsplitter, arm 2 reflected by polarizing beamsplitter. A f221 camera create a focus on the detector. The tip and tip-tilt mirrors are used for dithering of the 3.5 arcsec (on sky) field, but can also be used for field selection for a total 8 arcsec diameter field of view.

2. INTRODUCTION TO THE ZIMPOL ALIGNMENT

The alignment of SPHERE-ZIMPOL can be divided into 3 levels, from top down it is: ZIMPOL alignment into SPHERE, Optical subsystems into ZIMPOL and optical components into subsystems.

The ZIMPOL alignment into SPHERE is based on pre-aligned of dummy-ZIMPOL in SPHERE by classical alignment by means of an alignment telescope, reference targets on pupil and focus positions at the SPHERE instrument. The ZIMPOL instrument is located on so called spherelinders, what are iso-static mounting points with an accurate repositioning within a few microns. After alignment of the dummy-ZIMPOL into SPHERE, the dummy can be easily exchanged by the real instrument ZIMPOL and no post-alignment of the ZIMPOL instrument on SPHERE should be required, just verification of the position.

The alignment of ZIMPOL sub-systems onto the ZIMPOL bench is based on positioning by production accuracy of the parts, so no alignment is required. The alignment of the main components is in that respect reduced to verification and check. An exception in this are the tip and tip-tilt (flat) mirror system, what exist of several mechanical and optical components mounted in series to position the mirrors, what creates a one-time error on the mirror angle. In combination with an optical sensitive system with long optical arms (f-ratio 221) and strict requirements on the tip and tip-tilt, an adjustment is needed for both sets of tip and tip-tilt mirrors and even optical fine tuning of the angles with the complete ZIMPOL instrument is needed.

Optical component alignment within the subsystems: for the non-polarized optics the alignment is based on production accuracy. The polarimetric beamsplitter, what polarimetric splits the light into two arms, is also positioned by production accuracy of the optical components of the beamsplitter and its mechanical references of the subsystem. The remaining polarimetric components like the FLC (Ferro Liquid Chrystal, the heart of the system), Half Wave Plate, Zero Half Wave plate need to be positioned in the optical rotation to set within a few degrees the polarimetric angle in respect to its mechanical mount. They need to be aligned by special tooling to find it's polarimetric reference angle.

The alignment described in this paper starts with the optical verification and equality of dummy-ZIMPOL and ZIMPOL and the related positioning of ZIMPOL onto SPHERE (level 1 alignment). Then the alignment of the tip and tip-tilt systems (level 2 alignment). Also a setup is described on the polarimetric component alignment defining the reference axis of polarimetric components is described (level 3 alignment).

3. ZIMPOL OPTO MECHANICAL ALIGNMENT

This chapter describes the alignment principle of ZIMPOL and the Dummy Bench of ZIMPOL.

The alignment is better described as a check of position instead of real alignment of optics. The ZIMPOL instrument has no adjustment on optics and is used as nominal instrument. The Dummy is provided with a simple correction mechanism on the polarizing beamsplitter consisting of the method of polishing hard mechanical stops to correct any differences in respect to the ZIMPOL-Bench.

3.1 Requirements

The requirements are documented in the SPHERE-ZIMPOL Interface Control Document. A shortcut of this specifications dedicated to alignment is as follows:

As coordinate system we use the local ZIMPOL coordinate system, what is defined as Cartesian system located at the entrance pupil optical axis. Z-axis is the optical axis towards the detector. X-axis is the other horizontal axis. Y-axis is the vertical axis.

The alignment budget is equally divided over SPHERE and ZIMPOL:

Common Path	ZIMPOL
$\Delta x = \pm 140\ \mu m$	$\Delta x = \pm 140\ \mu m$
$\Delta y = \pm 140\ \mu m$	$\Delta y = \pm 140\ \mu m$
$\Delta z = \pm 140\ \mu m$	$\Delta z = \pm 140\ \mu m$
$\Delta\theta_x = \pm 1.7$ amin	$\Delta\theta_x = \pm 1.7$ amin
$\Delta\theta_y = \pm 0.7$ amin	$\Delta\theta_y = \pm 0.7$ amin
$\Delta\theta_z = \pm 0.7$ amin	$\Delta\theta_z = \pm 0.7$ amin

The alignment tolerances of ZIMPOL need to be divided equally over the alignment of SPHERE to Dummy-ZIMPOL and of Dummy-ZIMPOL to the ZIMPOL instrument. Assuming a Gaussian distribution the alignment budget is:

CPI to Dummy-ZIMPOL	Dummy-ZIMPOL to ZIMPOL
Δx = ± 100 µm	Δx = ± 100 µm
Δy = ± 100 µm	Δy = ± 100 µm
Δz = ± 100 µm	Δz = ± 100 µm
$\Delta\theta_x$ = ± 1.2 amin	$\Delta\theta_x$ = ± 1.2 amin
$\Delta\theta_y$ = ± 0.5 amin	$\Delta\theta_y$ = ± 0.5 amin
$\Delta\theta_z$ = ± 0.5 amin	$\Delta\theta_z$ = ± 0.5 amin

