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FEA Testing the Pre-Flight Ariel Primary Mirror

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ABSTRACT

Ariel (Atmospheric Remote-sensing Infrared Exoplanet Large-survey) is an ESA M class mission aimed at the study of exoplanets. The satellite will orbit in the lagrangian point L2 and will survey a sample of 1000 exoplanets simultaneously in visible and infrared wavelengths. The challenging scientific goal of Ariel implies unprecedented engineering efforts to satisfy the severe requirements coming from the science in terms of accuracy. The most important specification – an all-Aluminum telescope – requires very accurate design of the primary mirror (M1), a novel, off-set paraboloid honeycomb mirror with ribs, edge, and reflective surface. To validate such a mirror, some tests were carried out on a prototype – namely Pathfinder Telescope Mirror (PTM) – built specifically for this purpose. These tests, carried out at the Centre Spatial de Liège in Belgium – revealed an unexpected deformation of the reflecting surface exceeding a peek-to-valley of 1µm. Consequently, the test had to be re-run, to identify systematic errors and correct the setting for future tests on the final prototype M1. To avoid the very expensive procedure of developing a new prototype and testing it both at room and cryogenic temperatures, it was decided to carry out some numerical simulations. These analyses allowed first to recognize and understand the reasoning behind the faults occurred during the testing phase, and later to apply the obtained knowledge to a new M1 design to set a defined guideline for future testing campaigns.

Keywords: Space Telescope, Ariel mission, aluminum mirror, optical test, FEA.

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1. INTRODUCTION

This paper focuses on the evaluation, by means of the Finite Element Analysis (FEA), of the effect of gravity during the pre-flight testing of the primary mirror (M1) of the Ariel mission's telescope.

1.1 Mission and spacecraft design

The Ariel mission will address the fundamental questions on what exoplanets are made of and how planetary systems form and evolve by investigating the atmospheres of many hundreds of diverse planets orbiting different types of stars. This large and unbiased survey will contribute to answering the first of the four ambitious topics listed in the ESA's Cosmic Vision: "What are the conditions for planet formation and the emergence of life?". Ariel will use transit spectroscopy in the 1.1-7.8 μm spectral range and photometry in multiple narrow bands covering the optical and near-infrared (NIR). Observations of these warm/hot exoplanets will drive understanding of the early stages of planetary and atmospheric formation during the nebular phase and the following few million years. Ariel will thus provide a complete picture of the chemical nature of the exoplanets and relate this directly to the planetary parameters and the type and chemical environment of the host star.

For this ambitious scientific program, Ariel is designed as a dedicated survey mission for transit and eclipse spectroscopy, capable of observing a large and well-defined planet sample within its 4-year mission lifetime.

Ariel will sit underneath the Dual Launch Structure, while Comet-Interceptor will ride on the top. The nominal operations orbit is a large amplitude orbit around the Sun-Earth L2 point. This orbit provides a stable environment, along with a large instantaneous field of regard, both of which are keys to allowing Ariel to meet its science objectives.

1.2 Payload Architecture

The spacecraft is designed in a modular way, with a service module (SVM) and a payload module (PLM) that can be procured and tested in parallel. The SVM contains all the units required to operate the spacecraft and maintain the payload in its nominal operating conditions. The spacecraft has a wet mass of ~ 1.5 t and a power generation capability of ~ 1 kW. 236 Gbit of science data are generated every week and are down-linked in three ground contacts totalling 14 hours / week using an X-band system and the 35 m ESTRACK ground stations. The pointing requirements achieved by the AOCS system in the fine pointing mode are (3 sigma): APE $\leq 1''$; RPE (within 0.1s) $\leq$ 180 mas; RPE (up to 90 s) of the MPE (on 0.1 s) $\leq$ 130 mas; PDE $\leq$ 70 mas up to 10 hours for integrations of 90 seconds. This is achieved with a Fine Guidance Sensor (FGS, part of the payload instrument suite) and reaction wheels only as the sole actuators (accommodated on dampers to minimise any micro-vibrations). The PLM design is optimised to fulfil the science requirements while keeping the technical risks and costs within the M4 programmatic constraints of the payload consortium.

