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Optical and Opto-mechanical Analysis and Design of the Telescope for the Ariel Mission

Paolo Chioetto – 35th Cycle

Supervisors: Dr. Paola Zuppella / Dr. Vania Da Deppo

Admission to Final Exam – September 6th, 2022

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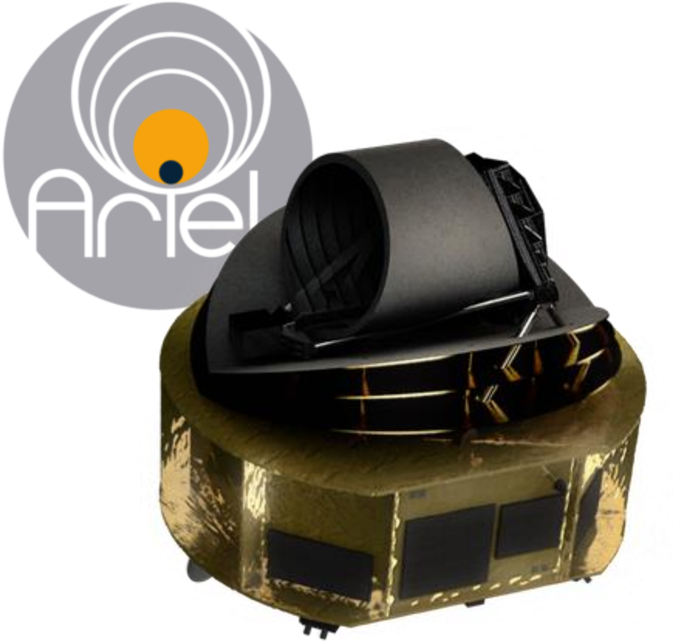


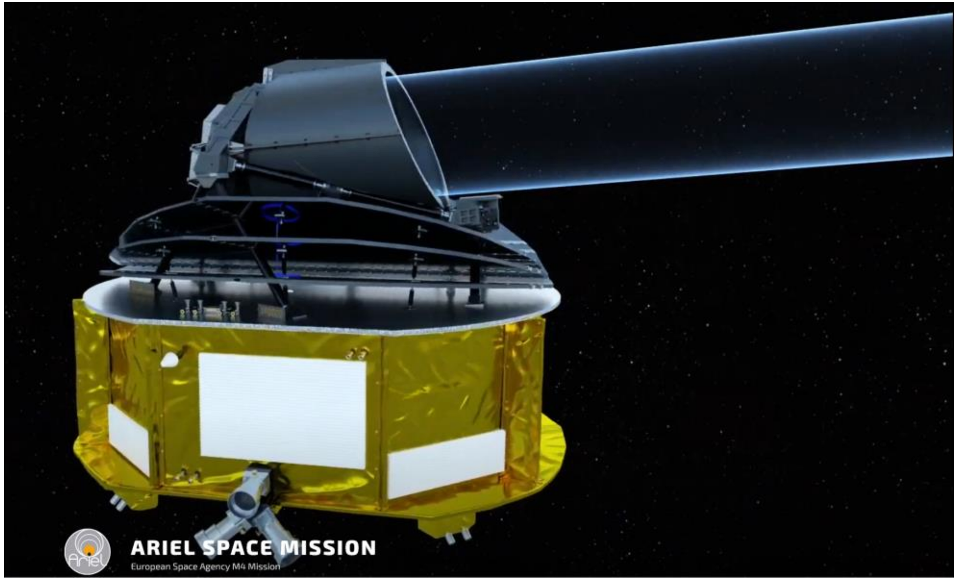
Mission logo and artist's rendering of the Ariel spacecraft from Phase A. Credit: ARIEL/Science Office