3.2 The basic principle of alignment of ZIMPOL:

1. Benches:
   a. There are 2 ZIMPOL instrument benches: the ZIMPOL-Bench and the Dummy-ZIMPOL-Bench. Both are produced on the same machine in the same timeframe. The difference between the Dummy and original bench is: the dummy has no overall grid of M4 (25mm pitch) for general mounting points and is not lightweighted at the back side.
   b. A standard stainless steel optical bench is equipped with 3 spherolinders. The spherolinders represent the interface to the SPHERE mechanical structure for ZIMPOL. These spherolinders are positioned by a setting plate with alignment features with a position accuracy within 10 micron. The nominal position of these spherolinders are copied from the SPHERE-ZIMPOL interface. This bench with the spherolinder features we call Dummy SPHERE.
   c. Onto this bench an alignment telescope is placed what can be fine adjusted on all degrees of freedom.
2. ZIMPOL instrument:
   all ZIMPOL units and parts are placed by mechanical production accuracies, no adjustment are required (Roelfsema et al [2]).
   a. The ZIMPOL-Bench is mounted with its spherolinders onto the Dummy SPHERE
   b. The ZIMPOL-Bench will be equipped with a transparent target at the entrance pupil called pupil-reference-target. Also targets for arm1 and target arm2 will be placed at the position of the tip mirrors (2). The position of these targets (and tip mirrors) are defined by a dowel pin in the bench at the nominal position of the optical surface of the tip mirror.
   c. The pol.beamsplitter is positioned to its mechanical references and iso-static fixated.
   d. The alignment telescope is aligned such that the pupil-reference-target and target1 are aligned.
   e. A check is done on target 2 to check it's position. No adjustment are made to correct for eventual error on this target.
3. ZIMPOL Dummy:
   The Dummy Bench will have at the entrance a transparent pupil-reference-target and target number 1 and 2 at the tip mirror position, likewise the ZIMPOL Bench.
   a. The Dummy-ZIMPOL-Bench is mounted with its spherolinders onto the Dummy SPHERE
   b. The polarizing beamsplitter is such aligned by dowelpins and spacers, that its equal as ZIMPOL
4. We checked a few times the repeatability of replacing dummy-ZIMPOL and ZIMPOL to check whether the targets stay stable and aligned and the benches replaces correctly. Besides a minor variation, the repositioning and alignment is alright and it stays within the 20 micron level.

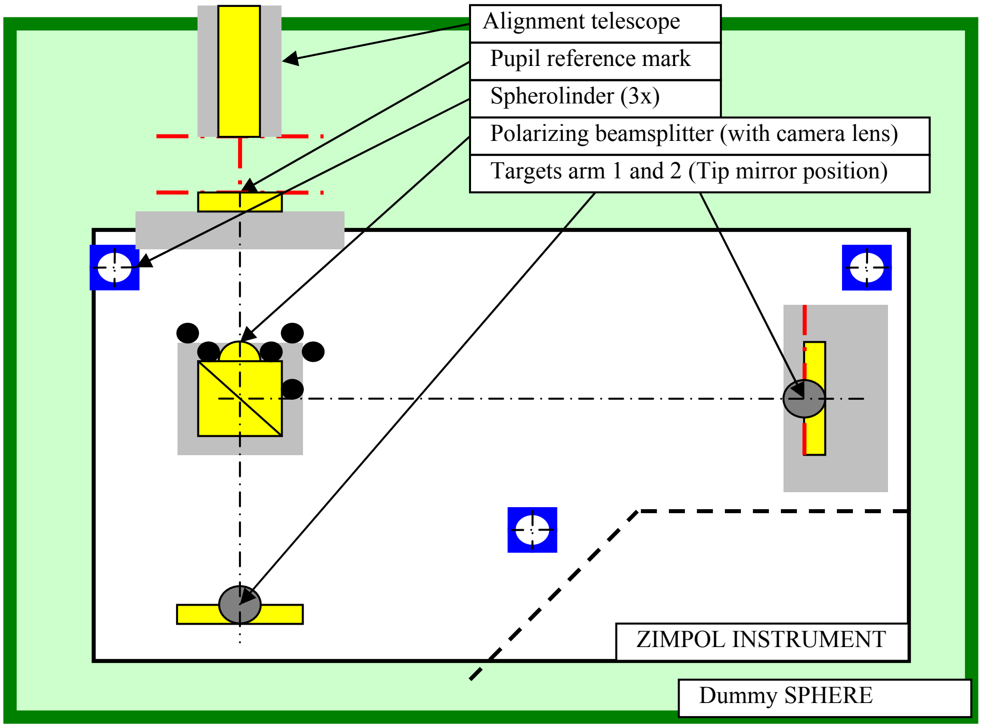
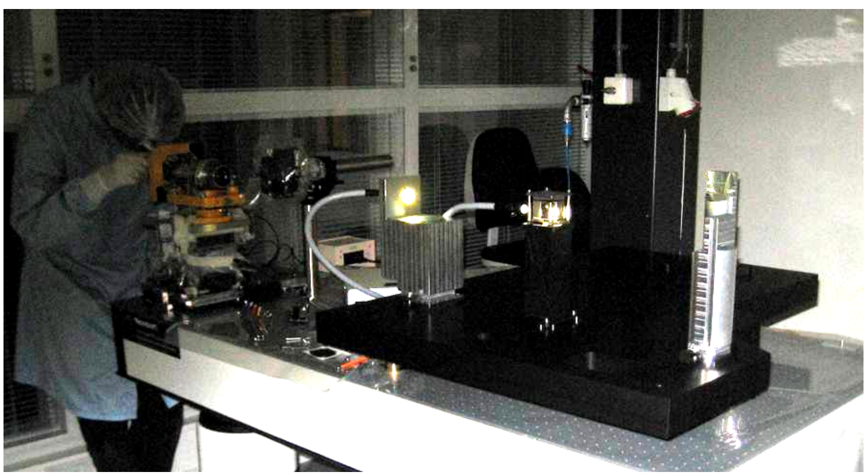


