Aluminum based large telescopes: the ARIEL Mission case

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ABSTRACT

Ariel (Atmospheric Remote-Sensing Infrared Exoplanet Large Survey) is the adopted M4 mission of ESA "Cosmic Vision" program. Its purpose is to conduct a survey of the atmospheres of known exoplanets through transit spectroscopy. Launch is scheduled for 2029. Ariel scientific payload consists of an off-axis, unobscured Cassegrain telescope feeding a set of photometers and spectrometers in the waveband between 0.5 and 7.8 µm, and operating at cryogenic temperatures.

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The Ariel Telescope consists of a primary parabolic mirror with an elliptical aperture of 1.1 m of major axis, followed by a hyperbolic secondary, a parabolic recollimating tertiary and a flat folding mirror. The Primary mirror is a very innovative device made of lightened aluminum. Aluminum mirrors for cryogenic instruments and for space application are already in use, but never before now it has been attempted the creation of such a large mirror made entirely of aluminum: this means that the production process must be completely revised and fine-tuned, finding new solutions, studying the thermal processes and paying a great care to the quality check. By the way, the advantages are many: thermal stabilization is simpler than with mirrors made of other materials based on glass or composite materials, the cost of the material is negligeable, the shape may be free and the possibility of making all parts of the telescope, from optical surfaces to the structural parts, of the same material guarantees a perfect alignment at whichever temperature. The results and expectations for the flight model are discussed in this paper.

Keywords: ARIEL mission, IR Space telescopes, cryogenic optics, metal mirrors, NiP treatment

1. INTRODUCTION

The Telescope Assembly (TA) of the ARIEL space mission passed the Preliminary Design Review (PDR) in 2023. Due to the high degree of innovation and risk of the implementation (see [1] for details regarding the activities done before the PDR phase), the Design Authority remained with the team headed by INAF both for the structural model (SM) and for the engineering one (EM) which are under construction in the recent months. At the same time it continues the Research & Development activity on some critical parts of the telescope, mainly the Primary Mirror M1 with its mechanical support and the M2-M4 mirrors.

2. ARIEL TA DESCRIPTION

In this section they will be described the latest update at the design level of the ARIEL TA, focusing in particular on the advances regarding manufacturing, design and performances of the telescope and of the Aluminum mirrors.

Optical design and analysis

ARIEL is a Cassegrain telescope composed by a parabolic primary M1 and hyperbolic secondary M2, with a third mirror M3 used to recollimate the beam. A fourth mirror M4 directs the collimated beam onto the optical bench, where the instruments are installed. Figure 1 shows the telescope optical layout also including the first common optics mirror, M5. The aperture stop, located at the primary mirror, M1, defines the elliptical entrance pupil, of size 1104 mm x 732 mm. M1 is oriented at 12.165° with respect to the scientific target beam direction. The entrance baffle, a cut cylinder extending the length of the Telescope Metering Structure, limits M1's view of the sky. In combination with placing the stop at the first optical surface (M1), this provides the first line of defense to block out-of-field light. An additional baffle is positioned over the 'top' of M2 to block any direct view of the sky from M2 past the end of the entrance baffle. Both baffles are used to limit straylight but also for thermal stability. M2 has a refocus mechanism with three degrees of freedom (focus and tip/tilt) to correct for one-off movements due to launch loads and cool-down and potentially to make occasional adjustments (for example to compensate for any long term drifts in structural stability). The Cassegrain focus after M2 provides the possibility of inserting a field stop to aid stray-light rejection. After the Cassegrain focus, the beam is recollimated by M3.

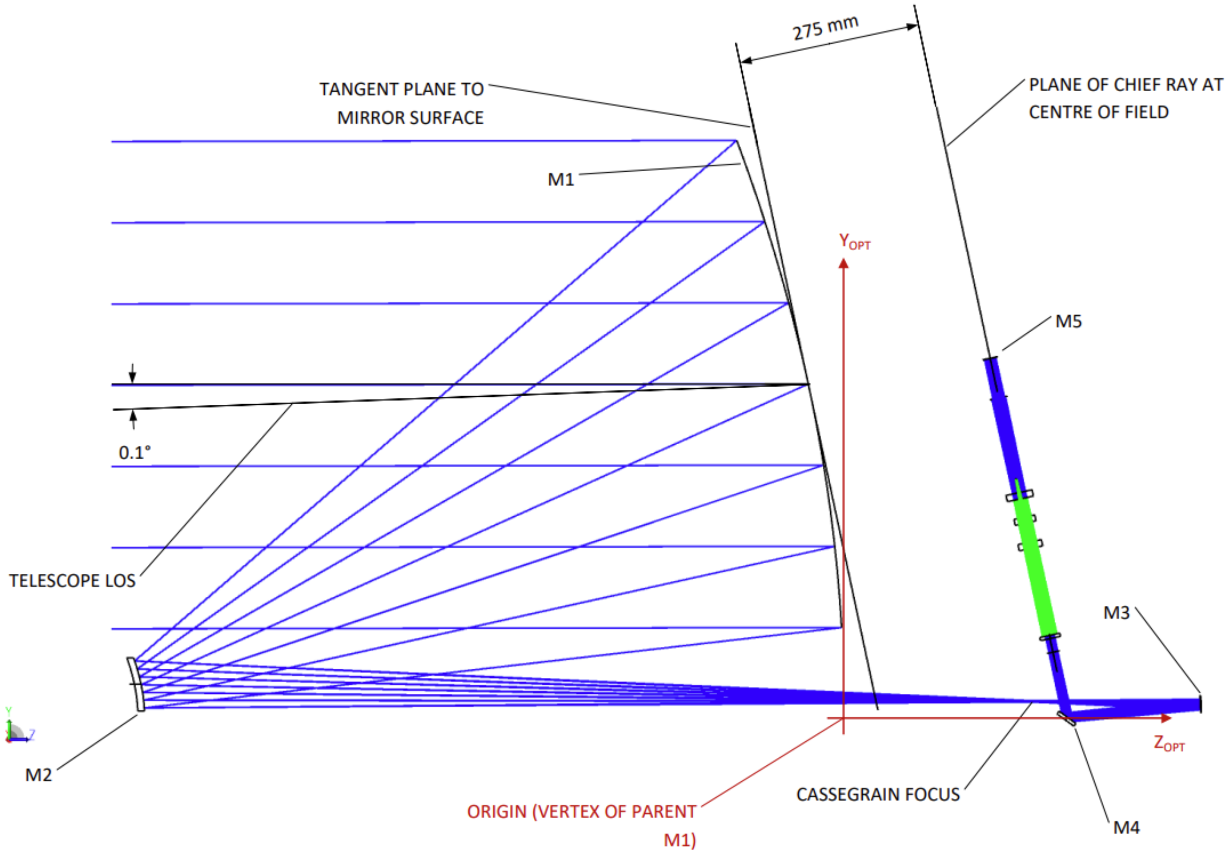


Figure 1 ARIEL Telescope optical layout.

The baseline design has M3 as an off-axis-paraboloid on the same symmetry axis as that of M1, M2. This results in a recollimated beam, i.e. M1, M2 and M3 form an afocal telescope, with the exit pupil size 20 mm x 13.3 mm. Then the beam is directed toward the fold mirror M4, used to direct the beam onto the optical bench. For the mirrors sizing, the telescope mirrors M2 to M4 are sized to meet a requirement for FOV of 50" diameter on sky without vignetting of the beam. The common optics, components M5 onwards, are sized to meet their FOV requirement of 30" diameter on sky. The telescope wavelength coverage spans from 0.5 µm to 7.8 µm, and it is required to be diffraction limited at 3 µm, which equates to an rms WFE of about 200 nm. Detailed description of the optical design of the telescope is outlined in **Errore. L'origine riferimento non è stata trovata.**.

Mechanical design

The ARIEL spacecraft assembly consists of two main modules: the Service Module (SVM) and the Payload Module (PLM), as shown in Figure 2.

