Integration and alignment of adaptive optics system:
10 years of experience at the VLT

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ABSTRACT

The number and importance of the adaptive optics instruments has grown in the world through the last two decades. Such systems are becoming key elements for large telescopes, with increasing types and complexity. The Very Large Telescope (VLT) has been equipped with many instruments using adaptive optics such as Shack-Hartmann, curvature or pyramid wavefront sensors. In this framework the European Southern Observatory (ESO) has collected a large expertise in the field of instrument integration and in particular the integration of adaptive optics systems. The purpose of this article is to share this expertise with the community and tell how instruments are being built in our organization. Therefore this article is aimed at persons who have some or little experience in integration and optical alignment.

Keywords: ESO, adaptive optics, VLT, integration, alignment, MAD, MACAO, AOF, GRAAL, GALACSI

1. INTRODUCTION

Astronomical instruments differ in many aspects and as a consequence there are multiples expertise and ways of performing a successful integration. The integration phase is often critical and requires specific care. These issues have first to be addressed at system design level choosing a good tolerance strategy and analysis. The quality of the opto-mechanics and the design of integration tools are of great importance. In general a good preparation work will boost the work efficiency and lead to the best alignment and system performances. This article tackles system integration over optical and mechanical aspects only (we are not covering software and electronics integration here).

We describe the experience gained in the integration of such instruments at the European Southern Observatory (ESO) and in particular at the Very Large Telescope (VLT). We will tell first how assembly, integration and testing are performed all along the instrument lifetime and what are the important issues related to integration to be addressed at the different building stages. We will focus on some important rules and practical hints in instrument alignment. For each alignment issue we will discuss problems, impact on the system, means of diagnostic and control giving some quantitative information based on our experience. In the third section of this article, we want to give clues about the specificity of adaptive optics integration, answering the following question: what should one do to manage successfully the integration of an AO system? We will illustrate this article with examples of VLT adaptive optics systems and relevant test results.

2. INSTRUMENT INTEGRATION STRATEGY AT ESO

In this section we want to remind how instruments are built at ESO, at which stages an integration specialist must intervene in the construction process and which roles he takes. This participation can have different levels depending on whether the instrument is built entirely at ESO Garching or held by a consortium. Of course it depends also on the manpower available and the distribution and type of expertise among the team work. What we describe here should not be considered as a unique way of organizing integration at ESO, nevertheless most of instruments built in the past by our integration and cryo-vaccum department have been built with such strategy.

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2.1 Instrument design and reviews

The birth of an instrument is a rather long process in which conceptual, management and financial issues are discussed. Once the concept and the feasibility are settled and accepted by the ESO management (Science and Technical Committee, Council and Finance Committee) the instrument design begins. In the best case an integration specialist starts being involved in a project as soon as the first 3D conceptual drawings are elaborated. At this level we help mechanical designers who sometimes need input for technical aspects. During the design phase the project is reviewed at least twice by an external board in what we call the PDR and FDR (Preliminary Design Review and Final Design Review). A large part of the documentation is presented and written at those reviews. During the review the board investigates all major critical and technical aspects in order to ensure the project will fulfill its specifications.

On the integration side, we have to issue the Assembly Integration and Test (AIT) plan in which we present how we intend to align and assemble an instrument. In fact many aspects are reviewed like for instance the compatibility of the facilities with the construction of the instrument: laboratory, integration space, crane capabilities, handling equipment and strategy, test stand, measuring equipment must be adequate to the instrument design. We also review the integration and tests of subsystems, how they are performed, the sensitive parameters to check and the tools required. The optical alignment procedure is as well of prime importance: it should describe accurately the different steps of alignment with emphasis on the accuracy requirements, the optical and mechanical references used, the list of alignment tools, and the adjustments available in the mechanical design description. In addition, we of course care about the task scheduling, manpower and we require during the FDR review a first re-integration plan and strategy at the observatory.

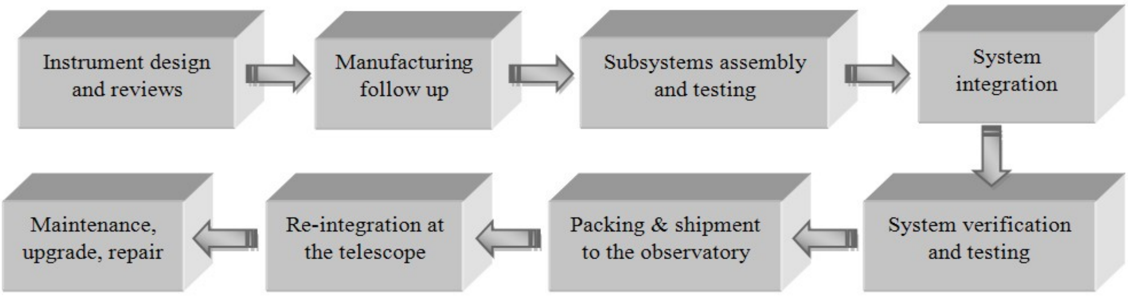

Figure 1. Instrument integration flow chart. This figure shows the main stages where the integration specialist plays a role in the construction of an instrument.

2.2 Manufacturing follow up

The instrument being designed, reviewed and accepted by ESO board members, the procurement of mechanical and optical parts can start. Some parts can be found on-the-shelves; some cannot and must be manufactured especially for ESO. In that case, it is important to follow up the manufacturing of these pieces. For instance the instrument housings are very particular parts with tight specifications and special requirements. Some interactions between ESO and the manufacturer are unavoidable. Together with mechanical designer the integration specialist often plays an important role to ensure the quality of individual parts and subsystems.