1. Introduction – The Ariel ESA Mission

1. Introduction

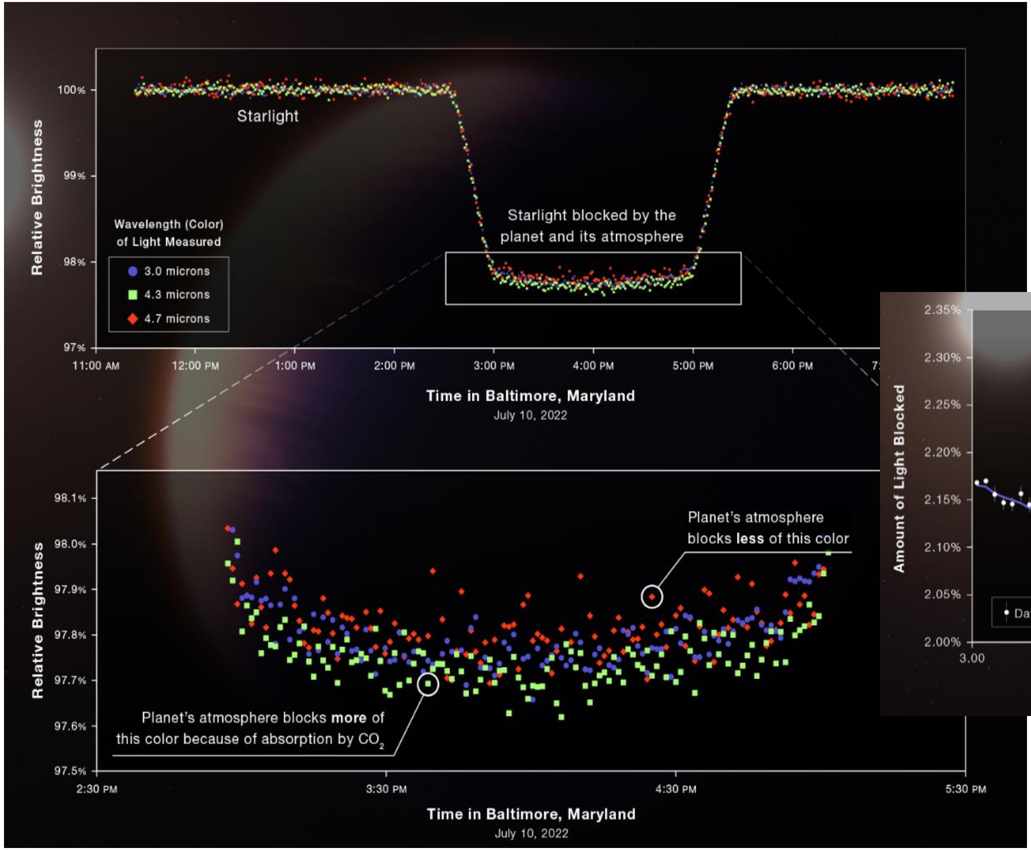
The Ariel Mission

- 4th **medium-class mission** of ESA Cosmic Vision program to **survey exoplanet atmospheres** through infrared transit spectroscopy
- **Payload**. An **all-aluminum telescope** feeding two instrument modules: a **spectrometer** (1.95–7.8 µm), and a combined fine guidance system/visible photometer/NIR spectrometer



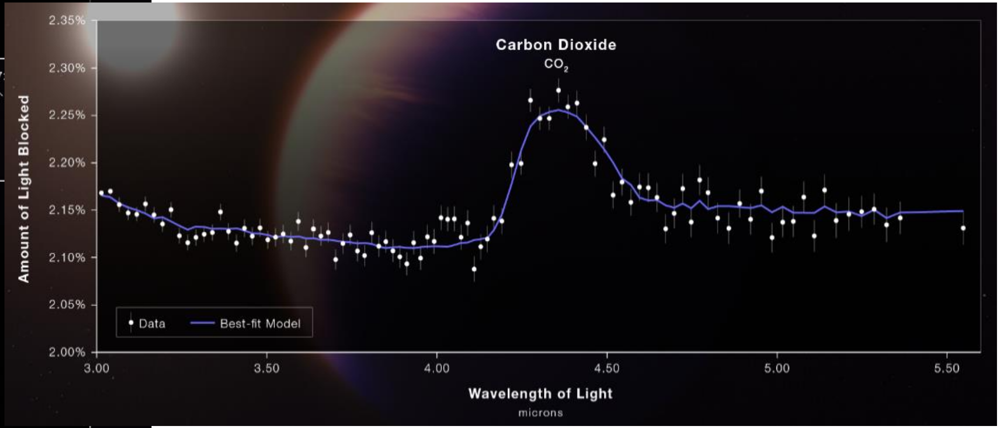
Frame from the concept video of Ariel detecting light from a distant star https://arielmission.space/ Credit: ESA / STFC RAL Space / UCL / UK Space Agency / ATG Medialab

1. Introduction



Transit spectroscopy

Example from JWST: CO_2 detected on Hot Gas Giant WASP-39 b



Credit: NASA, ESA, CSA, Leah Hustak (STScI), Joseph Olmsted (STScI)

Mission Schedule

Assessment	Definition		Development			Operations	Disposal
Phase 0	Phase A	Phase B1	Phase B2	Phase C	Phase D	Phase E	Phase F
Mission analysis and identification	Feasibility	Preliminary Definition	Preliminary Definition	Detailed Definition	Qualification and Production	Utilization	Disposal

PhD Program

Mission Selection	**SRR/ Mission Adoption**	**Preliminary Design Review**	**Launch**
Mar 2018	Nov 2020	2020/2021	2029

2. Summary of Main Personal Contributions

2. Main Personal Contributions

PhD Dissertation in *paper collection* form

1. Chioetto, P. et al. *"Preliminary Analysis of Ground-to-Flight Mechanical Tolerances of the Ariel Mission Telescope"* Proc. SPIE (2022) doi:10.1117/12.2628900

2. Chioetto, P. et al. *"Qualification of the Thermal Stabilization, Polishing and Coating Procedures for the Aluminum Telescope Mirrors of the ARIEL Mission"* Exp. Astr. (2022) doi:10.1007/s10686-022-09852-x

3. Chioetto, P. *et al. "The Primary Mirror of the Ariel Mission: Cryotesting of AluminumMirror Samples with Protected Silver Coating"* Proc. SPIE (2020) doi:10.1117/12.2562548

4. Chioetto, P. *et al. "Test of Protected Silver Coating on Aluminum Samples of ARIEL Main Telescope Mirror Substrate Material"* Proc. ICSO (2021) doi:10.1117/12.2599794

5. Chioetto, P. *et al. "Long Term Durability of Protected Silver Coating for the Mirrors of Ariel Mission Telescope"* submitted to ICSO 2022

6. Chioetto, P. *et al. "Initial Estimation of the Effects of Coating Dishomogeneities, Surface Roughness and Contamination on the Mirrors of Ariel Mission Telescope"* Proc. SPIE (2021) doi:10.1117/12.2603768

Telescope Tolerance Analysis (1)