The baseline integrated payload consists of an all-Aluminum off-axis Cassegrain telescope (primary mirror 1100 × 730 mm ellipse) with a re-focussing mechanism accommodated behind the M2 mirror that allows correction for any misalignment generated during the telescope assembly or launch and cool down[1].
Extensive details of the design of the Ariel payload are contained in Ariel Payload Design Description (2020). The overall layout of the payload and the baseline design are shown in Fig.1.

A detailed trade-off of the material to be used for the telescope mirrors and structures has been carried out during the assessment phase. The conclusion is that for the consortium provision of the telescope the optimum solution is a telescope with all mirrors and structures made from Aluminum 6061 T651 alloy[2].

2. THE ARIEL PRIMARY MIRROR M1

The challenging scientific goal of Ariel has implied unprecedented engineering efforts, to satisfy the severe requirements coming from the science in terms of accuracy. The most important specification — an all-Aluminum telescope — has implied a very accurate design of the primary mirror (M1) — a novel, off-set paraboloid honeycomb mirror with ribs, edge, and reflective surface. As M1 is the most delicate optical component of the telescope, it is to be accurately designed, to maximize the stiffness while minimizing the mass. For this reason, the thicknesses of all the components require an optimization, iterative process which must satisfy the following constraints:

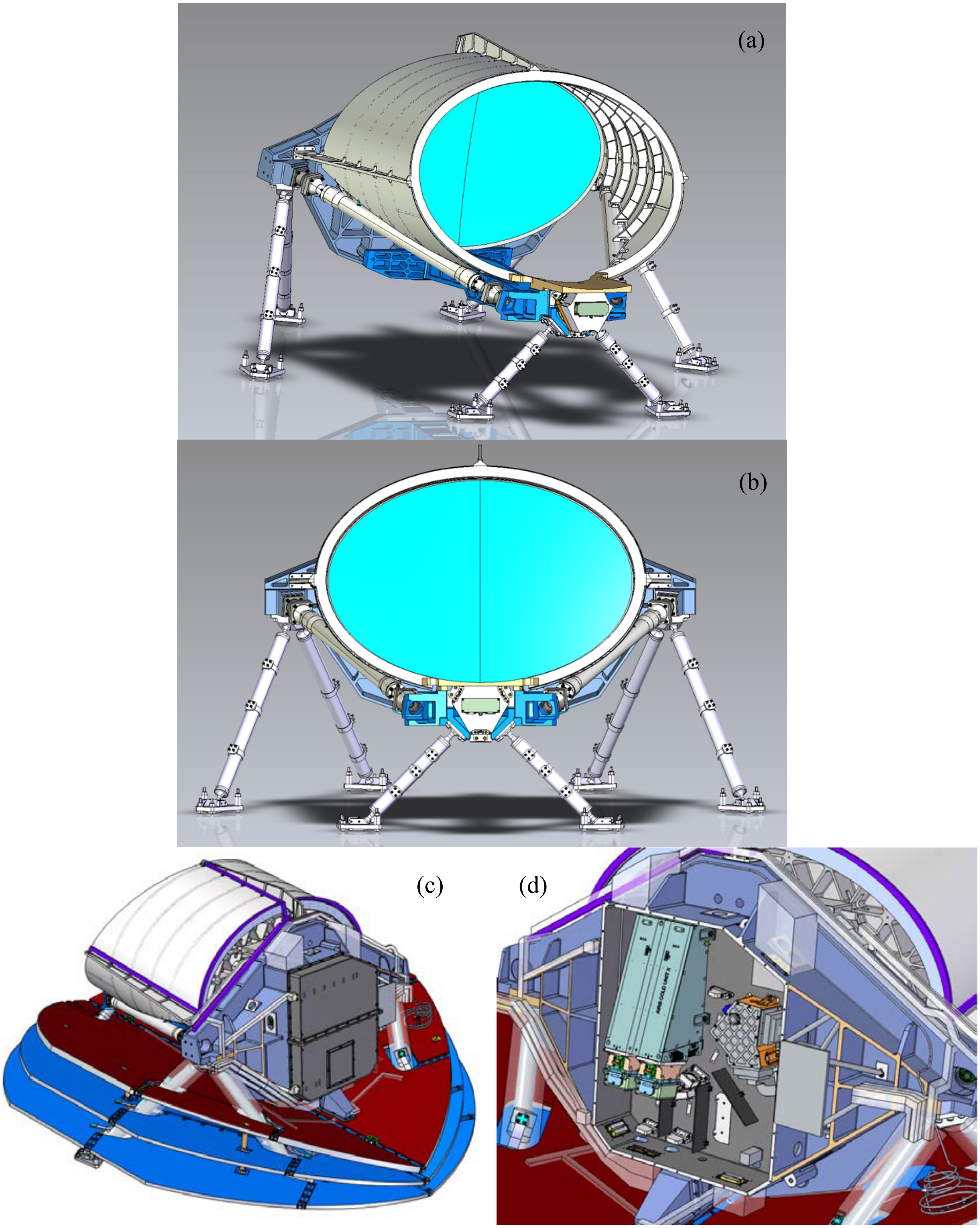

Figure 1. Ariel PLM overall mechanical configuration and layout.

- Distance from the reflective surface to the optical bench on which the mirror is mounted.
- Position of the connections (via flexure hinges) between the mirror and the optical bench.
- Relative position of the mirror with the baffle.
- Fixed position of the reflecting surface with the optical path.
- Total mass of the mirror has to be < 80 kg.
- The first natural frequency of the mirror in free-free configuration has to be > 120 Hz.