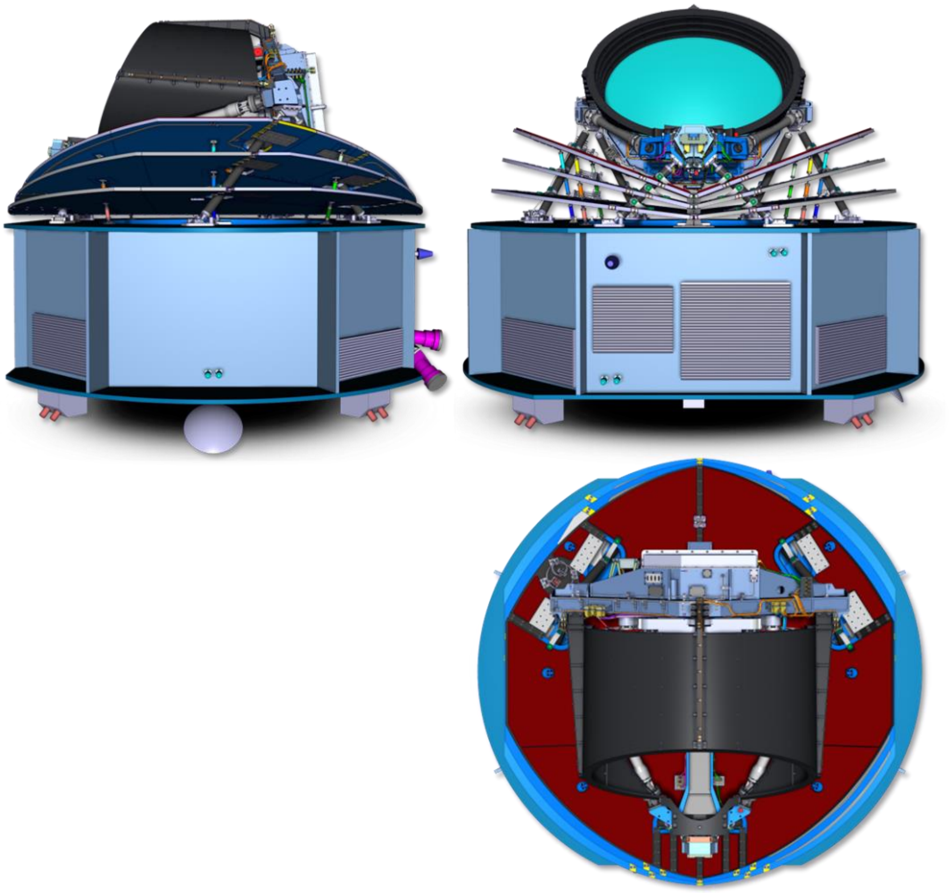


Figure 2. Diagram of 3 views of the ARIEL spacecraft, composed by the Payload Module and Service Module.

The SVM is provided by ESA, which is also responsible for the launch and operations, the latter being carried out in cooperation with the consortium involving more than 50 institutions from 16 countries.

The PLM is composed of different subsystems, the main one being the Telescope Assembly (TA), which provides support to the other subsystems.

The TA (see Figure 3) is an off-axis Cassegrain telescope, designed and manufactured entirely in monolithic EN AW 6061 aluminum alloy structure chosen for its excellent performance verified in previous missions.

The TA is composed of four mirrors (from now on, M1 to M4) fixed to the structure which is defined by the Telescope Optical Bench (TOB) and the Telescope Metering Structure (TMS) supported by two struts. In addition, to limit stray light on the main mirror (M1), the system is equipped with an entrance baffle (Baffle).

The TA includes a refocusing mechanism with three degrees of freedom to correct any deviations that may occur during launch and subsequent cooling.

The system is mounted on 3 pairs of bipods, two at the rear and one at the front, which connect it to the SVM.

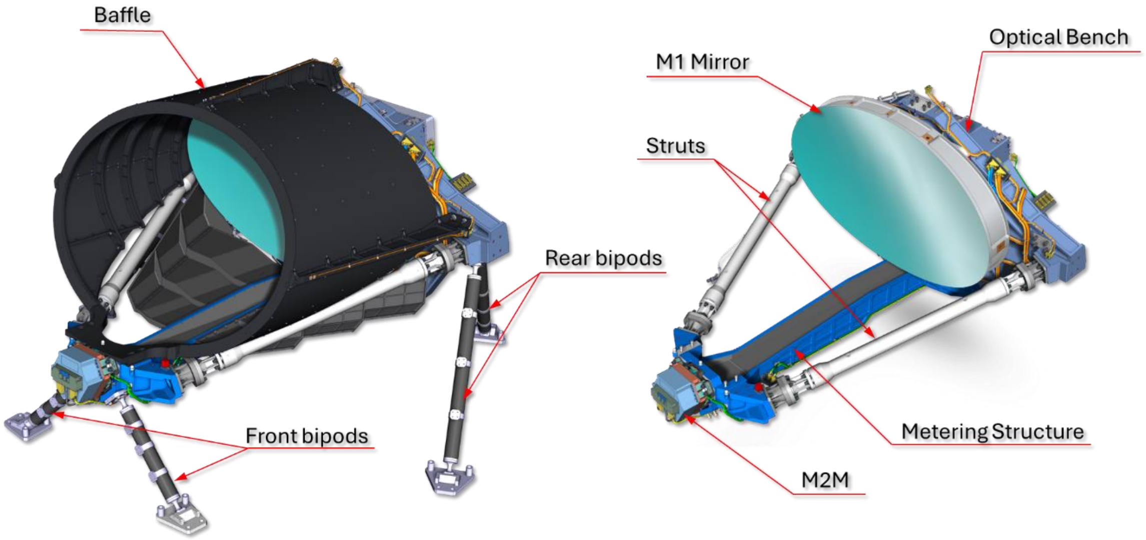


Figure 3. Telescope Assembly components.

Special care has been taken in the design of the main components of the TA, maintaining their structural characteristics, reducing the mass as much as possible, allowing maximum access for the integration of the different equipment and instruments.

The design of the TOB component has been particularly complex to allow the integration of an infrared spectrometer called AIRS (Ariel medium-resolution InfraRed Spectrometer), as well as the Fine Guidance System (FGS) module containing three channels of visible to infrared photometers and a low-resolution near-infrared spectrometer, plus the optics associated with these instruments, see Figure 3.

Thermal model and analysis

The ARIEL spacecraft is divided into two modules: the warm Service Module (SVM) and the cold Payload Module (PLM). The TA is located in the PLM. During operational observations, the entire TA reaches temperatures below 60 K due to the combination of passive elements. Firstly, the TA is mounted on bipods which conductively isolate the TA from the warm SVM (with a temperature between 253 K and 293 K). Secondly, a combination of three V-grooves dissipates heat to space, with the final V-groove, VG3, defining the coldest passive environment for the TA. Thirdly, the TA is conductively coupled to a black painted radiator. In addition, the TA, along with the black painted baffle and the TOB, act as radiating surfaces to enhance the TA's thermal performance.

The TA thermal model has been built in ESATAN-TMS as it is shown in Figure 4. It consists of 2599 thermal nodes, most of which are quadrilateral or rectangular aluminum shells.

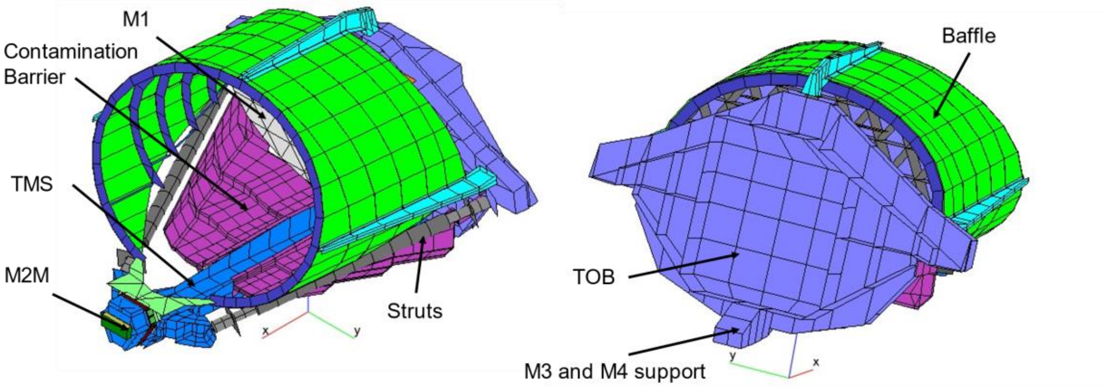


Figure 4: Geometrical Mathematical Model of the ARIEL TA.

