University of Padova

Department of Management and Engineering

Master Thesis in Management Engineering

Product assurance management and coating qualification of the Telescope Assembly mirrors in the Ariel mission

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to all those who have been part of this journey.
to my parents who always supported me wherever I wanted to go.

Abstract

The Atmospheric Remote-sensing Infrared Exoplanet Large-survey (Ariel), selected as ESA's fourth medium-class mission in the 'Cosmic Vision' programme, is set to launch in 2029. The objective of the mission is to conduct spectroscopic observations of approximately one thousand exoplanetary atmospheres enhancing our understanding of planetary system formation and evolution. Additionally, it seeks to establish a clear link between the characteristics of exoplanets and their parent stars.

The realization of the Ariel's telescope is a challenging task that is still ongoing. It is an off-axis Cassegrain telescope (M1 parabola, M2 hyperbola) followed by a re-collimating off-axis parabola (M3) and a plane fold mirror (M4).

The Telescope Assembly is made of EN AW 6061 and designed to operate at visible and infrared wavelengths, between 0.5 μm and 1.95 μm. The aluminum mirrors of the telescope are coated with a protected silver recipe, qualified to operate at cryogenic temperatures, to enhance reflectivity performance.

Object of this thesis work is the study of Product Assurance/ Quality Assurance (PA/QA) responsibilities applied in the context of the Ariel space mission, highlighting the importance of stringent quality controls in ensuring mission success.

Moreover, the activities carried out at CNR-IFN in Padua, Italy, concern the verification of the ageing effect on the mirrors coating which pose a specific technological challenge. The mirrors samples has been analyzed through Atomic Force Microscopy (AFM) for morphological characterization and with the aid of Fourier Transform Infrared (FTIR) spectroscopy for reflectance measures.

Contents

Listing of figures

Listing of tables

Listing of acronyms

AFM .... Atomic Force Microscopy

AOI .... Angle Of Incidence

ARIEL .... Atmospheric Remote-Sensing Infrared Exoplanet Large-survey

ASI .... Agenzia Spaziale Italiana

AMC .... Ariel Mission Consortium

CCB .... Configuration Control Board

CDR .... Critical Design Review

CI .... Critical Item

CIL .... Critical Item List

CNR .... Consiglio Nazionale delle Ricerche

DCU .... Detector Control Unit

DML .... Declared Material List

DMPL .... Declared Mechanical Parts List

DPL .... Declared Processes List

ECSS .... European Cooperation for Space Standardization

EEE .... Electrical, Electronic and Electromechanical

ESA .... European Space Agency

FMEA .... Failure Mode and Effect Analysis

FMECA .... Failure Modes, Effects, and Criticality Analysis

FTIR .... Fourier Transform InfraRed

ICU .... Instrument Control Unit

IFN .... Istituto di Fotonica e Nanotecnologie

IR .... Infrared

M1 .... Primary Mirror

M2M .... M2 mirror mechanism

MIP .... Mandatory Inspection Point

MS .... Metering Structure

MRR .... Manufacturing Readiness Review

MMPP .... Materials, Mechanical Parts and Processes

NC .... Non-Conformance

OB .... Optical Bench

PA .... Product Assurance

PAM .... Product Assurance Manager

PDR .... Preliminary Design review

QA .... Quality Assurance

RAL .... Rutherford Appleton Laboratory

RFD .... Request For Deviation

RFW .... Request For Waiver

SFE .... Surface Figure Error

TA .... Telescope Assembly

1 Introduction

Humanity's curiosity has always been the guiding star to explore the universe's mysteries. At the heart of this pursuit lies our deep desire to understand the origins of Earth and its unique ability to sustain life.

Leading the charge in the study of planetary formation of exoplanets, planets outside our Solar System, is the Ariel mission. In recent years, the focus has shifted from merely detecting planets to characterizing them. This involves observing their properties with high-resolution data from next-generation telescopes such as the James Webb Space Telescope and the Ariel Space Mission. Scientists aim to utilize this data to address various questions related to the processes leading to the formation and evolution of planets, which in turn will enhance the understanding of our own Solar System.

Space is one of the most extreme environments, presenting significant challenges for man-made machines such as satellites, spacecraft, and space telescopes. These challenges make each space project unique, necessitating the development of custom-built hardware and software.

Achieving success in space projects requires complex management skills and each mission involves teams made of many professionals and extensive resources, requiring diligent coordination.

The aim of this thesis is to provide an insight into how product assurance is managed, drawing from the experience of the Ariel mission. Product and Quality Assurance is a critical aspect of space mission, ensuring that all components and systems meet the stringent quality and reliability standards necessary for success.

By integrating engineering principles with advanced management strategies, these missions can not only achieve their scientific objectives but also be reliable and safe.

This chapter will outline the European context of the Ariel mission. It will offer an overview of the mission, detailing its scientific objectives and describing the Italian payload and associated responsibilities. A general explanation of the development phases will also be included to provide context. Finally, I will present my contributions to the mission.

1.1 Cosmic Vision

The European Space Agency (ESA) is an inter-governmental organization established in 1975 dedicated to promoting – for exclusively peaceful purposes – the exploration of space and space-related fields including Earth observation, human spaceflight, planetary exploration, satellite navigation, and telecommunications. The agency's mission is to coordinate the financial and intellectual resources of its members to undertake programs and activities far beyond the scope of any single European country [2].

Scientists, technologists, national funding agencies, space industry and international partners, all rely very heavily on the existence of ESA's long-term plan to build confidence in the success of a project that can take decades to develop [3].

Starting from April 2004, a new long term planning exercise was initiated by the ESA Science Programme. This plan is the third step in a decadal series: previously the Horizon 2000 plan was prepared in 1984 and Horizon 2000 Plus in 1994-1995.

The present 'Cosmic Vision 2015- 2025' document is the logical continuation into the next decade of the ESA science planning cycles. It aims at setting the scientific priorities and guides the selection of ESA missions [3].

The program addresses four main questions that are high on the agenda of research across Europe concerning the Universe and our place in it:

a **What are the conditions for planetary formation and the emergence of life?** This theme focuses on understanding the processes leading to the formation of planets and the conditions that might support life

b **How does the Solar System work?** It includes missions to various planets, moons, comets, and asteroids to study dynamics and processes of Solar System

c **What are the fundamental physical laws of the Universe?** This theme investigates the fundamental forces and laws governing the Universe.

d **How did the Universe originate and what is it made of?** This theme seeks to understand the origins and evolution of the Universe, from the Big Bang to the present day

The Science Programme is populated by different types of missions, each of which fulfil a clearly defined role. The four categories are based on the planned size and breadth of scientific goals addressed, and therefore reflecting on the cost and development time required.

Large (L-class) missions are European-led flagship missions with a launch cadence of approximately one every decade.

Medium (M-class) missions may be ESA-led or carried out with international partners. These provide flexibility within the programme and have an expected launch cadence of two per decade. Current M missions are: Solar Orbiter (M1) launched in 2020, Euclid (M2) launched in 2023, PLATO (M3) planned for 2026, Ariel (M4) with a launch planned in 2029, and EnVision (M5), selected in 2021.

Small (S-class) missions are a relatively new concept that enable Member State agencies to lead missions.

Fast (F-class) missions focus on innovative and rapid development and they are intended to be launched alongside an M-class mission.

In response to the call for the next medium-class opportunity, Cosmic Vision M4, the Atmospheric Remote-sensing InfraRed Exoplanet Large-survey (ARIEL) proposal was selected for the assessment phase in January 2015.

By June 2015, ARIEL was one of three missions chosen for a competitive Phase 0/A study.

In March 2018, ARIEL was officially selected as the M4 mission and advanced to Phase B1, the definition study phase. Following its selection, the mission's name was changed to Ariel. ESA formally adopted the mission in November 2020.

1.2 The Ariel mission

Ariel is the first space mission dedicated to measuring the chemical composition and thermal structures of a large, well-constructed sample of transiting and eclipsing exoplanets, pushing planetary science far beyond our Solar System. This comprehensive and unbiased survey addresses one of ESA's Cosmic Vision's core questions: "What are the conditions for planet formation and the emergence of life?" [4].