2.3 Subsystems assembly and testing

As soon as enough components are stored in house, they can be assembled into subsystems. It can be for example a filter wheel or a cryostat. For critical components which properties and behaviors must be within specifications, we perform individual acceptance tests. It can be optical measurements for a mirror, motion accuracy for a translation stage, reproducibility of an actuator, etc... These measurements must be performed in similar final operational conditions and environment; for instance at LN2 temperatures for cryogenic instruments or simply with the proper load or stress for opto-mechanical components. The variety of tests is huge and requires fully equipped facilities.

2.4 System integration

System integration is the main step in which all components and subsystems can be assembled together to make an instrument. The integration specialist takes its full responsibility at this stage. Cryogenic instruments must be tuned to reach good vacuum and temperature levels. It consists also in making the optical alignment which is always a critical step in the integration phase. Typical instruments contain several tens of optical and mechanical components that must be aligned accurately according to design specifications. Alignment quality criteria are in general wavefront aberrations and image stability. They are controlled with interferometers, detectors and CCDs. For cryogenic instruments, the task is even more difficult since alignment is done at warm temperature whereas the verifications must be done at cryogenic temperatures, leading to long iterations, in which the instrument has to be pumped, cooled down, and warmed up again. In parallel to this, electronic and software engineers must work on instrument control.

2.5 System verification and testing

Once aligned and operational, the system can be tuned to reach its optimal performances. This stage is under the system engineer responsibility although the integration specialist gives its support to solve potential problems that always come when starting to use and debug such complex systems. This stage usually lasts for several months depending on the instrument complexity and ends with the so called Preliminary Acceptance in Europe (PAE) where instrument functionalities and performances are reviewed by an internal board which includes the observatory staff. This applies also to ESO instruments built externally by consortia. When an instrument is declared compliant, it gets the authorization to be shipped to the observatory and installed at the telescope.

2.6 Packing and shipment to the observatory

At ESO, the instrument packing is often led by the integration responsible. It is prepared well in advance and optimized to be as fast as possible since schedules are always very tight. Most often the shipment is sent by plane to the Chilean ESO Observatory sites. During this long trip, the boxes encounter shocks and vibrations especially on desert’s road and during handling. Therefore, instruments are often shipped partially disassembled. Specific and adapted transportation crates are built for each instrument. Packing is a crucial operation because of potential damages and failures which sometimes cannot be solved on the Observatory sites.

2.7 Re-integration at the telescope

Instruments are sent at the telescope several weeks before the 1rst observing night. There, the integration department takes care of the re-integration in collaboration with ESO local staff. Our work consists in re-building the instrument and bringing it at the same acceptance level as in Europe. In addition, it must be attached and aligned with the telescope. All this lasts for few weeks and must be finalized at a very strict deadline (the observatory night observation scheduling being settled six months in advance). The instrument is then commissioned which means it is declared capable for scientific observations. In this process the system is tuned to reach its optimal performances under telescope and sky conditions by system engineers and astronomers.

Figure 2. An example of AO instrument being integrated at the VLT on the Nasmyth platform: CRIRES

2.8 Maintenance, upgrade and repair

Instrument maintenance, upgrade and repair are an opportunity for the integration specialist to “put his hands” in instruments at the telescope. Typical upgrades are motions or detector upgrades. Failures can happen too and are unavoidable, especially considering the huge amount of components and subsystems installed at the telescope. For example shutters are sensitive units with a limited lifetime and can fail after years of use. These stages are again organized and performed in close collaboration with ESO Chile staff.

3. ADAPTIVE OPTIC SYSTEM ALIGNMENT

Classical AO assisted instruments are made of three main optical paths which are split with a dichroic mirror and need to fulfill the required alignment accuracy:

- The common path, which includes the telescope itself and one or several corrective optics (tip/tilt mirrors and deformable mirrors) to compensate for the atmospheric turbulence. In some cases the corrective optics is directly integrated to the telescope or in the instrument. In this last case relay optics are required to re-image the pupil on the corrective optics.
- The wavefront sensor (WFS) path, which role is to detect the optical disturbance and hosts one or several wavefront sensors and associated relay optics.
- The science path that contains the science instrument. For correction performance reasons most of the existing AO systems have infrared instruments and visible wavefront sensors.