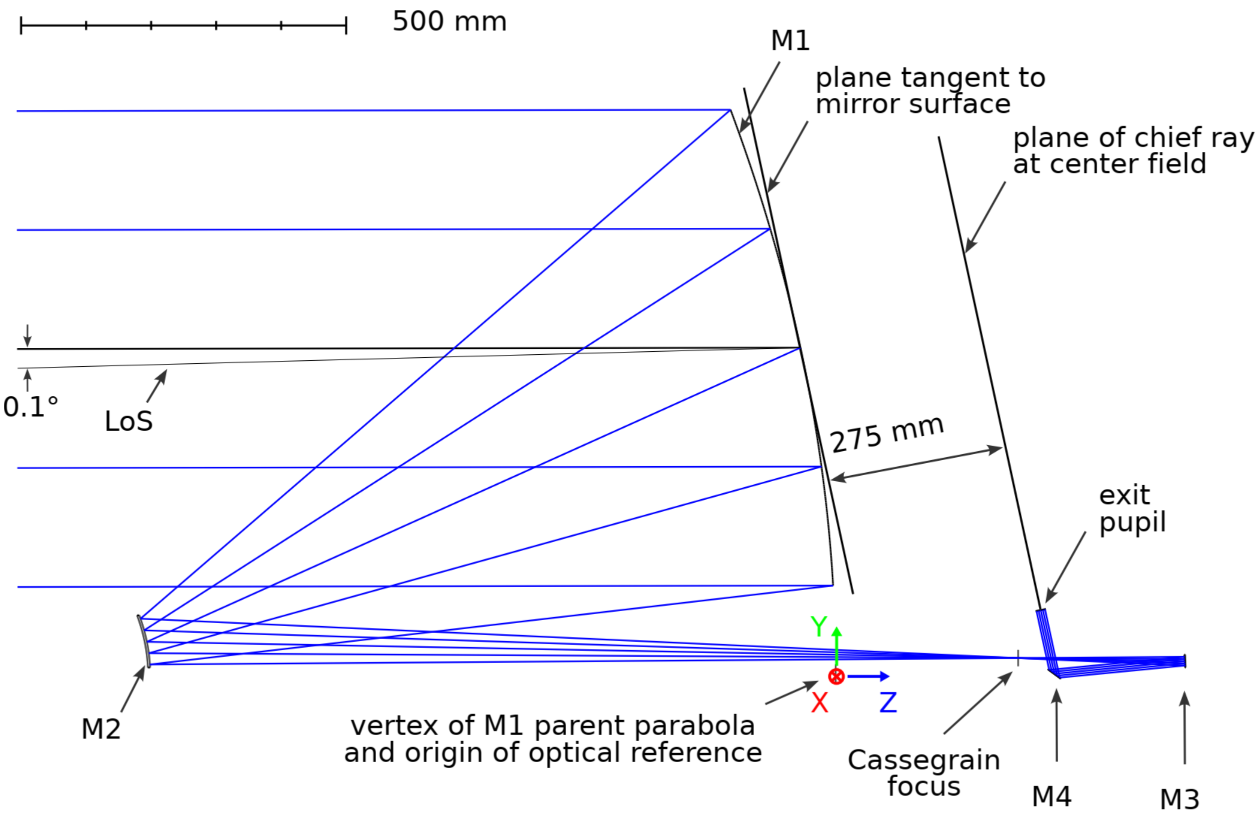
Mirrors Technological Development (2)

Mirrors Coating Qualification (3, 4, 5)

Telescope Throughput Analysis (6)

3. Telescope Opto-mechanical Design and Tolerancing

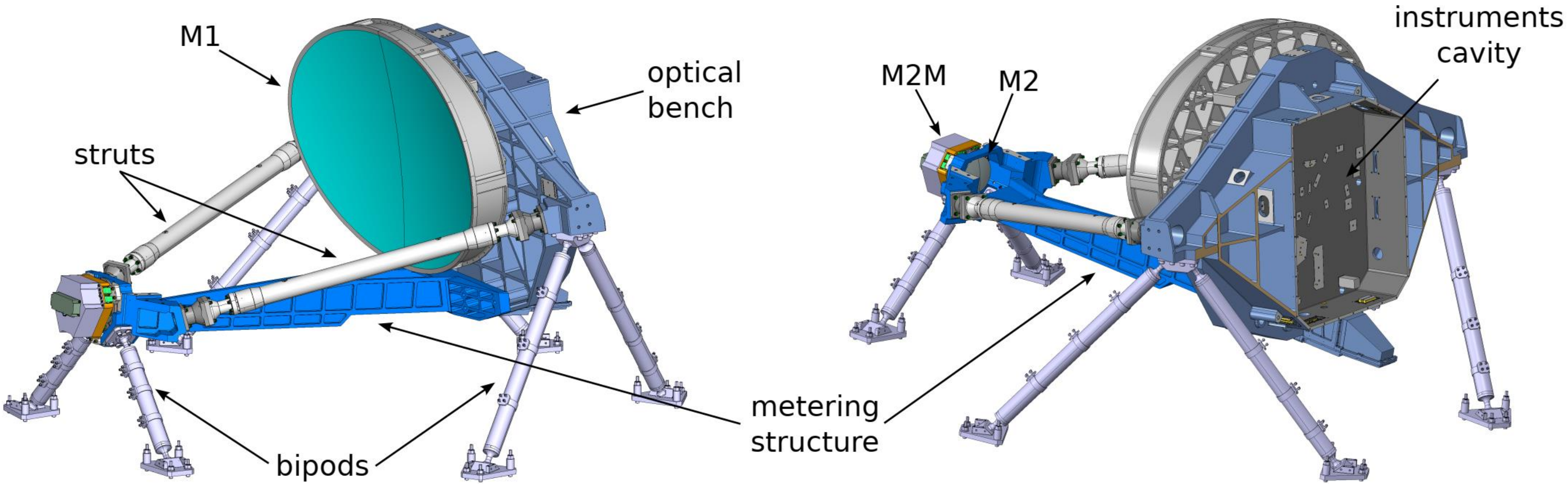
3. Telescope Opto-mechanical Design



Optical Design

- Off-axis, unobscured, afocal Cassegrain
- Collecting area: 0.6 m^2
- FoV: 30” (diff. limited), 50” (unvignetted)
- Wavefront Error: diff. limited at 3 μm
- Avg. throughput: >0.82
- Angular magn.: 55

Telescope Assembly Structure (interim design)



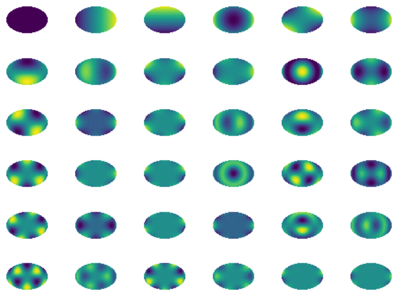
Highlights: all-aluminum telescope, large primary mirror (1.1 m x .7 m optical aperture, first time flying in a space mission), refocusing M2 mechanism.

