International Conference on Space Optics—ICSO 2018

Chania, Greece

9–12 October 2018

Edited by Zoran Sodnik, Nikos Karafolas, and Bruno Cugny

Study and realization of a prototype of the primary off-axis 1-m diameter aluminium mirror for the ESA ARIEL mission

Vania Da Deppo

Emanuele Pace

Gianluca Morgante

Mauro Focardi

et al.

International Conference on Space Optics — ICSO 2018, edited by Zoran Sodnik,
Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 11180, 111806V · © 2018 ESA
and CNES · CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2536166

Study and realization of a prototype of the primary off-axis 1-m diameter aluminium mirror for the ESA ARIEL mission

Vania Da Deppo*[a,b], Emanuele Pace[c], Gianluca Morgante[d], Mauro Focardi[e], Marco Terraneo[f], Fabio Zocchi[f], Giovanni Bianucci[f], Giuseppina Micela[g] and the ARIEL Team

[a]CNR-Istituto di Fotonica e Nanotecnologie, Padova, Via Trasea 7, 35131 Padova, Italy
[b]INAF-Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, 35122 Padova, Italy
[c]Dip. di Fisica ed Astronomia-Università degli Studi di Firenze, Largo E. Fermi 2, 50125 Firenze, Italy
[d]INAF-Osservatorio di Astrofisica e Scienza dello spazio di Bologna, Via Piero Gobetti 93/3, 40129 Bologna, Italy
[e]INAF-Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, 50125 Firenze, Italy
[f]Media Lario S.r.l., Località Pascolo, 23842 Bosisio Parini (Lecco), Italy
[g]INAF-Osservatorio Astronomico di Palermo, Piazza del Parlamento 1, 90134 Palermo, Italy

ABSTRACT

ARIEL (Atmospheric Remote-sensing Infrared Exoplanet Large-survey) has been selected by ESA as the next medium-class science mission (M4) to be launched in 2028. The aim of the ARIEL mission is to study the atmospheres of a selected sample of exoplanets.

The payload is based on a 1-m class telescope ahead of a suite of instruments: two spectrometric channels covering the band 1.95 to 7.80 µm and four photometric channels working in the range 0.5 to 1.9 µm.

The production of the primary mirror (M1) is one of the main technical challenges of the mission. A trade-off on the material to be used for manufacturing the 1-m diameter M1 was carried out, and aluminium alloys have been selected as the baseline materials both for the telescope mirrors and structure. Aluminium alloys have demonstrated excellent performances both for IR small size mirrors and structural components, but the manufacturing and thermo-mechanical stability of large metallic optics still have to be demonstrated especially at cryogenic temperatures.

The ARIEL telescope will be realized on-ground (1 g and room temperature), but it shall operate in space at about 50 K. For this reason a detailed tolerance analysis was performed to assess the telescope expected performance.

M1 is an off-axis section of a paraboloidal mirror and will be machined from a single blank as a stand-alone part. To prove the feasibility of such a large aluminium mirror, a pathfinder mirror program has been started. The prototype has been realized and tested, so far at room temperature, by Media Lario S.r.l.. Cryogenic testing of the prototype will be performed during Phase B1.

Keywords: 1-m class space mirror, infrared optics, off-axis surface, tolerance analysis, free-form manufacturing

1. INTRODUCTION

In the framework of the M4 call in the ESA Cosmic Vision program, the ARIEL mission has been selected with a launch foreseen in 2028 [1]. ARIEL is conceived to study the atmospheres of exoplanets orbiting close to nearby stars. The aim is to measure the atmospheric composition and structure of hundreds of exoplanet atmospheres, using spectroscopy in the infrared wavelengths. This will allow the exploration and sounding of the nature of the exoplanets' atmospheres, to collect information about the planets' interiors and to study the key factors affecting the formation and evolution of planetary systems.

*vania.dadeppo@ifn.cnr.it; phone +39-049 9815639

ARIEL is designed as a survey mission for transit and eclipse spectroscopy. During its 3.5-year scientific mission lifetime in L2 orbit, it will provide spectroscopic information on the atmospheres of a large and well-defined sample of exoplanets (about 1000 in the present scientific scenario) allowing the compositions, temperature (profile), size and variability to be determined at a level never previously attempted [2]. It will measure the reflected/emitted/transmitted spectra of these exoplanetary atmospheres over the visible to the thermal IR wavelength range. Planets under study will extend from gas giants, i.e. Jupiter-like planets, to Neptune-like and super-Earths [3].