Figure 3 Sketch of the layout of the alignment setup



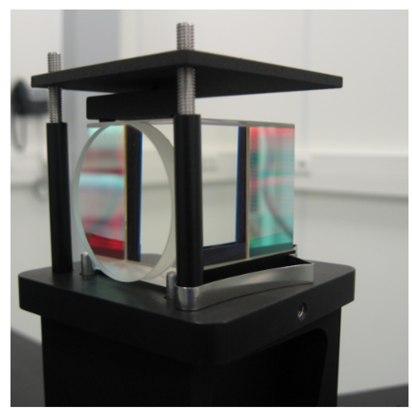


Figure 4 Left picture: ZIMPOL-Bench with pupil-reference-target (thick alumimium block with illuminated target) with a transparent grid at the pupil position, beamsplitter mount in the middle and 2 targets (target 1 and 2) at the position of the tip mirrors 1 and 2.
Right picture: Polarizing Beamsplitter in its mount. Positioned by 3 dowel pins at the side and 3 pads at the bottom. Note the special camera lens glued to the front side of the beamsplitter to prevent for ghosts.

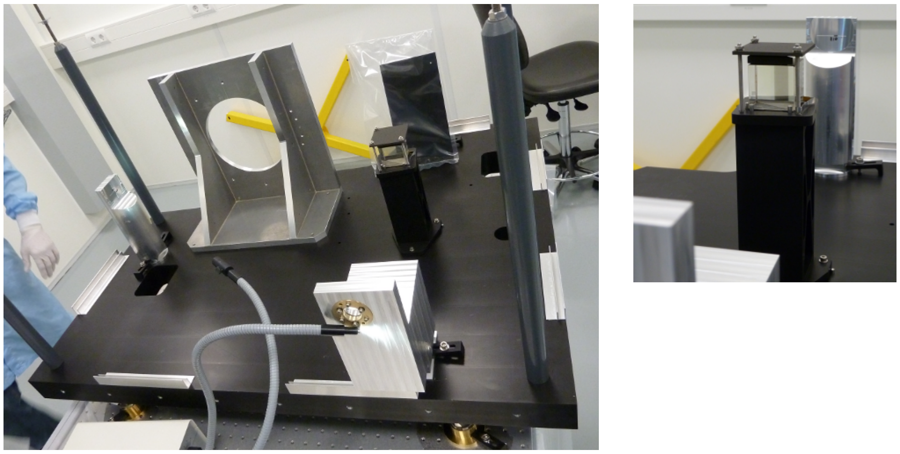


Figure 5 The Dummy table. The pupil target at the right bottom of the picture. The top left aluminum construction is the dummy detector holder.
Right picture is the dummy polarizing beamsplitter, no camera lens is provided to this BS.

The alignment telescope has a 50 micron adjustment resolution on an adjustment scale. Optically one can verify below that and 20 micron errors are identified as measurement resolution on positioning. The applied alignment telescope is a classical Taylor Hobson telescope.

ZIMPOL-Bench and Dummy-ZIMPOL-Bench uses alignment targets with a measured effective overall position accuracies within +/- 20 microns on all targets, made by production accuracies (measured data). The ZIMPOL-Bench sub-units are by design not required to be aligned: the position of all parts are defined by production accuracies.

3.3 Alignment results

The following pictures show the alignment target of the Dummy and ZIMPOL. The photographs are made with a digital camera with view via the alignment telescope to the targets. The digital camera is handled manually. That's the reason the target are not perfect vertical/horizontal. The pupil- reference-target is transparent and by refocusing of the alignment telescope the target 1 and 2 can be found without removing the pupil-reference-target.

