The Plato Opto-Mechanical Unit Prototyping and AIV Phase

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ABSTRACT

PLATO is the acronym of PLAnetary Transits and Oscillations of stars, and it is a mission proposed for the ESA Cosmic Vision program in the Medium size program, with the target to detect and characterize exoplanets by the means of their transit on a bright star. The instrumental overall layout proposed by the Plato Payload Consortium consists in a multi-telescope concept instrument, composed by several tens of telescope units, for which we are developing an all refractive optical solution. These devices are characterized by a very large Field of View (more than 20 degrees on one side) with an optical quality that fits most of the energy into a single CCD pixel. Such a goal can be achieved in a variety of solutions, some including aspheric elements as well. A complete prototype of one telescope unit is foreseen to be built initially (during phase B1) to show the alignment feasibility and, only in a second moment (Phase B2), to perform full environmental and functional test. The aim of this article is to describe the alignment, integration and verification strategy of the opto-mechanics of the prototype. Both the approaches of testing the telescope at the target working temperature or to test it at ambient temperature around a displaced zero point, taking into account the effects of thermal deformations, are considered and briefly sketched in this work.

Keywords: ESA Cosmic Vision, Exoplanets, Telescope Optical Unit, Opto-Mechanical Prototype AIV

1. INTRODUCTION

PLATO (PLAnetary Transit and Oscillation of stars)[1][2][3][4]) is one of the three medium class (M class) missions selected for definition study in the framework of the ESA Cosmic Vision 2015-2025 program.

The aim of PLATO is to observe a large sample of bright stars in order to detect and characterize exoplanets by means of their transit in front of the stars, and to measure the seismic oscillations of the parent stars to understand the properties of the exo-planetary systems. To achieve this, Plato has been conceived as an instrument composed by several small and very wide field telescopes (32 in the current design) covering a huge fraction of the sky, more than two thousands square degrees. The choice of having several small telescopes instead of a single one with bigger aperture is driven both from the too short F/# that such a telescope should have had, given the very large FoV required, and from other important
issues connected to the launch, such as volume and weight. Moreover, this fact allows using a technique described in the following, called “overlapping line of sight”.

The PLATO project has been proposed to the European Space Agency in 2007, and it has been selected with other 5 M class missions between 52 proposals. A second selection happened in January 2010, when PLATO has been recommended for the definition phase with other 2 projects, Euclid ([5]) and Solar Orbiter ([6]).

The Plato consortium is composed by several European countries (Austria, Belgium, Denmark, France, Germany, Italy, Spain, Switzerland and United Kingdom), co-ordinated by ESA and organized in two additional consortia, the Payload one and the Science one.

Italy is responsible of the Opto-Mechanics of the Telescope Optical Unit (TOU) ([7]), a work-package shared with Switzerland which is doing the mechanical design of the TOU, while in Italy the optical design is carried out.

In this article we will describe the activities that will be performed during the definition phase for the Assembly, Integration and Verification (AIV) on a prototype of the TOU, which will be build and tested in co-operation with the industry.

2. PLATO SCIENTIFIC TARGETS

As already said, PLATO is essentially a Planet finder, the scientific target of Plato being the research of planetary systems by observing the planet transit on the parent star, together with seismic oscillation measure of the latter useful to understand the property of the exoplanetary system under observation. In fact, the transit of a planet on the parent star is causing a change in the star brightness which is decreasing due to the planet obscuration (see Figure 1), and the detection of the light curves of about 400.000 stars brighter than m_v=14 is the main PLATO scientific target, aiming to discover earth-like planets.

![Figure 1: The change in the light curve due to the planet transit](image)

The other target is, on a sample of about 50.000 stars brighter than m_v=11, observed continuously and for several years, to make both transit search and asteroseismology.