In particular, during its 4-year mission, Ariel will address key questions:

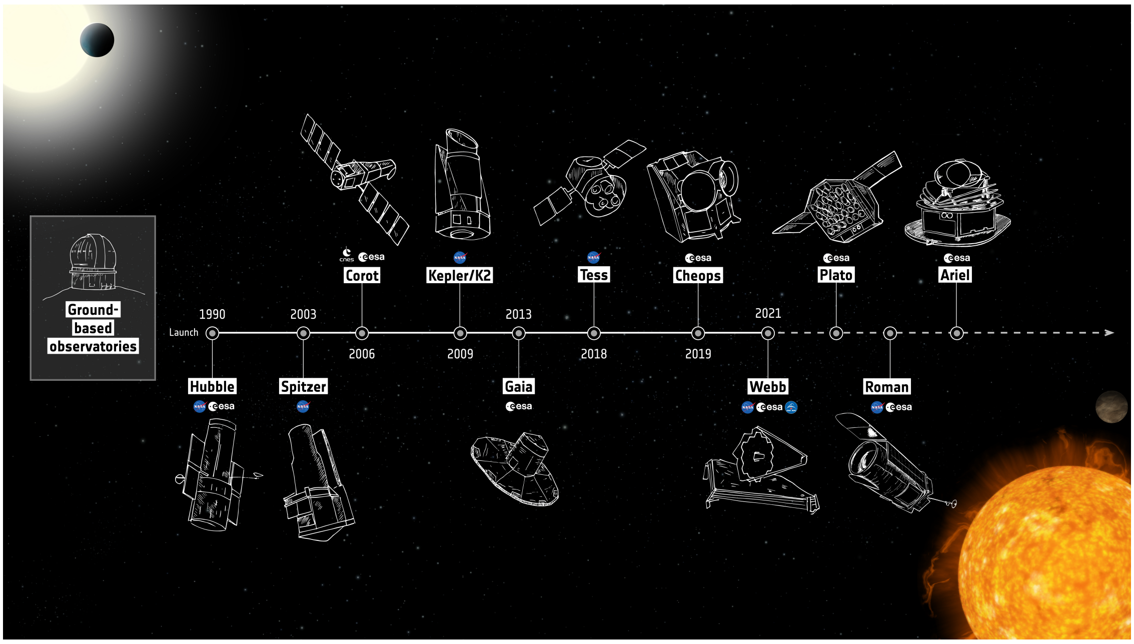


Figure 1.1: Graphic of exoplanet missions timeline. Source: ESA

- How do planets and planetary systems form?
- How do planets and their atmospheres evolve over time?
- What are exoplanets made of?

The primary objective of Ariel is to conduct an extensive survey by observing the atmospheres of exoplanets and their parent stars using near-infrared spectroscopy. To achieve this, the mission will utilize a dedicated space telescope, operating at cryogenic temperatures (50 K), which will be feeding a collimated beam through a Common Optics system into two separate instrument modules: the FGS, a combined Fine Guidance System/VIS-Photometer/NIR-Spectrometer and AIRS, a 2-channel low resolution IR spectrometer [5].

Throughout its four years of flight operations, Ariel will examine the chemical and physical properties of approximately 1,000 known exoplanets to study planetary formation and evolution. Ariel will focus on a large population of exoplanets already discovered by other facilities. An unbiased survey is essential for a statistical understanding of gas giants, Neptunes, super-Earths, and Earth-sized planets around various types of bright stars. Ariel will achieve this through transit spectroscopy and multi-band photometry across the 0.5µm to 7.8µm range of the electromagnetic spectrum, primarily targeting warm and hot exoplanets with temperatures from several hundred to a few thousand Kelvin [5]. An impression of the Ariel spacecraft is presented in Figure 1.2.

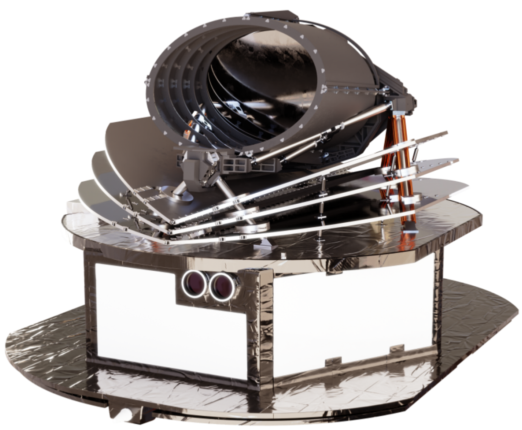


Figure 1.2: Artist impression of Ariel. Source: ESA

1.3 Mission lifetime cycle

Following ESA guidelines on Project Planning and Implementation [6], defining phases and formal milestones ensures that the project's progress is controlled with respect to cost, schedule, and technical objectives. Each phase concludes with project reviews that determine readiness to proceed to the next phase.

The life cycle of space projects is typically divided into 7 phases, as follows:

- Phase 0 - Mission analysis/needs identification.
- Phase A - Feasibility.
- Phase B - Preliminary Definition.
- Phase C - Detailed Definition.
- Phase D - Qualification and Production.
- Phase E – Utilization.
- Phase F – Disposal.

In the case of Ariel mission for phase 0 and A, it was competing with two other candidate missions (THOR and XIPE), with only the selected mission advancing to Phase B. Phase B was split into two parts: B1 (definition phase) and B2 (implementation phase), following its formal adoption by ESA in November 2020. This included identifying all activities and resources for developing the space and ground segments, initial assessments of technical and programmatic risk, and initiation of pre-development activities.

In December 2023, the payload concluded Phase B2 with the Preliminary Design Review (PDR), which describes the complete system and its subsystems, including operational and interface requirements [7]. Ariel's payload critical technology is now considered at Technical Readiness Level 6 [8], indicating that the mission can proceed to the payload Critical Design Review (CDR) and begin manufacturing its first prototype models. In figure 1.3 the Technological Readiness levels chart for estimating the maturity of a technology.

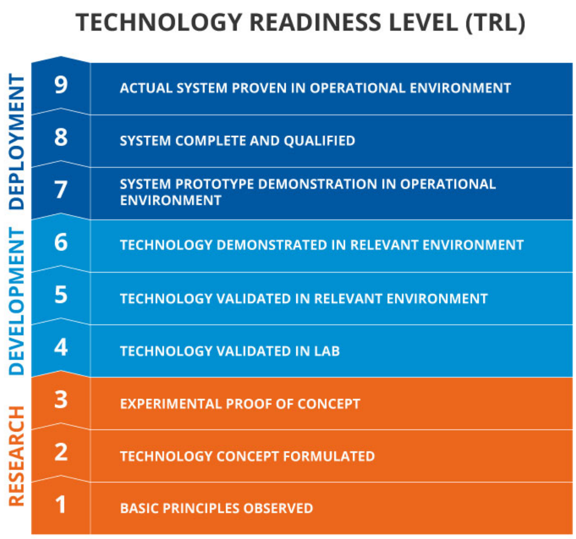


Figure 1.3: Technology Readiness Levels (TRLs) provide a measure of the maturity of a technology, from initial concept to deployment. The levels range from TRL 1 to TRL 9, with each stage marking progress toward realization. Source: TWI Global.

The next Phases C and D, will focus on developing and qualifying the space and ground segments. Phase E normally encompasses all activities required to launch, commission, utilize, and maintain the orbital elements of the space segment and the associated ground segment. Finally, Phase F will concentrate on the safe disposal of all launched products and the ground segment.

1.3.1 Reviews

The transition between the various phases is clearly marked by a comprehensive review of all documentation describing the system of interest.

Below is a list of the main reviews conducted at the end of each mission phase:

- Phase A concludes with the Preliminary Requirements Review (PRR).
- Phase B: The system requirements review (SRR) is held during the course of Phase B which ends with the Preliminary Design Review (PDR).
- Phase C concludes with the Critical Design Review (CDR).
- Phase D: The qualification review (QR) held during the course of the phase, which Ends with the Acceptance Review (AR) and the Operational Readiness Review (ORR).
- Phase E: The Flight Readiness Review (FRR) is held prior to launch while the Launch Readiness Review (LRR) is completed immediately prior to launch. The Commissioning Result Review (CRR) is held after completion of the on-orbit commissioning activities. The phase Concludes with the End-of-Life Review (ELR).
- Phase F ends with the Mission Close-out Review (MCR).

In Figure 1.4 a summary of a mission Phases and corresponding Reviews.

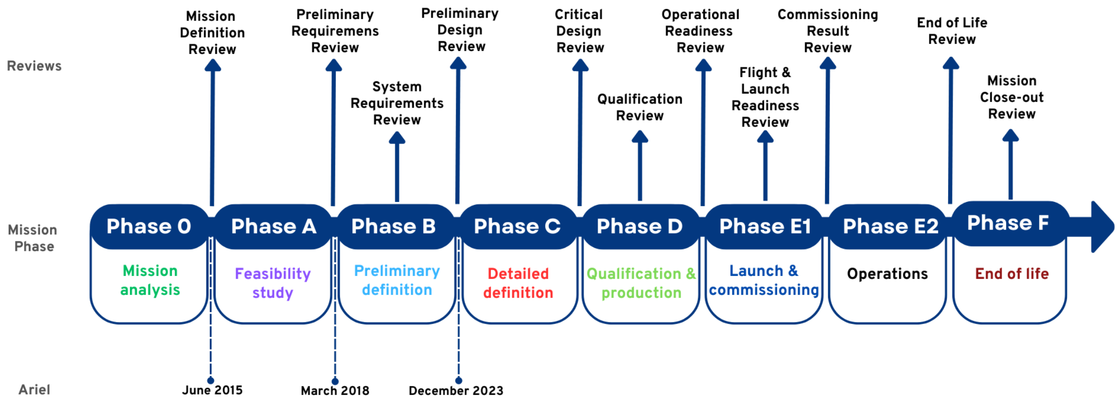


Figure 1.4: Phases of a mission, Reviews and Ariel's current timeline.