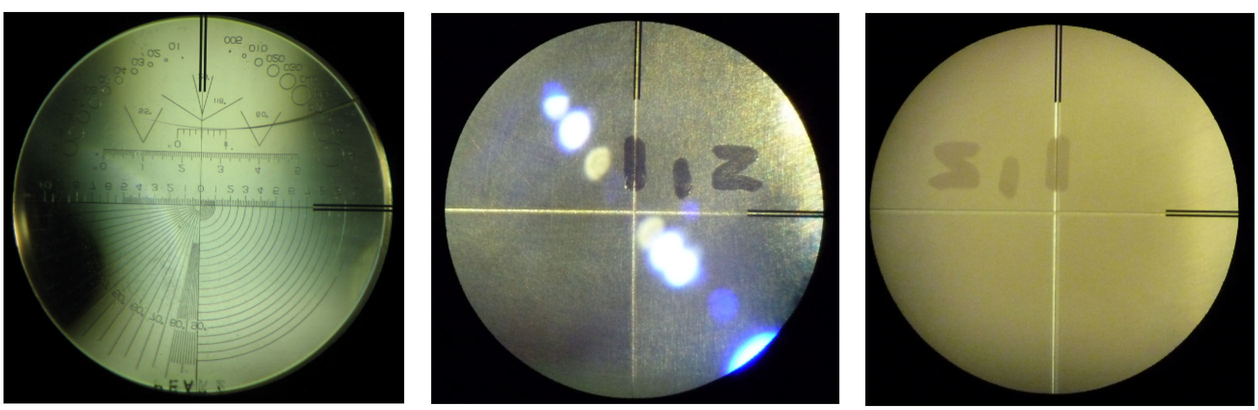


Figure 6 ZIMPOL alignment targets
Left picture: Pupil-reference-target of ZIMPOL-Bench. The alignment telescope is spot-on aligned to this target.
Middle picture: This target is positioned on arm 1 at the Tip-mirror location. The alignment telescope is also spot-on aligned to this target (within 20 micron) for both axes. The sideways illumination of the V-groove could mislead. Careful zoom in on the photograph shows a very good alignment of telescope and target.
Right picture: This target is positioned on arm 2 at the Tip-mirror location. The alignment is spot-on (within 20 micron) for the horizontal axis. The vertical axis is aligned within about 60 micron. This is within specification.

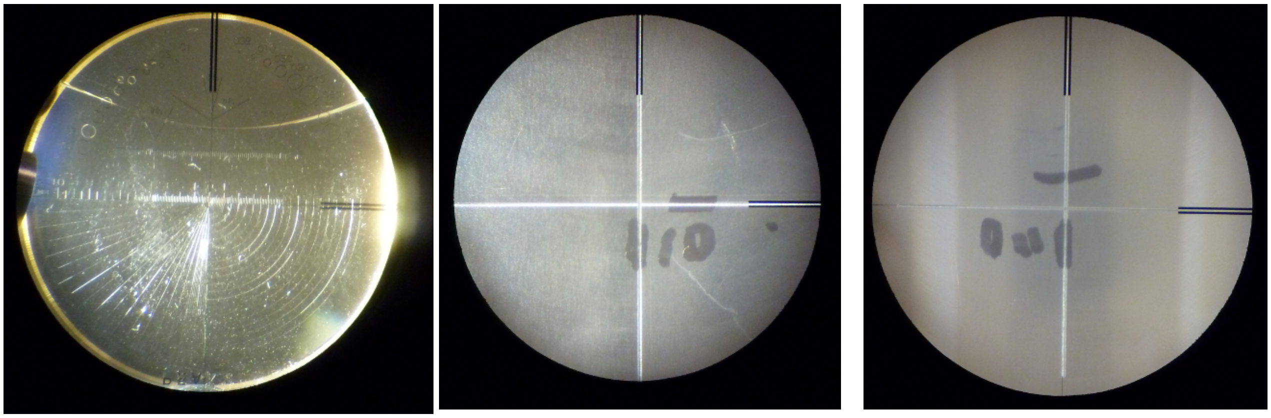


Figure 7 Dummy ZIMPOL alignment targets
Left picture: Pupil-reference-target of Dummy-ZIMPOL-Bench is within the 20 micron range equal to the ZIMPOL-Bench.
Middle picture: Target of beam 1, spot-on in Horizontal direction (<20 micron), Vertical direction <40 micron
Right picture: Target of beam 2, in Horizontal direction a shift of 80 micron, in vertical direction 20 micron. The target looks spot-on, but the telescope is adjusted in horizontal direction to compensate and with that to measure the error on the target.

4. ZIMPOL ALIGNMENT WITHIN SPHERE

The Dummy-ZIMPOL, representing the ZIMPOL instrument on opto-mechanical interface and features is shipped early to Grenoble for the pre-alignment, while ZIMPOL was still at ASTRON in the Netherlands. The Dummy was installed for more than a half year into SPHERE before the real ZIMPOL instrument arrived at Grenoble. During that period ZIMPOL could be further build and verified at ASTRON in the Netherlands, while in France in Grenoble the alignment procedure could be tested, the Dummy aligned, interfaces, space envelope and weights checked. After shipment of the ZIMPOL instrument to Grenoble the alignment of ZIMPOL onto SPHERE is reduced to a few steps: a one day check of correct ZIMPOL shipment on alignment and motor movement, exchange of the Dummy for the real ZIMPOL instrument onto the SPHERE bench and a check on optical alignment of ZIMPOL in SPHERE. The optical check required operational detectors and the total procedure took a few days, including cooling of the detectors of the ZIMPOL instrument.