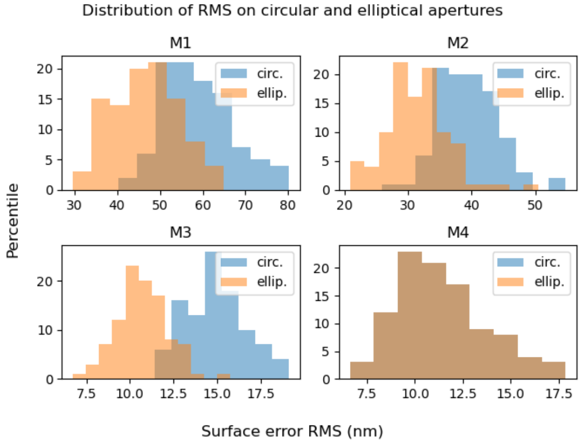
3. Telescope Opto-mechanical Design

Analysis of the Effects of Mirrors Surface Errors

- Each mirror is represented as sum of Zernike polynomials
- Inverse sensitivity analysis to find initial tolerances
- Monte Carlo analysis with Zernike coefficients sampled randomly from initial tolerances
- Telescope performance (PSF Encircled Energy) computed for each random realization
- Statistical analysis of results

Zernike polynomials on elliptical aperture (left) and coefficients from inverse sensitivy analysis (right)



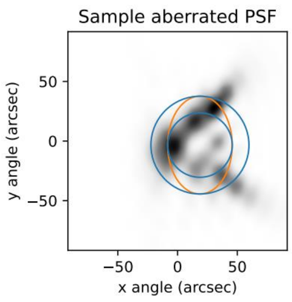


Histograms of RMS distributions of MC realizations for each mirror

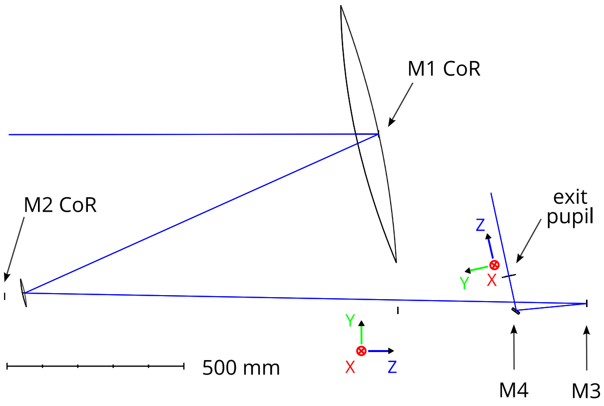
Analysis of the Effects of Mirrors Displacements

- **Statistical analysis** of the **effects of rigid body motions** of the four telescope mirrors (caused eg. by dynamic loads during launch)
- Optical performance evaluated in terms of **Enclosed Energy in the PSF**, and position and orientation of the **exit beam**.

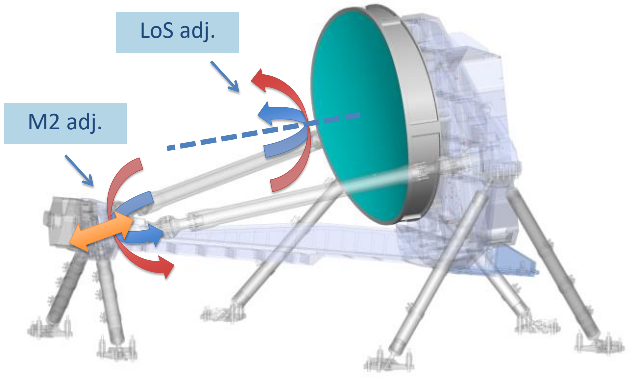
Enclosed Energy calc.



Simulation setup



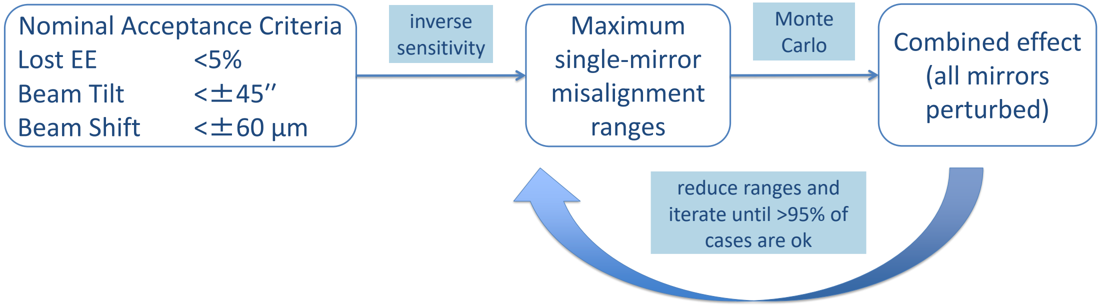
Compensators



3. Telescope Opto-mechanical Design

Analysis Procedure

1. Inverse sensitivity: determine the range of admissible misalignments for each element individually, based on the acceptable ranges (acceptance criteria).
2. Monte Carlo simulation on the ranges identified in Step 1 to evaluate the combined effect.