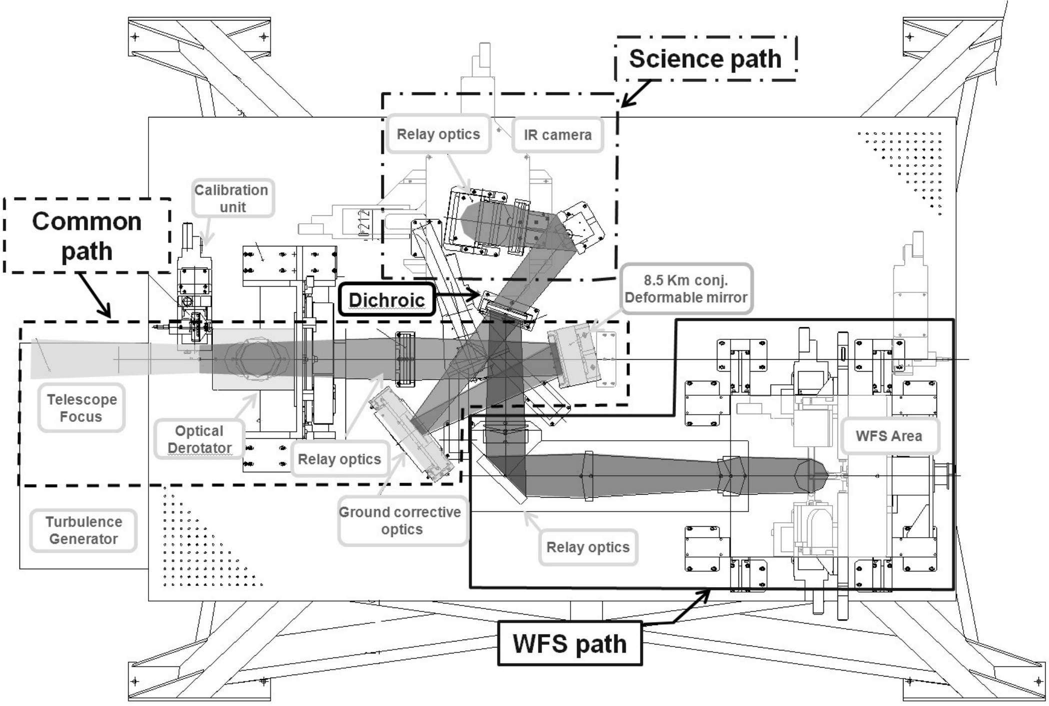

Figure 3: Top view of the MAD multi-conjugate adaptive optics system. It represents a typical exemple of AO instrument made of 3 main interdependent optical paths split through the dichroic mirror. The IR camera is actually not seen here because it is located below the optical breadbord. MAD hosts two deformable mirrors which must be aligned with 3 Shack-Hartmann sensors and a layer oriented wavefront sensor.

In this section we will discuss the specificities of AO system alignments giving some practical examples and quantitative information. A very common and simple way of aligning an instrument is to install a sighting telescope on the main optical axis and to align individual subsystems one by one along the line of sight using mechanical and optical references like targets, masks, auto-collimation mirrors. Such references must precisely represent the optical axis of their subsystem. For instance a simple mask placed closed to a deformable (DM) mirror surface and used to identify its center, must be previously positioned to the mirror center taking into account its distance to the mirror surface and the incident angle of the optical axis. Note that the use of laser beam is often not accurate enough to properly place the components on the optical axis.

3.1 Alignment of the instrument versus telescope

At ESO most of the instruments are first integrated in an assembly hall and then attached and merged with the telescope. When this merging happens one must avoid making major corrections to the internal alignment of the instrument to match its optical axis with the one of the telescope. That means, when the instrument is plugged to the telescope there should be a simple way of having both optical axes merged without using the instrument internal adjustments: this is achieved using precise mechanical references.

For a system whose flange is attached directly to the adaptor rotator, Cassegrain or Nasmyth, the flange surface will be a good reference for the angular position of the optical axis and its three flange pins will be the reference for the optical axis lateral position. This method has limitations due to the flange flatness and pinhole positioning accuracies. Moreover it will be also limited by the adaptor rotator alignment precision with the telescope, its wobbling and run-out errors. But this approach represents a very good start and using these references one can hope plugging AO bonnets to the telescope without having to perform major alignment corrections. Typical accuracies that can be achieved at the VLT are of the order of 40-60 arcseconds (angular) and 100-200 microns (lateral).

For a Nasmyth or Coude focus system which is built on a breadboard and not attached to the telescope adaptor like for instance MAD, SPHERE, CRIRES or APE, the merging of optical axes is performed using the lateral and angular adjustments of the breadboard. The references will then be directly the telescope pupil (M2 in the VLT case) and the adaptor rotator pins.

In the case of an adaptive optics instrument the pupil positioning accuracy is of prime importance. Any pupil vignetting can affect the sensor calibrations and decrease the performances. For an adaptive telescope where the deformable mirror is included in the telescope optical train, the actuator registration with the sensor sub-apertures can become critical for the same calibration reasons. The alignment requirements will vary from one system to another mostly depending on the amount of sensor sub-apertures. A general rough rule will be to have pupil lateral positioning and registration of 10% of a sub-aperture. Applying this rule at the VLT, a system like MAD would require an angular positioning accuracy of 3 arcminutes while AOF (GRAAL or GALACSI) or SPHERE adaptive optics would require the same positioning accuracy to be 40 arcseconds. But of course these values give only an order of magnitude; the required accuracy must be assessed through simulation or computation and taken into account in a global error budget.

Figure 4: An example of alignment set up on HAWK-I. It consists in a sighting telescope mounted on a five axes adjustment mount which legs are interfaced on the instrument flange. The flange being the reference to define the instrument optical axis, we must align first the sighting telescope perpendicular to it. This is achieved by using an auto-collimation mirror installed on the flange and rotating the telescope mount by steps of 90 degrees with respect to the flange.

3.2 Optical aberration issues

We have discussed about the importance of pupil and focal plane re-imaging for adaptive optics systems. Re-imaging is done with relay optics which can be of any type depending on the instrument needs in terms of transmission, performance, field of view and wavelength. It can be collimator lenses, objectives, parabolic or spherical mirrors. The optical alignment of a relay optic is of prime importance for several reasons. Obviously optical aberrations can degrade the system performances. The "non-common path aberrations" introduced by relay optics in the science path are not seen by the WFS and therefore not corrected. On the WFS path, optical aberrations are measured and added to the science path. Of course both sources can be calibrated and taken into account using the so called reference slopes. Reference slopes are basically offsets applied to the WFS measurements to compensate for several sources of wavefront errors, among them, the non-common path aberrations. Using these offset measurements, the correction commands sent to the deformable mirror(s) will allow optimizing Strehl performances for the science instrument. But this method has several kinds of limitations depending on the types and characteristics of the sensor(s) used. For instance low order systems will of course not compensate high order aberrations, and even multi-conjugated AO systems cannot fully correct differential aberrations in the field of view.

From the quantitative point of view most of "non low order AO systems" must achieve reasonable point spread function, therefore aberrations introduced by alignment errors should remain of the order of the theoretical ones (given by the optical design). This is never easy to achieve and one should know what kind of design and manufacturing wavefront errors are expected in the system to have a good reference of what can actually be achieved after alignment. Typically for a 60 actuators curvature AO system like SINFONI we achieved from 40-50nm rms WFE at the field center to maximum 120nm rms at 1 arcminutes field distance. In this case of single conjugated adaptive optics, wavefront errors in the field of view are anyway dominated by anisoplanetism so that their presence is less critical. In the case of MAD, multi-conjugate AO, it was more important to flatten field aberrations: wavefront errors were ranging from about 25nm rms at the field center to about 60nm rms at the field edges (1 arcminute as well).