The focal plane instruments IRDIS and IFS had the same approach of alignment strategy by a opto-mechanical Dummy as the ZIMPOL instrument.

During check it appeared there was a slight offset. This was due to some alignment corrections over time at the SPHERE bench when installing the coronagraph focal masks and pupil masks.

This alignment check is split in two levels:

- Imaging of a focal mask of the coronagraph focal plane of SPHERE onto the detector of ZIMPOL; the centers should match. On this way the lateral angular alignment is checked (θx and $\Delta\theta y$).

- Imaging of the pupil mask of the coronagraph onto the detector of ZIMPOL by applying the pupil imaging lens in the filterwheel of arm2 of ZIMPOL. Besides the coronagraph there is for transport and alignment check a pupil target plate mounted to ZIMPOL with a crosshair. On this way the lateral position alignment is checked (Δx, Δy).

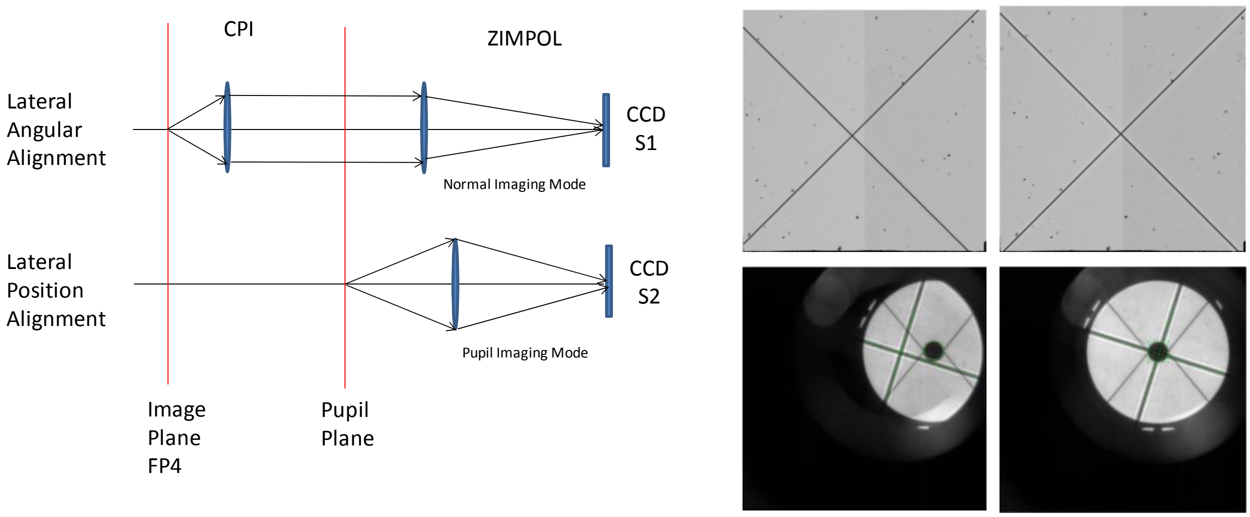


Figure 8 CPI is the SPHERE Common Path optics and bench.
The top row shows the imaging of a focal mask on the ZIMPOL detector. The pictures at the top right show the 4QPM (Four Quadrant Phase Mask) imaged on CCD S1. On this way the lateral angular alignment is checked. The center of 4QPM1 must be imaged on the center pixel of the CCD. Left the uncorrected alignment, right the corrected alignment. The bottom row shows the imaging of the pupil Imaging of a pupil mask of the coronagraph onto the ZIMPOL detector CCD S2 to check lateral position alignment. The pupil imaging mask (with central obscuration) and the ZIMPOL Pupil Target plate (with crosshair), what is only used during transport and align check. The pupil is perfectly aligned if the crosshair is imaged on the center of the central obscuration. Left the uncorrected alignment, right the corrected alignment.