Plato, compared to other missions with similar purposes (Kepler and CoRoT) can reach very high sky coverage (see Figure 2), of the order of 45%, thanks to the huge surveyed area and to the following observing strategy:

- Two main fields observed sequentially for three years each
- A number of “step and stares” phases with duration between 2 and 5 months
Of course, Kepler and CoRoT are focusing their attention on possible planetary systems very faint and very far, and this also explains the much smaller fraction of the sky covered, but just for this fact PLATO, which is aiming to bright and nearby targets, is somehow complementary to the work of such missions having in this way a very important scientific task to be pursued.

![Image of Kepler, CoRoT, and PLATO coverage of the sky](image)

The integration of the work of PLATO with space and ground telescopes observation will give the possibility to obtain a complete characterization of the planetary systems which will be discovered.

## 3. PLATO CONCEPT: A MULTI-INSTRUMENTAL APPROACH

PLATO is based on a multi-instruments approach: it is composed by 32 telescopes (Figure 3), observing in a very broad band (500-1000nm) and 2 specialized telescopes observing with high cadence in two broad bands (blue and red). The disposition of the cameras on the optical bench has been optimized for the “overlapping line of sight strategy”.

![Image of PLATO instrument and multi-telescope concept](image)

Figure 3: Left – the PLATO instrument inside the Ariane 5 vector; Right – the multi-telescope PLATO concept
The 32 cameras have been divided in four subsets of eight cameras (see Figure 4). Each subset looks at the same circular Field of View (having a diameter of 37 degrees). The line of sight of the four subsets are misaligned in such a way that the overlapping Field of View areas guarantee the required number of stars at given noise level and the required number of stars at given magnitude (the overall Field of View is 2180 square degrees).

Moreover, the overlapping line of sight strategy allows continuous observation of the same sky area with 90 degrees field rotation every 3 months. Currently, as already mentioned, the observation strategy has been divided in two parts: the first part will be dedicated to the observation of two sky areas for a long period of 2-3 years; the second part will be dedicated to a step and stare strategy with each fields observed for 2-5 months (1-2 years). As result, the coverage will be of the order of 50% of the sky.

4. TELESCOPE OPTICAL UNITS

The opto-mechanical design of the TOU is shown in Figure 5. We just recall here the main drivers used for both the optical and the mechanical design, which evolved quite a lot with the development of the project going from an initial hybrid reflective/refractive design to a 6-lenses all refractive design.

Concerning the mechanics (actually foreseen in AlBeMet for the tubular structure and Titanium alloy for the lenses mounts and for the isostatic mounts) these are the guidelines for the current design:

- The temperature gradients along the TOU shall be limited to a few Kelvin to guarantee the necessary optical performance.
Due to the stringent mass requirement only very limited thermal hardware can be implemented, and therefore the heat dissipated in the focal plane assembly is removed through the mechanical structure and radiated by the baffle into deep space.

Since the integration is carried out at room temperature, while the TOU will be operated at about -80°C, the design must allow the compensation of the thermal stress between the different materials used inside TOU and between the TOU units and the optical bench.

Low density and high stiffness materials are necessary to cope with the launch environment and limited mass budget.

<table>
<thead>
<tr>
<th>Spectral range</th>
<th>500 – 1000 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entrance Pupil Diameter</td>
<td>120 mm</td>
</tr>
<tr>
<td>Field of View</td>
<td>&gt; 1000 degree² (~1062 degree²)</td>
</tr>
<tr>
<td>Image quality</td>
<td>90% EE ≤ 2x2 pixel²</td>
</tr>
<tr>
<td>Plate scale</td>
<td>15 arcsec/pixel</td>
</tr>
<tr>
<td>Detector format</td>
<td>4810×4810 pixels²</td>
</tr>
<tr>
<td>Pixel size</td>
<td>18 micron</td>
</tr>
<tr>
<td>FPA size</td>
<td>164 mm</td>
</tr>
<tr>
<td>Weight (lenses)</td>
<td>&lt; 6 Kg</td>
</tr>
<tr>
<td>Working temperature</td>
<td>-80°C</td>
</tr>
</tbody>
</table>