- The ratio between the thickness of the optical surface and the radius of the circle inscribed in the triangle of the hollow between the ribs is > 1/9 to allow an effective polishing of the surface.

2.1 The Pathfinder Telescope Mirror program

Bare aluminum silver-coated mirrors as large as the Ariel primary mirror operating at cryogenic temperature (50K) have never been operated in space. M1 has several critical technical issues: Aluminum thermal stability process, mirror lightening, mirror diamond turning (to the final shape), mirror polishing, coating, and mounting. This motivated a de-risking Technology Development Activity (TDA) for M1 during the Ariel Phase A and Phase B1 based on a Pathfinder Telescope Mirror (PTM), i.e., a prototype mirror having size equal to Ariel M1 and very similar characteristics. At the completion of this TDA TRL4/5 has been achieved, thus requiring further activity to achieve the required TRL6 at the payload PDR. The development activities were focused on the choice of the mirror material, on the processing of the M1 primary mirror with the creation of a prototype, coating the M1 prototype, and verifying the performance at cryogenic operating temperature.

Such prototype was subject to some interferometric measurements at Media Lario — an Italian mirror manufacturing company — as well as a cryo-optical test campaign at the Centre Spatial de Liège (CSL) — a research centre of the University of Liège in Belgium. These tests obtained errors exceeding 3 µm PtV and around 1 µm RMS, exceeding the requirements[2].

3. THE ANALYSIS

A static structural analysis was setup in Ansys to assess the problems occurred during the test campaign on the prototype. For this purpose, a very detailed solid model of the PTM including flanges, holes and fillets was imported as geometry for the FEA.

The mirror is supported on two lines of nodes in the bottom part (as shown in Fig.2) that prevent displacement in the Y global coordinate, and on the internal surface of the top hole to prevent displacement along the X and Z global coordinates — the so-called anti-tilt support. These boundary conditions mimic the cylinders and the locking knob that were used by CSL during testing.