1.3.2 Milestones

At the time of writing, Ariel has successfully completed its payload Preliminary Design Review (PDR), demonstrating that the mission's payload design meets all the required technical and scientific specifications. As presented in Table 1.1 the launch is planned for 2029. Its final destination is the Sun-Earth Lagrange point 2 (L2), approximately 1.5 million kilometers from Earth, providing a stable environment away from Earth's and Moon's disturbances. Ariel will be launched from Kourou, French Guiana, on board of Ariane 6.2 rocket in a dual launch configuration with Comet Interceptor. Ariel will be positioned underneath the Dual Launch Structure, while Comet Interceptor will ride on top. The nominal mission lifetime is 4 years + 2 years of possible extended operations.

Milestone	**Schedule**
Mission Adoption	Nov 2020
Phase B2/C/D/E1 industrial KO	Sept 2021
System SRR	Q1/2022
System PDR	mid-2023
System CDR	Q2/2025
FAR	Q1/2029
Launch (L)	2029
LEOP	L + 48 hrs
Start of Satellite and Payload commissioning phase	L + few days
Start of performance verification and science demonstration phase	L + < 3 months
Start of nominal in-orbit science operations phase	L + < 6 months
End of nominal in-orbit operations phase	L + 4 years
End of extended in-orbit operation phase (goal)	L + 6 years
S/c disposal (in parallel with post-operations phase)	L + 4/6 years + 3 months
End of post-operations phase	L + 6/8 years

Table 1.1: Key dates of the Ariel mission. Source: Ariel Red Book

1.4 Mission Implementation

In this section is presented an overview of the Ariel mission implementation.

Ariel, for both the space and ground segments, will be implemented and operated by ESA and the Ariel Mission Consortium (AMC) in collaboration.

1.4.1 Ariel Mission Consortium

The Ariel mission concept has been developed by the Ariel Mission Consortium, led by Prof. Giovanna Tinetti (Principal Investigator) and Paul Eccleston (Consortium Project Manager), comprising teams from 16 European countries, with external contributions from NASA (USA), Japan Aerospace Exploration Agency and Canadian Space Agency. The Ariel Mission Consortium is supported by their respective national funding agencies, with each team responsible for specific modules or design/analysis functions [4].

AMC has allocated tasks based on the skills and resources of the participating institutes, aligning with national interests in Ariel's science. This approach ensures a comprehensive range of state-of-the-art knowledge and technical design expertise is applied to the design, construction, and testing of the instrument.

The Italian contribution is directed by Dr. Giusi Micela[1] of INAF Palermo and Dr. Giuseppe Malaguti[2] of INAF Bologna as co-principal investigators, along with Prof. Emanuele Pace of the University of Florence (national project manager). This effort is supported by a large team of researchers from additional national institutions and coordinated by the Italian Space Agency (ASI). At this stage of the project, the Italian team has the design authority of the telescope.

Within the Italian contribution to the mission, the team at CNR-IFN (Institute for Photonics and Nanotechnologies of the National Research Council of Italy) in Padova is responsible for the Assembly, Integration, and Verification (AIV) management of the telescope and for the National Product and Quality Assurance (PA/QA) management.

1.4.2 Payload Architecture

The Ariel telescope's fundamental structure divides into two primary sections according to their operating temperatures:

- The cold payload module, maintained at cryogenic temperatures;

[1] INAF-Osservatorio Astronomico di Palermo, Piazza del Parlamento 1, 90134 Palermo, Italy

[2] INAF-Osservatorio di Astrofisica e Scienza dello spazio di Bologna, Via Piero Gobetti 93/3, 40129 Bologna, Italy

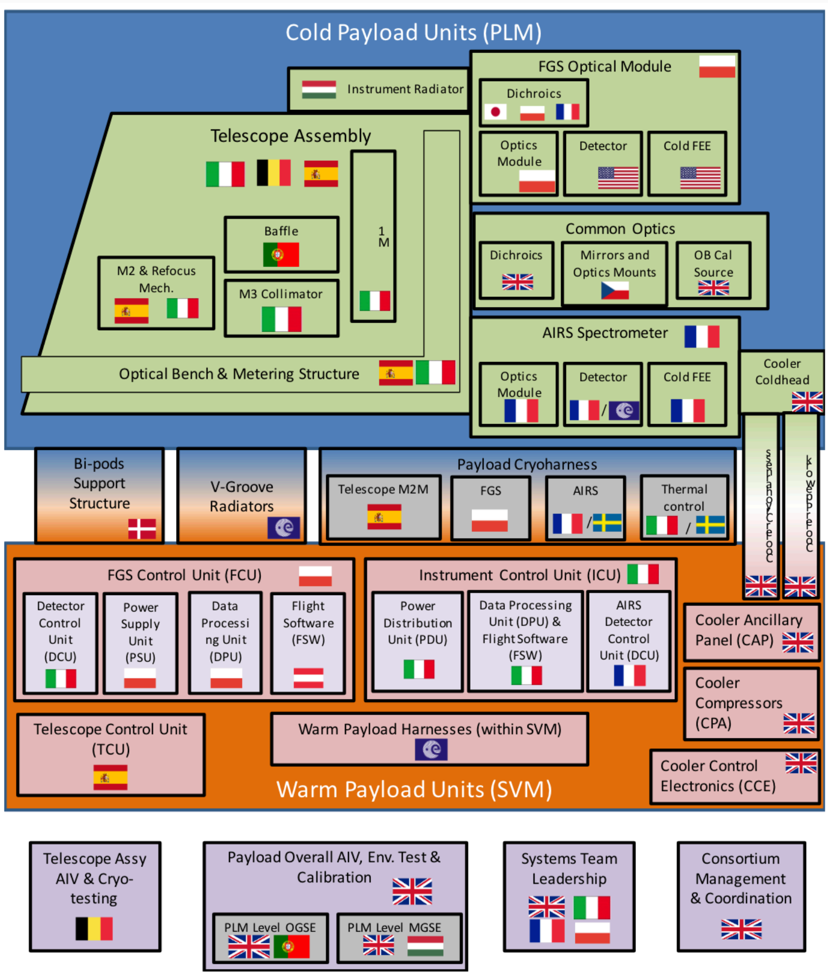


Figure 1.5: Ariel Payload architecture and responsibilities of the members of the Ariel Mission Consortium. Source: ESA

- The warm payload electronics that mount within the spacecraft service module (SVM).

The payload module undergoes passive cooling, achieving temperatures below 50 K by being isolated from the spacecraft bus through a series of three V-Groove radiators. The only components necessitating active cooling to below 42 K are the detectors for the AIRS, achieved through an active Ne JT cooler.

In Figure 1.5 is reported a schematic representation of the Pyaload architecture of Ariel.

The main mechanical units composing the PLM are:

- The Ariel Telescope Assembly including an optical bench, all mirrors, baffles and structures plus the M2M refocusing mechanism;
- The AIRS and FGS instruments, common optics and the on-board calibration system;
- The telescope assembly support structure (isolating bipods);
- The thermal control system (instrument radiators, thermal straps, active cooler heat exchanger, and integration of the ESA provided V-grooves into the PLM).

1.4.3 Telescope Assembly

The Ariel Telescope Assembly consists of all-aluminium telescope, M2 Mechanism and baffles. The off-axis Cassegrain telescope, operating at cryogenic temperature (55 K) feeds a collimated beam into two separate instrument modules located on the Telescope Optical Bench (TOB) behind the Primary Mirror M1. Moreover, M1 mirror is mounted on the Optical Bench (OB) with a support based on flexure hinges [9].

The two instruments are the Fine Guidance system (FGS) and the ARIEL InfraRed Spectrometer (AIRS), that accommodate photometric and spectroscopic channels covering the band from 0.5 µm to 7.8 µm in the visible to near-IR range [5].

The Ariel Telescope optical system is composed of four mirrors, all made of aluminium alloy Al 6061-T651, which ensures excellent thermal stability due to its high-quality optical specifications. This builds on the significant design heritage within Europe of building all-aluminium space instruments for cryogenic operation.

