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Alignment and integration of large optical systems based on advanced metrology

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Abstract. Optical alignment is a key activity in opto-mechanical system Integration. Traditional techniques require adjustable mounting, driven by optical references that allows the tuning of the optics position along all 6 Degree of Freedom. Nevertheless, the required flexibility imposes reduced stiffness and consequently less stability of the system. The Observatory of Brera (OAB) started few years ago a research activity focused onto the overcoming of this limits exploiting the high metrology performances of Coordinate Measuring Machines (CMM) with the main objectives of relax the manufacturing tolerances and maximize mounting stiffness. Through the T-REX grants, OAB acquired all the instrumentation needed for that activity furthermore considering the ESPRESSO project training and testing also oriented to large scale instrumentation like the E-ELT one. We will present in this paper the definition of the VLTs convergence point and the feasibility study of large mirrors alignment done by mechanical measurements methods.

Key words. Laser Tracker – Coordinate Measuring Machines – Alignment – ESPRESSO – MAORY

1. Introduction

Nowadays a large number of high accuracy measurement devices is available on the market. Unfortunately those instruments are usually dedicated to specific tasks making them difficult to use for the alignment of optomechanical systems. In recent years there's been a boost in the development of CMMs, a series of devices capable to calculate the relative position of different points and, as a consequence, to calculate the geometrical characteristic of one or more objects. For contact measurements the main representatives of this family are the articulated arm, the laser tracker (LT) and the cartesian CMM. The articulated arm is a medium to low accuracy passive system composed by a series of connected bars with 3 to 7 encoders used to calculate the angular position of the joints and, then, to reconstruct the position of a probe. The LT is a medium accuracy active system that use 2 motorized encoders, 2 lasers and a position sensing detector to track the position of a Spherical Mounted Retroreflector (SMR) and produce a series of points in a spherical reference system over a large volume. The cartesian CMM, usually simply indicated as CMM, is composed by a series of three beams orthogonal to each other with a probe attached to the third one used for high accuracy points acquisition. Even if a large number of different configurations are possible the most common one is the bridge type with a motor for each axis and a triggered contact probe at the end of the vertical one. The motors and the trigger give to the CMM a large advantage in terms of productivity, accuracy and repeatability with respect to manual systems like LTs and Articulated Arms. The first two systems here presented are already in use in OAB for geometrical acceptance of mechanical parts and for the alignment of mechanical and optomechanical systems. An example of this alignment will be presented in the next chapter. After some encouraging results we have decided to investigate the feasibility of using a CMM in order to increase the alignment capabilities by directly touching the optical surfaces. The results of those studies and the next foreseen steps will be shown in the further chapter.

2. Mechanical metrology: ESPRESSO Front End main structure integration

ESPRESSO is the next generation echelle spectrograph to be installed at Paranal's VLT and that will be characterized by an extreme radial velocity precision (Mégevand et al. 2012). The spectrograph will be placed at the Combined Coudé Lab and will be fed with the light incoherently coming from the four telescopes thanks to the Front End (Riva et al. 2012). In order to define the optical path linking each of the 4 Telescope Coudé Trains to the 6 fibers corresponding to the different modes a reference system with the origin located in the center of the mode selector must be defined and all the mechanical interfaces must be aligned with respect to it. A list of the steps followed to achieve this goal are here briefly summarized.

2.1. Reference system definition

The first part of the alignment consisted in the definition of a starting ESPRESSO reference system. The LT has been placed in the Combined Coudé Lab and the center of each circular flange of the 4 coudé rooms have been acquired. The best fit of those 4 points provided the position of the optical plane (XY). A pin and a spherical joint have been used as origin placing it in an X and Y position roughly defined by Paranal design as the intersection of the 4 coudé tunnels at an appropriate height (Z0). The projection of the line connecting the origin with the center of UT2 flange onto the optical plane defined the Y axis.

2.2. Ground plates alignment

A virtual hole pattern, aligned with respect to the previously defined reference system has been projected on the floor using the LT. Targets have been glued in the proper position to guide the drilling of the holes for all the 7 interface plates. After the drilling a special balancer holding the plates has been placed over the pin and has been aligned in tip tilt and clock using 2 LT markers previously characterized with respect to the plates (see Fig. 1 (a)). After the grouting the balancer has been removed and the tip tilt error between the optical plane and the plane defined by the 7 plates has been measured obtaining a tip-tilt value of $34.6 asec$.

2.3. Main structure and mode selector alignment

The structure with the final interfaces has been placed over the pin and aligned in the correct clock position and finally fixed to the plates. It was necessary to center in X and Y with respect to the structure interfaces and in tip-tilt with respect to the optical plane the mode selector rotary stage, in order to achieve the proper position. The angular alignment has been done comparing the optical plane with the one generated by a full rotation of the table (an extension bar and a retroreflector for the LT were mounted on it). The error obtained, after a proper shimming of the plate under the rotary stage, was $2.85 asec$ along the X axis and $-0.61 asec$ along the Y axis.