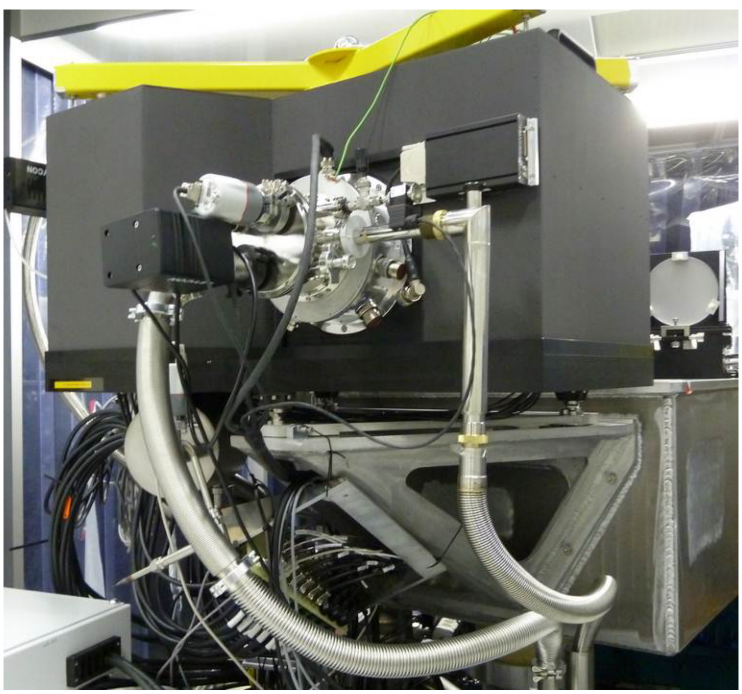


Figure 9 ZIMPOL positioned on the SPHERE optical table, 3 spherolinders applied as iso-static mechanical interface. The backside of cryostat of the 2 detectors is sticking outside the black dust cover. The yellow hoist tool still on top of ZIMPOL.

5. ALIGNMENT OF THE TIP AND TIP/TILT MIRRORS WITHIN ZIMPOL

The tip and tip/tilt mirror subunits (Roelfsema et all [2]) need to be aligned in situ ZIMPOL. These flat mirrors fold the optical beam to create a compact instrument and take care of field selection. The tip/tilt mirrors are also used for dithering.

Both arms do have a tip mirror and a tip/tilt mirror. The tip mirror, a folding flat after camera and filterwheel, has a manual adjustment to steer the optical beam in the x-plane (horizontal), and a motorized adjustment to steer in the y-plane (vertical). The tip/tilt mirrors are identical to the tip mirrors, except both adjustments are motorized.

The alignment of the tip and tip/tilt mirrors are in two steps:

A. The first step is alignment by the aid of mechanical targets, using the same setup as used for ZIMPOL and Dummy-ZIMPOL alignment check as described in chapter 3.

B. The second alignment is the final alignment by the aid of the detectors and it's microlenses/maks combination in front of it (Schmid et all [3]), to secure an optimal illumination of the detector by the microlens through the open rows of the mask .

The alignment step A: This alignment is pretty straight forward. The targets of arm 1 and 2 as described in figure 3 are replaced by the tip mirror unit and these targets are positioned on the tip/tilt mirror position. The tip mirror has now to be adjusted such that the new target position is again spot on with the previous target position, checked with the alignment telescope. Then the targets are removed and the tip/tilt mirrors are placed on it's position. A dummy detector plate with targets representing the middle of the two detectors is placed in the detector mount. The same procedure is applied for the tip/tilt as for the tip mirror, now using this dummy detector plate.

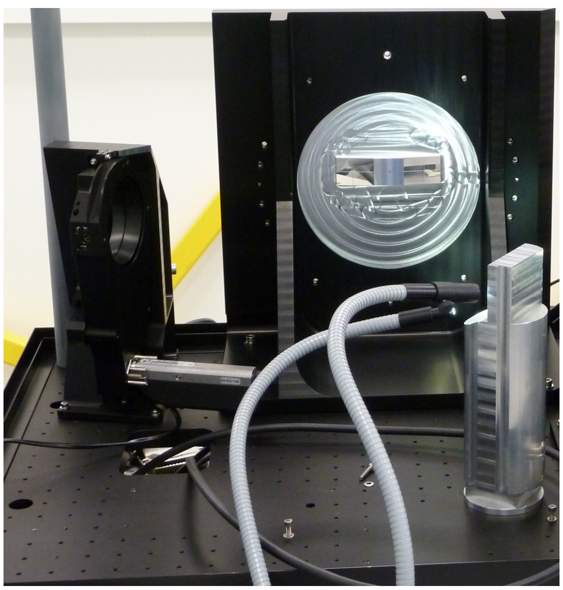


Figure 10 at the left a tip-mirror unit. In the middle the dummy detector plate in its mount with 2 flat surfaces with crosshair representing the middle of the detectors. At the right a target at tip/tilt position, illuminated with flex-light.

The alignment step B: The detector is provided with a mask and microlens array just in front of the detector surface. The cylindrical microlenses and the long slitted masks are such that every other binned (horizontal) row of the detector is covered and the light is focused on the non-covered binned rows. The 15 micron pixels are binned to 30x30 effective pixels. The covered rows are used as a temporarily memory during operation (Schmid et al [3]). The optical setup of the microlenses requires a very accurate perpendicular illumination onto the detector in the vertical plane (optical beam should be nicely horizontal). For this reason the tip and tip/tilt are motorized for the vertical plane adjustment. The tip and tip/tilt settings need to be optimized for the optical and mechanical errors in the total optical train from incoming collimated beam at ZIMPOL up to and including small errors of the microlens/mask assembly in relation to the detector and small detector angular errors.