We have seen that measuring them in the field of view is valuable and it is therefore recommended to foresee the proper light sources, translation mounts and interfaces to perform these measurements. Performing measurements over the field of view has another advantage: with the analysis of the Zernike coefficient dissymmetry like focus, coma or astigmatism one can actually find out and diagnose alignment mistakes and eventually correct them. The results should tend to be a flat or symmetric wavefront error map.

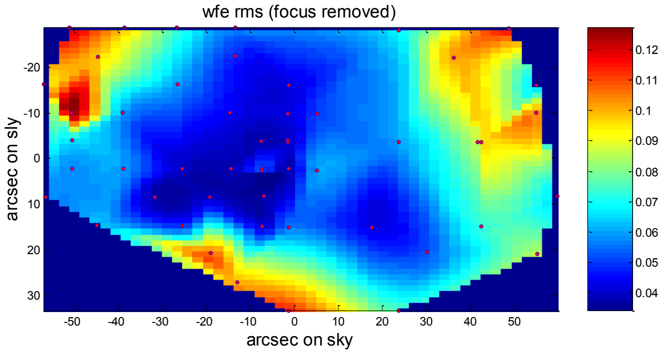

Figure 5: Wavefront error mapping obtained over SINFONI field of view. There is a clear degradation along 3 directions. This is mainly astigmatism (the plot of the field astigmatism is almost identical to this one). It could be caused by constraints on one of the main optics mirror. This degradation is to be compared to the effect of the anisoplanetism. In typical Paranal conditions, the anisoplanetic angle is 20 arcsec in K. At this distance, the rms wavefront degradation expected from anisoplanetism is 1 rad, i.e. 360nm, which 3 times more than the worst case field aberration of the instrument (120nm).We therefore decided to consider these field aberrations is acceptable even though the situation here could have been improved.

Note that scanning the field of view with a wavefront measuring device is also a good opportunity to check vignetting problems which sometimes occurs at the field edges. Another interesting matter is the comparison of aberrations for the three different paths (figure 3). It can help finding alignment errors and can be used also to assess the non-common path aberration and therefore the intrinsic performances of the adaptive optics close loop.

Diagnostic of optical aberrations are done using interferometer or Shack-Hartmann wavefront sensors. For infrared imager, PSF measurements or even phase diversity measurements will be preferred. When possible, we also prefer replacing deformable mirrors with good optical quality flat mirror. The flattening of deformable mirrors is computed after the measurement of influence functions that are not always perfectly determined and can drift with temperature changes. It is difficult to fully guaranty a stable flat shape of the mirror over time before the system is fully integrated and characterized. Dummy deformable mirrors (plane mirrors) will prevent this issue and allow starting the optical alignment at an early stage when the driving electronics and software are not yet installed.

Fine tuning of the alignment to correct for optical aberrations can help improving the system performances but on the other hand this task can be very time consuming. A careful system budget error and system performance analysis will produce optimal requirements and optimize the effort put on this alignment aspect.

3.3 Optical properties issues

Not only optical aberrations can reduce instrument performances, optical properties specifications not fulfilled can also affect the instrument. Some beam characteristics are set during alignment or verified during the integration. In adaptive optics instrument, we will for instance carefully check the F-number or plate scale properties. Both can have an impact on Strehl computation and system calibration. Usually these two parameters can be specified and tuned down to 1-2% accuracy. To achieve these values it is crucial that the optical components fulfill the optical prescriptions and that should be checked at manufacturing level. During alignment it is important to well place the optics at their nominal position along the optical axis. Device like shear plate, collimator, interferometer and target at focal plane will help in setting the optimal beam collimation and focal plane position. Through focus curves of PSF full width at half maximum (FWHM) will allow measuring the optimal focal plane position as well. Plate scale ratio between input and output focal plane, re-imaged pupil size and re-imaged image position can be good criteria to check these specific properties.

Focal plane curvature and perpendicularity matter too. A wrong image plane curvature will introduce pure defocus in the field of view of an imaging device or at the level of wavefront sensors moved in the field of view. In the case the focal plane is not perpendicular to these sub-systems, the instrument will suffer a global linear variation of defocus over the field. While it is hard to correct for image plane curvature errors, it is possible to optimize focal plane tilt. In any case it is worth measuring both in WFS path and in science path that sub-systems are well perpendicular to the optical axis. This applies as well to any moveable calibration source used at the instrument entrance focal plane. Usually using an auto-collimation mirror placed on accurate mechanical references is a good method to align devices perpendicular to the optical axis down to few arcminutes accuracy.