Results

Reducing the perturbation range to ±10 μm for linear shifts and ±10'' for rotations brings most of the Monte Carlo cases (>95 %) within requirements. These ranges are deemed as realistic by the telescope manufacturing Prime Contractor.

	beam shift (mm)		beam tilt (arcsec)		EE lost
	x	y	x	y	
min	0	0	0.1	0.4	4.15%
50%	0.021	0.023	45.0	45.0	4.18%
75%	0.034	0.039	45.0	45.0	4.20%
90%	0.048	0.051	45.0	45.0	4.23%
95%	0.055	0.057	45.0	45.0	4.66%
max	0.061	0.065	45.3	46.4	6.54%

4. Telescope Mirrors Technological Development and Prototyping

4. Telescope Mirrors Technology Dev.

Objective

Develop aluminum Al6061-T651 mirrors manufacturing technologies to **TRL 6**: "System/subsystem model or prototype demonstration in a relevant environment (ground or space)" (ISO 16290:2013)

Materials

1. 25 mm sample disks
2. 150 mm sample disks
3. Full-size primary mirror demonstrator (PTM)

Processes

1. Thermal Stabilization
2. Machining and Polishing
3. Optical Coating

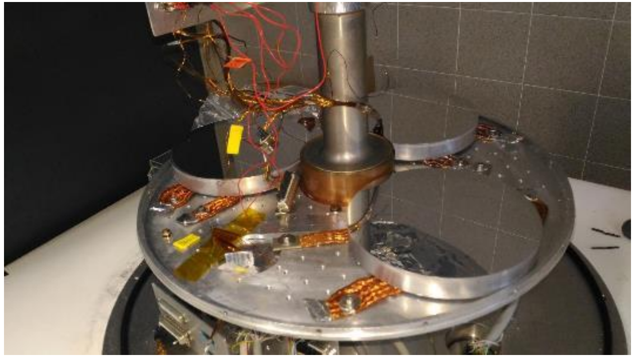
25 mm disc. Credit: CILAS-ArianceSpace

PTM and 150 mm disks in climatic chamber. Credit: TAG S.r.l. / Media Lario S.r.l.

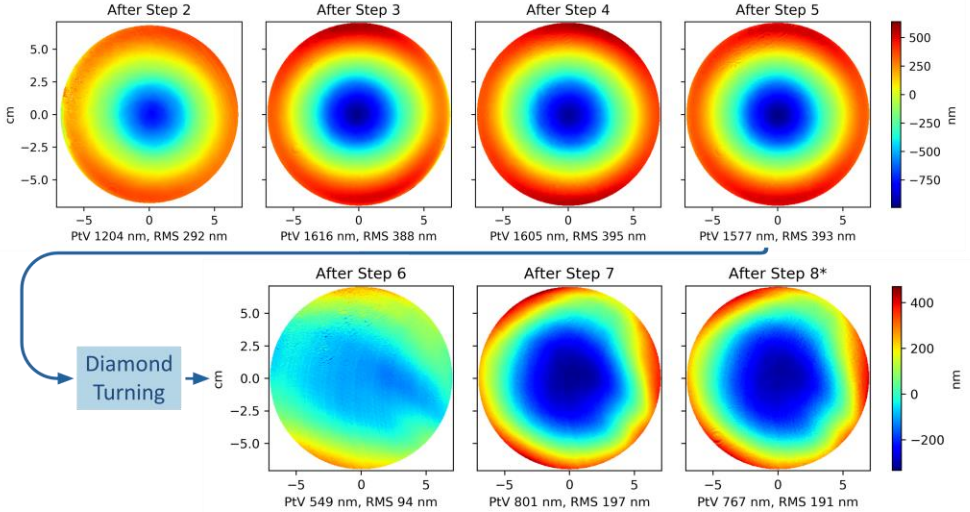
4. Telescope Mirrors Technology Dev.

Substrate Thermal Stabilization

- Improves cryogenic opto-mechanical stability reducing residual stress
- Customized recipe based on the work of R. G. Ohl et al. from NASA/Goddard, consisting of quenching and temperature cycling steps
- Developed on the 150 mm disks



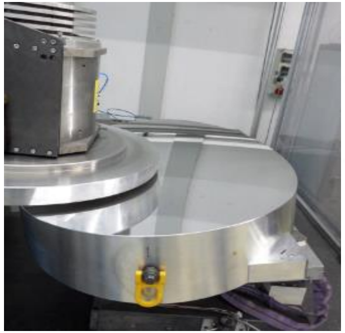
150 mm samples being loaded in a cryochamber (credit: G. Morgante/INAF OASBO)



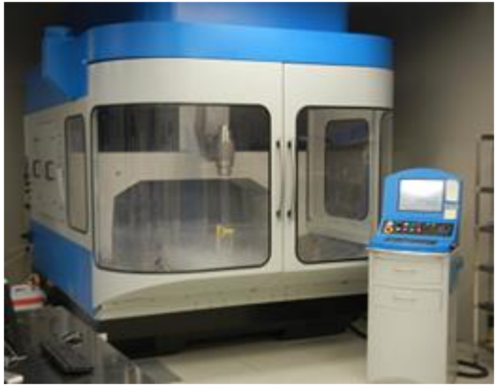
Evolution of the interferometric measurements on the first 150 mm disk during thermal stabilization (credit: Media Lario S.r.l)

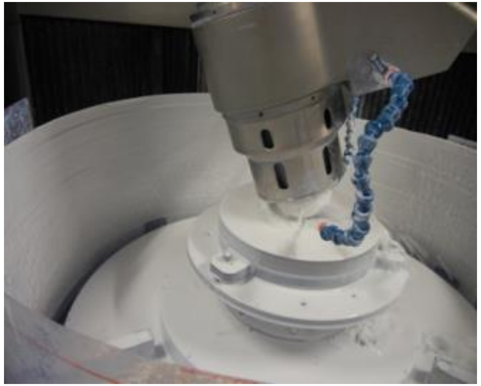
Machining and Polishing – 1

- Final shape approximated to within 1 µm RMS with fly-cutting and diamond turning (SPDT) technologies
- Achieving final specifications of shape (80 nm RMS) and surface roughness (10 nm RMS) with several runs of deterministic polishing technology



Fly-cutting (left) and SPDT (right) machines. Credit: LT Ultra-Precision Technology GmbH



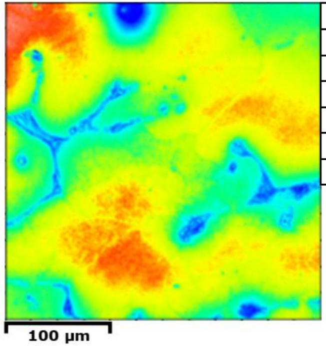


Zeeko IRP 1200X robotic polishing machine (left) and detail of the polishing bonnet (right). Credit: MediaLario S.r.l.