The primary mirror (M1) is an ellipse, with an aperture measuring 1.1 meters by 0.73 meters. This is followed by a hyperbolic mirror (M2) with a diameter of approximately 112 mm, a recollimating off-axis parabola (M3) with a diameter of about 30 mm, and a flat folding mirror

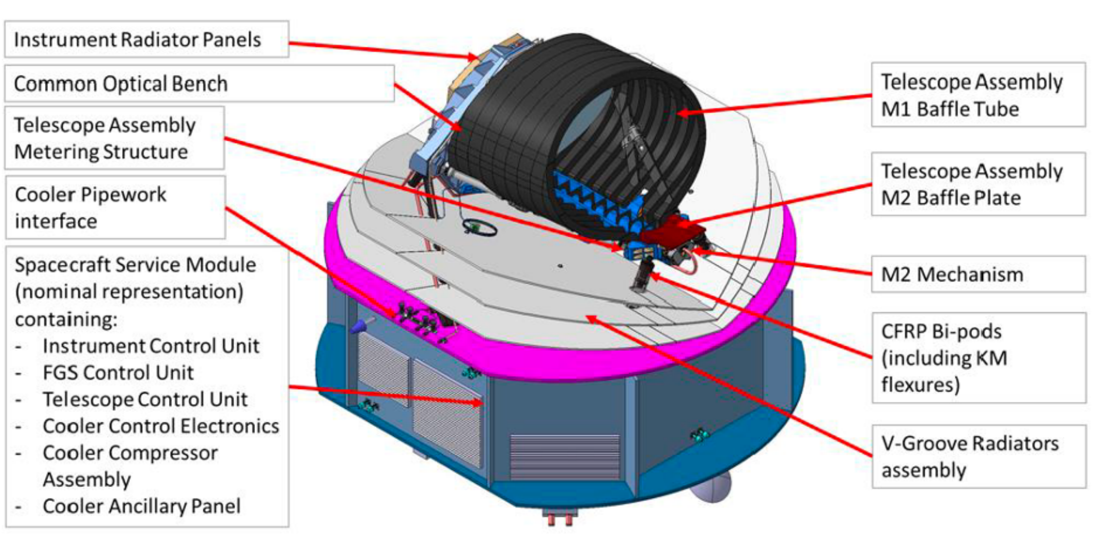


Figure 1.6: Cold Payload Module elements. Source: AMC

(M4) with a diameter of 31 mm. The primary mirror's significant size necessitated a lightweight design to reduce its overall mass.

To increase the reflectance of the optical surfaces within the working spectral range of 0.5 μm to 7.8 μm, a protected silver coating has been applied to the mirrors. This coating enhances the telescope's performance by maximizing the reflectivity, ensuring optimal efficiency and sensitivity in its observations. This sequence of mirrors, combined with the high-reflectance coating, forms an highly efficient optical path, optimizing the telescope's overall performance.

As shown in Figure 1.6, the TA also includes the Metering Structure (MS) which is an aluminium bracket rigidly connected to the Optical Bench (OB). MS subsystem is linked to the PLM module by means of bipods, which are not part of the TA. Additionally, there are lateral struts to reinforce the structure of the TA and contamination shield developed by Leonardo SpA [3] and Media Lario s.r.l[4].

Subsystems of the TA include:

- The baffle system surrounding M1 and the optical bench, which reduces the M1 view factor and blocks any direct view of the sky from M2. This baffle is made from an Al 6061 alloy honeycomb structure and is thermally connected to the optical bench to enhance

[3] Leonardo S.p.A. Space Division, Via delle Officine Galileo, 1, 50013 Campi Bisenzio (FI), Italy.
[4] Media Lario S.r.l., Via al Pascolo, 23842 Bosisio Parini (LC), Italy.

TA thermal stability. Portugal contributed this baffle to the consortium, with Active Space [5] as the manufacturer

- M2M refocusing mechanism on which M2 in mounted on. M2M has three degrees of freedom (focus and tip/tilt) based on the heritage of GAIA and EUCLID [10]. This mechanism aims to compensate for settling effects after launch and cooling. Additionally, it allows for adjustments during the mission to compensate for long-term structural effects. Spain, specifically SENER [6], is responsible for the M2M subsystem.

Figure 1.7: Details of the Telescope Assembly elements. Source: AMC

1.5 Contribution

The activities carried out at CNR-IFN concerned the ageing of the mirrors silver coating which pose a specific technological challenge. This work also focuses on PA/QA aspects applied to the space sector.

More specifically:

- Product Assurance management in a space mission and the responsibilities of this role;
- PA/QA in the space sector and in particular for the Ariel mission, with description of specific document management tools;
- Description of the the mirrors materials and specifically of M1;
- Analysis of possible ageing effect of the silver coating of the telescope mirrors through morphological characterization of the samples based on Atomic Force Microscopy (AFM);

[5] Active Space Technologies S.A., Parque Industrial de Taveiro, Lote 12 3045-508 Coimbra, Portugal.
[6] SENER Grupo de Ingeniería, Cervantes, 8, 48930 Getxo, Spain

- Reflectance measures of sample mirrors in the infrared spectrum by Fourier Transform InfraRed (FTIR) spectroscopy.

2
Product Assurance

For space science projects within ESA, the policy is to comply with the set of established standards by the European Committee for Space Standardization (ECSS). The Ariel mission development is considered to be a large project, which requires a product assurance plan as a standalone document.

Product and Quality assurance is about delivering what the customer needs and expects. However, for the type of project covered in this thesis, there is no single delivery to the customer [11]. The products and services of such projects will evolve according to the phases of a space mission; therefore it is crucial that these products are meticulously evaluated and documented.

This chapter outlines the role and responsibilities of a Product Assurance Manager, both in general terms and specifically in the context of the Ariel mission. Some aspects and documents are discussed in greater detail, as they were addressed during the internship at CNR-IFN.

2.1 European Cooperation for Space Standardization

For space science projects within ESA, the policy is to comply with a set of standards. The applicable standards are those produced and maintained by the European Cooperation for Space Standardization body.

The European Committee for Space Standardization (ECSS) was created in 1993, replacing ESA as the European authority responsible for the creation and publishing of standards for space projects. ECSS includes members such as ESA, European national space agencies like ASI (Italian Space Agency), CNES (Centre national d'études spatiales), and DLR (German Aerospace Center), Eurospace representing the European industry, and the Canadian Space Agency (CSA) [12].

The ECSS standards are a collection of technical guidelines developed to regulate and harmonize European space activities. These standards ensure the efficiency, safety, and quality of European space missions while promoting cooperation and interoperability among ESA member states and other European space organizations. They are presented in the form of requirements, recommendations, or permissions and are periodically updated to incorporate technological advancements and industry best practices. ECSS standards play a significant economic and social role by enabling the space industry to remain competitive and address new markets. They serve as neutral, unambiguous benchmarking tools.

The ECSS also maintains links with international standards organizations, such as the International Organization for Standardization (ISO), to promote harmonization. Among the ISO standards, the ISO 9000 series focuses on quality management principles, emphasizing customer satisfaction, process approach, and continuous improvement [13].

The ECSS is a system of coherent standards that supports a wide range of diverse space projects. In their original form may not perfectly suit the specifics of individual projects. This misalignment can reduce project performance in terms of technical outcomes, life cycle cost-effectiveness, or timeliness of deliveries. To address this, a process known as tailoring is employed. Tailoring involves adjusting the requirements of the standards to fit the unique aspects of each project. This customization is essential for applying the coherent yet generic ECSS standards effectively to the specific needs of a project, thereby optimizing performance and ensuring successful mission outcomes [14].

2.1.1 ECSS architecture

Most ECSS standards documents follow a systematic naming approach: ECSS-[branch]-[type]-[number] [version]. The "branch" is a specific area/ specialisation relevant to space missions and projects. The "type" is referred to the style in which they are written which can be standard (ST), handbook (HB), technical memoranda (TM). "Number" is one or two group of digits and "version" is a letter from "A" onwards [15].

The ECSS system organizes its standards into five different branches:

1. ECSS-P and ECSS-S: This branch deals with the ECSS itself, describing how standards

are developed and providing a glossary of aerospace terms.

2. ECSS-M: These standards address management topics.

3. ECSS-U: This branch focuses on sustainability issues, such as space debris and protecting alien planets from terrestrial life forms.

4. ECSS-Q: These standards outline requirements for Product Assurance.

5. ECSS-E: This branch concern engineering standards.

Within each branch, there are several top-level standards (denoted by a number that is a multiple of 10) addressing specific disciplines.

More specifically, the Q branch analysed in this thesis includes:

- Q10: Product assurance
- Q20: Quality assurance
- Q30: Dependability
- Q40: Safety
- Q60: Electrical, electronic, and electromechanical components
- Q70: Materials, mechanical parts, and processes
- Q80: Software product assurance

The ECSS standards are organized into levels to provide a structured approach:

- Level 0: Describes the policy and objectives of the ECSS system.
- Level 1: Outlines the strategy and general requirements applicable to a domain and describes the interface between level 2 disciplines.
- Level 2: Defines the objectives and requirements of an individual discipline.
- Level 3: Presents requirements and guidelines on a specific activity.

In Figure 2.1 the ECSS architecture is reported along with the reference levels.