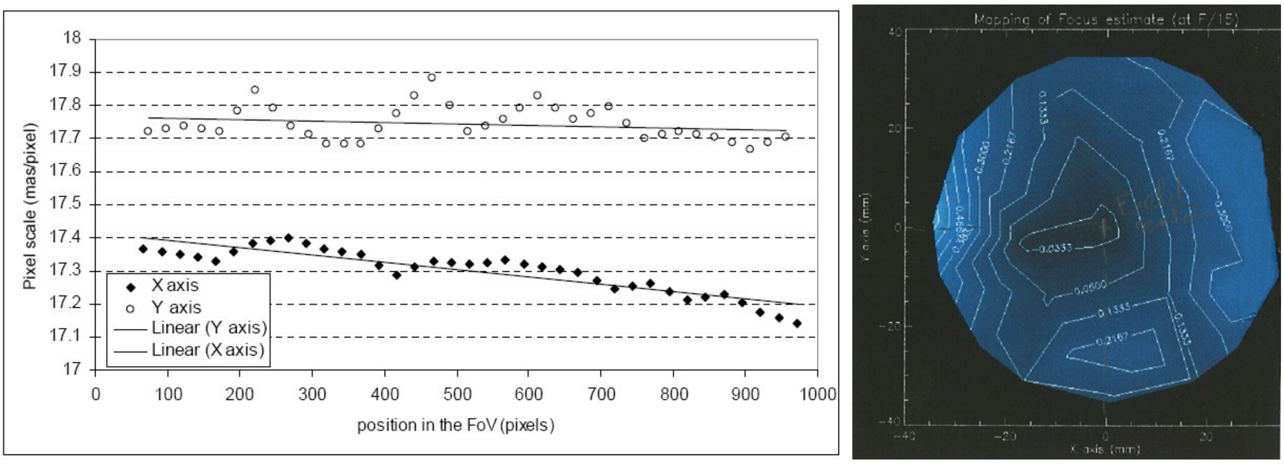

Figure 6: On the left an example of linearity measurement on the IR detector. On the right an example of field curvature obtained during integration. The measuring is obtained sliding the calibration unit fiber in the field of view and mapping the defocus term (in millimeters) on the WFS path. The result obtained is the field curvature map of the instrument. After alignment optimization, residual focus errors can be corrected using phase diversity and reference slopes (for Shack-Hartmann systems).

Optical layout of adaptive optics systems will often be designed such that beams at the WFS or science focal planes are telecentric. Non-telecentricity often come together with field curvature. One way to check this property without using sensing devices (and therefore before the instrument is fully integrated) is to use the sighting telescope placed on-axis and aligned to sight at the pupil centre. Using a mirror tuned in autocollimation at the exit focal plane, one can slide the telescope in the field of view and check that the autocollimation is kept while sighting at the pupil for any position in the field.

In order to evaluate correctly the Strehl Ratio, it is mandatory to have a measurement of the pixel scale of the detector. The Figure 6 measurements were done for several points across the FoV of the camera, and along 2 axes to measure a significant anamorphism. We see that on the Y axis the pixel scale is varying between 17.7 and 17.9 mas/px, but it is quite constant over the FoV (see the trend curve). On the contrary, on the X axis the pixel scale seems to follow a decreasing trend from 17.4 to 17.2 mas/px. Thus the anamorphism, quite strong, can vary in the FoV between 1.034 and 1.023.

Other integration issues can reduce the instrument performances. Among them vignetting is easy to diagnose and correct while the optical transmission is harder to control and diagnose. The baseline is to have good transmission curves measured by the manufacturer. The use of narrow band filter is frequent in adaptive optics. A wrong knowledge of the central wavelength or bandwidth will introduce bias to the Strehl performance computation. Compact spectrometers or photodetectors can be used to measure throughput and spectral properties when necessary. With respect to optical transmission the instrument cleanliness is important. Therefore the integration environment matters. Laboratory regular cleaning, instrument protection covers, optical component covers will obviously contribute to cleanliness. For AO systems built for planet finder like instrument using coronagraphs, this parameter becomes crucial. A good hint would be to take reference frames with all sensing devices at an early stage and monitor regularly any dust particles or degradation of the device cosmetics.

3.4 Pupil registrations issues

Adaptive optics sensors like curvature, pyramid or Shack-Hartmann systems require the instrument pupil and deformable mirror actuators to be re-imaged precisely in the sensor. Misalignments or instabilities would introduce calibration errors and reduce performances. The registration between sensor apertures and DM actuators is the most critical issue. For instance any lateral pupil shift or rotation on a Shack Hartmann lenslet array will make the interaction matrix (IM) obsolete. Sources of registration errors are multiple. It can occur because of misalignment of moving functions (like focusing objectives, derotators) in the optical path between the deformable mirrors and the sensor. Sensors moved in the field of view to pick up guide stars or using field selectors can suffer misregistration because of pitch and yaw of translation stages or beam non-telecentricity. In the case of adaptive telescopes where the deformable mirror is one of the telescope mirrors, the global flexures and the wobble of adaptor rotator can be sources of errors as well.

The instrument alignment must take into account all these potential sources of misregistration. During integration it is possible to measure them with the alignment telescope sighting at the pupil. In that case proper alignment masks should be installed. It is also possible to use at a later stage pupil flux measurements to assess potential shifts or rotations. For sensors using lenslet arrays the differential flux measurement of edge subapertures would be used. This method of course assumes an adequate pupil mask dimensioning. Another way of misregistration assessment is to push actuators and record the corresponding wavefront distortion with the wavefront sensors. In other words the interaction matrix can be used to measure these errors, provided that one finds the proper criteria and computation. Note that monitoring regularly interaction matrices is a rather common way of following the behavior of these systems (sensors and DMs) and comparisons of these matrices helps making diagnostics when problems occur.

All these techniques can provide measurements down to a fraction of a percent of pupil accuracy. As said previously in this article the requirements depend on the instrument performance specifications. For high order systems like for the SPHERE instrument or the Adaptive Optics Facility project (AOF) at the VLT, an active control of the registration drifts is required. The difficulty consists in performing these measurements and corrections on sky during the night observations. Such active controls make the instrument more complex, thus increasing the importance of reducing misregistrations at alignment and integration level.

3.5 Other wavefront sensor alignment issues

Pupil registration is not the only issue when it comes to wavefront sensor path alignment. Sensors like Shack-Hartmann use field stops to prevent the light of a star or extended object from falling on an adjacent subaperture which induces cross talk and measurement errors. Therefore a field stop is dimensioned such that it is slightly undersized compared to the field of view of sensor apertures. A typical reduction factor would be 2-4% less which corresponds to the margin left for alignment. It is important to avoid that the field stop vignettes the aperture and truncates the measurement. Masks can be round or square. Square masks are optimized for square apertures but require an additional rotation adjustment. In case of laser guide star where the Shack-Hartmann spots are actually elongated, the square field stops present a clear advantage. The few percent alignment specifications correspond to few tenth of microns which is rather tight and require the use of micrometric translation and rotation stage. One alignment method is to use a pinhole with the same mechanical interface as the field stop to make sure it can be positioned at its center (within 10-20 micrometers). Imaging of the pinhole on the WFS allows measuring its position with respect to the aperture field of view. Another method consists in the full illumination of the field stop. In that case the image of the full illuminated field is measured on the sensor. The little number of pixel per subaperture makes the center estimation difficult to assess. Nevertheless cross correlation methods can help to compute accurately the pattern centering within the required 2-4%.