To validate the TA thermal model, a standalone TA thermal case is run. It consists of the PLM hot nominal case conditions, defining the radiative and conductive I/Fs as boundary conditions in terms of temperature, and including the power dissipation in the instrument cavity, which represents the incoming instrument conductive heat flow.
An overview of the TA temperature obtained (in Kelvin) is shown in Figure 5 and Figure 6. It is of interest the good thermal uniformity, particularly in the M1 (a total variation less than 5 mK), due to the good thermal conductance between the M1 and the mounting interfaces (Flexure Hinges) to the TOB, and the M1 itself.

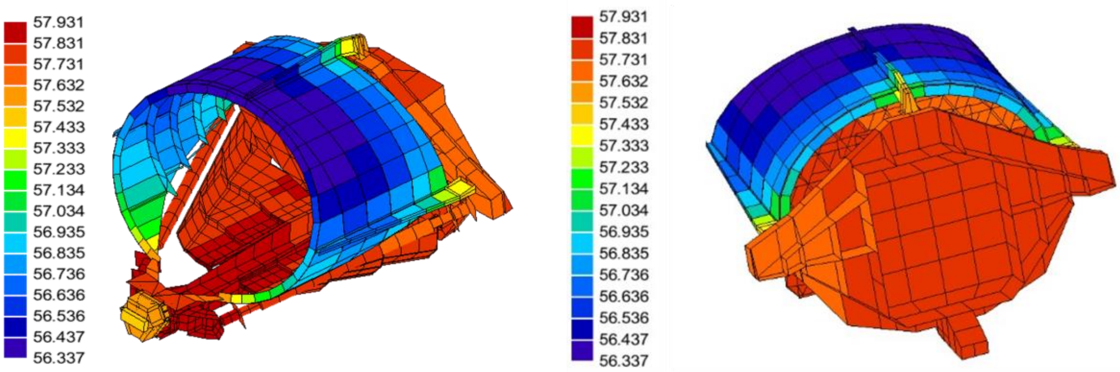


Figure 5: TA temperature distribution for the thermal analysis check.

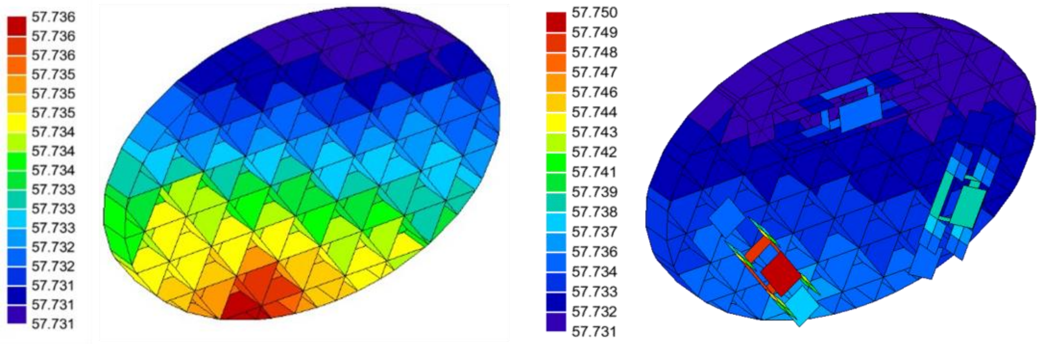


Figure 6: TA M1 temperature distribution (at left) and M1 and Flexure Hinges temperature distribution (at right) for the thermal analysis check.

Structural model and analysis

For the structural evaluation of the TA, a detailed finite element model (FEM) has been created (see Figure 7) in NASTRAN, including the bipods that support the TA structure and some other equipment such as the instrument radiator and the Common Optics attached to the Optical Bench. The main structural parts, as well as the main mirrors and their supports are modelled in detail with 3D elements. Thin parts such as the main baffle and the instrument radiator are modelled with 2D planar elements, while the bipods' tubes are represented by 1D beam elements. The representation of the bolted joints between the parts is made by combination of rigid elements (RBE2) and elastic 1D CBUSH elements.

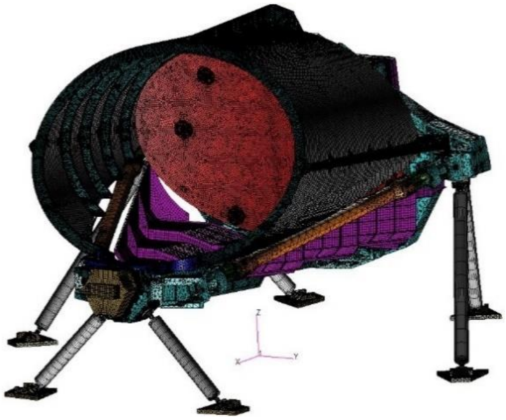
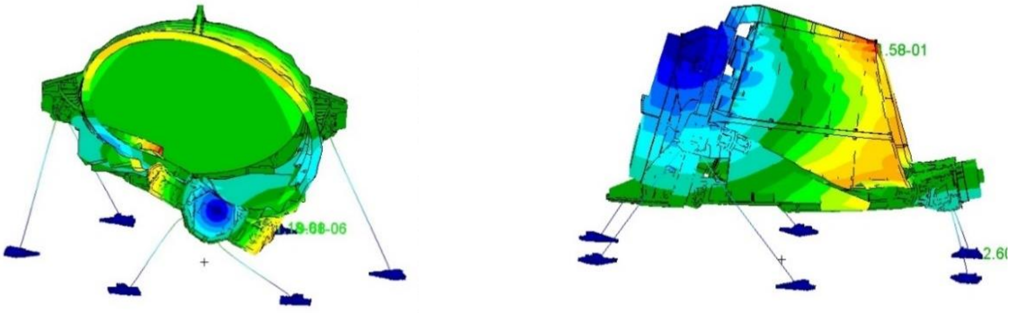


Figure 7: Finite Element Model of the ARIEL TA.

The FEM simulations include normal mode analysis to verify that the TA structure mounted on its bipods and with all the attached units meets the requirements concerning the minimum values for the first natural frequencies (25 Hz for lateral modes and 42 Hz for vertical modes). The first modes of the TA are shown in Figure 8, whose frequencies are higher than the required minimum limits.



a) Mode 1 (lateral): 35.8 Hz b) Mode 3 (vertical): 58.8 Hz

Figure 8: Normal modes of the TA on its bipods.

Other structural simulations performed with the detailed TA FEM include static analyses with gravity loads, sine vibration analyses and thermoelastic analyses. One of the most important thermoelastic cases corresponds to the transient cooldown, where the temperature distribution calculated by the thermal analysis is transferred to the FEM to later compute the generated stresses (see Figure 9) and I/F forces. In all these load cases, it is evaluated that the margins of safety regarding stresses, as well as all the relevant margins for bolt analysis are positive to demonstrate the structural feasibility of the proposed design for the TA. Additionally, the deformation generated on the main optical elements (mirrors) are used for the optical engineers to calculate the impact on the optical performance.

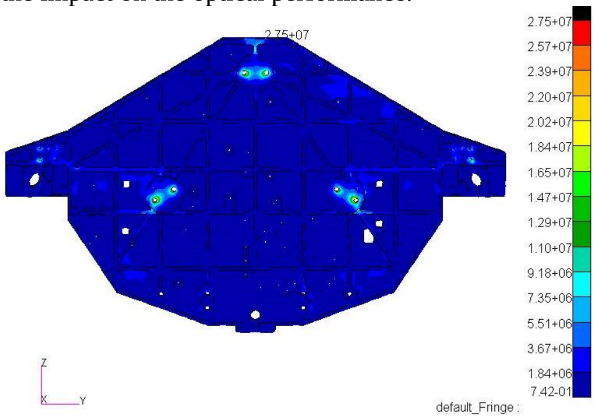


Figure 9: Stress distribution (in Pa) on the TOB for the thermoelastic transient.

3. ARIEL MIRRORS STATE OF THE ART

The ARIEL Telescope Assembly is composed of four mirrors that brings the star light to the entrance of the Telescope Optical Bench (TOB) and the instrument with a magnification factor of -55 (see Figure 1 for a schematic representation of the optical path).
In Table 1 are resumed the optical specifications and main characteristics of the ARIEL telescope mirrors. Please note that the real collecting area of M1 will be of 1104x732 mm, since, as described in § 2, the mirror is inclined by 12.165° with respect to the semi-major axis.

