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From a demonstration model to the flight model: AIV procedures and results for CHEOPS telescope

M. Bergomi[*a], F. Biondi [a], D. Magrin [a], L. Marafatto [a], R. Ragazzoni [a], V. Viotto [a], M. Dima [a], D. Greggio [a], J. Farinato [a], L. Lessio [a], M. Munari [b], I. Pagano [b], E. Portaluri [a], M. Baroni [c], E. Battistelli [c], M. Marinai [c], A. Novi [c], M. Salatti [d], E. Tommasi [d], A. Deep [e], T. Beck [f], D. Piazza [f], W. Benz [f]

[a] INAF - Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, 35122 Padova, Italy
[b] INAF - Osservatorio Astrofisico di Catania, Via S.Sofia 78, 95123 Catania, Italy
[c] Leonardo S.p.a - Eo Payloads/ Propulsion Techn. & Assembly, Via delle Officine Galileo 1, 50013 Campi Bisenzio (Firenze), Italy
[d] ASI - Via del Politecnico snc, 00133 Roma, Italy
[e] ESA-ESTEC- Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands
[f] Physikalisches Institut - Universität Bern, Sidlerstrasse 5, 3012 Bern, Switzerland

ABSTRACT

CHEOPS (CHaracterizing ExOPlanets Satellite) is an ESA Small Mission, planned to be launched in early 2019 and whose main goal is the photometric precise characterization of the radii of exoplanets orbiting bright stars (V<12) already known to host planets. The telescope is composed by two optical systems: a compact on-axis F/5 Ritchey-Chrétien, with an aperture of 320 mm and a Back-End Optics, reshaping a defocused PSF on the detector. In this paper we describe how alignment and integration, as well as ground support equipment, realized on a demonstrator model at INAF Padova, evolved and were successfully applied during the AIV phase of the flight model telescope subsystem at LEONARDO, the Italian industrial prime contractor premises.

Keywords: CHEOPS, exoplanets, transits, ESA, Small mission, telescope, AIV, prototyping, flight hardware

1. INTRODUCTION

CHEOPS (CHaracterizing ExOPlanets Satellite) [1][2] is a joint ESA-Switzerland Small Mission, adopted in 2014 and planned to be launched in early 2019 [3]. The satellite will occupy a low Earth (about 700 km) sun-synchronous orbit, with the main goal to perform, through the transit method, by means of ultrahigh precision photometry, the characterization of the radii of exoplanets orbiting bright stars (V<12) already known to host planets.

The payload is based on a detector fed by a single telescope composed by two optical systems: a compact on-axis F/5 Ritchey-Chrétien two mirrors centered telescope, with a 320 mm clear aperture and a re-imaging optics system, the Back-End Optics (BEO), reshaping a defocused PSF of the target star onto the detector. The defocused PSF is due to the choice of spreading the PSF over a quite large amount of pixels to average for single-pixels anomalies, as a best compromise between jitter mitigation and Signal-to-Noise ratio[4]. This solution has been selected aiming to obtain very high photometry stability together with an intermediate pupil mask and a baffle with vanes preceding the telescope, for the straylight rejection and the mechanics design efforts toward a μm-level thermal stability of the structure[5].

CHEOPS is a fast-track mission (selected in late 2012), with a launch opportunity originally foreseen in 2018, nevertheless as for every space mission, the development of several intermediate models to reduce main identified risks was foreseen. One of the identified risk areas was the demonstration of the feasibility of the AIV procedures and identification of the critical aspects, as well as the development of adequate Ground Support Equipment (GSE), ahead of their implementation on the Proto-Flight Model (PFM) by the Italian industrial Prime contractor LEONARDO, supervised by INAF.

* maria.bergomi@oapd.inaf.it

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In this framework, we developed a Demonstration Model (DM) of CHEOPS telescope subsystem. The description of the DM assembly and alignment activities performed at INAF Padova until mid-2016 can be found in [7], while in this paper, after recalling the main requirements of the subsystem, we show the DM alignment final results and how the alignment and integration procedures, as well as GSEs developed for the DM and the lessons learned, evolved into the final alignment approach used at LEONARDO premises. The alignment results of the flight model (hereafter PFM) will also be presented and discussed.

2. CHEOPS TELESCOPE SUBSYSTEM (TEL)

The main parameters of the final optical configuration of the CHEOPS telescope, hereafter called TEL subsystem, are collected in Table 1, while Figure 1 shows a CAD view of the TEL structure, made by the assembly of:

- an opto-mechanical Tube, consisting of a mechanical structure mounting the hyperbolic primary (M1) and secondary (M2) mirrors
- an Optical Bench Assembly (OBA)
- the reimaging optics BEO, consisting of a mechanical part mounting a set of small optics, namely a doublet (D1), collimating the light coming from the tube, a pupil mask, a folding mirror (M3) and a second doublet (D2) to focus the PSF onto the detector.