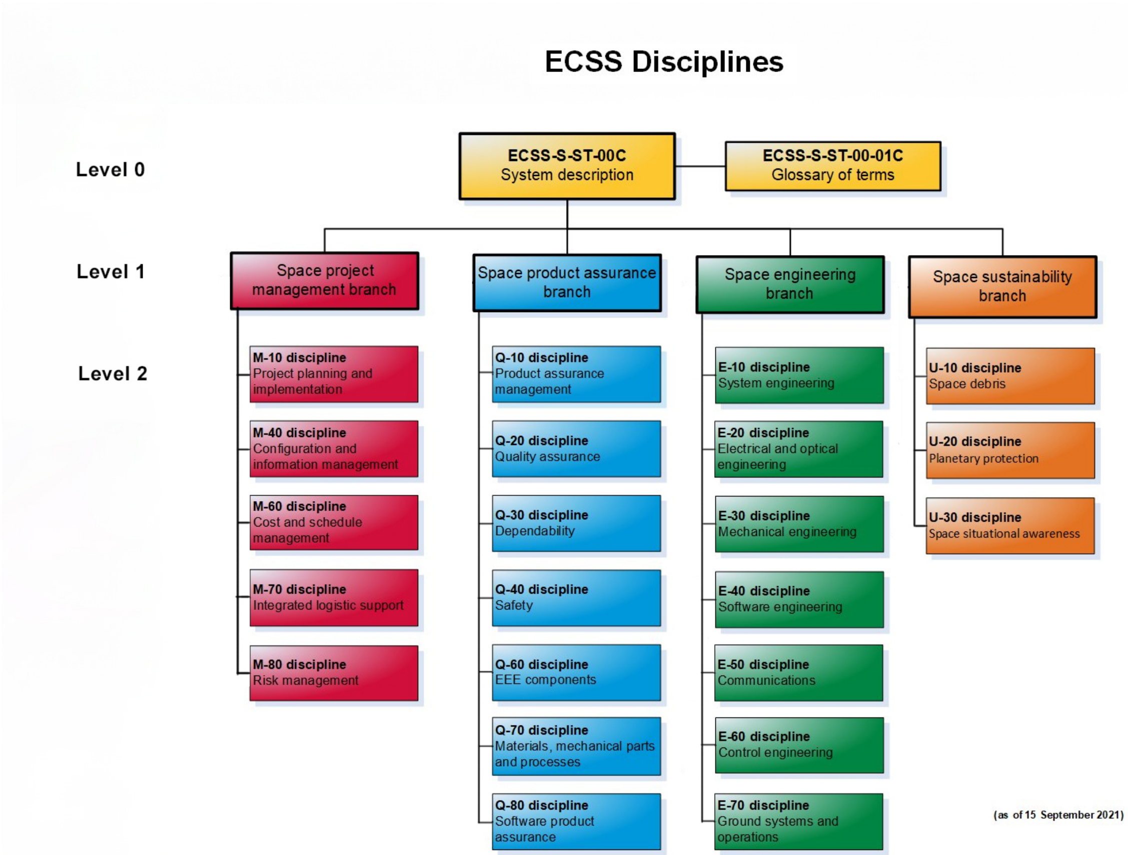


Figure 2.1: Document tree of the ECSS architecture. Source: ECSS.

2.2 Product Assurance

Product assurance (PA) is one of the three primary functions in a space project, alongside project management and engineering. While project management focuses on nontechnical aspects such as project planning, resource allocation, and budgeting, engineering deals with the technical development and execution of the project [16]. However, these functions are interconnected. System Engineers and Project Managers work closely with the Product Assurance Manager (PAM), whose role is to support activities to ensure technological and scientific success.

In the ECSS document "System Description, Implementation, and General Requirements" ECSS-S-ST-00C [15], PA is defined as "a discipline that plans and implements the essential activities to meet the specified requirements throughout the product life cycle" and is further elaborated in "Product Assurance Management" (ECSS-Q-ST-10C) [17].

As shown in Figure 2.2, there are seven disciplines in the space PA branch, namely:

- Product Assurance Management
- QA
- Dependability
- Safety
- Electrical, electronic and electromechanical (EEE) components
- Materials, mechanical parts and processes
- Software PA

The primary output of product assurance management is the product assurance plan, which is prepared, maintained, and implemented by the supplier and delivered to the customer, as required by ECSS-Q-ST-10C.

In the development of space instrumentation, product assurance and quality assurance management are crucial to ensure the success and safety of missions. Product Assurance and Safety (PA-S) engineers do this by providing engineering support to all ESA activities, verifying compliance to Product Assurance requirements. They represent an independent technical authority in the materials, mechanical parts, processes and electrical component domains, while also providing bespoke space environmental exposure facilities for use in support of European programmes [18].

The Product Assurance Manager plays a crucial role, having access to the highest management levels. Major tasks of the PAM include communicating with the project manager to ensure that schedule and contractual requirements are met and that product assurance activities are properly executed. The PAM stays in close contact also with the supplier and the supplier's product assurance to ensure that development processes fulfill the requirements and are suitable to ensure the quality of the product.

By overseeing these activities, the PA manager ensures that the project adheres to the necessary quality and safety standards throughout its life cycle.

2.3 Product Assurance: the Telescope Assembly

In this paragraph it's described how Product Assurance applies to the Ariel Mission.

As described in the introduction 1 of this thesis the Telescope Assembly, which is part of the cold payload, includes the telescope, the M2M mechanism and the baffles.

The CNR-IFN is responsible for the National Product Assurance management within the Science team, which means coordinating PA efforts for the Italian scientific contributions to the Ariel mission, including the Telescope Assembly by CNR-IFN, the ICU (Instrument Control Unit) hardware/software by INAF (Istituto Nazionale di Astrofisica), the DCU (Detector Control Unit) hardware by OHB[1].

As the PA Manager of the Telescope Assembly, CNR-IFN oversees the PA activities for the telescope and its subsystems.

This includes ensuring the flow-down of PA requirements to the telescope (Leonardo SpA, Media Lario s.r.l.), baffles (Active Space), and the M2M mechanism (SENER). The implementation of these PA programs is monitored throughout the TA project life cycle.

Meanwhile, ASI PAM, ESA, and AMC PAM supervise the PA TA activities.

Each Italian contributor to Ariel within the Science team also has an industrial counterpart PAM:

- **Leonardo SpA** for telescope manufacturing.
- **Media Lario s.r.l.** for telescope mirrors.
- **Kayser**[2] for ICU hardware.

[1]OHB-SE Italia, Via Gallarate, 150, 20151 Milan, Italy
[2]KAYSER ITALIA Srl, Via di Popogna, 501, 57128 Livorno, Italy

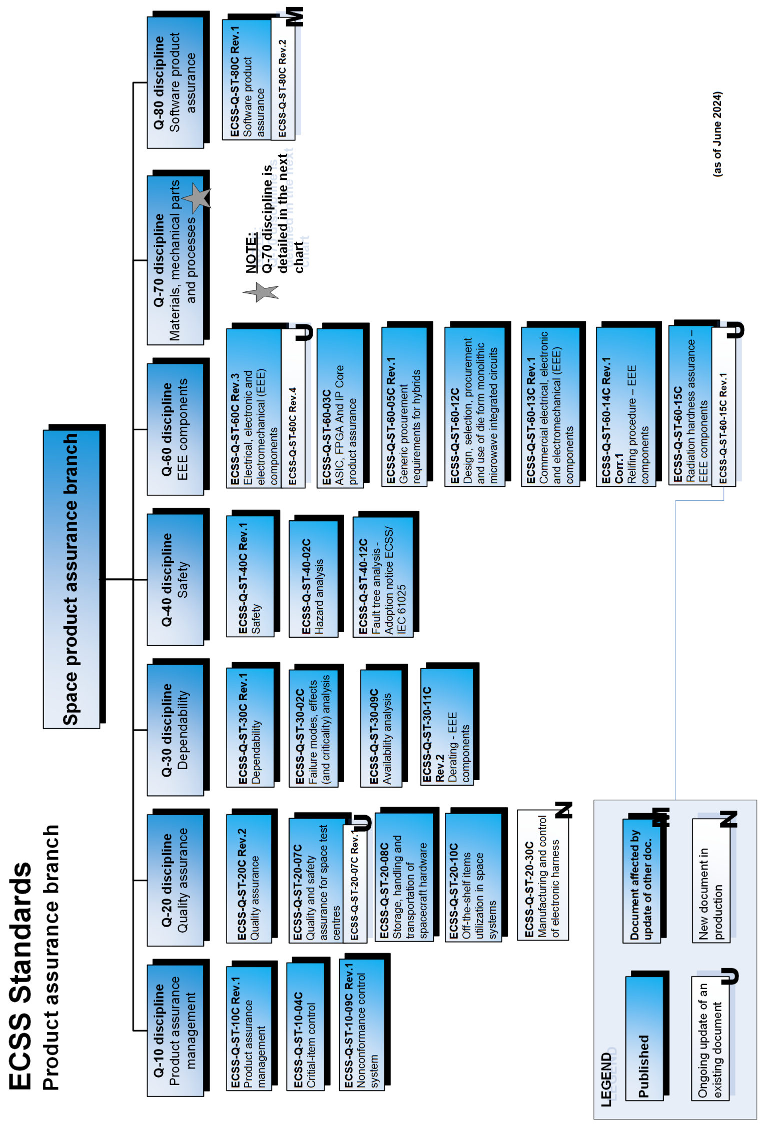


Figure 2.2: Document tree of the Q-branch and its disciplines. Source: ECSS.