ARIEL features an afocal telescope unit providing a collimated beam for two separate modules. A combined Fine Guidance System(FGS)/VIS-Photometer/NIR-Spectrometer that contains three photometric channels in the wavelength range between 0.50 µm and 1.2 µm to monitor the photometric stability of the target stars. Two of these channels will also be used as a prime/redundant system for providing guidance and closed-loop control to the high stability pointing Attitude and Orbit Control System (AOCS) of the S/C. Integrated in this same module is a further low-resolution (R=~10) NIR spectrometer channel in the 1.2–1.95 µm waveband. This first combined module is often simply referred to as the FGS. The second module, acting as the main instrument, is the ARIEL IR Spectrometer (AIRS), providing variable resolving power in the range 30–180 for a waveband between 1.95 µm and 7.8 µm [4].

The payload is passively cooled to ~50 K by isolation from the S/C bus via a series of V-Groove radiators [5]. The AIRS detectors are the only items that require active cooling to <42 K via an active Ne-based JT cooler [6].

In the assessment phase of the mission a detailed material trade-off analysis has been conducted [7]; as a result, the material chosen for the realization of the entire telescope, i.e. mirrors and structure, is aluminum.

To prove the capability to manufacture and handle a large 1-m diameter primary mirror in aluminum, a dedicated pathfinder mirror telescope program has been undertaken to study, realize and test an ARIEL primary mirror prototype.

In this paper, the ARIEL telescope characteristic will be summarized; then the material trade-off analysis will be presented. Finally, the M1 prototype characteristics and the obtained performance results will be described.

2. TELESCOPE CHARACTERISTICS

2.1 Telescope design requirements

The optical requirements the telescope design has to satisfy are reported in Table 1.

Table 1. Summary of the telescope optical requirements.

Parameter	Value
Collecting area	> 0.6 m^2
WFE	Diffraction limited @ 3 µm
Wavelength range	0.55–8 µm
Wavelength range	0.55–8 µm
FoV	30" with diffraction limited performance 41" with optical quality TBD allowing FGS centroiding 50" unvignetted
Output beam dimension	20 mm x 13.3 mm

The collecting area is related with the minimum intensity (magnitude) of the observable targets. A collecting area of at least 0.6 m^2 is required, which implies an entrance pupil of the order of 1 m in diameter.

The required final as-built quality of the telescope, i.e. diffraction limited at 3 µm over a FoV of 30", is equivalent to ask for an RMS wavefront error (WFE) of 220 nm.

To guarantee the required throughput without increasing the size of the primary mirror, that is the entrance pupil of the telescope, the optical design has to be unobscured. The unobstructed solution also assures the energy in the PSF is primarily contained inside the first Airy disk and not spread towards the secondary rings.

The characteristics of the instruments following the telescope, i.e. the FGS and the AIRS [8], have determined the wavelength coverage (0.55-8 μm) and the global FoV of the telescope. A diffraction limited FoV is needed for the target observations, a slightly larger FoV with suitable optical performance is required to allow the FGS to acquire the star and thus guiding the instrument, and a slightly larger unvignetted FoV is needed for background subtraction.

2.2 Telescope design characteristics

The baseline telescope design is an afocal unobscured eccentric pupil Cassegrain telescope (M1 and M2) with a recollimating off-axis parabolic tertiary mirror (M3). All the mirrors share the same optical axis. An M4 plane mirror is redirecting the exiting beam parallel to the back of M1 where the optical bench is located and the instrument will be mounted (see Figure 1) [8].

The center of the FoV of the telescope is inclined of 0.1° (in the YZ plane) with respect to the optical axis of the telescope defined by the mirrors common optical axis.

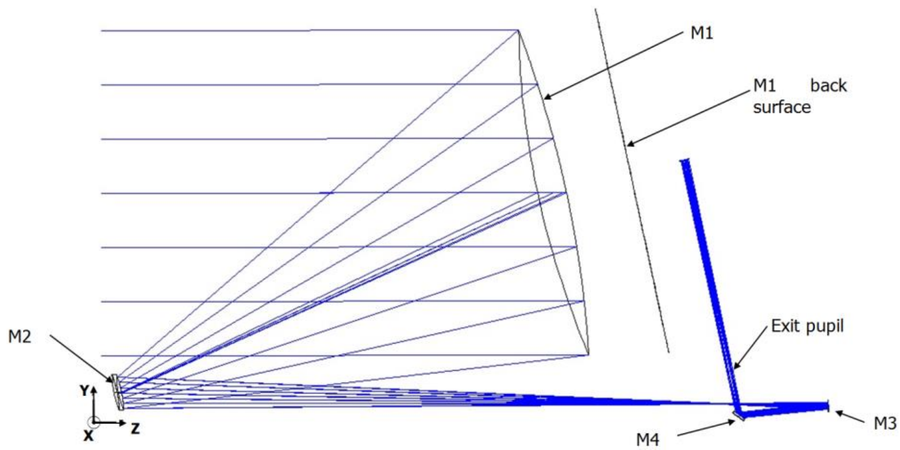


Figure 1. Scale drawing of the telescope – view in Y-Z plane.