Table 1: the requirements driving the optical design

Concerning the optical design, the main requirements which guided the development of the actual design are reported in Table 1. The baseline 6 lenses optical design has been obtained at a temperature of -80 °C and a pressure of 0 atm (i.e. in the working environmental conditions) and it is a quite fast camera (F/2). With respect to previous designs, a lot of effort has been put in going from 2 (initial all refractive design) to 1 aspherical surface, characterized by less stringent parameters, in order to make the fabrication process easier in term of costs and delivery time. From the beginning, in fact, the work on the opto-mechanics has been done in close connection with the industry trying to feedback their suggestions and recommendations in updated versions of the design, and trying to find the best possible compromise between the scientific requirements and the technical, alignment and feasibility constraints.

5. ROADMAPS TO PROVE THE 32 UNITS AIV FEASIBILITY

The ESA board, together with the recommendation for PLATO to proceed to the definition phase, raised a few warnings concerning the production and the AIV phase of the TOU units during the delivery phase, all concerning the feasibility of the 32+2 TOU units in a relative short time schedule (about 2 years).

We have thus decided a strategy to address ESA warnings during the definition phase, which consist of two roadmaps:

- The 1<sup>st</sup> one is involving the industry, to which we will ask:
  - A paper study concerning the a-spherical lenses procurement feasibility on a 2 years time schedule
  - A paper study concerning the AlBeMet structure procurement feasibility on a 2 years time schedule
- The 2<sup>nd</sup> one is involving the research institutes in collaboration with the industry:
  - Test on a TOU prototype of the AIV procedure, defined in agreement with the industry
  - Test on the prototype of the warm/cold system performance, defined and performed together with the industry
In the following section we will describe the alignment and the test strategy that we are defining in this period in collaboration with the industry, with the purpose to show that the AIV and the test of a TOU unit is feasible in a timeline which is compatible with the delivery of 32 units in a two years timeline.

5.1 Identification of the TOU alignment procedure

After preliminary discussion with the industry, we have devised a very easy but flexible setup to perform the alignment on a prototype of the TOU system, described in Figure 6. By using Airy and Newton rings both of the back reflected and of the transmitted light (introducing one lens at a time) the alignment of the TOU prototype will be performed; to maximize fringe contrast and airy rings visibility:

1. the detectors are conveniently mounted on linear stages which can move along the optical axis, in order to position them in correspondence of the position where the transmitted and back-reflected spots shall focus
2. light shields can be inserted between each lens, to isolate the back reflected light, when needed, coming only from that lens
3. A variable diameter iris is inserted on the collimated beam, to maximize the transmitted and back-reflected spot sharpness and visibility

Figure 6: the TOU prototype alignment setup

The strategy that we will follow for the prototype alignment is divided in two phases:

1. Identification of commercial lenses with, as much as possible, the same curvature of the final design lenses, with the aim to build a pre-prototype (completely realized with commercial parts) to test the alignment procedure and learn from the test setup (Airy and Newton rings visibility, decenter and tilt misalignment sensitivity, tuning of the test setup components, like for example the movement range of the detectors)
2. Realization of an “equivalent mechanical structure” (in term of thermal behaviour) to perform the real final alignment procedure and eventually test also in cold conditions the optical performance of the system. This phase will be performed both with the commercial lenses used in phase 1 (mounted with proper interface plates) and with a set of lenses as close as possible to the final design lenses, possibly differing only for the glasses and for the usage of a spherical lens instead of the aspherical one

The alignment procedure just described will be performed in warm conditions, but of course the system performance test will be performed both in warm and in cold conditions, as we are going to describe.

5.2 Warm test on the TOU prototype

Being the alignment performed in warm conditions, a few test on the expected TOU “warm performance” are foreseen.