Four different configurations of supports were considered:

- 15° from the vertical (Y-Z) plane w.r.t. the center of the ellipse
- 25° from the vertical (Y-Z) plane w.r.t. the center of the ellipse
- 35° from the vertical (Y-Z) plane w.r.t. the center of the ellipse
- 45° from the vertical (Y-Z) plane w.r.t. the center of the ellipse

By doing this, different supporting solutions for future ground testing were evaluated. Moreover, three different cases were considered to evaluate the mounting procedure of the mirror on the testing facility:

- no anti-tilt support, fixed support on the two node lines
- anti-tilt support + fixed support on the two node lines
- anti-tilt support + simple support on the two node lines

The first configuration represents the case in which the mirror is first set down on the supporting cylinders and then, after the mirror is completely at rest, the anti-tilt support is screwed just as a safety measure.

The second one is an intermediate one in which the slipping between the outer edge and the supporting cylinders is somehow negated (highly frictional contact) and the set down happens with the anti-tilt support already fixed.

Lastly, the third configuration represents the case in which the anti-tilt support is preventively set-up and then the mirror is set down on the cylinders. In this case the contact between the cylinders and the mirror is supposed to be frictionless.

The most relevant result is the Z deformation of the optical surface. Figs. 3 and 4 show such deformation in the four relevant support geometries in the case of simple support + anti-tilt.

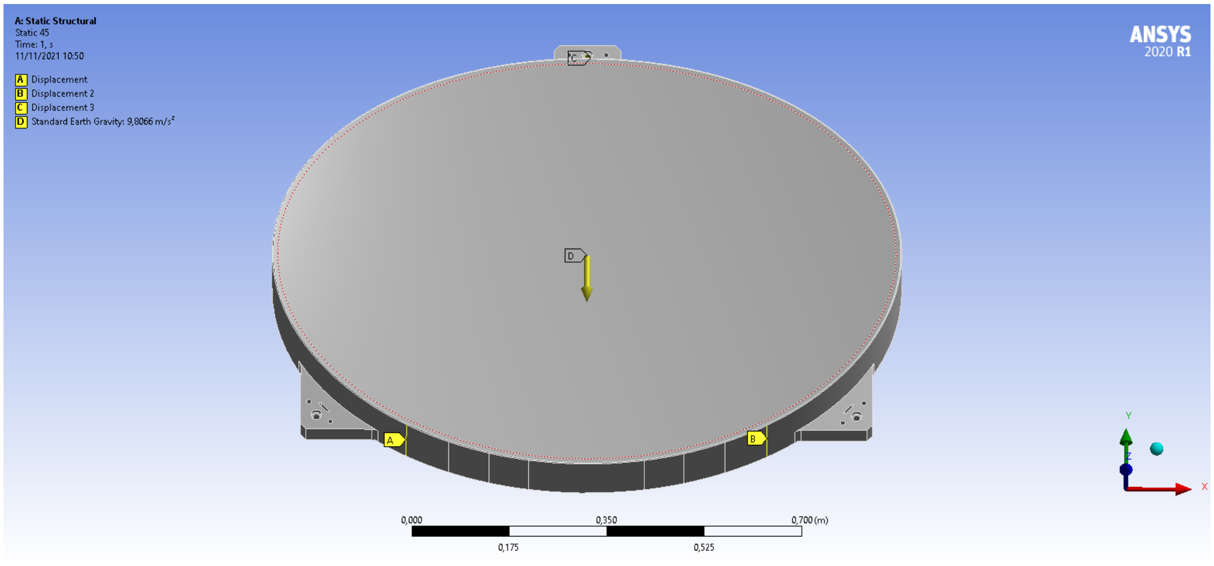

Figure 2. PTM analysis setup: line of contact of the supports (A, B); anti-tilt support (C); acceleration of gravity (D).