Table 2. (a) Summary of the telescope optical design characteristics. (b) Mirrors parameters description.

(a)

Parameter	Values
Optical concept	Afocal design. Eccentric pupil Cassegrain telescope plus off-axis paraboloidal mirror and folding.
Focal length	14.17 m
FoV centre	0.1° - Off-axis YZ plane
Pupil size	Ellipse with major axis 1.1 m x 0.73 m
Focal ratio @ intermediate telescope focus	13 (x)/19.4 (y)
Angular magnification	-55

(b)

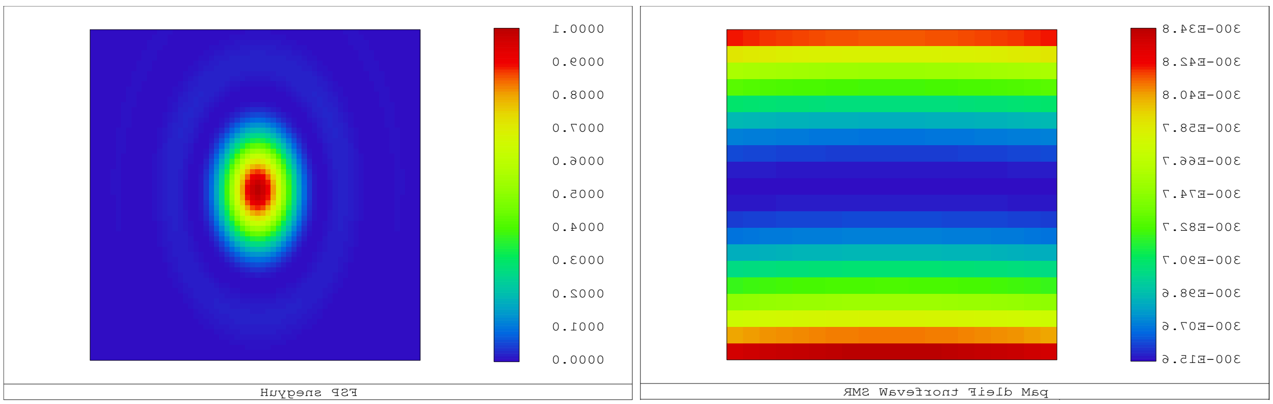
Optical element	M1	M2	M3
R (mm)	-2319.5	-239.0	-491.5
K	-1	-1.4	-1
Off-axis (mm) (y direction)	500	50	20
Clear Aperture Radius (mm)	Elliptical, 550 (x) by 365 (y)	Elliptical, 56 (x) by 40 (y)	Elliptical, 15 (x) by 11 (y)
Type	Concave mirror	Convex mirror	Concave mirror

The system aperture stop/entrance aperture is located at the M1 surface. The M1 aperture is an ellipse with major/minor axes dimensions of 1100 mm x 730 mm. The complete characteristics of the optical design are summarized in Table 2a, while in Table 2b the telescope mirror parameters (radius of curvature, conic constant, off-axis, etc.) are described.

2.3 Telescope optical performance

The raytracing analysis and design optimization have been done by means of the raytracing software Zemax®. Being the telescope afocal, the spot diagrams can be derived using an ideal focusing paraxial lens with a defined focal length, or using the afocal image space option appropriate for systems with collimated output. Note that the spot diagrams obtained with this second method have their size expressed in milliradians.

The nominal diffraction PSF at 3 µm wavelength has an Airy radius respectively of 0.2 mrad and 0.29 mrad in the X and Y directions. A picture of the expected theoretical PSF is depicted in Figure 2a. The telescope RMS wavefront error is always less than 26 nm over the 30" nominal telescope FoV (see Figure 2b); this value is well below the telescope diffraction limit at 3 µm, i.e. 220 nm.



(a) (b)

Figure 2. In (a) PSF calculated at the telescope FoV centre for a wavelength of 3 µm depicted over a 1 mrad square box. In (b) RMS wavefront error field map calculated for the 3 µm wavelength over the 30" nominal telescope FoV. Units are λ.