Fig. 1. From left to right: (a) balancer and plates during alignment; (b) detail of the Front End structure with the mode selector and the pentaprism; (c) Front End structure interfaces.

2.4. Coudé axis definition

For the definition of the 4 coudé axis a green laser has been optically aligned along the Z axis. At the end of this phase the beam, coming from the ceiling, can be shined into the 4 tunnels up to the center of the 4 flanges thanks to a pentaprism mounted over the mode selector (see Fig. 1 (b)). To reference this laser with all the other elements previously acquired an SMR has been mounted at the proper height and acquired by the LT. Merging this information with the ones obtained by the mode selector encoder the definition of the final reference system defined by the laser has been done.

2.5. Front End interfaces acquisition

All the relevant interfaces have been acquired (see Fig. 1 (c)) in order to have all the data needed for the integration of the other Front End subsystems.

3. Mechanical metrology for large optics: MAORY Fore Optics

The use of a CMM instead of manual LT or Measuring Arms will be a strong step forward alignment of large optomechanical elements like the MAORY ones (Diolaiti et al. 2010). This is related to a number of intrinsic characteristics of those machines; in particular:

- The Maximum Permissible Error (MPE) is the order of a few micrometers while for the typical manual measuring machine is about one magnitude worse. Moreover the uncertainty of the measure can be estimated using different methods (ISO/TS 15530).
- The contact pressure of the probe can be extremely low and repeatable.
- It's possible to set up the measurement plan with different sampling strategies.

Those characteristics of the machine could allow for the alignment of the optical elements directly touching and acquiring the optical surfaces. In order to check its feasibility and to estimate the performance required a software performing a Monte Carlo uncertainty calculation has been implemented. For this kind of analysis a number of factors can influence the results: mechanical characteristics of the machine, feature form error, environmental factors (mainly temperature, temperature distribution and vibrations), probe system errors, feature form errors, fitting algorithms used and sampling strategy (Baldwin et al. 2007). In our case we decided to focus the simulations to understand the effect that different sampling strategies and the knowledge of different geometrical parameters can have on plane, spherical (as the example shown in Fig. 2) or aspherical surfaces reconstruction.

Those analysis showed us that a similar approach can be used and, most important, that when some geometrical parameter is unknown touching the optical surface clear aperture can improve the quality of the measurement. In order to verify that this operation won't effect the quality of the optical element (Meli et al. 2007) a robust and complete damage evaluation will be done. This analysis will have to account a large number of situations related to

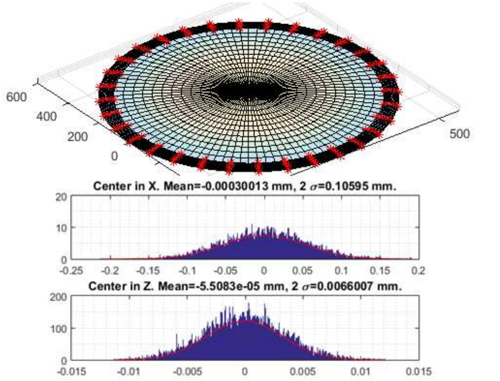

Fig. 2. An example of sampling strategy simulation (1200*mm* spherical mirror with known radius).The histograms shows the error in X and Z direction and the 2σ value

the CMM itself see (Hocken et al. 2011) like stylus ball material, probe geometrical properties (mainly due to inertia effects), adhesion, dynamic effects (approach speed, measurement effects, structural and stylus eigenfrequencies,...) and travel direction with respect to CMM axes and object surface. Different conditions also on the optical element side must be considered. Those are in general related to the substrate and coating materials and to the deposition method. The CMM acquisition of an optical surface for one or more times in a specific condition could cause microscopic damages on the optical surface like scratches, digs, cracks and coating delamination resulting in immediate or over time optical quality degradation. This degradation will be quantified and the main parameters will be identified in order to choose the best strategy for the alignment of both lenses and mirrors.

4. Conclusions

The alignment of mechanical and optomechanical systems using contact measurements by different measurement machines like LTs and Articulated Arms has been proven feasible and a successful example of this has been shown. After a preliminary theoretical analysis and different simulations the use of a CMM for the alignment of optical elements could be a big step forward in mechanical alignment mainly due to its higher accuracy and repeatability and the low measurement forces. An extensive test campaign will then be done to validate and improve the theoretical model, to choose the best measurement strategy and to optimize the machine configuration.

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