4. Telescope Mirrors Technology Dev.

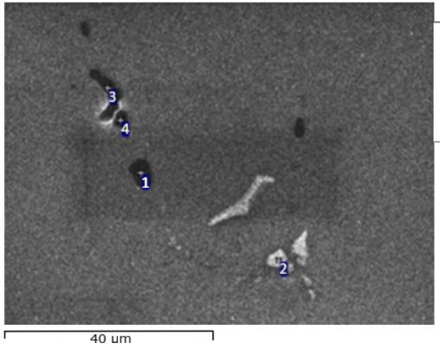
Machining and Polishing – 2

- Challenges due to material specificities (Al 6061-T651 rolled plate)
- **Mg and Si agglomerates** form during forging and treating, and scratch the surface during polishing
- Process development ongoing alternating figuring and super-polishing steps with carbon-based slurries



ISO 25178	
Height Parameters	
Sq	21.0 nm
Sp	48.2 nm
Sv	99.3 nm
Sz	148.0 nm
Sa	15.7 nm

Profilometry image of sample after a step of aggressive figuring polishing highlight agglomerates. Credit: Media Lario S.r.l.



Spectrum	O	Mg	Al	Si	Fe	Total
1	15.15	19.27	43.36	22.22		100.00
2			76.87		23.13	100.00
3	14.10	18.92	48.32	18.66		100.00
4	18.45		66.68	14.87		100.00

Processing option: all elements analyzed (normalized)
All results in weight%

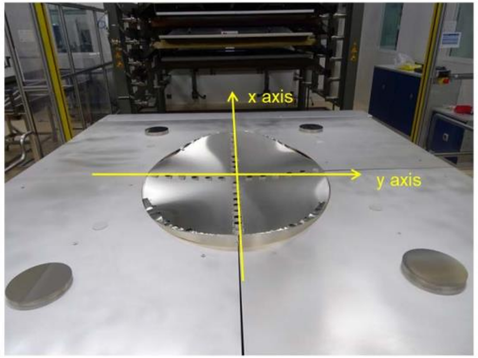
SEM-EDX report of the analysis of one of the 25 mm sample in Al 6061-T651. Credit: Media Lario S.r.l.

5. Mirrors Optical Coating Qualification and Performance Assessment

5. Optical Coating Qualification

Telescope Mirrors Optical Coating Qualification Campaign

- **Protected Ag coating** with space heritage from CILAS-ArianeGroup. Deposition through magnetron sputtering
- Additional **qualification** required because of **substrate size** and **cryogenic** operating environment
- Qualification campaing on 25 mm disks on holder shaped as primary mirror
- Verification tests on additional samples and PTM
- **Ageing monitoring**



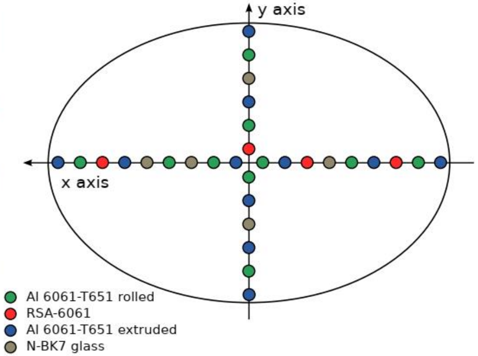


Photo and schematic drawing of the disks on the samples holder ready for coating. Credit: CILAS-ArianeGroup

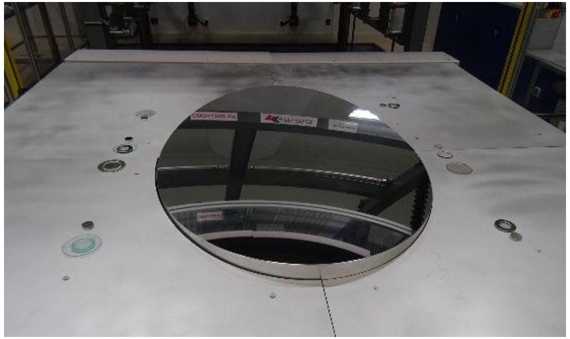


Photo of the PTM and samples ready for coating. Credit: CILAS-ArianeGroup

5. Optical Coating Qualification

Qualification Test Program

Environmental

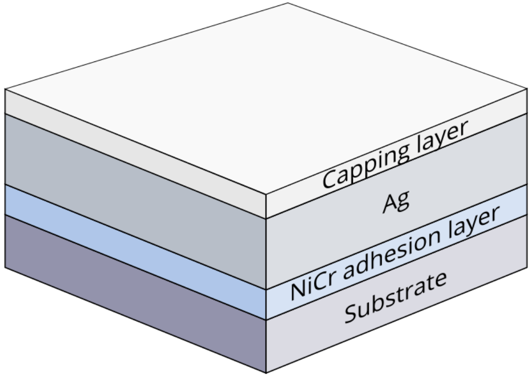
- Humidity: 24 hours, 90% humidity, 55 °C
- Temperature: 30 cycles, -40°C / 70°C, <2°C/min (accelerated aging)
- Cryogenic: 10 cycles, 54 K / 293 K, <5 K/min