3. TELESCOPE MATERIAL SELECTION

The ARIEL consortium undertook a trade-off study to determine the best materials for the ARIEL telescope structure, mirrors and instrument optical bench.

3.1 Parameters for material selection

The selection of the substrate for the mirrors, in particular for the primary mirror which is the largest one, has to take into account many parameters. The first is the availability of the material in the proper form and size, since the ARIEL primary mirror is of about 1 m in diameter. Then the characteristics related to the handling/manufacturing/polishing process and, in particular, to the required surface accuracy and surface roughness have to be accounted for.

Use of an overcoat can be considered for materials that are difficult to polish bare. In addition the mirror has to be mounted and integrated in the telescope structure, so the coupling of the mirror substrate coefficient of thermal expansion (CTE) with that of the mechanical structure has to be borne in mind.

For the ARIEL payload, the impact of the temperature change between the ambient temperature, i.e. the one at which the elements will be manufactured, aligned and tested, to the operative temperature, of about 50 K, has to be considered. The selected material has to scale uniformly with temperature without static or transient distortion and at the proper operative temperature it's required to be as stable as possible and with minimum gradients, the dimensional stability is very important since few adjustments can be made for static or transient distortion once in operation. A high thermal conductivity is required coupled to a as low as possible CTE at the operative temperature, that is a high thermo-optical stability is required.

Other parameters are related to the requirements on the minimum throughput that impacts on the mirror reflectivity and thus on the choice of the coating. It is worth considering which coatings can be deposited on the material. The temperature range of use and storage should also be accounted for in matching, as well as, the CTE of the coating to the substrate. If an overcoat is present also that thermo-mechanical coupling has to be evaluated.

Because the diameter of the primary mirror is quite big (~ 1 m), the effects of the gravity changes and the impact of the lightweighting of the substrate has to be taken into consideration together with the allowable total mass of the telescope. Therefore, the specific stiffness and specific strength of the material selected should be high in order to optimize this aspect of the design.

The materials that can be used for the ARIEL M1 mirror are rather limited. Those identified for the trade-off through brainstorming within the ARIEL Consortium and a review of the literature on other space telescopes [9] of a similar scale are:

1. Aluminum or Aluminum alloy;
2. Glass / ceramic such as Zerodur;
3. Silicon Carbide (SiC) or C/SiC;
4. Beryllium.

Glass materials have very good polishing properties, but are difficult to mount. Beryllium is very difficult to handle. SiC structures suffer from moisture release. An aluminum mirror mounted on an optical bench with the same material allows for automatic temperature compensation.

3.2 Criteria for material assessment

Six criteria have been used to assess each possible material against:

1. Availability: the availability of the raw material blank for the ARIEL primary mirror (at least 1.1 m diameter, 200 mm thick) in the proper form has to be assessed. The procurement lead times and the cost to purchase the raw material have to be determined.
2. Ability to polish: what level of confidence and literature data are available to demonstrate that the consortium team and their subcontractors will be able to polish the material to meet the ~200 nm RMS WFE specification on the telescope.
3. Thermo-mechanical design: consider the complexity of designing the telescope system for manufacture at ambient and operation at cryogenic temperature. Level of confidence in the ability of coatings to survive the thermal environment, and the complexity in the design of the mounting scheme for the optics.
4. Machinability for light-weighting: asses how easy it is to design and then machine a light-weighted structure of the given material.
5. Thermo-optical stability: this criterion depends on more than one parameter, i. e. thermal conductivity and CTE. A specific parameter called thermo-optical stability (thermal conductivity of the bulk material at 80 K divided by its CTE at 50 K) is used as a quantitative assessment for this characteristic.
6. Specific stiffness / strength: it is desirable that the telescope mirror and structure is as stiff as possible – it is expected that the first frequency requirements will likely drive the structural design of the telescope assembly. Similarly, a low-density material is desirable in order to minimize mass. Therefore, specific stiffness (Young Modulus at ambient temperature divided by density) is used as a quantitative assessment.

The material properties assumed for each of the five possible materials are shown in Table 3.

Table 3. Material properties.