- The ICU software is developed by **INAF** without industrial contributions.
- **OHB** for DCU hardware.

In Figure 2.3 is presented the diagram of Product Assurance Managers relationships at TA level.

The high-level PA documents of the Telescope Assembly, such as the PA plan, are managed by CNR-IFN. Other TA Product Assurance documentation include:

- Product Assurance requirements to suppliers;
- TA Critical Items List (CIL);
- TA Qualification Status List (QSL);
- TA Dependability and Safety Analyses (supported by the industrial PA team - Leonardo SpA);
- Parts (EEE and mechanical), materials, and processes list and documentation (DCL, Parts Approval Documents, and Radiation Test Plans);
- Inspection and audit reports;
- Non-conformance status list;
- Request for Deviation (RFD)/Request for Waiver (RFW) list;
- Quality records providing objective evidence of complete performance of QA tasks.

Coordinated PA actions are planned throughout the design and development phases to ensure that the Telescope Assembly meets all functional and technical requirements and that the design is thoroughly verified and validated.

A subset of the main responsibilities of the PA manager includes:

- Ensuring all applicable documents and data necessary for PA activities are available;
- control of the development, execution and maintenance of the programme PA tasks defined in the PA plans released by the PAM of the subsystems;
- control and monitoring the critical items and technologies;
- supervision of the MMPP (Materials, Mechanical Parts and Processes) program;

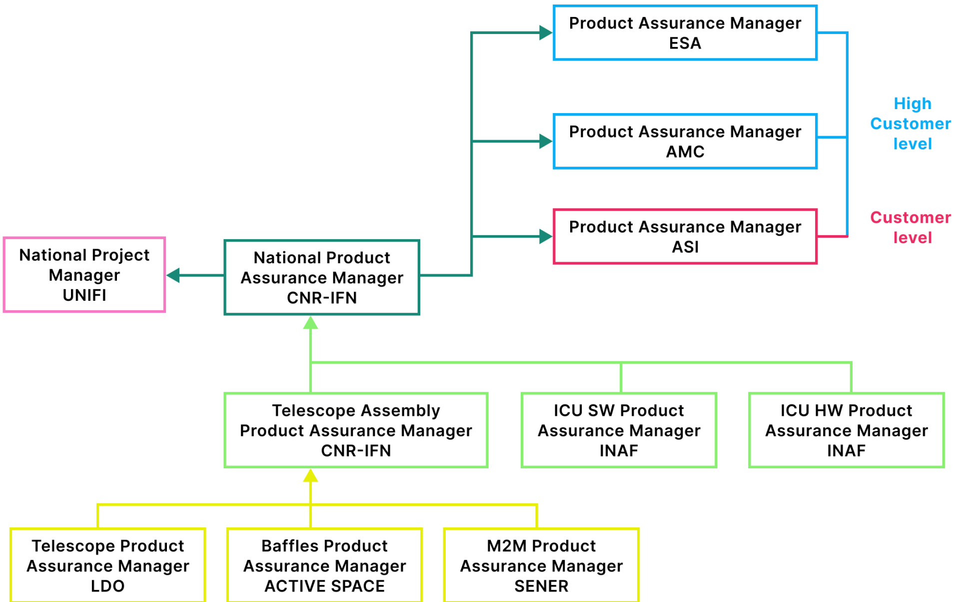


Figure 2.3: Diagram of the PA managers within the Telescope Assembly.

- reporting and documentation of the PA activities towards the National PAM, the Customer ASI, ESA and AMC;
- organization and management of the TA Manufacturing Readiness Reviews (MRRs);
- update of the DMPL tool for the TA.

2.3.1 Critical Item List

Ensuring the reliability of every component is a core responsibility of PA. This is achieved through the Critical Item List (CIL), which serves as a comprehensive inventory of items and processes within a space project considered critical to the mission's success and safety.

As stated in ECSS-Q-ST-10-04C [19] critical items (CI) pose potential threats to the performance, quality, dependability, and safety of a system. They are managed through a specific action plan to mitigate the associated risks and prevent undesirable consequences.

By their nature, critical items can introduce risks into a project. While the CI control process manages these critical items, the risk management process addresses the associated risks. In the domain of product assurance management, risk management and the control of critical items ensure that management is informed of all potential unexpected situations and risks. This coordination makes it easier to align risk management and critical item control with overall management functions [20].

ECSS-Q-ST-10-04C explains that CI control process consists of 11 tasks:

1. Establish the CI definition for the project, identifying applicable requirements and classification criteria.
2. Define the scope and objectives of the CI control process.
3. Plan the implementation of the CI control process for the project. The supplier shall assign responsibility for CI control management in accordance with the product assurance plan.
4. Identify critical items per the project's documentation and determine the nature of their criticality. Inputs from various PA analyses, such as FMECA results and hazard analysis, help in identifying critical items.
5. Classify critical items.
6. Prioritize critical items with inputs from the risk management process.
7. Propose CI control measures and determine verification methods.
8. Decide on the CI control measures.
9. Implement the agreed CI control measures.
10. Monitor and communicate the results of the CI control process.
11. Close out the CI control process for the project. The supplier shall submit the completed critical item list for formal acceptance by the next higher-level project management.

CI control activities are conducted at various levels of the customer-supplier chain, with lower-level activities integrated into the system-level activities. The Critical Item List CIL evolves throughout the project life cycle, starting with a preliminary CIL at PDR.

All critical items identified during the Critical Design Review (current document phase of the Ariel mission payload) are subject to evaluation.

More specifically, the Telscope Assembly-CIL contains items classified as critical because of:

- single point failures;
- limited life items;
- hazardous items of categories catastrophic and critical;
- critical technologies;
- fracture critical items;
- other critical items e.g. vulnerable items.

Partners are required to maintain a CIL to provide information to the Ariel Mission Consortium PA Manager on critical items they are responsible for, ensuring that project critical items are correctly identified and managed.

The TA CIL is updated to the main reviews and will be maintained permanently.

2.3.2 Non Conformance Control System

Within the PAM discipline, the Nonconformance Control System ECSS-Q-ST-10-09C [21] is utilized. A Non-Conformance (NC) refers to an apparent or proven condition of any item, process, operation, or service where one or more characteristics fail to meet specific requirements. When a NC is detected, the project PA representative analyses it to determine its extent and cause. NC are classified as major, or minor based on severity of their consequences.

Major NC are those that can have an impact on the customer's requirements in the following areas and cases:

- Safety of people or equipment;
- operational, functional or any technical requirements described in the business agreement;
- reliability, maintainability, availability;
- lifetime;
- functional or dimensional interchangeability;
- interface with hardware or software regulated by different business agreements;
- changes to or deviation from approved qualification or acceptance test procedures;
- project specific items which are proposed to be scrapped;

- for EEE(Electrical, Electronic and Electromechanical) components in case of:
  - Lot or batch rejection during manufacturing, screening or testing at the manufacturer's facilities;
  - NC detected after delivery from the manufacturer.

Non-conformances of the telescope and subsystems will be reviewed and dispositioned by a formal Non-conformance Review Board (NRB). The NRB for major Non-Conformances will include at least the AMC PAM, ASI PAM, TA PAM, representatives from the Engineering organisations and, if necessary, relevant experts involved in the review, investigation, and disposition of non-conformances.

ECLIPSE Suite

In the space sector, a significant amount of documentation is created and exchanged among the many actors involved in any given project or mission. Managing and maintaining a high level of document configuration, status accounting, and control over such documentation, including its traffic and exchange, is a challenge. The solution lies in using tools and software for version control, issue tracking, document storage, testing, continuous build, and scripting.

For the TA, the implementation of the NC control system is a collaborative effort with industrial partners, specifically done through the ECLIPSE software Suite provided by Sapienza Consulting [22].

The CNR-IFN and ASI is informed of Major NCRs at TA subsystems/suppliers/ subcontractors level within 48 hours after the discrepancy is observed. AMC PAM is informed by CNR-IFN of Major NCRs at TA subsystem level. Moreover, minor NCRs are reported to the next higher contractual level.