Table 1. ARIEL EM mirrors main specifications resume.

Mirror	**Mirror type**	**Clear aperture shape**	**Clear aperture dimensions at 293 K (mm)**	**Clear aperture dimensions at 50 K (mm)**	**SFE at room temperature (nm)**
M1	Concave parabolic mirror	Elliptical	1104.48 x 749.81[3]	1100 x 746.8	65[1]
M2	Convex hyperbolic mirror	Elliptical	110.44 x 80.32	110 x 80	40[2]
M3	Concave parabolic mirror	Elliptical	28.11 x 20.08	28 x 20	18[2]
M4	Plane mirror	Circular	24.1	24	12[2]

[1]: The indicated SFE is measured.

[2]: The indicated SFE is as per specification and not still measured, since the mirror manufacturing shall still to be completed.

[3] : The collecting area, seen by the scientific object, is 1100x730 @50K (1104.48x732.97 mm at room temperature)

due to the angle of 12.165° of M1 with respect to the scientific object.

The design of the M1-M4 mirrors has been optimized to meet the requirements defined at the subsystem level. These requirements include dynamic frequency requirements, necessary to ensure that the TA subsystems are dynamically decoupled, with the first natural frequency set at 130 Hz for M1 and the Flexures Hinges (FH), and at 140 Hz for M2, M3, and M4 (and their respective supports) [3]. Additionally, the design addresses deformation requirements under operating conditions to ensure good optical performance, targeting the SFE indicated in Table 1.
There are several factors that influence the deformation of the mirrors, including:

- mounting preloads associated to stud bolts or screws;
- in-flight alignment;
- manufacturing tolerances that do not allow perfect coupling between components;
- different behaviour of materials at cryogenic temperatures (50 K).

In general, when these contributions cannot be evaluated together, they are assessed separately and then combined in RSS.

M1 and Flexure Hinges

The ARIEL mission primary mirror (M1) is an off-axis, parabolic mirror of elliptical shape made of Aluminum Al6061-T651. After PDR, the manufacturing of the Structural Model (SM) and Engineering Model (EM) started and it’s currently completed. The SM model is of elliptical geometry, but of spherical shape; the scope of this model is to verify mechanical integration and assembly, no performance tests at telescope level are foreseen. In fact, from the optical point of view, it went only the diamond turning process and not the polishing nor the coating. The RMS SFE of the SM mirror is around 1.4 µm.

The design of the primary mirror M1 has been optimized in conjunction with the FHs. Regarding M1, new connection interfaces have been implemented, featuring a total of 36 M8 stud bolts, 6 for each pad. Some cuts in the ribs near the pads has been implemented to reduce stress distribution towards the reflective surface.

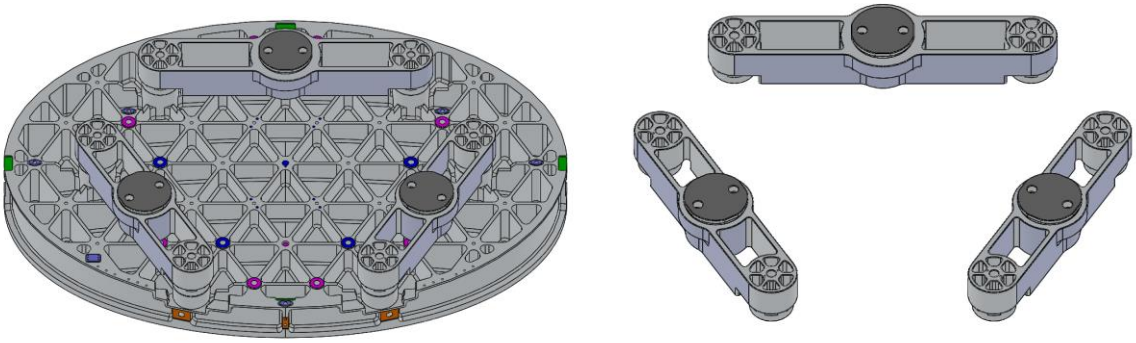


Figure 10. M1 mirror and FHs subsystem.

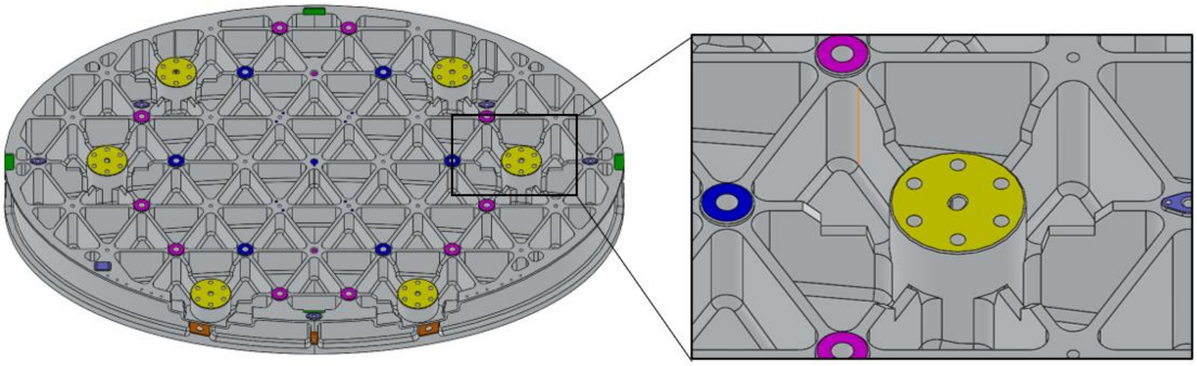


Figure 11. M1 mirror, focus on interfaces with FHs.

The design of the FHs consists in a dual-blade structure that provides radial flexibility in the back plane of M1. Hemispherical pads have been interposed between the flexure hinges and the Optical Bench to compensate, ideally through rigid rotation, for the effects of manufacturing tolerances (see Figure 12).

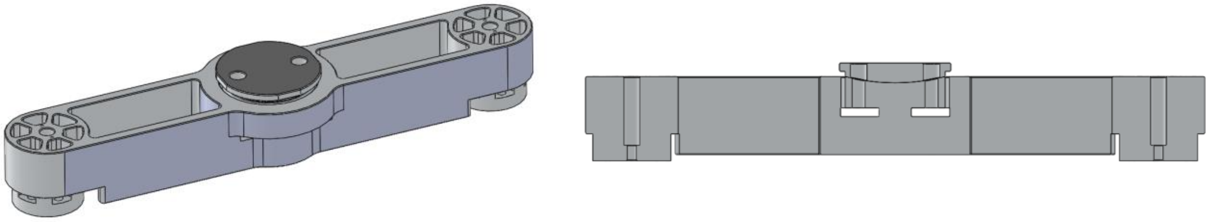


Figure 12. FH different sections.

The first natural frequency of the assembly of M1 and FHs amounts to 131 Hz.
Figure 13 and Figure 14 show the main results of tightening analysis, which are discussed in [5]. Preloads were estimated from Bolt analysis [6], which was previously performed at TA level.

Due to the linearity of the analysis, and thus its scalability, tightening between FHs and M1 was simulated using 1N of preload, resulting in a deformation of 1.866e-3 nm RMS. It is noteworthy that the deformation is distributed across the entire surface and without significant local effects or bumps (see Figure 13).

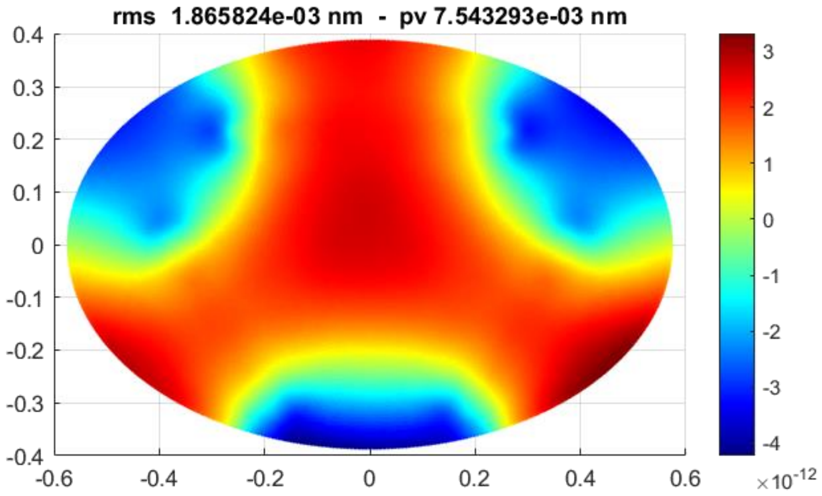


Figure 13. tightening M1-FHs (1N preload)

The above-mentioned bolt analysis set different requirements, in terms of preload, depending on the use of screws or stud bolts: 12052 and 9523 N respectively. The worst case, characterized by the use of screws, was considered in additional non-linear analyses taking into account of tolerance coupling in addition of the preload.
A flatness tolerance of the interface of 4 um and a preload of 12052 N have been considered, resulting in a deformation of 22 nm rms (see Figure 14).