Material	**Conductivity @ 80K (W/K/m)**	**Stiffness - Young Mod (GPa)**	**Density (kg/m^3)**	**CTE @ 50K (μm/m/K)**	**CTE @ 293K (μm/m/K)**	**Specific Stiffness (GPa m^3/kg)**	**Thermo-optical stability (W/μm)**
Al (RSA443)	135	100	2540	-NA	13.5	0.039	10.0 (*)
Al 6061	250	68.9	2700	2.9	23.6	0.029	86.2
Zerodur	0.7	90.3	2530	-0.5	0.001-0.1	0.036	-1.4
SiC	70	550	3210	<0.4	4.4	0.171	>175.0
Be	200	287	1850	<1	11.4	0.155	>200

(*) This value is for ambient T CTE

As a conclusion of the material trade-off study for the telescope mirrors, and specifically for M1, considering the consortium provision of the telescope, the optimum solution is a telescope with mirrors and structure made from aluminum 6061 T651 alloy [7]. The viability of using aluminum as the baseline material for the telescope mirrors has been assessed during the phase A by producing the pathfinder M1 mirror.

4. TELESCOPE TOLERANCE ANALYSIS AND IN-FLIGHT PERFORMANCE

The ARIEL telescope will be realized on-ground, at 1 g and room temperature environmental conditions, but it shall operate in space at about 50 K. For this reason, a detailed tolerance analysis was performed to assess that the all-aluminum design for the telescope is able to guarantee the expected as-built optical performance during its operation in flight [11] [12].

The tolerance analysis has taken into account the different parts of the realization and life of the instrument:

1. Manufacturing, integration and alignment.
2. Launch loads and change from 1 g to 0 g.
3. Cooldown in orbit from ambient temperature to the nominal (about 50 K) operating temperature.
4. Stability in flight: short term (over 1 single exposure to about 10 hours) and long term (over the whole mission operative lifetime).

Optical element standard manufacturing and mounting tolerances have been considered for the manufacturing, integration and alignment phase. The mirrors are foreseen to be equipped with a reference cube, or reference surfaces, and, with respect to these references, the mirror local axis will be measured with high precision (∼10/20 microns in position and 2/4" in rotation). M1 surface shape will be measured after manufacturing, and if it's not inside the allowable tolerance, to avoid the time consuming process of re-working a 1-m diameter mirror, the possibility of re-optimize M2 will be considered. The total impact of the manufacturing, integration and alignment process on the RMS WFE is expected to be of the order of 40 nm.

The primary mirror will be lightened and its mechanical shape has been studied in order to give high bending stiffness both during manufacturing and in operating condition. The selected mounting system ensures isostatic thermal fixation of the primary mirror. M1 is supported directly by the optical bench via a 9-point whiffletree structure, which is connected to the optical bench via three triangular mountings [8].

A slightly inclined position of the telescope, with the gravity acting parallel to the optical bench, is suggested to be adopted to reduce the deformation effects induced by gravity during the alignment and tests on-ground. The whole telescope structure should be rotated about 12° with respect to the telescope interface to the spacecraft [10].

A preliminary thermo-elastic analysis has been performed to verify the deformation of the primary mirror, and the telescope structure, during the cooling phase from ambient, 293 K, to the operating temperature. The considered operating temperature map is the one calculated using the thermal model for the reference worst case condition [5].

The variation of the distance between the centers of primary and secondary mirrors is of about 20 µm along the X direction, about 600 µm and 4.7 mm respectively in the Y and Z ones. These numbers are in line with the expected displacements, in fact the mean Al6061 coefficient of thermal expansion (CTE) in the considered temperature range is about 17 µm/(K m) [8]. Globally, the telescope results to be rotated approximately 4' around the X axis, the distance between M1 and M2 is about 200 µm more than expected and the estimated variation for the shape of the primary mirror is about 20 µm PTV. The first effect can be recovered re-orienting the whole S/C, the second, and partly the third, by moving M2 via the refocusing mechanism. The residual WFE after refocusing is expected to be of the order of 200 nm.

For the stability in-flight, at present, the foreseen seasonal changes are estimated to be less than 1 K corresponding to an expected RMS WFE of about 130 nm.

The results of the whole tolerance analysis show that the telescope, thermally stable after cooldown and refocused via M2 mechanism, will have a WFE of the order of 220 nm RMS. The total RMS WFE error in flight, including the stability, will be within 250 nm. Comparing these results and the allocated WFE budget, it can be demonstrated that the telescope assembly will deliver the required optical quality suitable to achieve the scientific purpose of the instrument.

5. M1 PROTOTYPE PROGRAM: DESIGN, MANUFACTURING AND TESTING

The primary mirror of the ARIEL telescope is an off-axis section of a paraboloidal mirror and will be machined from a single blank as a stand-alone part [13]. To prove the feasibility of such a large aluminum mirror, a pathfinder mirror program (PTM) has been started. The prototype has the same size of the M1 flight mirror but it has a simpler spherical surface profile. To be as representative as possible with respect to the flight model, the PTM curvature radius has been determined calculating the best-fit sphere of the foreseen M1. The prototype has been realized and tested, so far at room temperature, by Media Lario S.r.l.. Cryogenic testing of the prototype will be performed during Phase B1.