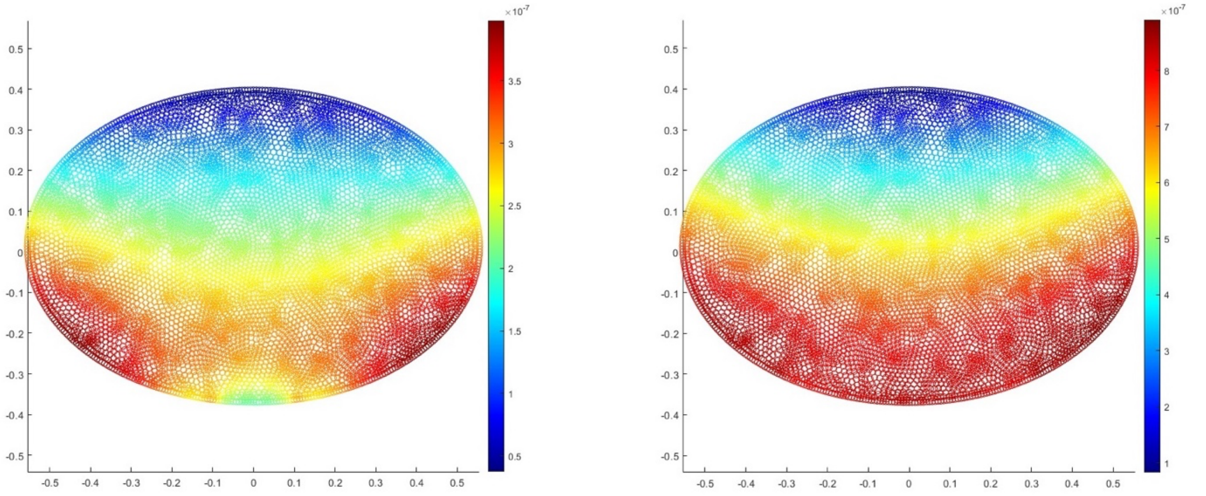

Figure 3. The directional deformations on the z direction for the cases with supports at 15° (left) and at 45° (right) are shown as an example of the results of the analysis. The units on both the axes are meters.

We note that not only the position of the supports is important, but also the sequence of operations used can strongly affect the results with deformation as large as microns.

Moreover, this analysis pointed that, using a simple support, the mirror slides on the supports. Since the visual inspection of the mirror after the test has shown evidence of friction between the mirror lateral surface (outer edge) and the two quartz cylinders, that were supposed frictionless, their contact can’t be precisely modelled with a simple support or a bonded connection. Moreover, the presence of mentioned sliding led to the need to setup further analyses to evaluate the response in large displacement conditions. The use of an explicit dynamic analysis was first considered to better model these displacements but was later discarded due to its extremely higher complexity (and thus extremely longer calculation times) in favour of negligible increase in accuracy. While the PTM was a prototype, designed to perform some preliminary optical tests, the same problems regarding its response under the effect of gravity also affect the actual mirror to be launched.

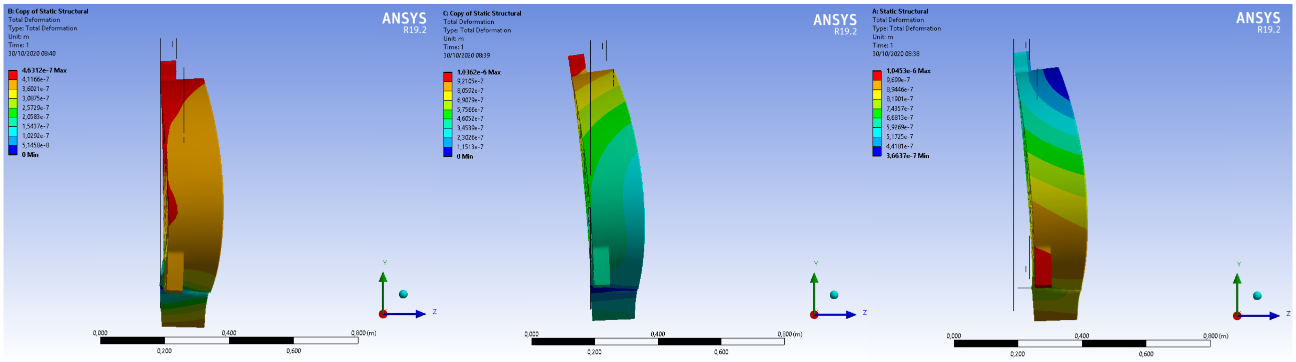

Figure 4. Side view of the total deformation of the PTM, 45° configuration. From left to right: fixed support on the lines of nodes at the bottom; fixed support on the line of nodes at the bottom + anti-tilt constraint; simple support on the line of nodes at the bottom + anti-tilt constraint.