Slope non-linearity and anamorphism can affect Shack-Hartmann performance too. It is important to measure these parameters once, to validate the alignment.

3.6 LGS related issues

When using sodium laser guide star on wavefront sensors, the altitude variation of the sodium layer have to be compensated at the instrument level to avoid retrieving the focus component in the science path. This compensation is done using trombone or focusing units. Trombones are made of reflecting prisms that move on translation stage thus allowing adjustment of the optical path length.

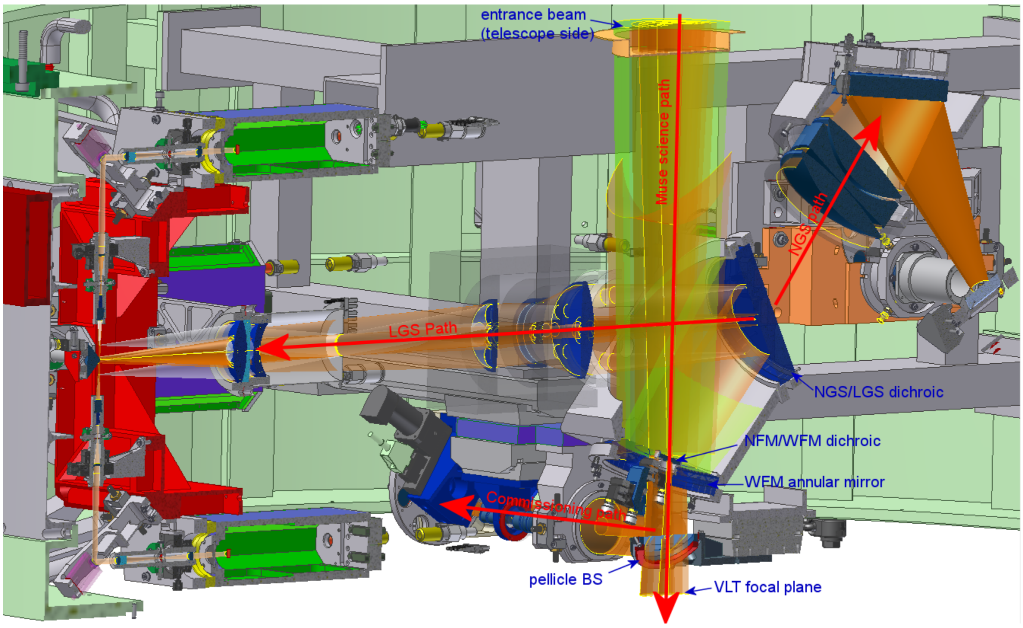

Figure 7: View of the opto-mechanical layout in GALACSI. The Laser guide star path is made of a focusing unit to correct for variation of sodium layer altitude. The four laser stars are re-imaged on a pyramid that split the beam in four different WFS channels. The wavefront sensors, based on Shack-Hartmann technology, receive the laser beam through a set a re-imaging objectives, field stops and jitter mirror. The focusing unit is made of a set of lenses (square shaded box at the picture center). Lenses and translation stage must be perfectly aligned on the optical axis to avoid pupil registration errors on the four channels.

Focusing units are made of lenses mounted on translation stage which allow for refocusing in the wavefront sensor laser path. In both cases the straightness of travel and the coaxiality of the incident optical axis, the moving lens optical axis and the translation axis are crucial to maintain the pupil registration and lateral optical axis position. The tuning and verification of these parameters can be done at the integration and alignment stages. One can use a sighting telescope with proper focal plane and pupil plane alignment target, or one can diagnose the optical axis drift directly with the WFS. In any case the tuning must be done at an early stage. While lenses or prisms should have manual actuators, the linear stage adjustment is often done by shimming down to few arcminutes. The use of shims is time consuming, requires several iterations and can affect slightly the WFS path alignment.

3.7 Flexure measurements

Spectrograph or imaging instrument attached to an adaptor rotator can suffer from flexures. Flexures in Adaptive optics modules can mainly impact the pupil registration and the point spread function stability. From a practical point of view, flexure issues are difficult to solve at integration level. The measurements are time consuming and require the instrument to be fully integrated and installed on a rotating adaptor simulator. In the adaptive optics field, flexures are measured in the laboratory by rotating the instrument and measuring point spread function variations in the science path at different angles. Comparison between open and close loop images will help understanding the part of flexures induce by the adaptive optics. The contribution of the corrective optics can be deduced with the comparison between deformable mirror flat vectors (or IM) for different instrument angles. Comparison of measurements for different instrument modes (for instance between WFS channels or between LGS versus NGS) will serve the same goal.

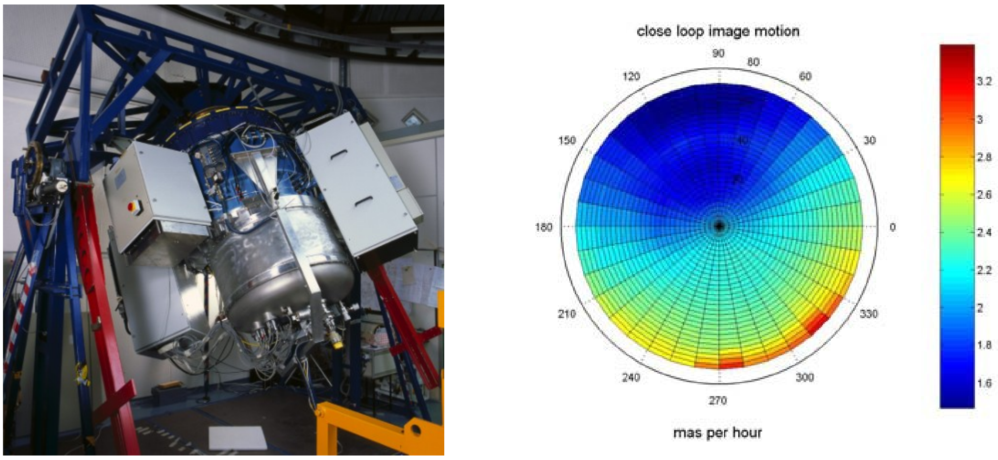

Figure 8: Left: SINFON installed on a cassegrain simulator to measure flexures. Right: flexures obtained in close loop.