In Figure 7 we show the setup of a test concerning the PSF quality over the FoV. An optical fibre, fed by a visual illuminator, illuminates an off-axis parabola which creates a collimated beam of about the size of the TOU first lens. The collimated beam is then sent to a flat mirror, which folds the light toward the TOU optical unit. A test camera (the final Focal Plane Array will not be available at the moment of the test) will then collect the focussed beam and record the PSF images to be analyzed. To simulate stars in different position of the FoV, the flat mirror is equipped with tip-tilt
micrometric adjustments that allow to change the light input angle on the TOU system. Correspondingly, the test camera is mounted on a XYZ stages system to be moved along the complete FoV. The PSF obtained in the various position of the field shall of course be compared with the foreseen ones coming out from the optical designed “warmed out”.

In Figure 8 we present an interferometric test of the TOU optical quality, with a normal setup foreseeing a spherical output element F/1.5 for the interferometer sending the light to the TOU system and a flat mirror sending back the light to perform a double-pass optical quality test.

5.3 Cold test on the TOU prototype

This test is under definition and will be performed in close co-operation with the industry, being a crucial test that will be required during the construction phase to test the TOU units performance in the final PLATO working conditions.

After initial discussion with the industry, we have identified possible problems due to the low testing T and to the gradient between inside and outside the Climate Chamber that will be used to create the working environmental conditions:

- The input optical window of the Climate Chamber is affected by aberrations (“lens” effect, see Figure 9)
- If the test requires auxiliary optical components inside the chamber, they will also be affected by aberrations and particular care shall be given to their mounts

With these constraints in mind, we have derived a strategy to follow for the TOU cold test:

- Characterize the Input Optical Window aberrations
- In any case, to minimize the lens effect of the Input Optical Window, it is strongly preferable to use parallel beams setup at the climate chamber entrance
- It is better to identify test with no need of additional optics inside the climate chamber
• If additional optics inside the chamber is necessarily needed, it is better to use flat mirrors instead of concave mirrors, again to minimize the “lens effect” that will affect also this optical element.

Figure 9: the “lens effect” of the Climate Chamber input optical window

The test which have been proposed with the TOU unit in working conditions simulated in a climate chamber are essentially a PSF optical quality test on axis, an optical quality interferometric test and an optical quality Hartmann-like test. The latter, described in Figure 10, is characterized by a parallel beam at the entrance window of the climate chamber and does not need any additional optical component inside the climate chamber, requiring only one motorized linear stage working in cold.

Figure 10: the cold TOU optical quality test Hartmann-like

Looking at Figure 10, knowing with precision the relative position of P1 and P2 (linear stage with encoder), we can know very precisely where is the TOU focus and measure the optical quality in term of Encircled Energy, even without going with the CCD there.

The interferometric test (in whichever setup shown in Figure 11 and Figure 12) requires instead additional optics inside the Climate Chamber, while also the PSF test doesn’t need any additional optical element inside the chamber (see Figure 13), but being an on-axis test will give of course the quality only on-axis. For the latter test, to check the PSF also off-axis, we might think to use a setup similar to the one shown in Figure 7, having a tip-tilt adjustment on the flat mirror outside the climate chamber to change the light input angle on the TOU system, but then we shall also add two cryogenic linear stages with very long travel (150mm) inside the camera to move the detector over the complete FoV.
For these reasons, the actual baseline for the cold test to be performed together with the industry is the Hartmann-like test presented in Figure 10, even if before taking a final decision a complete characterization of the aberration of the climate chamber input optical window has to be performed.
6. CONCLUSION

The TOU telescope AIV prototyping phase here presented will work on two different aspects: industry paper work and definition of the alignment and test procedure (to be proven on a TOU prototype) in close collaboration with the industry. This strategy shall give, at the end of the definition phase, clear indications on the feasibility of the 32+2 telescope optical units on the relatively short timeline that such a mission has to meet if eventually selected for the flight.

REFERENCES