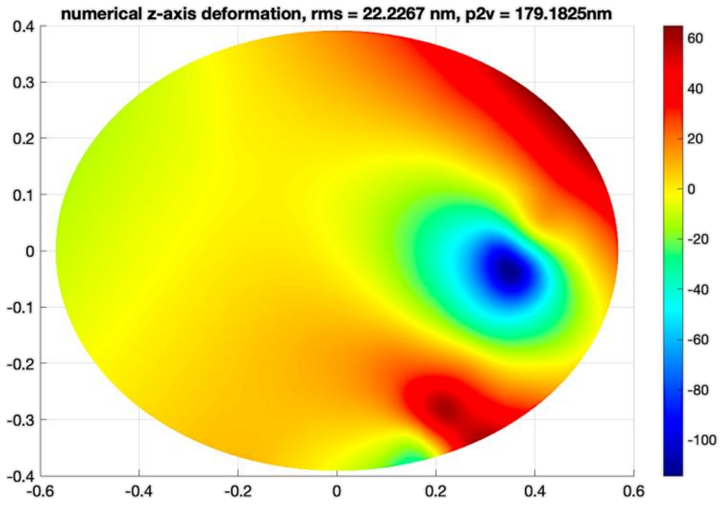


Figure 14. Tightening + tolerances at M1-FH interface (screws worst case)

Table 2 shows a comparison, in terms of RMS of the surface, between the use of screws and stud bolts in the analysed interface. This evaluation highlighted a slight improvement in the behaviour of the system when using stud bolts, further contributing to the selection of such fasteners for the interface.

Table 2. comparison between screws and stud bolts at M1-FH interface.

Interface	**Fasteners**	**Remaining Preload at 50 K**	**SFE RMS**
FH-M1	screws	12052 N	22.2 nm

	stud bolts	9523 N	20.6 nm

A similar analysis was carried out at the TOB-FHs interface resulting in negligible deformation (3.5 nm RMS with 26587 N of preload) (see Figure 15). Manufacturing tolerances were not considered in this simulation because their effect should be mitigated by the presence of the hemispherical pads.

Given the use of bronze helicoils, a simulations was carried out to consider the impact of different CTEs at cryogenic temperatures. Results show low deformation (12 nm rms), localized at the pads (see Figure 15).

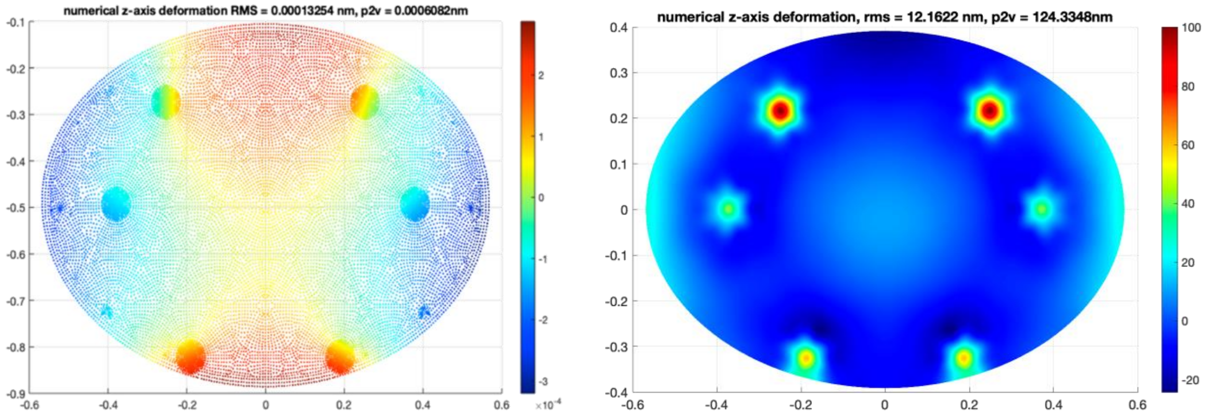


Figure 15 Figures showing tightening at TOB (left, 1 N of preload) and helicoil impact at 50 K (right).

A summary of the results, for the selected configuration, is reported in Table 3, including combined effect.

Table 3. *M1 FEA results*

Analysis	**Preload**	**SFE RMS**
tightening on TOB interface	26587 N	3.5nm
tightening on M1 interface + planar tolerance (on all the 3 FHs)	9523 N	35.7 nm
effect of helicoils	-	12.2 nm
Combined effects with helicoils contribution (RSS)	-	37.9 nm

Currently, dedicated interferometric tests, lead and conducted by INAF and UniFi personnel, are ongoing at the INAF Arcetri Astronomical Observatory to quantitatively measure the FH deformation effects on the M1 surface and to derive the deformations induced by gravity on M1. This is crucial to eventually guide future polishing activities. If, for instance, the FHs induce a relevant deformation on M1, then it shall be considered to polish M1 in compensation with the FH mounted on it. The details of these measures will be shown in a dedicated paper. The model under test is the SM.

M2, M3 and M4

In this section the state of production and definition of M2, M3 and M4 of the EM model is given. Like for M1, all of the mirrors are going through the approved manufacturing process, with the difference that M2, M3 and M4 have also a Nickel-Phosphorus layer on top of the aluminum. M2, M3 and M4 production is ongoing and it is near the end final polishing and coating will be finished in the next few months. Currently, all of the mirrors have been produced respecting the mechanical specifications, while for the optical we will wait for the interferometric tests, once their production process will be ended, see the subsequent paragraphs.

M2

M2 is a convex, hyperbolic, partially collimating mirror with an aperture of 110x80 (at 50 K) and a final required SFE of 40 nm.

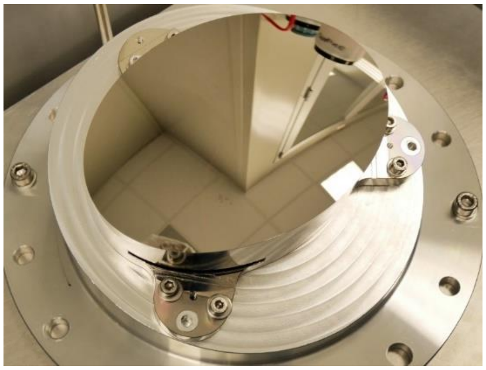


Figure 16. M2 EM ARIEL mirror after diamond turning.

With respect to mechanical deformations, the design of M2 has been optimized with the aim of reducing deformation under operational conditions, primarily due to bolt tightening and in-flight alignment provided by M2M. To mitigate the effect of tightening, slots have been implemented at the connection pads (first natural frequency of 1902 Hz).
The effect of tightening and deformation due to M2M movements (worst tilt case at 298 K was considered) are shown in Figure 17, resulting in 7.3 and 1.2 nm rms respectively (see Table 4) [8].