Mechanical/chemical

- Abrasion test with cheescloth
- Adhesion test through tape stripping
- Cleaning test: CILAS proprietary cleaning procedure, ethanol and acetone solutions

Verification methods

- Visual inspection, to check coating integrity
- Spectral reflectance, to verify unaltered performance
- Additional inspection/imaging with Optical and Atomic Force Microscopes (AFM)



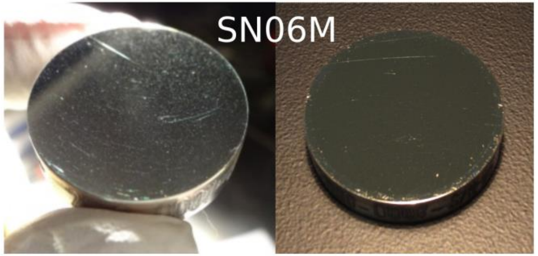
Schematic representation of the coating layers (not to scale)

5. Optical Coating Qualification

Tests Results

Measurements performed after each test, and periodically after qualification

- no visible signs of degradation
- no significant reduction in performance (reflectance)

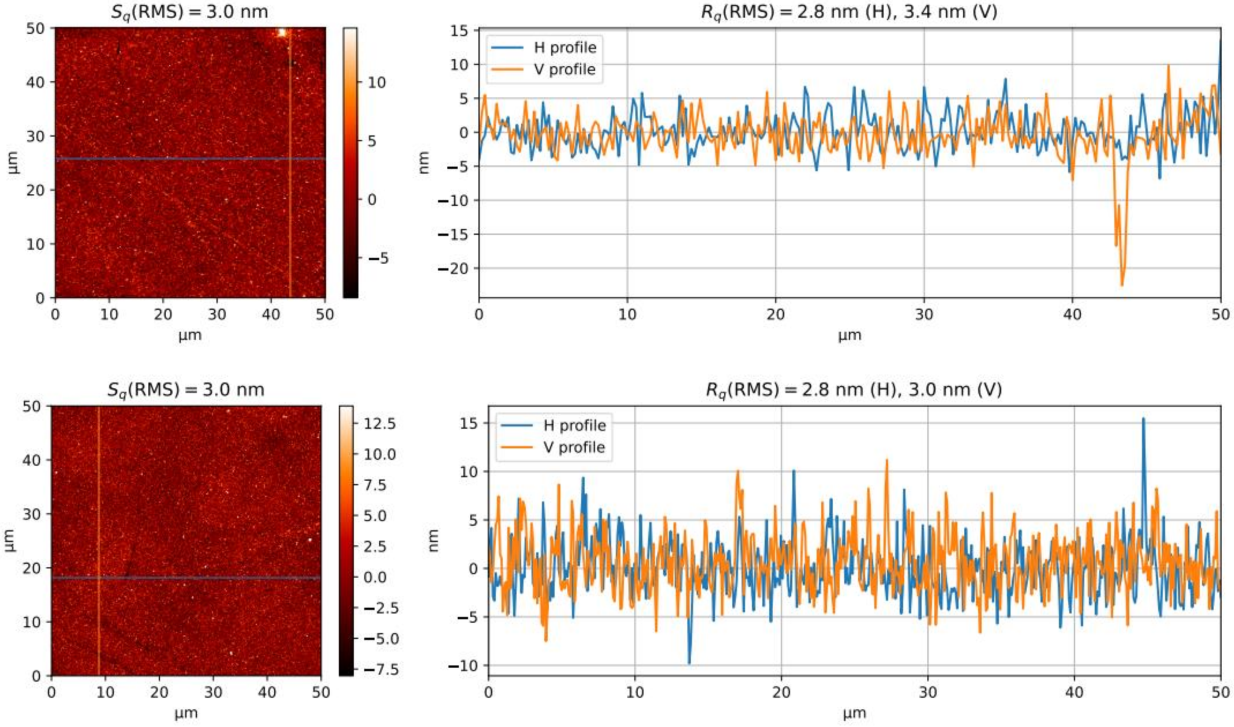


Comparison of visual inspection pictures of a sample right after coating (left) and after testing and storage (right)

Darkfield photograph of a sample after storage

Atomic Force Microscopy

- Imaging of one sample immediately after coating (top) and after tests and storage (bottom)
- Morphology is qualitatively unaltered and roughness is unchanged

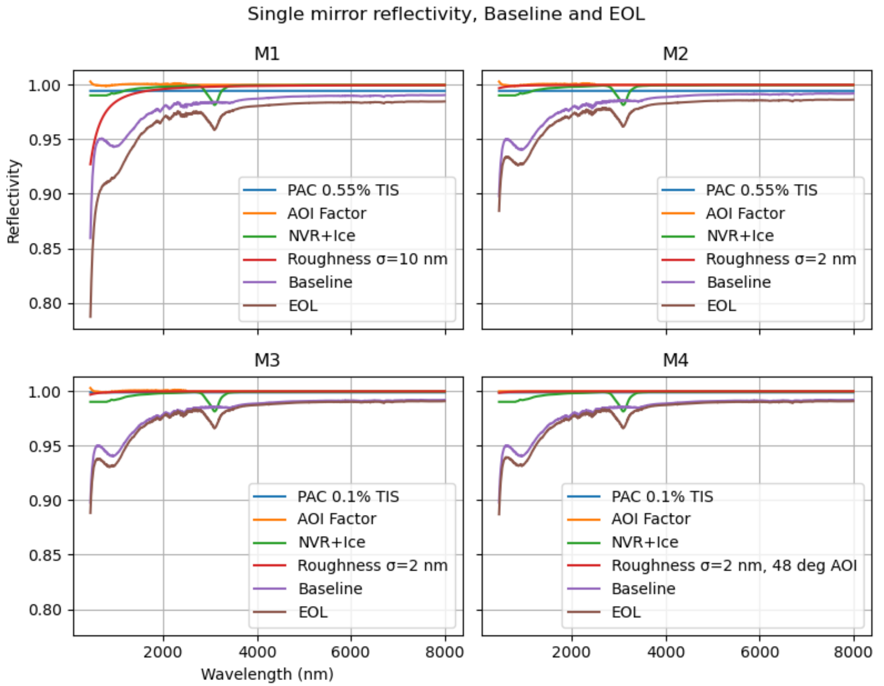


5. Coating Performance Assessment

Update of the Telescope Throughput Model

Evaluation of the expected end-of-life throughput performance of the telescope

- using measured reflectivity data from coating qualification
- scattering losses from surface roughness and particulate contamination
- absorption losses from molecular contamination