In the Tube, glue acts as interface between mirror mount and TEL mechanics and it is injected after the alignment of each mirror is completed, allowing to use all degrees of freedom for the mirrors during the alignment phase. BEO optics, instead, were precisely aligned and glued to their mechanics such that the degrees of freedom left for alignment mostly rely on the mechanical couplings, with the exception of D2 focusing. The full BEO can anyhow be aligned with respect to the M1-M2 Tube thanks to three mechanical fixing points onto the OBA.

Spectral range	400 – 1100 nm
Entrance pupil diameter	320 mm
Central obstruction diameter	68 mm
Working F/#	8.38 @ 750 nm
Field of View (diameter)	0.32 degrees
Effective focal length	2681 mm @ 750 nm
Pixel size	13 micron
Plate scale	1 arcsec/pixel

Table 1: Main parameters of the optical configuration.

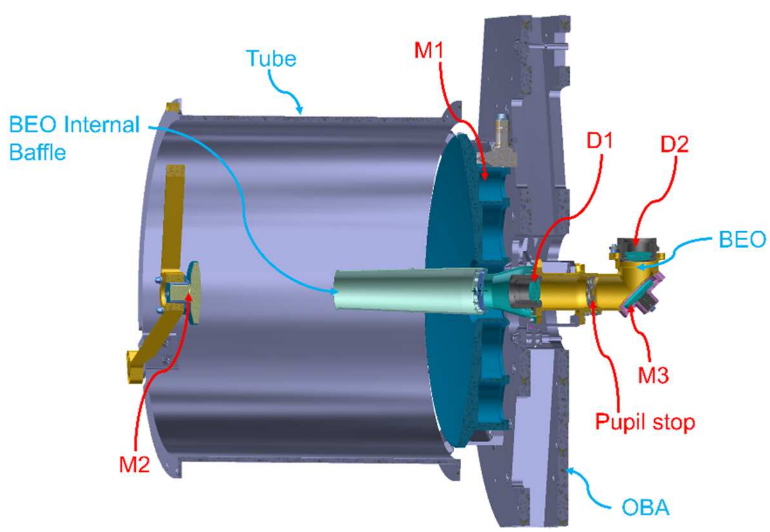

Figure 1. CAD section view of TEL DM. Main components are indicated (blue mechanics, red optics).

3. REQUIREMENTS & ALIGNMENT PROCEDURE

The main requirements related to the TEL alignment are:

#1. the optical axis shall be aligned with respect to (wrt hereafter) the OBA reference frame references with a precision of $\pm$ 500 µm in centering and $\pm$ 400 µrad in tilt

#2. the center of the focal plane (defocused) shall lay in a cube of size ± 0.5 mm and ± 1.5 mm.

#3. the Line of Sight (LoS) must be characterized with a precision lower than 100 µrad and the focal plane position within ±40 µm and ± 3mrad.

The adopted alignment procedure strategy, in order to fulfill the previously given requirements and whose preliminary version was described in [6], and its evolution in [7], consists in a four-step alignment. Firstly, the M1 is aligned wrt to the OBA; afterwards the M2 is aligned (tilt, centering, focus) wrt M1; then BEO D1+M3 are centered wrt the Tube assembly to guarantee the location of the focal plane in the plane orthogonal to the chief ray, and finally BEO D2 is focused to guarantee the required focal plane location along the optical axis. Alignment of M1 wrt to reference frame is performed by means of metrological characterization and measurements, while for the alignment of M2 to M1 and BEO to the Tube a double-pass interferometric setup is conceived, with Zygo interferometer fringe and Zernike coefficients minimization as feedback for the alignment.

The optical axis is defined as an imaginary line passing through the center of the optical system pupil (M1 in CHEOPS) and coincides with the axis of rotational symmetry in the case of an on-axis optical system. Although the requirement #1 is given for the full telescope, it can be directly flown down to M1 hyperboloid axis, since all the other optics will be aligned to it in order to meet the requirement. Clearly, this depends also on the metrological accuracy in the positioning of the gauges element to be used during the alignment. As a matter of fact, M2 acts as a compensator for M1 alignment to guarantee #1 and BEO as a compensator to guarantee #2. BEO tilt is guaranteed by the tolerances on the opto-mechanical interfaces of its optical elements, which we will not detail in here, while focal plane position is guaranteed by centering and focusing of the BEO structure D1+M3. The only optical element inside BEO with autonomous adjustment capability is D2, along the optical axis. Simulations proved that the displacements needed to recover M1 or optical gauges misalignments affect negligibly the optical performances.