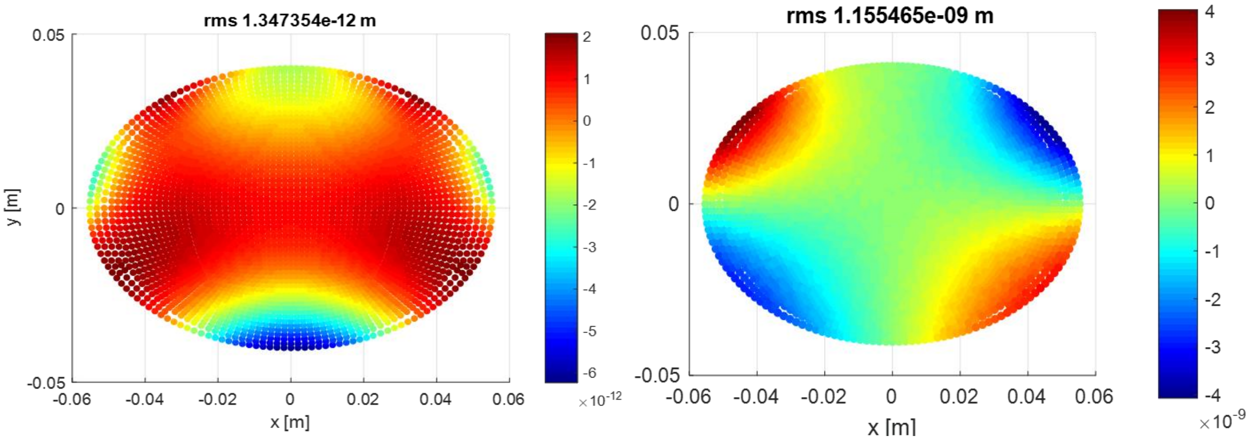


Figure 17. Deformations effects of tightening (left), effect of M2M movements (right).

Table 4. *M2 FEA results*.

Contribution	**load**	**SFE [nm RMS]**
tightening on M2M	5380 N	7.25
M2M movement (worst case)	-	1.16
Combined effect (RSS)	-	7.34

M3 and M4

M3 is a concave, elliptical focusing mirror with an aperture of 28 x 20 mm (at 50 K) that brings the telescope beam at the intermediate focus toward M4.

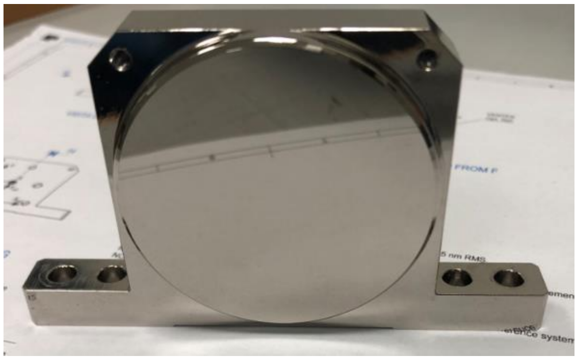


Figure 18. M3 EM after diamond turning .

M4 is a flat folding mirror with an aperture of 24 mm (at 50 K) placed after the intermediate focus of ARIEL that will send the collimated beam into the optical bench, in input to the various ARIEL instrumentations.

Figure 19 M4 EM ARIEL mirror after diamond turning.

The design of M3 and M4 has been developed together with their supports to allow specific degrees of freedom during ground alignment and to ensure reduced deformation under operating conditions. First natural frequencies for the two assemblies are 462 and 1330 Hz respectively.

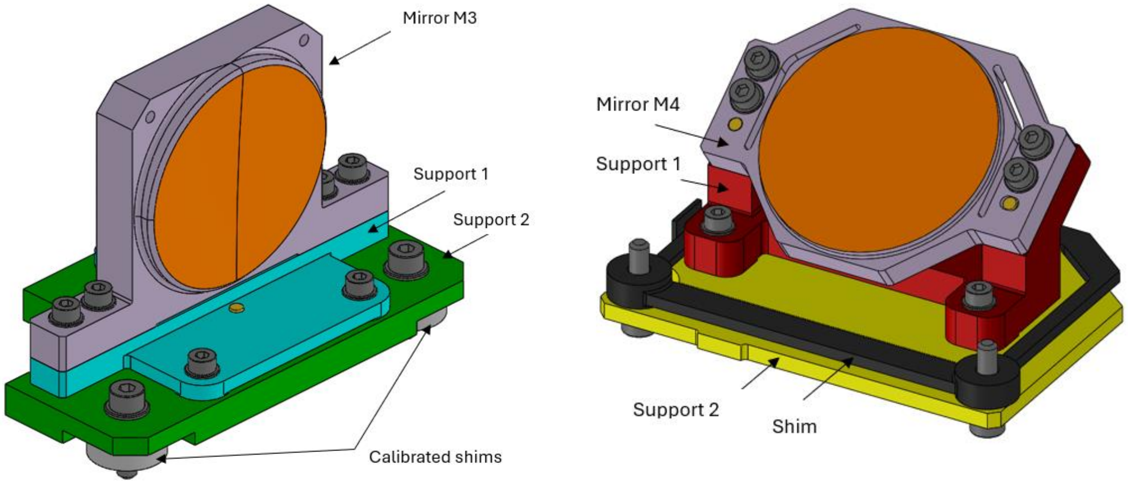


Figure 20. M3 and M4 CAD models.

Analyses focused on the effect of tightening, which has been evaluated between the mirrors and their supports (see Figure 20), as well as among all the supports used for alignment. Overall, the deformation amounts to approximately 0.5 nm for M3 and 1 nm for M4 (see Table 5) [9].

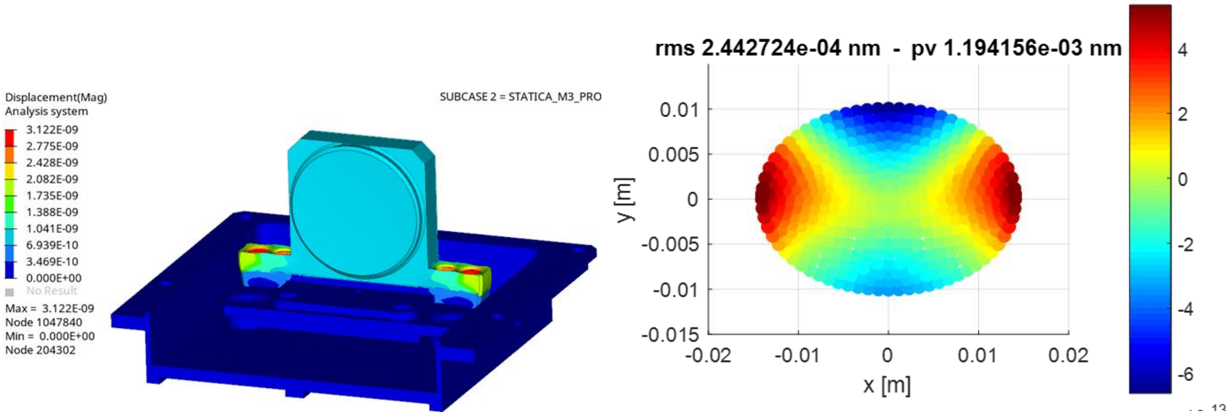


Figure 21. - tightening M3-support1 (1N preload).

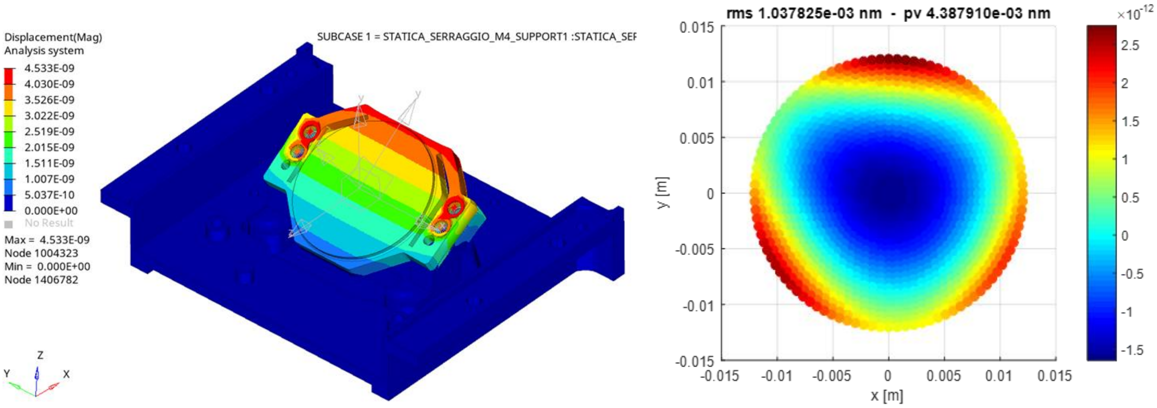


Figure 22. T*ightening M4-support1* effects *(1N preload)*.

Table 5. M3 and M4 FEA results.