5.1 Pathfinder mirror program (PTM) characteristics

The baseline scope for the PTM was to verify and assess, on a full-size demonstrator, the critical manufacturing technology to be adopted for the primary mirror realization. Given the time constraints and available funding, the project agreed to adopt a nominal spherical shape and focus on the demonstration of the diamond machining process used for the preparation of the Aluminum substrate for the subsequent figuring and polishing steps. As such, the surface error and roughness requirements for the PTM were relaxed with respect to the flight requirements but still very representative for the diamond machining step. In summary, the primary objectives of the PTM were the following:

- Full size mirror (1.1 m x 0.76 m elliptical substrate);
- Spherical design derived from best-fit of the nominal paraboloid;
- Mild light-weighting (≈30%);
- Alloy 6061-T651;
- Diamond machining with 1 µm RMS surface figure error and 10 nm RMS surface roughness;
- Analyze and measure gravity release.

5.2 PTM design and manufacturing

In order to minimize mass and complexity, the backside plane of the PTM is tangent to the nominal paraboloid at its decentering point. In this configuration, the mirror is geometrically symmetric. The nominal optical shape of the mirror is spherical with a radius of curvature of 2,400.725 mm, with a tolerance of ±2 ‰. A margin of 10 mm on the external dimensions has been added to account for possible edge effect during machining and polishing.

Triangular pockets ensure 36% light-weighting, setting the overall mass at approximately 156 kg. The mechanical interface configuration is very preliminary and consists of three pads equally spaced 120° apart and protruding from the external rim of the mirror. Each pad has a 12.5 mm through-hole each. A preliminary planarity requirement of 0.005 mm was set for these interface pads.

The first manufacturing steps consisted of standard CNC milling runs to create the light-weighting structure, the lateral perimeter with the interface pads and the spherical front surface (Figure 3). In order to leave enough material for the subsequent diamond machining step, the spherical surface was machined with a radius of curvature 0.7 mm shorter than nominal. The substrate was measured at Media Lario on the CMM, yielding a radius of curvature of 2,394.154 mm and residual error of 30 µm RMS or 190 µm PV. The substrate was then ready for diamond machining of the optical surface. Diamond machining was performed by LT-Ultra Precision Technology GmbH, Germany. The size of the mirror required some tuning of the machining strategy and speed in order to ensure adequate quality of the diamond tool throughout the entire machining process. In the end, the mirror was delivered to Media Lario according to the agreed schedule and quality (Figure 4).

Figure 3. Front (left) and backside (right) of the PTM mirror prototype after milling.

Figure 4. Two views of the PTM mirror surface after diamond turning.

5.3 PTM measurement results

In order to minimize the gravity sag during the final CMM measurement, the mirror was accommodated on a 9-point isostatic support system consisting of a simple whiffletree structure (Figure 5). This set-up had previously been analyzed to check that the gravity sag were at least one order of magnitude smaller than the surface figure error specification of the mirror. According to our simulations, the gravity sag with a 9-point isostatic support is 0.09 µm RMS, with 21 µm impact on the radius of curvature. We calculated that a more complex 18-point support would have only marginally reduced the gravity sag to 0.07 µm RMS

The CMM measurement showed a residual error of 1.98 µm RMS or 11.6 µm PV on the diamond machined optical surface (Figure 6). This value is approximately double the goal set for the PTM. However, we remark that half of the measured value is a low-frequency astigmatism error that can be reduced with further tuning of the diamond machining process and easily corrected by the subsequent figuring and polishing steps. The radius of curvature was measured at 2,403.404 mm, that is 1.1 ‰ longer than nominal, confirming that the substrate meets the requirement of the next figuring and polishing steps. The measurements are summarized in Table 4.

In order to experimentally assess the gravity sag, the PTM surface was measured both on the 9-point support and on the three standard interface pads. The latter is shown in Figure 7, while Table 5 compares the measurement results in the two configurations. The residual error of the mirror on its interface pads is smaller because the center of the mirror drops a little under gravity thus smoothing the low frequency error of the mirror.