6. Acknowledgements

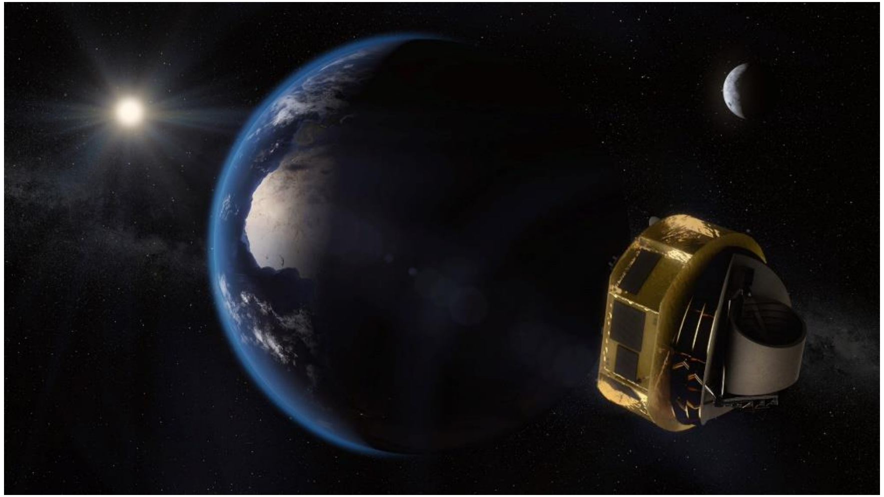
Sources of funding

- Implementation Agreement n. 2018-22-HH.0 of the ASI-INAF Framework Agreement “Participation to the B1 study phase of the Ariel mission”)
- ESA – CSL/INAF contract “Cryotesting of Ariel M1 mirror and coating process qualification”
- Implementation Agreement n. 2021-5-HH.0 of the ASI-INAF Framework Agreement “Italian Participation to Ariel mission phase B2/C”.

I wish to thank the advisors Dr. Paola Zuppella and Dr. Vania Da Deppo for their guidance and support, Professors Emanuele Pace, Andrea Tozzi, Enzo Pascale and the rest of the Ariel team for their insights and support.

Mission Credits

- **PI**: Prof. G. Tinetti, University College London, UK
- **Mission Scientist**: Prof. E. Pascale, Sapienza University of Rome
- **Italian PM**: Prof. E. Pace, University of Florence
- **Italian Co-PIs**: Dr. G. Micela, INAF-OAP; Dr. G. Malaguti, INAF-OASBO



Artist's impression of Ariel on its way to L2. Credit: ESA / STFC RAL Space / UCL / Europlanet-Science Office.

Selected References

1. *CosmicVision: Space Science for Europe 2015-2025, BR* **247.** 109 pp. isbn: 978-92-9092-489-0 (ESA Publications Division, ESTEC, Noordwijk, The Netherlands, 2005)
2. Tinetti, G. *et al.* A chemical survey of exoplanets with ARIEL. *Exp Astron* **46**, 135–209 (2018). 10.1007/s10686-018-9598-x
3. Tinetti, G. *et al.* Ariel: Enabling Planetary Science across Light-Years. Version 1. doi:10.48550/ARXIV.2104.04824 (2021).
4. Da Deppo, V. *et al.* An Afocal Telescope Configuration for the ESA ARIEL Mission. *CEAS Space Journal* **9,** 379–398. issn: 1868-2502, 1868-2510. doi:10.1007/s12567-017-0175-3 (2017).
5. Diolaiti, E. *et al. Telescope Assembly Zemax OpticStudio® Tools for Statistical Analysis of Optical Tolerances* Ariel Payload Consortium Phase B2 Payload Study ARIEL-INAFPL-TN-015 Issue 1.0 (2021).
6. Ohl IV, R. G. *et al. Comparison of Stress Relief Procedures for Cryogenic AluminumMirrors* in *Proc. SPIE 4822, Cryogenic Optical Systems and Instruments IX* (eds Heaney, J. B. & Burriesci, L. G.) (Seattle, WA, 2002), 51. doi:10.1117/12.451762.
7. Chioetto, P. *et al.* The primary mirror of the ARIEL mission: study of thermal, figuring, and finishing treatments and optical characterization of Al 6061 samples mirrors. in *Proc. SPIE 11116, Astronomical Optics: Design, Manufacture, and Test of Space and Ground Systems II* (eds. Hallibert, P., Hull, T. B. & Kim, D. W.) vol. 11116 46 (SPIE, 2019).
8. Grèzes-Besset, C. *et al. High Performance Silver Coating with PACA2M Magnetron Sputtering* in *Proc. SPIE 11180, International Conference on Space Optics — ICSO 2018* (eds Karafolas, N., Sodnik, Z. & Cugny, B.) (SPIE, Chania, Greece, 2019), 1118083. doi:10.1117/12.2536210
9. Zuppella, P. *et al. Optical Coatings: Applications and Metrology* in *The 2nd International Electronic Conference on Applied Sciences* (MDPI, Oct. 15, 2021), 50. doi:10.3390/ASEC2021-11137

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