While trying to maintain the same approach, after defining the alignment procedure (and iterating), the overall requirement has been translated into different ones for the DM (tighter on M1 alignment, looser on gauges positioning) and the PFM, due to different metrological and precision equipment and after further evaluation coming from the DM alignment activity experience. In both cases, however, requirement on M2 and BEO alignment translates into reducing the Zernike coefficients of Focus (Z4) below 0.05 waves (wv, hereafter) in single-pass and the quadratic sum of Tilt (Z2, Z3) and Coma (Z7, Z8) terms below 0.07 wv in single-pass.

Furthermore, concerning the PFM, after further evaluation on the procedure, two different observables have been identified to verify M2 and BEO alignment. The first one is the overall RMS of the wavefront, to be compared to the one computed from the worst case of a Montecarlo simulation run, taking into account the mechanical tolerances, the equipment precision and the actual shape of the optical surfaces; the second one is the equivalence between the two MTF values (tangential and sagittal) at frequency f = 38 cycles/mm (Nyquist frequency).

4. LESSONS LEARNED FROM DM AND APPLIED ONTO PFM

We recall here that the DM consists of a non-flying CHEOPS model. Its mechanics, realized by the University of Bern, is fully representative concerning interfaces but not thermally equivalent to the PFM (aluminum vs carbon fiber). Its optical groups, manufactured by LEONARDO and subcontractors, differ from flight optics for not being radiation-hardened, for their coatings and for the level of light-weighting of M1, however, their optical quality and handling capabilities, very close to the flight model, allow to productively test procedures for handling, integration and alignment.

The main lessons learned from DM and their translation into final alignment strategy for the PFM will be described for each step.

1. **M1 alignment and gluing to the OBA reference plane**

   During DM activities, it was devised that, given the tolerances, the best method to align both in tilt e decenter M1 was mechanical referencing. In the case of the DM, this was accomplished aligning a bearing mechanical axis (center and tilt) to the mechanical references on the OBA, therefore materializing the optical axis of the system. Afterwards, M1 position was adjusted using as observables: dial gauges installed on the bearing for centering, mechanical referencing for focus and minimization of the trajectory of a laser (connected to the bearing, shining on the mirror and reflecting on a CCD) for tilt. The adjustment was carried out through several iterations using a manipulator supporting M1 equipped with micrometers for center, tilt and focus adjustment, and micrometric screws for rotation adjustment (Figure 2 left). More details can be found in [7].

On the PFM, this concept was upgraded thanks to the availability of a Zeiss 3D measuring machine: UPMC 850 (with precision 1.5 + l/300 µm, with l=length of the area involved in the measurement in mm). The process included a full characterization of the OBA reference points and of M1 optical surface, internal and external cylinder and rear surface, as visible in Figure 2. A custom manipulator was devised, composed of 11 micrometers such that the position of M1 could be adjusted wrt references under Zeiss machine monitoring (also shown in Figure 2). The DM experience suggested the use of stiff interfaces to firmly hold the mirror in place wrt to its mount during screws tightening and monitoring of M1 position during this activity, mainly because of the effect due to an elastic o-ring, located in the interface between mirror mount and OBA, used to avoid glue spilling.

Another key point, which emerged from the DM activity, was the importance of a high planarity in the interface between M1 bipods and the tube, to avoid stress on M1. For this reason, in both cases CMM characterization (and lapping in the case of the DM) was required.

Also, during the DM activities we noticed that the mirror can be stressed once it has been fixed to the OBA. For these reasons, the PFM M1 was tested with an interferometric measurement before and after being aligned and glued to the OBA. Gluing occurred both for the DM and the PFM with a bi-component glue Hysol 9394 with the help of syringes and with teflon rings or o-rings to avoid glue spillage.