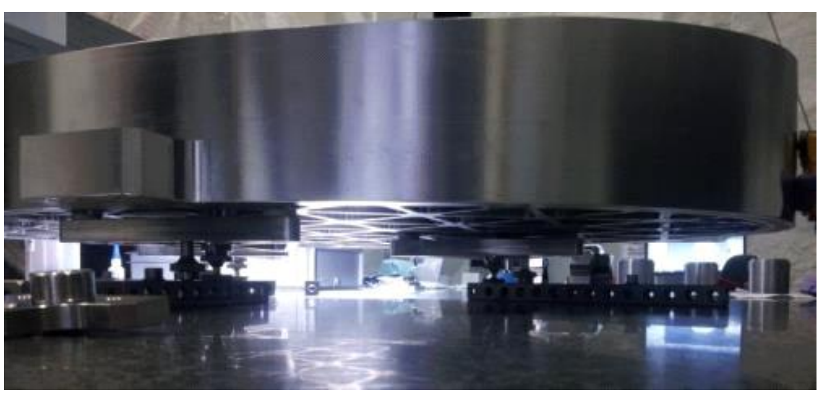


Figure 5. The PTM mounted on the designed whiffletree structure to counteract gravity effects.

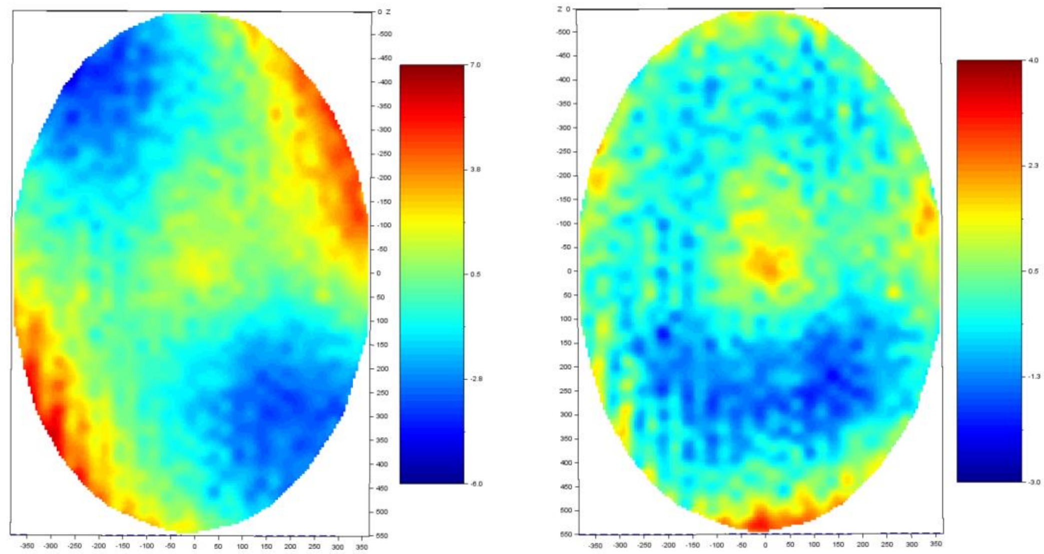


Figure 6. Surface figure error of the PTM on the 9-point support: total residual error (left) and with astigmatism removed (right).

Table 4. Measurements results of the PTM after diamond machining.

Parameter	**Specification**	**Result**	**Comment**
Radius of Curvature	2400.725 mm	2403.404 mm	Compensated by M2 design.
Tolerance on radius of curvature	±2‰ / ±4.8 mm	+1.1 ‰ /+2.7 mm	State of the art performance.
Shape accuracy (RMS)	≤1 µm	1.98 µm	0.8 µm after astigmatism removal.
Shape accuracy (PV)	-	11.6 µm	5.3 µm after astigmatism removal.

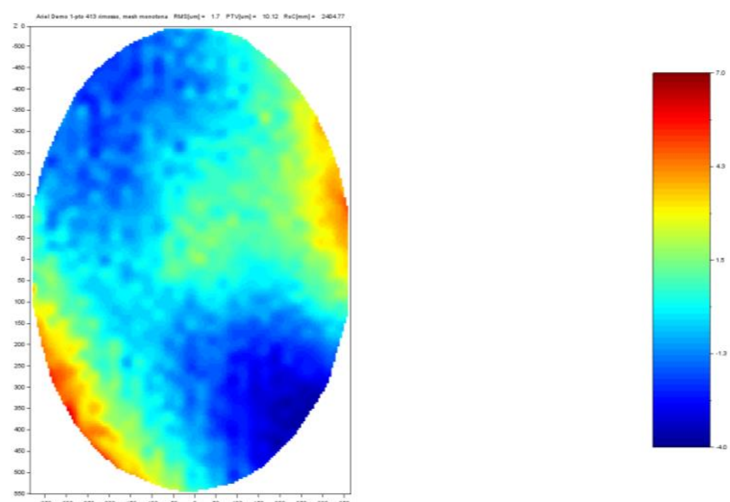


Figure 7. PTM measured surface error map when mounted on its 3 pads.