The alignment step B. can only be done with an operational ZIMPOL bench in a full illuminating test setup or with the SPHERE instrument calibration mode. By a half automated scanning procedure the optimal settings of the motor encoders of tip and tip/tilt (vertical plane only) can be defined and will be used as settings for the instrument. An illustration of one of the nine field settings for the 2 individual detectors with it scanning measurement.

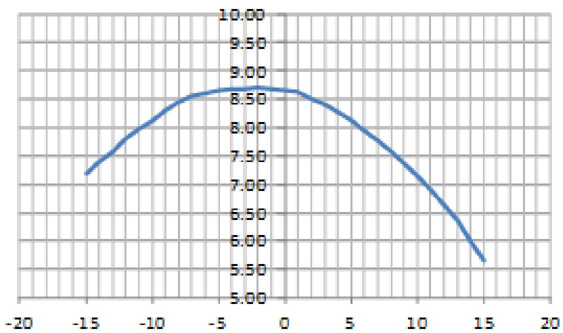


Figure 11 Example of an optimization scan by the tip and tip/tilt mirror, in this case for the so called O4 field for detector 1. The horizontal axis are measurement points of the angular setting of the tip and tip/tilt mirror, the vertical axis is the relative maximum (un quantified) flux (flat field source). Per setting the tip and tip/tilt are both rotated such that the middle of the optical field is pointed onto the middle of the detector. Herewith the optimal setting of the tip and tip/tilt mirror can be defined in the y-plane (x-rotation axis). In total 2x9 plots are produced: 9 different field settings for 2 detectors.

6. ALIGNMENT PROCEDURE OF SOME POLARIMETRIC COMPONENTS

The optical alignment of the polarimetric components relies on the production accuracy of the opto-mechanical parts. The polarimetric axis of most of these components is defined by a special setup or defined in-situ ZIMPOL. All ZIMPOL related components are, after installation, checked on polarimetric alignment with the aid of ZIMPOL. Some n-IR components for the sister focal plane instrument IRDIS are aligned with the same kind of setup as some ZIMPOL related components.

Below the alignment of the polarimetric components for the common path is described. The alignment setup is a small and easy transportable setup, what is used for the alignment of the polarimetric components what will be mounted in the so called Common Path of SPHERE. This setup is used prepared at NOVA@ASTRON and applied in Grenoble where the components were located and mounted in its unit.

Table 1 Tabel of some characteristics of the polarization components of the common path. The required polarization orientation is when installed, zero degree is parallel to the bench. The position of these components is close to the optical entrance of the SPHERE instrument, in or close by the calibration exchange mechanism.

No.	Name	Working range [nm]	Description	Clear apert [mm]	Req.pol. orientation [degree]
1	HWP1	500-900	Achromatic HWP, insertable and rotatable	14,5	± 1 degree
2	Pol-vis	500-900	Polarizer, insertable, fixed orientation	24,5	90 ± 1 degree
3	Pol-IR	1000-2300	Polarizer, insertable, fixed orientation	24,5	0 ± 1 degree
4	QWP	500-900	Achromatic QWP, insertable, fixed orientation	24,5	45 ± 1 degree
5	Pol+QWP	500-900	Polarizer + QWP, insertable, fixed orientation	24,5	45 ± 1 degree
6	HWP2-vis	500-900	Achromatic HWP, insertable and rotatable	24,5	± 1 degree
7	HWP2-IR	1000-2300	Achromatic HWP, insertable and rotatable	24,5	± 1 degree

Two reference polarizers, in this case polarizing beamsplitters, are mounted on (manual) rotation stages on both sides of the component under alignment. The center of both reference polarizers coincides with the external bench optical axis, defined by mechanical means Both reference polarizers are aligned such that polarizer axis can be set perpendicular/parallel to the external bench, by mechanical means in reference to the outer shape of the polarizer.

At one side of the setup an illumination source provides a relative uniform and unpolarized ($P < 0.001$) light. In this case a red LED, followed by a collimator lens (F=20) and an iris (45 after lens) is used on some distance from a pupil in front of the first polarizing beamsplitter. At the other side of the setup the flux measurement is done by a simple light flux meter, but also a simple webcam can be used as relative flux measurement device. If a rotation motor is applied for the component (e.g. for HWP1 and 2), set the component with a reference marker to a defined rotational position inside the component. The component under alignment, including its mount and eventual mechanism, is placed between the two polarizers to a stable accurate defined mechanical mount and such that the center of component coincides about with the optical axis. Prevent for vignetting of the beamsplitter cubes en the component to align.

As we take HWP1 as example, we set both reference polarizers perpendicular to the bench.

During rotating the motor mechanism of the HWP1, we define the minimum intensity. The minimum intensity can be found by scanning multiple points and fitting a curve or find two equal intensity points at either side of the minimum, around 20-30 degree apart: halfway will be the minimum. The defined minimum corresponds to HWP1 fast axis at +/-45 deg. Record the HWP1 rotation stage encoder setting.