This suite includes the Document Configuration and Change Management (DCCM), Non-Conformance Tracking System (eNCTS), Review Items of Discrepancy (eRID) and Action Items Manager (AIM).

Document Configuration and Change Management. The DCCM allows members of a project to create a document and its reference, applicability and status all in alignment with predefined user access rights and security protocols.

Non-Conformance Tracking System. The ECLIPSE eNCTS module enables recording, monitoring and closure of Non-Conformances (NCs) encountered throughout the various phases of space system engineering projects. This system significantly enhances the visibility of NC status for Quality and Space Product Assurance functions. eNCTS is utilized both internally by the organization overseeing product realization (ESA and RAL Space UK) and externally by suppliers of components and subsystems (Leonardo SpA, Media Lario Srl, Kayser Srl, OHB SpA).

Review Items of Discrepancy. The eRID module facilitates the preparation, management, and control of formal project and mission reviews, ensuring traceable and successful outcomes. It allows review participants to access deliverable data packs, contractual or technical baselines, and requirements documentation online.

Action Items Manager. The AIM tracks and reports on all workflow actions initiated by other modules within the ECLIPSE Software Suite. This feature is used for addressing technical challenges and monitoring the progress of their resolution and closure. By serving as a comprehensive dashboard, the Action Items Manager provides users with streamlined access to all ongoing actions within a specific project environment.

2.3.3 RFD/RFW

Requests for Deviation (RFD) and Requests for Waiver (RFW) are formal documents used to manage non-conformances and exceptions in space projects.

A RFD serves to identify the areas of non-compliance or deviation from a space project requirements. This deviation is typically requested before or during the production, testing, or operation phases.

A RFW is submitted when a permanent acceptance of non-compliance with a specified requirement is sought. This usually happens after a non-conformance has been detected that cannot be corrected.

Both RFDs and RFWs are subject to review and approval processes, ensuring that any deviations or waivers do not compromise the mission's overall safety and success. The approval involves technical evaluation, risk assessment, and acceptance by relevant stakeholders which are ESA/RAL Space in the case of the Ariel mission.

The RFD and RFW of the telescope and subsystems are managed at TA Configuration Control Board (CCB) level and subsequently discussed in the AMC CCB if they impact high-level requirements. In this case it's the TA PA that provides to ESA and to the Ariel Mission Consortium the list of requests for deviation and requests for waiver of the TA (telescope, baffle and M2M).

2.4 Quality Assurance

Quality management standard ECSS-Q-ST-20C [23] defines the requirements for establishing and implementing a Quality Assurance (QA) program for products in space projects. QA should be adopted from the beginning of the project and maintained throughout its duration. The standards state that QA principles should be followed for:

- Design and verification;
- Procurement activities, including selection of sources, control of purchase documents, and surveillance of suppliers;
- Manufacturing, assembly, and integration;
- Testing;
- Acceptance, delivery, and launch.

Among these activities, manufacturing, assembly, and integration involve the most intensive QA tasks. The production processes of spacecraft elements, which include complex avionics and critical mechanics, must be meticulously executed to achieve the desired design. The standard [23] emphasizes that "all manufacturing, assembly, and integration operations are planned and performed in coordination with inspections and tests to ensure that the deliverables are built, assembled, and integrated according to the approved configuration baseline"

It is essential for everyone involved in the production process to be aware of and attentive to quality concerns. To ensure this, the standard calls for various requirements, including:

- Planning of manufacturing, assembly and integration activities and associated documents Manufacturing Readiness reviews (MRR).
- Control of processes.
- Workmanship standards.
- Materials and parts control (Component List, Declared Material List, Declared Process List).

- Equipment control.
- Cleanliness and contamination control.
- Inspection points and acceptance criteria.
- Manufacturing, assembly and integration records.
- ESD (electronic data sheet) control.

Traceability is a fundamental principle of Quality Assurance. The supplier must ensure a bidirectional and unequivocal relationship between parts, materials, products, and their associated documentation or records. This includes the ability to trace data, personnel, and equipment related to procurement, manufacturing, inspection, testing, assembly, integration, and operations activities. Specifically, the supplier must:

- Maintain the capability to trace the location and history of materials, parts, and subassemblies backward through the supply chain.
- Ensure the ability to trace the forward movement and utilization of materials from raw stock through to the final product.

For the Ariel Telescope Assembly the PA is responsible for ensuring that all configuration and data management rules are followed throughout the program's development. The PA/QA Manager is tasked with verifying that:

- Necessary documents and data for PA activities are available as required.
- Within the Configuration Control Boards, the release suitability of drawings, plans, specifications, procedures, and changes is verified.
- The as-designed status is clearly defined before manufacturing.
- All as-built documentation is accurately defined and maintained to reflect approved modifications.
- Delivered items conform to the as-built documentation.
- Deviations and waivers throughout the contractual chain are managed using standard document templates.

In addition, QA ensures that all design reviews are conducted according to the Design and Development Plan for the Telescope Assembly.

2.4.1 Manufacturing Readiness Review

Project reviews are examinations of the technical status of a project and associated issues at a particular point in time.

A dedicated review called Manufacturing Readiness Review (MRR) will be held prior to release the manufacturing, assembly, or integration of:

- Structural model (SM);
- qualification models (EQM or QM);
- flight products (e.g. units, subassemblies, assemblies, integration of items onto spacecraft).

In the case of the TA the objective of the MRR is to provide ASI, RAL and ESA (high customer level of the TA) with the opportunity to formally review the manufacturing documents/drawings. The approval of the review establishes the compliance of the design of the equipment with all specifications.

This shall be achieved by presenting:

- the status of the hardware manufacturing project, in particular the procurement of components and materials;
- the completeness of the design files, in particular design and interface drawings;
- the status of all Deviation and Waivers;
- the status of the manufacturing drawings and CIDL (Configuration Item Data List);
- the completeness of the manufacturing files, in particular manufacturing flowcharts and plans for MIPs (Mandatory Inspection Points);
- the status of the declared components, material, and process list.

2.5 Dependability

The dependability assurance program and its requirements are defined in the standard ECSS-Q-ST-30C [24]. This program is iterative and is utilized throughout the entire project life cycle.

This discipline covers all aspects needed to ensure that the space product meets dependability performance standards, including system functions implemented in software and the interaction between software and hardware. The key components include:

- Design rules.
- Dependability analyses (e.g., failure mode and effects, criticality).

The dependability program of the TA ensures that analyses are conducted with consistent contractual ground rules and standards. The criteria for the analytical demonstration of specified quantitative and qualitative reliability requirements are set in the TA dependability plan. The plan is implemented and integrated alongside other product assurance functions, as well as the design, development, and production functions by the TA subsystems.

Dependability activities include:

- Implementing the dependability requirements within the program.
- Ensuring that dependability requirements are effectively incorporated into the design.
- Ensuring that dependability assurance plans from suppliers align with the dependability assurance requirements of the Ariel project.
- Verifying that subcontractors' dependability activities adhere to the dependability assurance requirements of the Ariel project.
- Providing necessary dependability data to demonstrate compliance with all dependability requirements.
- Reviewing non-conformance reports, change requests, and NRB decisions to ensure any impact on system reliability is addressed.

2.5.1 Failure Mode and Effects Analysis

As included in the dependability analysis, Failure Mode and Effects Analysis (FMEA) is a systematic approach designed to identify and prevent potential problems in systems, products, and processes before they occur. Its primary goal is to identify failure modes within a system, assess their potential impact, and propose preventive measures to avoid undesirable effects [25].

Failure Modes, Effects, and Criticality Analysis (FMECA) is an extension of FMEA. Criticality is typically qualitative and indicated by the severity level. It can also be quantitative and indicated by the probability of occurrence.

Key Concepts are:

- Failure: When a product or system operates differently than intended.
- Fault: A divergent state of the system caused by a failure.
- Failure Mode: The specific way in which a failure can occur.
- Hazard: A potential situation that can cause or contribute to damage, typically arising from causes such as human error or unpredictable events.

Origins of FMEA

FMEA originated in the 1960s during the U.S. Minuteman rocket program to identify and mitigate unforeseen design problems (Goble, 2012). Over time, the concept of Criticality was added to FMEA, resulting in the more comprehensive Failure Mode, Effects, and Criticality Analysis (FMECA). McKinney (1991) emphasized the importance of implementing FMECA early in development to allow design modifications that mitigate or eliminate catastrophic, critical, and safety-related failure possibilities. Bowles (1998) modernized FMECA by introducing a new standard that incorporates three major changes: treating FMECA as a process to be used throughout the development cycle, grouping failure modes with equivalent effects to reduce redundant work, and assigning Criticality based on the probability and severity of failure modes using a Pareto ranking procedure. More recently, Bozzano and Villafiorita (2010) have made significant contributions to the safety assessment of critical systems with their book focused on techniques and methods for dependability, reliability, and safety assessment [26]. Nowadays in practical usage, “FMECA” also means “FMEA” and the distinction between the two has become blurred.