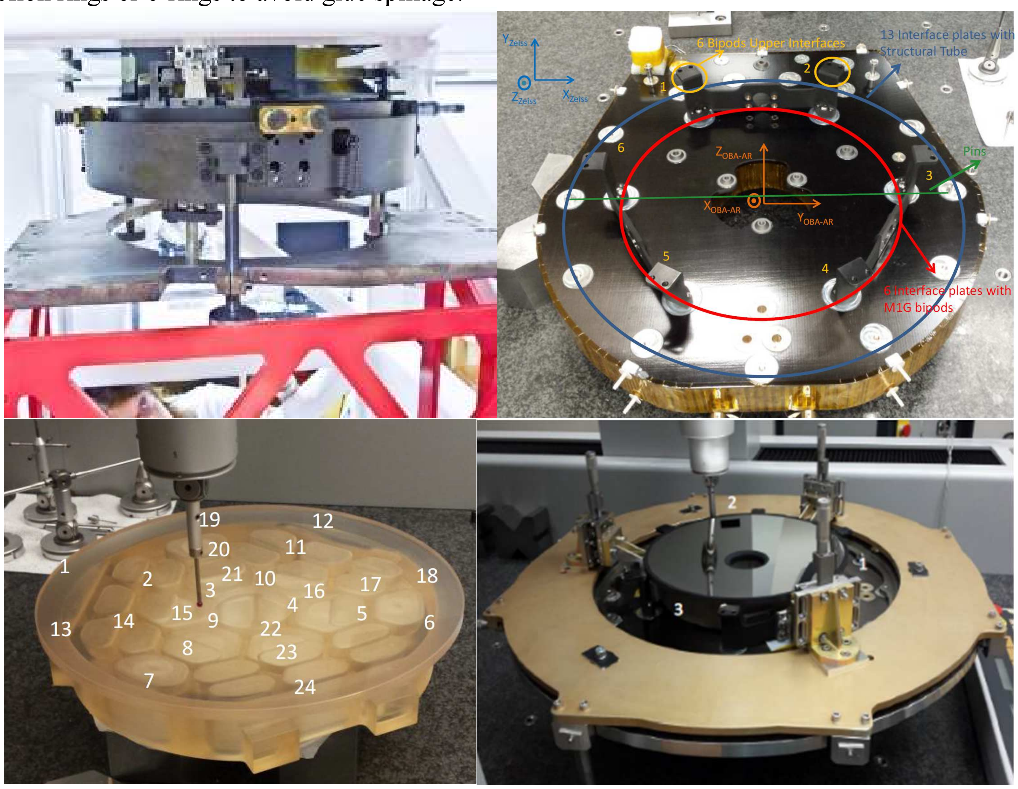

Figure 2: *Top-left:* DM M1 custom manipulator holding and allowing adjustment of M1; *Top-right*: CMM characterization of the OBA; *Bottom-left:* CMM characterization of M1; *Bottom-right*: PFM custom M1 manipulator allowing alignment wrt the OBA

2. Preliminary operations for M2 alignment

For both models, the chosen configuration for the integration was a custom handling to hold the tube vertically (with M1 facing the ground), in order to minimize gravity effect during M2 to M1 alignment. The setup for the alignment of M2 was a Zygo FlashPhase GPI interferometer (λ=632.8 nm) both for the DM and the PFM, feeding a wide collimated beam onto M1 (see Figure 3).

In the case of the DM, the collimated beam was obtained aligning an F/1.5 spherical element and a 330 mm Off-Axis Parabola, OAP, while in the PFM case a 300 mm Zygo beam-expander was used, due to a delay in the arrival of the needed high-quality OAP.

The reference for M2 OGSE alignment to the optical axis of M1 was a flat mirror laying over the OBA and aligned using an autocollimator fixed onto the bearing (which, we remind, materializes the optical axis of the system) on the DM. This strategy evolved for the PFM in the flat mirror alignment and characterization under CMM for the PFM.
In a similar manner, the TEL intermediate focal plane was materialized with a spherical gauge aligned to the bearing with a setup similar to the one used for M1 tilt alignment for the DM, and with CMM characterization and adjustment for the PFM.
The collimated beam was then aligned to the flat reference mirror (and therefore to M1 optical axis) using the same 480-mm-diameter flat mirror oriented at 45° and located under M1.