Table 5**.** Results of the shape accuracy measurements of the ARIEL PTM optical substrate supported on its nominal interface pads.

Parameter	**"0 gravity"**	**Nominal interface pads**
Radius of Curvature	2403.404 mm	2404.770 mm
Tolerance on radius of curvature	+1.1 ‰ /+2.7 mm	+1.7 ‰ / +4.1 mm
Shape accuracy (RMS)	1.98 µm	1.7 µm
Shape accuracy (PV)	11.6 µm	10.1 µm

6. CONCLUSIONS

For the next M4 ESA mission ARIEL, an all-aluminum telescope solution has been chosen. As a result of a material trade-off undertaken within the ARIEL consortium, the Al6061 T651 has been chosen as the preferred material for both the structures and the telescope mirrors.

The scientific requirements and the characteristics of the telescope optical design have been described. The telescope will be realized at room temperature and in 1-g environment, but it will work in space at cryogenic temperatures, so a tolerance analysis has been conducted to demonstrate the suitability of the as-built performance of the all-aluminum telescope.

A full-size pathfinder mirror (PTM) has been realized to prove the diamond machining technology for the production of a precise mirror substrate is suitable for the next figuring and polishing processes. The PTM has demonstrated diamond machining capability with 1.1 ‰ tolerance on the radius of curvature and 2 μm RMS residual error on the optical surface, which meet the requirements for the figuring and polishing steps. This confirms that the diamond machining technology for the production of this 1 meter class Aluminum mirror is in place.

Future activities planned for Phase B include deterministic figuring and polishing of this substrate to final spec and assessment of its performance in cryogenic environment.

ACKNOWLEDGMENTS

This activity has been realized under the Agenzia Spaziale Italiana (ASI) contract to the Istituto Nazionale di Astrofisica (INAF) ARIEL 2015-038-R.0.

The authors gratefully acknowledge the support provided by the ESA ARIEL Study Team, the University College of London (UCL), and the Rutherford Appleton Laboratory (RAL Space) managers and engineers.

REFERENCES

[1] Puig, L., Pilbratt, G. L., Heske, A., Escudero Sanz, I., and Crouze, P.-E., "ESA M4 mission candidate ARIEL", Proc. SPIE 9904, 99041W (2016).
[2] Tinetti, G., et al., "The science of ARIEL", EPSC Abstracts 11, EPSC-713(2017).
[3] ARIEL SST, "ARIEL Science Requirements Document", ESA-ARIEL-EST-SCI-RS-001, (2015).
[4] Eccleston, P., et al., "An integrated payload design for the Atmospheric Remote-sensing Infrared Exoplanet Large-survey (ARIEL)", Proc. SPIE 9904, 990433 (2016).
[5] Morgante, G., et al., "Thermal architecture of the ESA ARIEL payload", Proc. SPIE 10698, 10698-154 (2018).
[6] Focardi, M., et al., "Design of the Instrument and Telescope Control Units integrated subsystem of the ESA-ARIEL payload", Proc. SPIE 10698, 10698-162 (2018).
[7] Da Deppo, V., et al, "ARIEL telescope material trade-off", ARIEL-INAF-PL-TN-004_2.0 (2017).
[8] Da Deppo, V., et al., "An afocal telescope configuration for the ESA ARIEL mission", CEAS Space J. (2017).
[9] Edinger, D. J., and Nordt, A. A., "Selection of I-220H Beryllium for NIRCam Optical Bench", Proc. SPIE 5868, 58680X (2005).
[10] Eccleston, P., "ARIEL Payload Design Description", ARIEL-RAL-PL-DD-001_2.0 (2017).
[11] Da Deppo, V., et al., "The afocal telescope optical design and tolerance analysis for the ESA ARIEL Mission", Proc. SPIE 10590, 105901P (2017).
[12] Sierra Roig, C., et al., "The Telescope metrology Control Unit (TCU) on-board the ARIEL space mission", Measurement: Journal of the International Measurement Confederation 122, 443-452 (2018).
[13] Da Deppo, V., "Off-axis surface tolerance analysis: tips and tricks", Proc. SPIE 10690, 106902Q (2018).