Interface		SFE (nm RMS) - 1 N	Preload at 50K for screws (N)	SFE (nm RMS)
M3 assembly	M3-1st support	2,44E-4	1064	2,60E-01
	1st support-2nd support	3,82E-4	1034	3,95E-01
	2nd support-case	2,31E-5	1596	3,69E-02
	combined effect	-		0,47
M4 assembly	M4-1st support	1,03E-3	1064	1,10E+00
	1st support-2nd support	4,95E-5	1215	6,01-02
	2nd support-case	1,8E-5	1755	3,16E-02
	combined effect	-		1,10

4. NIP TREATMENT

To improve the quality of aluminum mirrors, a NiP treatment is applied. This material, whose thickness is usually of several microns, has different elastic properties than Aluminum. It is harder than Aluminium and can lead to better quality surface during polishing activities: it permits more control and precision in removing higher aberration orders, leading to improved encircled energy and less scattered light. In the ARIEL mission, this treatment was planned for each mirror; however, since the polishing on NiP is applied at ambient temperature and the telescope will work at cryogenic temperatures (50 K), it could, in principle, cause deformations on the surface of M1, introducing aberrations that could be a limitation for the optical performances of the telescope. The reason of this is that NiP and Aluminum have different Coefficients of Thermal Expansion (CTE) and Young Moduli (YM), see [7] for data on NiP. This effect is usually negligible on small size, not-lightened mirrors. However, for the primary mirror of ARIEL this could lead to unwanted deformations (see cryogenic tests showing this in [7]). Recalling that M1 is lightened is worse with respect to a monolithic one.

FEA simulations on M1

To quantitatively evaluate the role of NiP on the optical quality budget, FEA simulations have been performed on M1. In particular, the overall deformation has been derived and characterized in function of different parameters of the deposition, such as: NiP thickness, NiP Young modulus and NiP CTE, since no unique values are present.

Initially, in the simulations the treatment was deposited on all the M1 external surfaces, to ease the treatment process. However, it became apparent that to reduce the deformations, the NiP shall be limited to the optical surface only (see Figure 23). However, the deformations effects are still relevant. The main agent that induce unwanted deformations is the thickness of the treatment: more NiP is deposited and more deformation is expected. A sensitivity analysis has been performed and a linear trend it has been found. Ideally, less NiP as possible, to let the polishing working, shall be applied: it can be seen that with a 2 µm thickness NiP a total deformation of 408 nm is found, reduced to just 36 nm RMS once the first four Zernike terms (i.e., Piston, Tip, Tilt and Power) are removed (calculated with a set of 15 Zernike polynomials, see Figure 24).

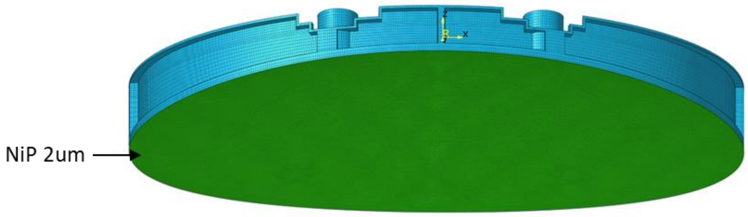


Figure 23. Surface with NiP coating.

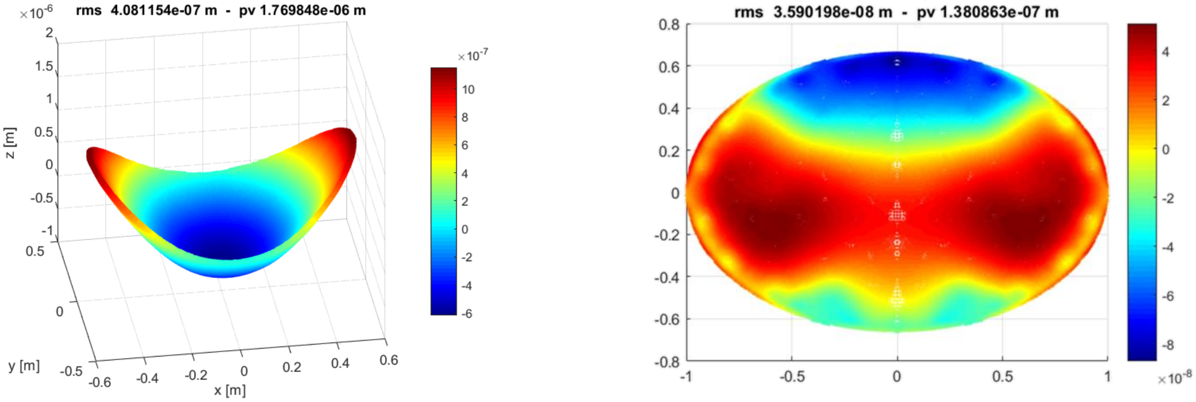


Figure 24. *Total deformation due to NiP treatment (right image), deformation due to NiP treatment without the first 4 Zernike terms (Piston, Tip, Tilt and Power, right image).*

However, the NiP coating is still under investigation, as there are numerous uncertainties regarding its mechanical characteristics, which vary significantly depending on Phosphorus content and temperature (simulations were carried out with data from [7]). In addition, it is necessary to establish the feasibility of depositing a very thin layer with uniform thickness to be subsequently machined while preserving the integrity and properties of the layer. The situation is under study and a probable substitute of NiP will be an additional polishing run using a new, proprietary technique that is focused on the removal of the medium and high frequencies, without affecting the surface form of the surface (low aberrations). This step is under evaluation by the Telescope Assembly team and by the provider of the polishing technique. These are R&D activities that have been never performed on parabolic aluminum mirrors of this size, so various tests are needed to first assess and then validate the process.

5. M1 EM MANUFACTURING

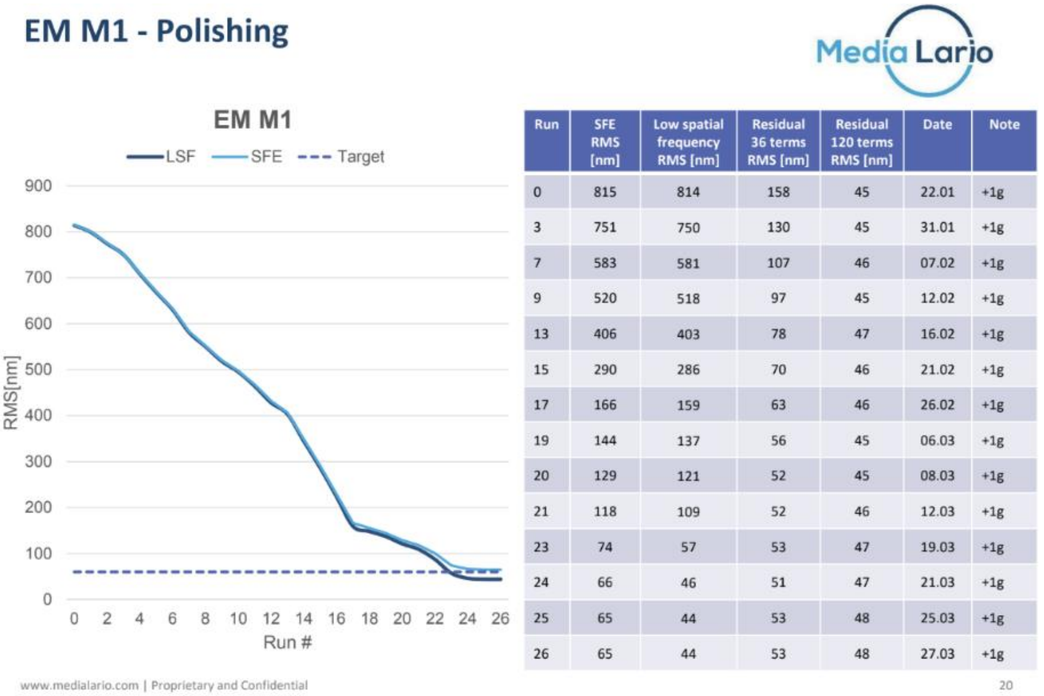
The R&D activities performed on the two breadboards of M1 have been important to set the road (and reduce the risk) to the achievements on the high manufacturing level needed for the M1 flight model. (regarding the BB activities, see [1] for details) The EM shall be fully representative of the Flight Model (FM) in terms of optical performances and interfaces. To arrive at the given results for the EM, the Structural Model (SM) it has been an important intermediate step: it is the first mirror of the same size as the FM but with spherical shape, not parabolic. This was needed to speed up the process and reduce the costs, since the SM purposes regard mechanical needs, such as the first integration on the telescope and vibrations at system level. In fact, this model didn’t go through the polishing phase, since it was not considered as necessary. It was also important to validate the diamond turning custom setup done by the company LT Ultra on a mirror as big as the FM model. At the moment, the process of diamond turning refinement is ongoing within the TA team to improve some manufacturing aspects and reduce the RMS value on the overall surface: this will benefit the subsequent polishing process, leading to better results in the final M1 shape.
Thanks to the objectives reached on the SM, the next step was to produce a mirror of the same size as the SM but parabolic: this intermediate process permitted to mitigate the risk on EM manufacturing.