It was then necessary to generate a CAD and FEM model of M1 to perform the same kind of analysis already carried out on the PTM and thus properly design the actual mirror to be launched. This is an analysis which aims set a guideline for the selection of a supporting mechanism during the testing phase of the mirror, so the results to be extracted aren't the precise values of the deformations, but the difference in behaviour in the various configurations. So, to reduce the complexity of the FEM model and thus the calculation time, a shell model was selected.

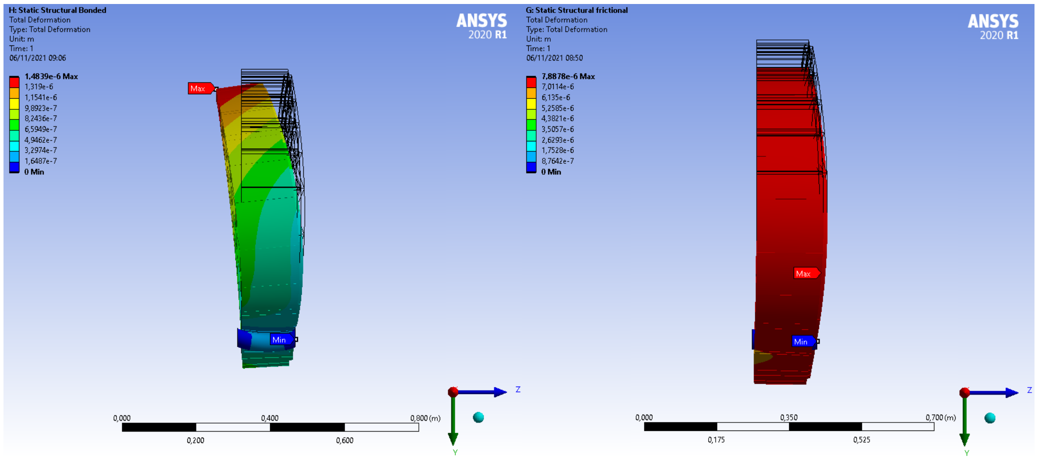

Figure 5. Side view of the total deformation of M1: bonded connection without anti-tilt (left); frictional connection + anti-tilt (right).

The results of these analyses show how the same tilting effect discovered in the PTM, also affects M1. The figures below show a side view of the 45° configuration of the mirror in the two cases of study: bonded contact without anti-tilt support, and frictional contact with anti-tilt support.

It is evident, when comparing the two pictures in Fig.5, the relevance of the mounting procedure on the resulting deformation of the mirror under the effect of gravity.

When looking at the optically relevant result – the Z deformation of the optical surface (Fig.6) – the most evident outcome is an unexpected asymmetry of the deformation. This is due to the mesh not perfectly symmetric. There is, in fact, also small (in the order of 10^{-8} m for the old version of the mirror) distance between the centre of gravity and the symmetry plane. This is an engineering negligible displacement, but we can see that in the case in which the cylinders are the closest (the 30° configurations), the resulting deformation in the frictional case has a not negligible asymmetry.