These methods using measurements at system level do not allow necessarily understanding the exact origin of the flexures. It is strongly recommended to make measurements at sub-system and device levels. In that case flexures are obtained by making differential displacement measurements between the instrument structure and the units, the chosen structure area being the reference considered as flexures free. Measurements at sub-system level are performed with capacitive or inductive displacement sensors or using autocollimators. Once the origins have been identified, the solutions found to solve flexures require often the implementation of opto-mechanical modifications which would stiffen the weak elements. A huge effort can be spent as well at this level, which can lead to several months of delay in a project. Therefore it is of prime importance to tackle the flexure issues at the instrument mechanical and system design level analyzing them for instance with a finite element method (FEM) analysis.

3.8 Reliability and Line Replaceable Unit (LRU) discussion

Maintenance of instruments on site requires lots of effort from the Observatory staff. At the VLT the number of instruments and system at the Observatory is enormous. When a unit or sub-system is faulty its replacement should require a minimum of effort and recalibration for the engineer or technician. This is what we call at ESO a line replaceable unit (LRU). At design level the system must be designed such as most of the sub-unit should have adequate reliability, access and references in order to minimize the maintenance effort. The exchangeability of each unit has to be tested at integration level. Some sub-systems like shutters or avalanche photo diodes require burn-in test to assess and optimize their life time. Burn-in tests consist basically in using a unit extensively (for instance power on/off) or in extreme conditions to accelerate its aging. Indeed this is another time consuming integration issue. Other sub-systems like wavefront sensor cameras or deformable mirrors are alignment sensitive; they must have very accurate mechanical references to allow an exchange without need of realignment. The design and integration efforts are the price to pay for this strategy, nevertheless the gain is real and allow saving maintenance time which translates also into telescope observing time. At ESO we perform for each instrument a daily health check. The instrument software automates this health check which consists in a set of functional checks and calibrations (like IM) for the main instrument modes. Performing these operations allow monitoring the system behavior and preventing problems like aging issues. Information related to problems is logged and emailed automatically through the Paranal Problem Reporting System (PPRS). PPRS allows a fast and direct communication and knowledge transfer of any problem between instrument operators and engineers which increases the responsiveness of the staff to tackle replacement and maintenance issues.

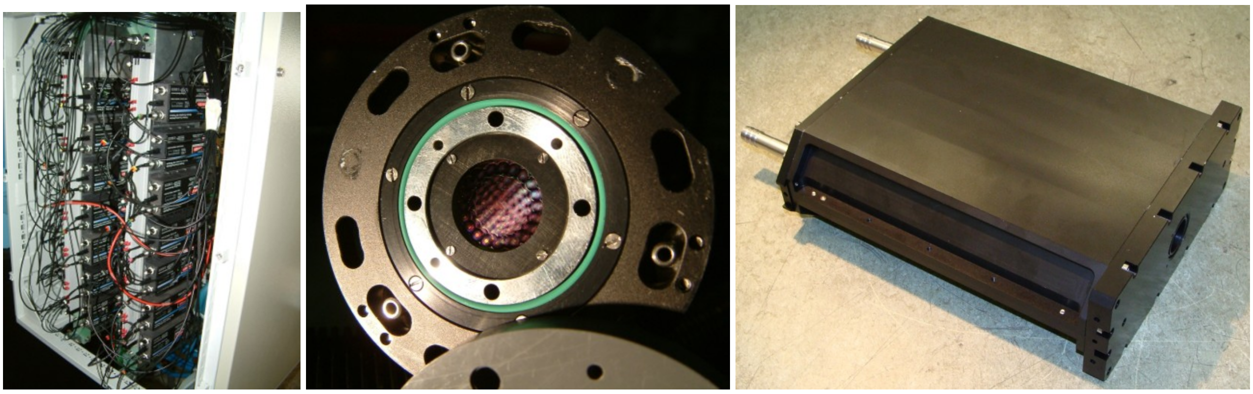

Figure 9: Three examples of line replaceable unit. From left to right: the MACAO avalanche photodiode (APD) cabinet, the MACAO lenslet array, and the Adaptive Optics Facility (AOF) wavefront sensor. The APDs are good examples of a units with a short lifetime. With more than 350 units at the observatory, the exchange frequency is almost on a weekly basis. Therefore the APDs, fibers, power plugs accessibilities and the exchange procedure have been optimized to facilitate the maintenance effort. The lenslet array and WFS provide another aspect of the LRU concept: the mounting reproducibility to avoid realignment and re-calibration of the adaptive optics system.

3.9 Integration tools and turbulence generator

Preparation of integration tools represents half way through a well done instrument integration. The variety of tools used is large and cover several fields: mechanics, optics, cryogenics, vacuum, electrics, cooling, and handling. The amount of time spent in purchasing, renewing, designing of these tools is significant and therefore require an intensive preparation work at the early stages of a project. This aspect is overriding.