Polishing

The EM is the first model (among those M1s already produced) that went through the complete manufacturing process, in particular:

1. Row machining
2. Diamond turning
3. Polishing
4. Coating deposition

The polishing activities were critical since it was needed a total SFE ≤ 65 nm RMS on the entire surface. The details regarding the polishing run evolution are shown in Figure 25.



EM M1 - Polishing

Media Lario

Run	SFE RMS [nm]	Low spatial frequency RMS [nm]	Residual 36 terms RMS [nm]	Residual 120 terms RMS [nm]	Date	Note
0	815	814	158	45	22.01	+1g
3	751	750	130	45	31.01	+1g
7	583	581	107	46	07.02	+1g
9	520	518	97	45	12.02	+1g
13	406	403	78	47	16.02	+1g
15	290	286	70	46	21.02	+1g
17	166	159	63	46	26.02	+1g
19	144	137	56	45	06.03	+1g
20	129	121	52	45	08.03	+1g
21	118	109	52	46	12.03	+1g
23	74	57	53	47	19.03	+1g
24	66	46	51	47	21.03	+1g
25	65	44	53	48	25.03	+1g
26	65	44	53	48	27.03	+1g

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20

Figure 25. M1 EM polishing run evolution as implemented by Media Lario. Final SFE of 65 nm is reached at the 26th run.

The specification was reached by Media Lario at the 26th run, demonstrating that the low orders aberrations can be efficiently removed. Looking at the third column, in fact, it can be seen how most of the residual, after removal of the first 36 Zernike, is due to the so-called "low- and high-mid spatial frequencies", specifically of 53 nm RMS. That frequency range spans roughly, in M1 geometrical space, between D/4 to 2 mm, where D is the M1 major axis and the lower limit is imposed by the resolution of the interferometer. The residual after 120 Zernike (involving higher order aberrations), indicates that the RMS is reduced by a 10% factor (48 nm RMS).

Preliminary measures on White Light Interferometer (test report still ongoing) show that the high-frequency end is in specification: 10 nm RMS.

This aberrations contribution weighted toward the mid spatial frequencies induce more scattered light than expected, spreading out the PSF and so reducing the Encircled Energy at the focus of ARIEL, reducing then the throughput, especially toward the visible range, where the FGS instrument is working. As indicated in § 4, polishing with the NiP treatment can efficiently remove the mid-spatial frequencies, drastically improving the telescope performances. However, it is problematic at cryogenic temperatures. To overcome this issue, an additional polishing activity (in substitution of the NiP deposition), that could remove the medium frequencies without affecting the lower ones, is under evaluation by the TA team.

Coating

After the polishing phase, the M1 EM went through the coating campaign. The deposition has been done at CILAS. The coating was deposited with success and the coating curve was withing the specification (see Figure 26).

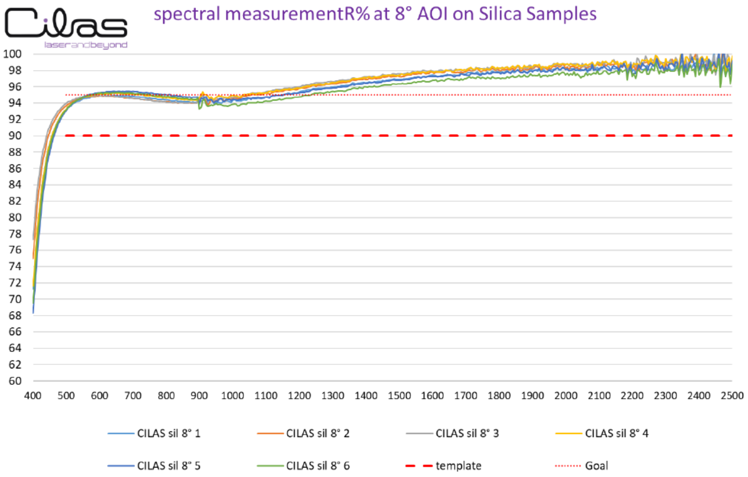

Figure 26. ARIEL reflectivity measure on the witness samples coated with the M1 EM treatment. The goal level is reached in the entire wavelength range expect that near the 500 nm region.

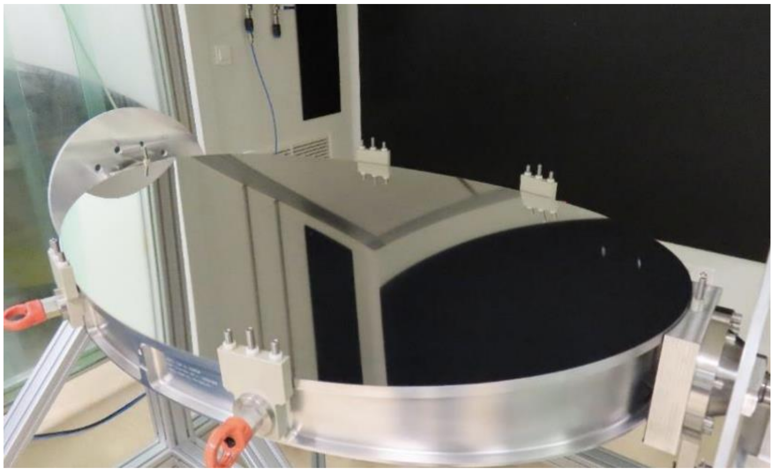

Figure 27. ARIEL M1 EM after the coating.

The EM model is now back in Media Lario and will be integrated on the TA EM model for the optical tests at system level. This will be a very important step since tests at ambient and cryogenic temperatures will be performed on the entire system, permitting an evaluation of the ARIEL telescope aberrations.

6. CONCLUSION

ARIEL's primary mirror is clearly one of the most complex components of the entire payload, both for its size and for the requirements of optical quality and mechanical stability. The use of aluminum to create such a structure offers great opportunities in terms of manufacturing, cost and time, but the production and qualification process of such a mirror requires a continuous research and development activity, since it is the first time that such a component of this size it has been used in a space mission at cryogenic temperatures.

From the PDR, progress have been made in defining the mechanical support toward the TOB (Flexure Hinges) and in reaching the desired level of manufacturing capabilities of M1. In fact, the EM mirrors have been successfully manufactured, polished and coated. The polishing campaign, carried out by Media Lario S.r.l., demonstrated to reach the required budget in terms of WFE for M1. This was not given as granted given the large aperture and topological characteristics of M1. No such activities were done on a lightened aluminum mirror of this size. The coating campaign has been carried out and the results are in agreement with the requirements.

Analyses and tests are currently in progress at INAF Arcetri Astronomical Observatory to measure deformations effects on the M1 optical surface induced by FHs and gravity. The results will be fundamental to guide and eventually refine the polishing process, to improve M1 quality and reduce the aberrations.

The NiP treatment for the flight model is still under consideration and requires analysis and study within the team. In particular, it is needed if the manufacturing process can be tuned to reduce the NiP thickness to reduce the deformations at cryogenic temperatures. In parallel, the TA team is considering additional polishing activities to remove the medium-low and medium-high frequencies by the Welsh OpTIC company. The feasibility of this process is under evaluation.

This activity has been going on for many months and involves many European research institutes and companies that are working together to overcome these difficulties. The modeling, testing and design processes are innovative for these mirrors and require a continuous R&D activity between each partner of the TA team. The consortium is in the process to build the first telescope model to validate the performances and each partner is continuously working to let the results as better as possible, and to be in line with the defined specifications.

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