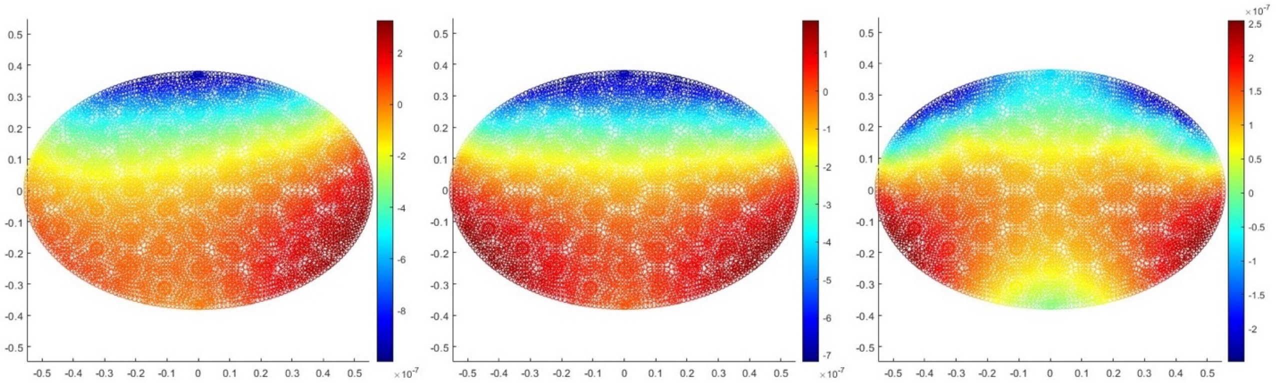

Figure 6. Left to right, the directional deformation in the Z direction (bonded boundary condition) in the 30°, 45°, 60° configurations.

This is of course a limit of the analysis, but also shows that the chosen configuration cannot properly manage slight model imperfections.

Although all the deformations contain a rigid tilt, they don't affect the quality of the reflecting surface. To have a better understanding of the aberrations at which the surface is subject, a MATLAB® script was generated to represent the deformation of the surface without the rigid rotation (subtraction of the deformation's best fit plane). Figs. 7 and 8 show how the map of deformations resulting from the script differs from the one coming out of the Ansys mechanical analysis. This manipulation was applied to the deformation of the optical surface in the Z direction for all six configurations.

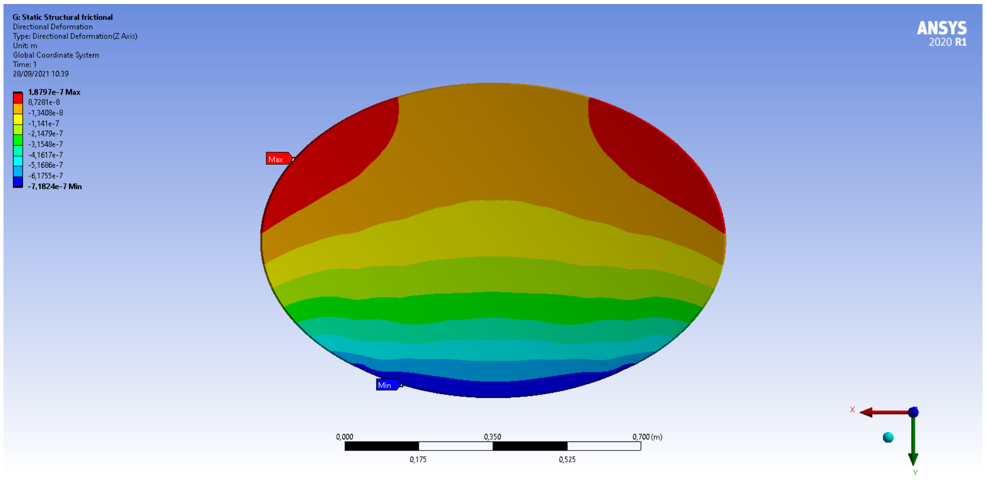

Figure 7. Directional deformation (Z direction) of the 45° configuration of the old version of M1, raw, directly from Ansys.

The analyses carried out and their manipulation by means of the MATLAB® script, allowed to obtain a set of guidelines for future testing campaigns.

- The effect of gravity causes a differential deformation of the two sides of the mirror, resulting in a rigid tilt of the optical surface; this fact doesn't affect the quality of the reflecting surface, so we must process the results obtained to disregard this effect.
- The position of the supporting cylinders, in addition to affecting the displacement distribution, also influences the capability of the system to tolerate imperfections of the mirror structure.