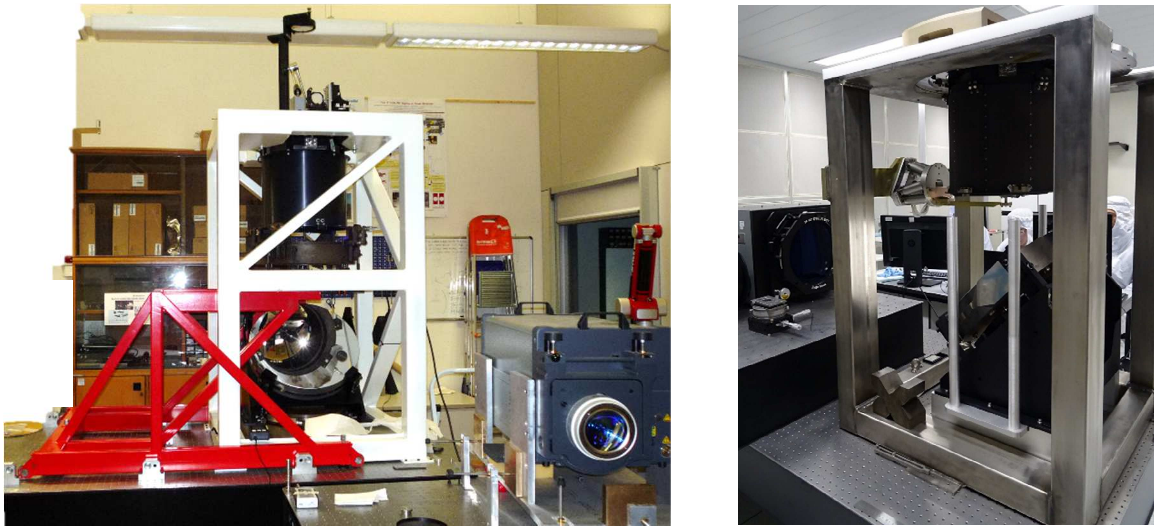

Figure 3: *Left*: DM M2 alignment setup. *Right*: PFM M2 alignment setup. In both cases is visible the Zygo interferometer feeding light to the tube thanks to a 45° oriented large flat mirror. The tube is held in vertical configuration, M2 is adjusted thanks to a manipulator fixed to the red handling on DM and to a hexapod or PFM. Also, the reference flat mirror located over OBA can be seen in both cases.

3. **M2 alignment to M1 and gluing**

We recall that M2 is aligned wrt M1 in tilt, focus and center minimizing the Tilt, Power and Coma Zernike coefficients retrieved by the interferometer. In the case of the DM, M1 manipulator was modified and used for the alignment, but the fact of not having a central pivot point along with the need for a higher precision translated in the use of a Symétrie BORA hexapod for the PFM M2 alignment. In order to increase the optical quality, DM activities suggested the rotation of M2 mainly to compensate, if possible, astigmatism and trefoil effect. This tuning was performed also on the PFM.

During DM M2 alignment, we noticed M1 mirror stress due to temperature variation, with a particular effect on trefoil, which would have translated in a triangular-shaped PSF as it can be seen in [10]. This is mainly related to the three-point connections between M1 and the mechanics.

Both for PFM and DM, after the alignment was obtained and stability verified, M2 could be glued to its support injecting bi-component glue Hysol 9493, while monitoring the interferometric pattern, adjusting M2 position during polymerization. DM experience, where excess glue came in contact with the back side of the Zerodur mirror substrate, rather than just be confined in the gluing area, suggested the use of a Teflon mask to protect any glue spillage from reaching the substrate.

4. **Align BEO with respect to the Tube (M1-M2)**

A strategy similar to M2 alignment is foreseen, with a spherical gauge mechanically positioned by means of a CMM onto the focal plane (both for the DM and the PFM) and the BEO adjusted in focus, center and rotation, minimizing interferometric Zernike coefficients. A few possible mechanical interferences were identified (and solved) in the DM and avoided in the PFM. A diaphragm installed in place of D2 allowed for verification of any vignetting. BEO was fixed to the OBA thanks to a custom tool devised by University of Bern, allowing the pre-tensioning of the threaded rot to the needed torque. The main lesson learned during this phase on DM was that the use of a single tool was very time-consuming and did not allow a satisfactory alignment. For this reason one tool per screw was requested and used during PFM alignment.