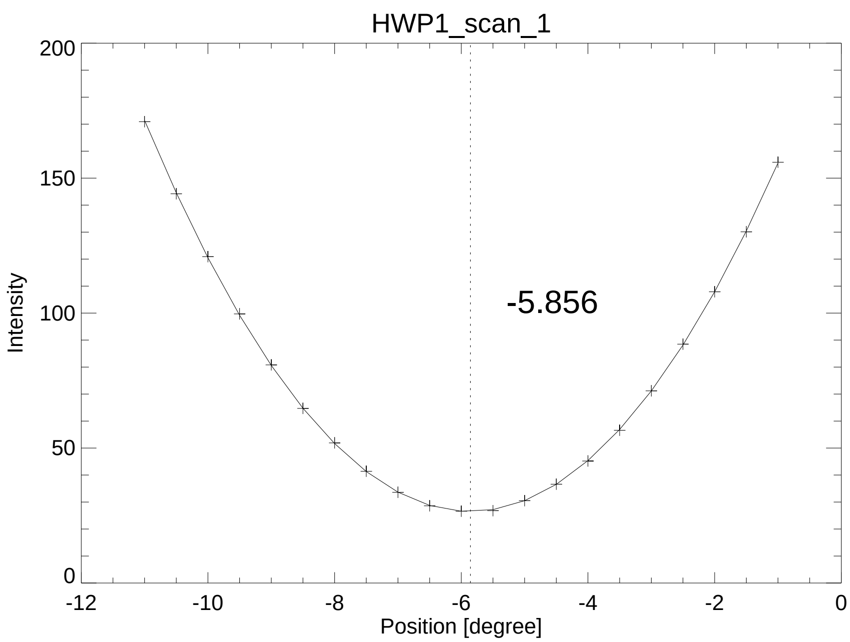


Figure 12 Example of a scan of HWP1, minimum found at -5.86 degree (corresponding to 354144 motor encoder steps of the HWP1 rotator)

The other components are likewise tested.

For measuring the polarizers, just one reference polarizers is required.

The Polarizer+QWP must be inserted such that light first sees the polarizer and then the QWP and just one reference polarizer on the side of the polarizer part is applied with a setting to 45deg. The accuracy can be a ±few degree, but the actual component is aligned to ±1.

For the QWP testing the reference polarizers need to be set to 45 degree offset of the bench.

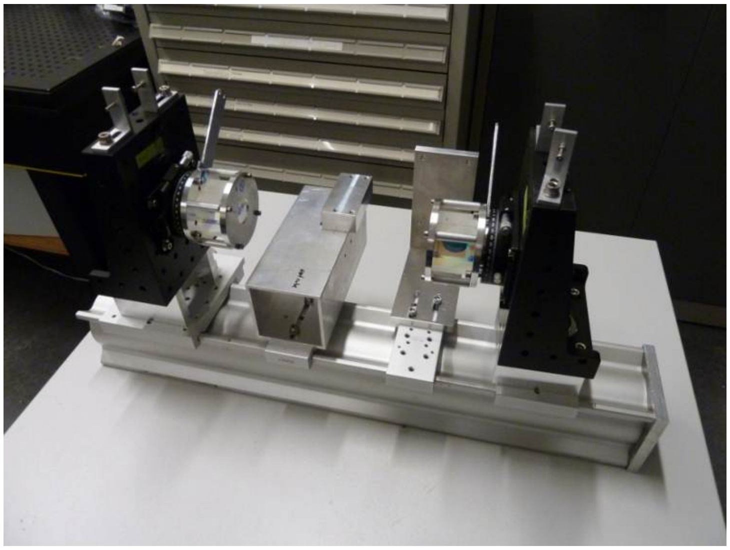


Figure 13 Implementation of the bench. It provides mounting interface for both the Polarizer Wheel (including motor) and HWP1 (including rotation and translation stage).

7. SUMMARY

This publication describes the practical alignment of the ZIMPOL instrument. The baseline alignment is by positioning to mechanical references with accuracies defined by production. This reduces the alignment to a simple check with eventual a small correction (not needed at ZIMPOL bench). A few components needed to be optical aligned like the tip and tip/tilt mirror angles. Also most polarizing components needed to be aligned in it's mount.

The alignment of ZIMPOL into SPHERE by means of a Dummy saves a lot of time and risk, but in practice it appeared that small adjustments were required. An additional pupil reference was made later on, it is advised to take this into account on for hand.

The tip and tip/tilt alignment was straight forward by simple special mechanical reference targets.

The alignment of polarization components was based on scanning the polarized light intensity by means of polarizing beamsplitters. These beamsplitters accurately aligned by it's mechanical outer shape and with that an accurate reference.

Above described procedure provided a good alignment of ZIMPOL itself and ZIMPOL within SPHERE, actual measurements underlines this statement.

REFERENCES

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