- It is necessary to better define — and document — not only the configuration of the supports, but also the sequence of procedures implemented to obtain the final configuration, as both heavily affect the results of the test

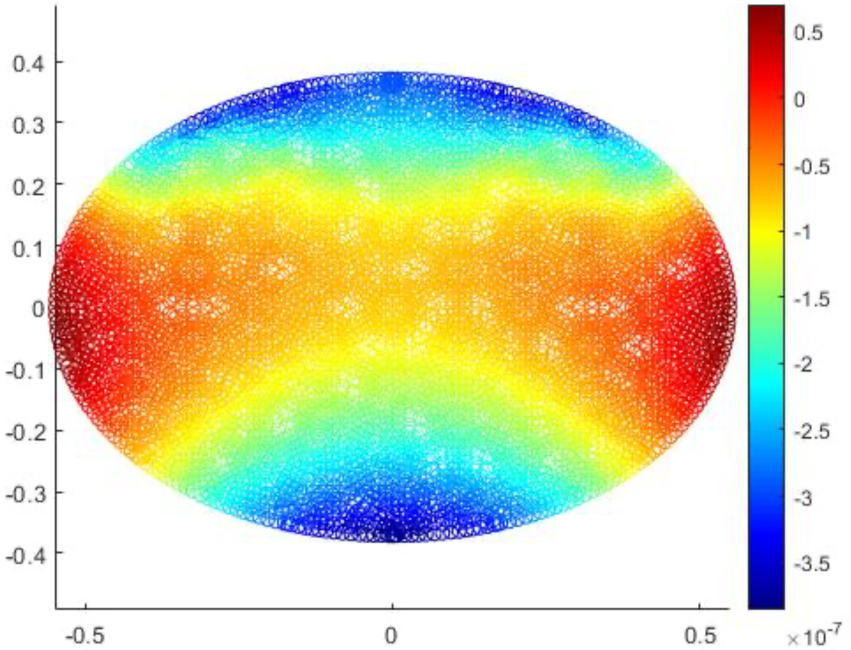

Figure 8. Directional deformation (z direction) of the same configuration after the subtraction of best-fit-plane.

4. CONCLUSIONS

The experimental data obtained by the optical tests underlined the ineffectiveness of the tests if not evaluated accordingly to expectations resulting from precise numerical simulations. To increase their reliability and efficiency — and thus reducing the cost, both in terms of time and money, of the future testing campaigns — it is necessary to increase the simulation activity on relevant models. In particular, the analyses carried out in the first part of this paper pointed out faults in the setup of previous testing operations:

- The effect of gravity on a complex structure like the PTM (or M1) was underestimated: the optical results obtained by the ground testing disregarded the tilting effect that resulted from the different stiffnesses of the two sides of the mirror, leading to a misunderstanding regarding the actual deformation of the optical surface.
- The lack of precise information regarding the actual supporting configuration, as well as the mounting procedure of the mirror on the mentioned supports, led to increasing difficulties regarding the interpretation and manipulation of its results. Moreover, this study pointed out how these mounting procedures heavily affect the response of the structure under the effect of gravity.
- Different configurations have to be analysed in advance, in order to reduce the number of tests required, resulting in extremely lower costs and shorter times of the qualification phase.

Since M1 is an innovative mirror with unique design, its qualification will require a stringent testing campaign. By means of this paper, the next testing phase (on the flight design of M1) will be better focused, saving several phases of troubleshooting.

Working on M1, an optimum configuration (cylinders at 45°, frictional contact + anti-tilt support) was found and will have to be better examined in future simulations and, possibly, testing also, some other crucial design aspects are to be carefully studied — for example, the connection system between M1 and optical bench.

All future studies regarding the ground testing of M1 will rely on the results exposed in this article as a point of reference for both the setup of the numerical simulations as well as the design of the mounting configurations for the tests.

ACKNOWLEDGMENTS

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