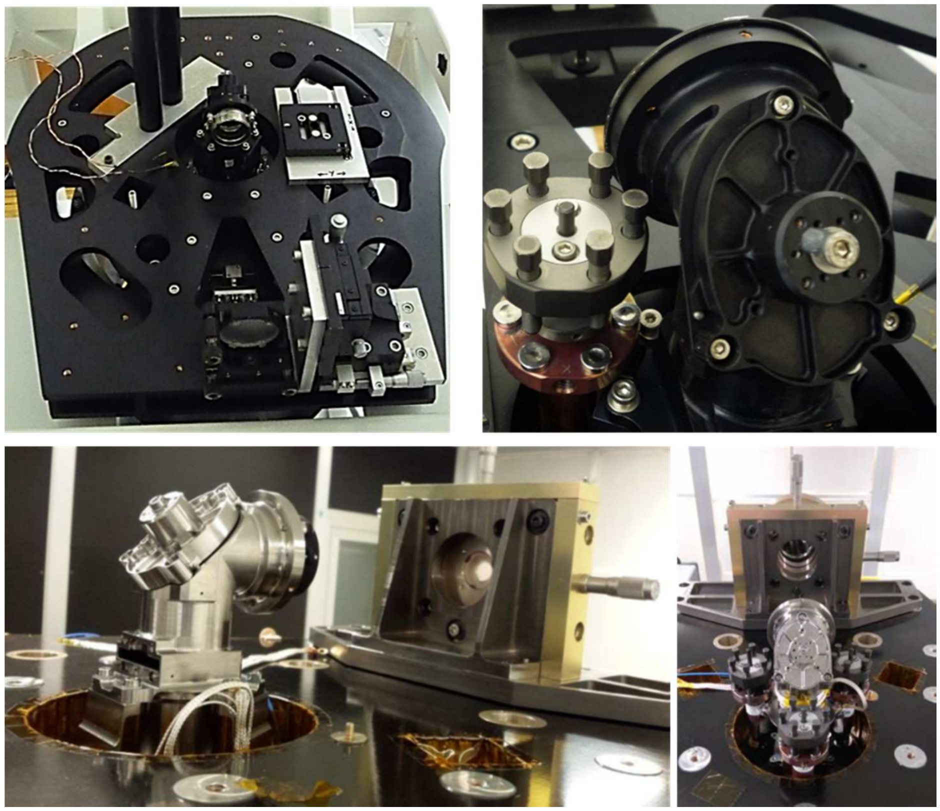

Figure 4: *Top panels*: DM BEO alignment. One pre-tensioning tool was used. *Bottom panels*: PFM BEO alignment setup. Three pre-tensioning tool were used as lessons learned from DM activities.

5. ALIGNMENT RESULTS

5.1 DM

The DM M1-M2 alignment results were presented in [7] and are summarized here. A typical interferogram and wavefront, taken at T= 23.8°C, after M2 alignment was completed, are shown in Figure 5. PtV is 1080 nm, while rms about 200 nm. As mentioned earlier, a dominant astigmatism was found. The analysis to understand its origin identified M1 coupling to mechanics as the main responsible. Coma and power terms were minimized below 0.1 wv. In Figure 5, right, it is shown also the wavefront after removing tilt, power, coma, astigmatism and spherical aberration, where trefoil is clearly distinguishable.

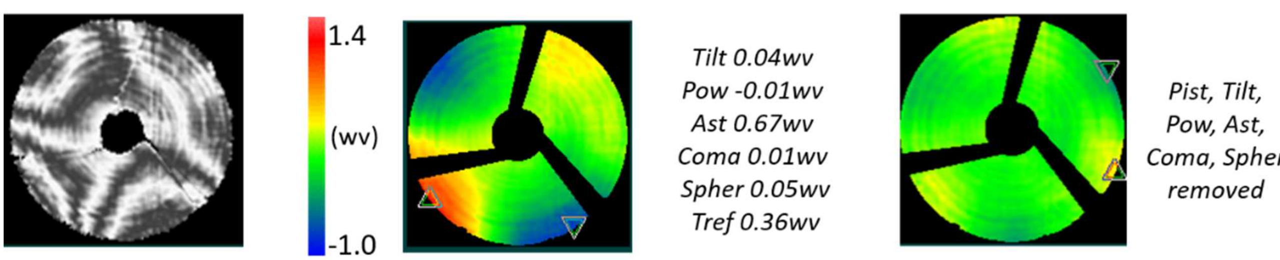

Figure 5. From left to right: a representative interferogram obtained averaging 50 after M2 alignment, with temperature at 23.8°C (we remind the dependence of the Zernike coefficients on the temperature); its relative wavefront (PtV is 1.8 wv -1080 nm; rms 0.3 wv – 200 nm) and the wavefront after removing main aberrations, where the trefoil is clearly visible.

Concerning BEO alignment, a discrepancy in the thickness size of D2 spacers (and the lack of time due to upcoming PFM alignment activity) did not allow to achieve the correct position along the optical axis (0.45 wv of Zernike defocus term). However, the precision needed for the fine-tuning was tested, increasing the thickness and measuring its correlation to the defocus term variation. For this reason in the interferogram shown in Figure 5, the power on D2 was removed, leaving a PtV of 1510 nm and an rms of 236 nm.

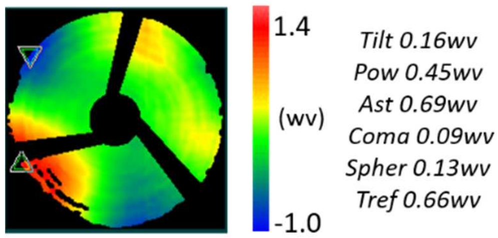

Figure 6. Representative wavefront obtained averaging 50 after M2 alignment, with temperature at 23.8°C (we remind the dependence of the Zernike coefficients from the temperature). PtV obtained after removing Piston, Tilt and Power terms is 2.2 waves -1510 nm; rms 0.37 waves – 236 nm.

5.2 PFM

As mentioned in Section 3, concerning the PFM alignment, other than using the Zernike coefficients as a merit function for the alignment, the overall specification to be matched was the wavefront rms and the equivalence between the two MTF values (tangential and sagittal) at frequency f = 38 cycles/mm (Nyquist frequency).

Figure 7 (top) and Figure 8 (top) show the estimated wavefront for the alignment of M1-M2 and the full TEL alignment, respectively, including the manufacturing error of the mirrors (in both cases the wavefront rms is 123 nm), and the expected MTF values.