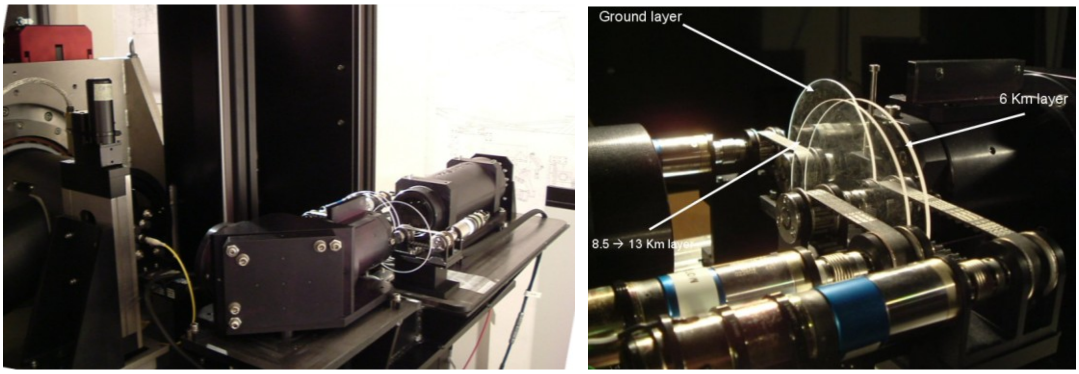

Figure 10: MAPS installed at the entrance focus of MAD. The phase screens have different turbulence power according to the expected vertical distribution. The evolving atmosphere is emulated by rotating the PSs at different speeds according to the wind speed profile. The PS separations and positions can be varied in order to modify the atmospheric anisoplanatism and vertical distribution. The speeds can be adjusted to reproduce a wide range of atmospheric correlation times.

In the adaptive optics domain, the main specificity is the need of a turbulence generator. Building a turbulence generator often represents a small project on its own that must be started well in advance. This device is the tool that defines the atmospheric parameters which will be used to test the instrument. The characterization of the turbulence is of great importance and must match the main properties of real atmospheric turbulence. The production of turbulence is usually done with phase screens although hot air systems can also be used. Phase screens can be transmissive or reflexive and simulate several layers of the atmosphere which is mandatory when testing multiple conjugate or ground layer adaptive optic systems. The alignment of the screens in the pupil plane or at a given distance from the pupil to simulate the right altitude is together with the turbulence characterization and the phase screens wobbling reduction, the challenging part of the integration.

4. CONCLUSION

ESO has developed a large expertise in term of instrument integration and in particular adaptive optics system. We have tried in this article to point out the specificities of such devices from the integration point of view. Unfortunately it is difficult to enter here into the detail of each discussed issues. There would be much more to tell. The complexity of AO systems has increased with time especially with the development of multiple guide star AO and laser systems in the last decade. Therefore their integration becomes more complex too, therefore we have emphasized the importance of an early organization and preparation work to facilitate the integration time and quality.

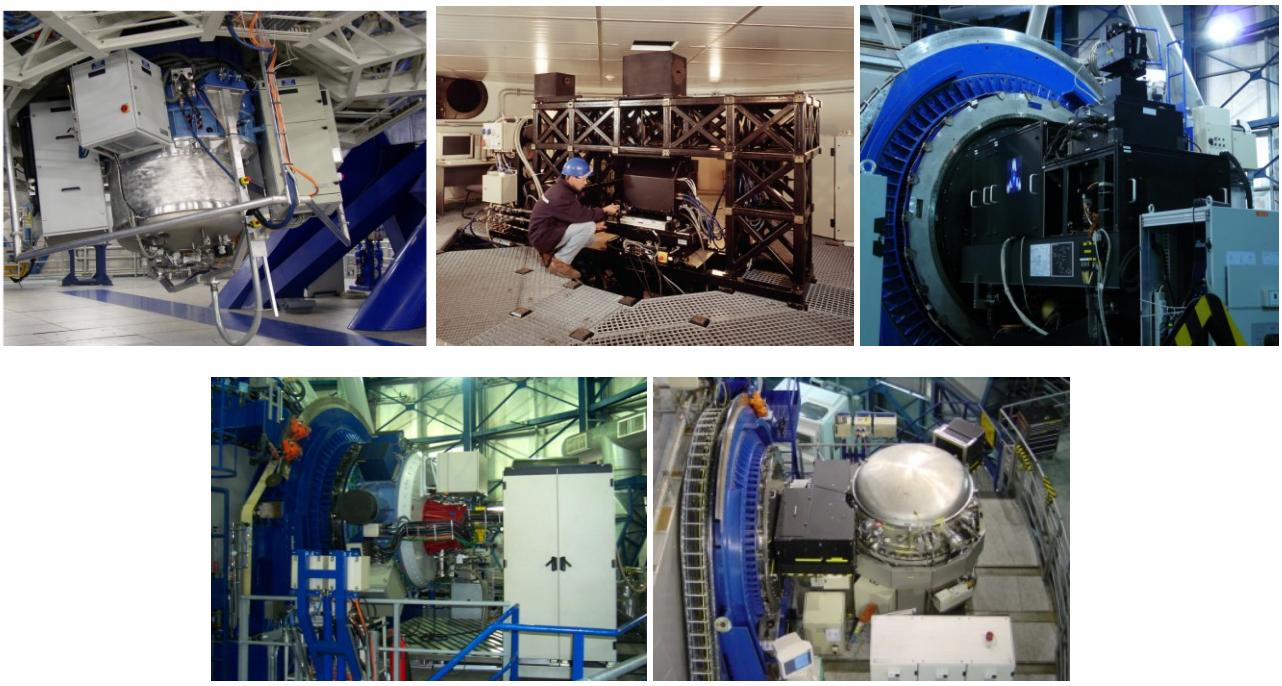

Figure 11: SINFONI, MACAO-VLTI, MAD, NACO, CRIRES. The adaptive optics systems that have been installed at the VLT during the last decade cover the three main techniques: Curvature, Shack Hartmann and Pyramid wavefront sensor. In the coming decade new instruments like SPHERE, GALACSI, GRAAL and NAOMI will be installed as well.

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