The retrieved wavefront and MTF in both cases is shown in Figure 7 and Figure 8 (bottom). The wavefront error obtained removing piston and tilt term in M1-M2 alignment had an rms of 125 nm (and a PtV of 667 nm), very close to the target, while concerning the full TEL alignment, the obtained rms retrieved was 141 nm (1395 nm PtV), which was defined to be acceptable for the system, after performing extra analysis. We remind that optical quality is not critical for this system, as it will also work with a defocused PSF, while its stability is very important to guarantee the needed accuracy for the very precise planet radii characterization. Tangential and sagittal MTF are very similar in both cases.

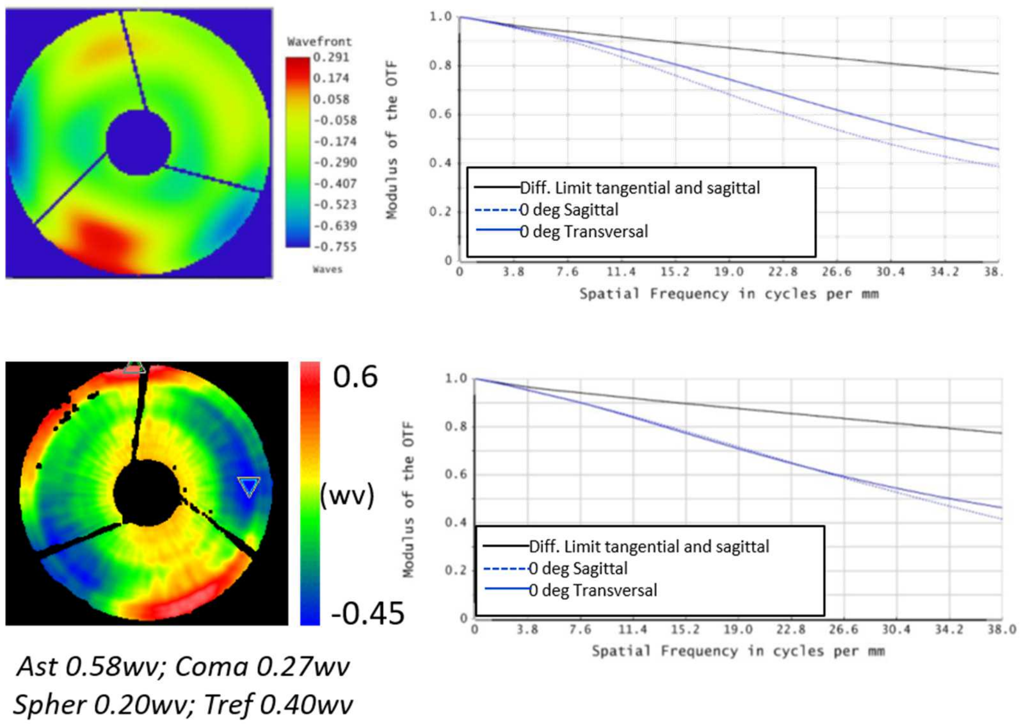

Figure 7: On the top line is shown the simulated wavefront (123 nm) and MTF curves for M1-M2 alignment *(left)*. On the bottom line the obtained interferograms (rms=125 nm) and the MTF curves.

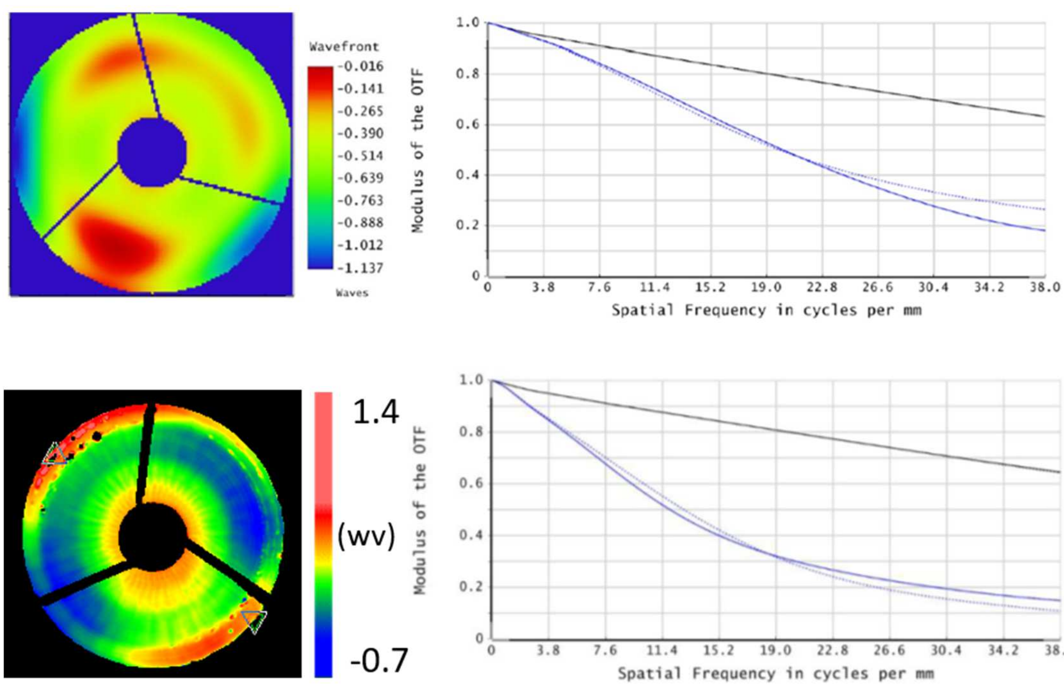

Figure 8: On the top line is shown the simulated wavefront (123 nm) and MTF curves for the full TEL alignment *(right).* On the bottom line the obtained interferograms (rms=141 nm) and the MTF curves.

Last step of this activity was the removal of the TEL subsystem from its alignment handling and a new interferogram taken with the TEL laying horizontally just in front of the Zygo collimated beam. Results, shown in Figure 9 showed an increase in the astigmatism term by about 0.2 waves, which can be justified by gravity.

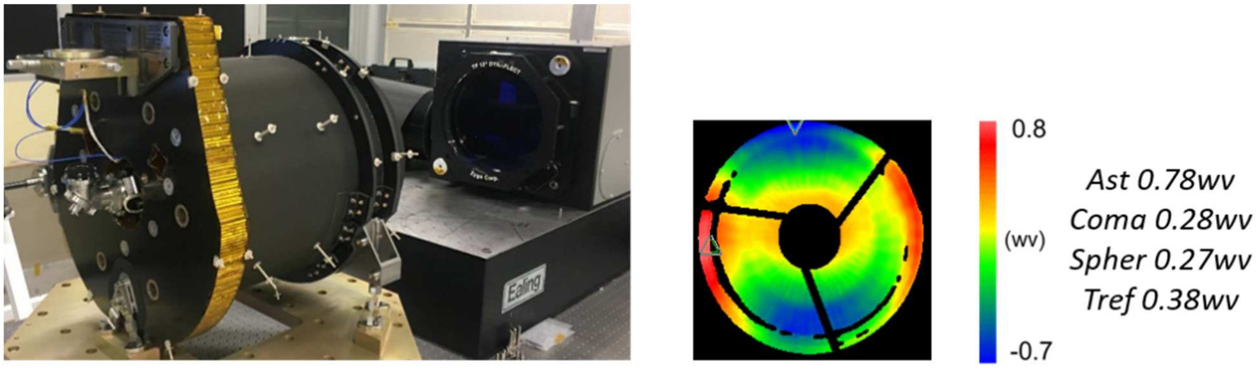

Figure 9: *Left:* The aligned PFM TEL subsystem tested in horizontal configuration in front of the Zygo collimated beam. *Right:* representative interferogram taken in horizontal configuration with PtV 980 nm rms 187 nm. Looking at the Zernike coefficients, it can be noticed the increase of about 0.2 waves in the astigmatism term, due to gravity effect.

A new interferogram was taken in the same conditions after environmental stress application (vibration and thermo-vacuum conditions) and confirmed similar results, with the wavefront rms of 182 nm and a difference in the Zernike main terms of less than 0.04 waves.

Also, concerning requirement #3, a characterization of the LoS was performed in this configuration. The interferometric optical beam identified the LoS and a flat mirror aligned to the beam and a theodolite aligned to the latter were used in order to define the position wrt to an optical cube located on the OBA.

6. CONCLUSIONS

CHEOPS is an ESA small mission, which will be launched in 2019 to precisely characterize the radii of exoplanets orbiting bright stars already known to host planets. It is currently undergoing tests on the spacecraft platform in Madrid at Airbus Defence and Space, the prime contractor that has designed the spacecraft. The PFM telescope subsystem alignment, integration and requirement match have been successfully completed at LEONARDO premises and the main results of the alignment were presented in this paper. Given the short time-scale of the project, a TEL DM was devised and its integration and alignment took place at INAF Padova laboratories in order to gain experience on such activities. The lessons learned translated into new strategies elaborated by LEONARDO for PFM, both in the definition of GSEs, in the glue injection process and the alignment strategy itself. Furthermore, hands-on experience, along with tips and tricks discovered along the way translated in a faster alignment process of the PFM.

7. ACKNOWLEDGMENTS

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