FMEA in space sector

In the space domain, the primary objective of product assurance is to ensure that all space products are safe, reliable, and capable of fulfilling all mission objectives and requirements. FMEA / FMECA identifies the way failures could occur (failure modes) and the consequences of the failure modes on spacecraft performance (failure effect) and the severity effect on mission objectives (criticality).

According to ECSS-Q-ST-30-02C [27], FMEA/ FMECA is conducted to systematically identify potential failures in:

- Products (functional and hardware FMEA/FMECA);
- Processes (process FMECA).

These analyses assess the effects of potential failures to define mitigation actions, prioritizing those related to failures with the most critical consequences.

In the hardware domain, FMEA focuses on tangible components, making it easier to identify and analyze failure modes. The effects of hardware failures are often more apparent and measurable. On the contrary, in the software domain, FMEA must address the potential for unexpected behavior, as software failures are not physical but rather functional anomalies that can be harder to predict and mitigate [28].

The results of the FMEA/FMECA are used as input to the design reviews and for implementing corrective actions.

This dependability standard classifies severity levels of consequences in four levels as described in Figure 2.4.

While the criticality level is determined by assigning two scores to the critical items:

- Severity Number (SN) of the failure effects, presented in Table 2.1
- Probability Number (PN) of the failure mode occurence, presented in Table 2.2

The Safety Risk (SR) number for a specific hazard is calculates as:
severity SN x likelihood PN

The Telescope Assembly FMEA/ FMECA is extended to the subsystem, assembly, and component levels to implement system design details.

Severity category	Severity level	Description of consequences (failure effects): Dependability effects (as specified in ECSS-Q-ST-30)	Description of consequences (failure effects): Safety effects (as specified in ECSS-Q-ST-40)
Catastrophic	1	Failure propagation (refer to 4.2c)	Loss of life, life-threatening or permanently disabling injury or occupational illness.
			Loss of an interfacing manned flight system.
			Severe detrimental environmental effects.
			Loss of launch site facilities.
			Loss of system.
Critical	2	Loss of mission	Temporarily disabling but not life-threatening injury, or temporary occupational illness.
			Major detrimental environmental effects.
			Major damage to public or private properties.
			Major damage to interfacing flight systems.
			Major damage to ground facilities.
Major	3	Major mission degradation	
Minor or Negligible	4	Minor mission degradation or any other effect	

Figure 2.4: Severity Categories of failure effects of a space mission according to ECSS-Q-ST-30-02C.

Severity Level	Severity Category	SN
1	catastrophic	4
2	critical	3
3	major	2
4	negligible	1

Table 2.1: Severity Categories

Likelihood	Probability of Occurrence (P_O)	PN
Probable	$P_O > 0.5$	5
Likely	$P_O > 0.1$	4
Occasional	$0.03 < P_O \leq 0.1$	3
Remote	$0.01 < P_O \leq 0.03$	2
Extremely Remote	$P_O \leq 0.01$	1

Table 2.2: Probability Levels and Their Occurrence

FMECAs are performed with the specific purpose of finding and limiting system/subsystem single point failure modes, unacceptable failure modes, failure mode propagation within internally redundant components, among externally redundant components, or within non-redundant components to prevent, eliminate, or mitigate such failure mode.

In this case the Hazard Analysis defines the compliance with the National safety standards in the country of origin, RAL/ESA and Launch Authority safety requirements.

2.6 Safety

The safety discipline described in ECSS-Q-ST-40C [29] encompasses all activities aimed at ensuring that safety risks associated with the design, development, production, and operation of space products are identified, assessed, minimized, controlled, and ultimately accepted through the implementation of a safety assurance program. This includes assessing risks based on both qualitative and quantitative analyses (e.g., hazard analyses, fault tree analyses)[30].

For the TA project, suppliers of the telescope and its subsystems must comply with the safety requirements set by launch authorities for the chosen launcher, as well as applicable national or international safety regulations concerning manufacturing, integration, testing, handling, and transportation. The PA manager is responsible for verifying that the implementation of safety requirements is not compromised by other project requirements.

Throughout the project, the telescope and subsystems teams maintain a safety data package, which include at least the following safety-related documentation:

- A Safety Analysis document, which contains Hazard Reports along with a verification tracking log.
- Supporting documents for the Safety Analysis, such as FMEA reports, test and inspection reports, operational procedures, and engineering analysis reports.
- A list of hazardous ground operations and the relevant procedures.

2.7 Electrical, Electronic and Electromechanical (EEE) components

The Electrical, electronic and electromechanical (EEE) components discipline [31] defines the requirements for the selection, control, and procurement of EEE components to ensure they meet the mission performance requirements.

This discipline covers:

- Component programme management;
- Component selection, evalutation and approval;
- Component procurement;
- Component handling, storage, relifing;
- Component quality assurance.

Given that the telescope design includes only operational/decontamination heaters and thermistors for the thermal control system as EEE parts, the customer level responsible for the telescope is asked to tailor the component control program accordingly.

The approval of the selection and usage of EEE parts is implemented through Parts Control board (PCB) held between the telescope, TA subsystems, ASI, ESA, Alter, CNR-IFN and AMC.

2.8 Materials, mechanical parts and processes

The Materials, Mechanical Parts, and Processes (MMPP) discipline is outlined in standard ECSS-Q-ST-70C [32]. Within this discipline, it is imperative that materials, mechanical parts, and processes are carefully selected to meet the needs and requirements of the mission. All chosen materials and mechanical parts must undergo testing under conditions that simulate the final operating environment of the product. It addresses:

- Requirements and processes for selection and procurement of materials (e.g. characterization, evaluation, qualification) and mechanical parts (e.g. thermal-cycling, radiation, cracking).
- Requirements and processes for avoiding planetary contamination (e.g. cleanliness).

Suppliers and subcontractors of the Telescope Assembly are responsible for preparing and maintaining documents such as the Declare Material List (DML), Declared Mechanical Parts List (DMPL), and Declared Processes List (DPL). These comprehensive lists encompass all materials, mechanical parts, and processes utilized in manufacturing the TA. They are managed through a management tool called 'DMPL tool'.

By compiling such lists, it becomes easier to assess the suitability of materials, mechanical parts, and processes for both the ground and flight functional requirements and constraints of the project. TA PA manager at CNR-IFN is responsible of supervising and coordinating the MMPP program.

DMPL tool

The DMPL tool, developed by ESA, serves as a valuable resource within this framework, aiding in the management and documentation of mechanical parts utilized throughout the product manufacturing process.

Through this tool, CNR-IFN and ASI are able to verify:

- the results of TA subsystems activities;
- control and monitor the status of materials, mechanical parts, and processes in accordance with project milestones.

2.9 Software PA

Standard ECSS-Q-ST-80C [16] outlines the requirements for product quality assurance to ensure the development of safe and reliable software. The standard includes requirements aimed at ensuring the quality of the final software product, with a focus on quality attributes and their relationships, measurable quality objectives, and metrics to verify these objectives [33]. ECSS-Q-ST-80 interfaces with space engineering and management, which are addressed in the Engineering (-E) and Management (-M) branches of the ECSS System.

The Telescope Assembly does not include any SW product, therefore this section was not applicable for the TA Product Assurance.

3

Ageing of Protected Silver coating

One of the tools for managing product assurance in a space project is the Critical Item List (CIL).

For the Ariel mission, the primary mirror (M1) component is one of the most critical part of the telescope, with stringent requirements for opto-mechanical performance. An item is defined as critical if "it has the potential to significantly degrade the quality of the product and thus the ability of the end-product to achieve its defined mission objectives" (ECSS-Q-ST-10-04C) [19]. Due to these characteristics, the primary mirror M1 of the Ariel telescope is included in the CIL.

This chapter will discuss the materials used in the manufacturing of the mirror and the tests performed to assess any aging effects on the mirror samples during their storage period in an ISO6 cleanroom. The analysis has been conducted on samples previously utilized for the qualification campaign of the protected silver coating.

The tests have been conducted at CNR-IFN using Atomic Force Microscopy (AFM) and Fourier Transform Infrared Spectroscopy (FTIR).

3.1 Primary Mirror

The Ariel telescope's optical system is composed of four mirrors, playing a critical role in directing and focusing light for astronomical observations. These mirrors are illustrated in Figure3.1 and include:

- **Primary Parabolic Mirror:** With an elliptical aperture of 1.1 x 0.7 meters, this mirror is the largest and most crucial, responsible for gathering light.
- **Hyperbolic Secondary Mirror:** Mirror M2, with a diameter of 112 mm, further focuses the light collected by the primary mirror.
- **Parabolic Collimating Tertiary Mirror:** M3 collimates the light into a parallel beam.
- **Flat-Folding Mirror:** Measuring 31 mm, this mirror M4 directs the output beam parallel to the optical bench.

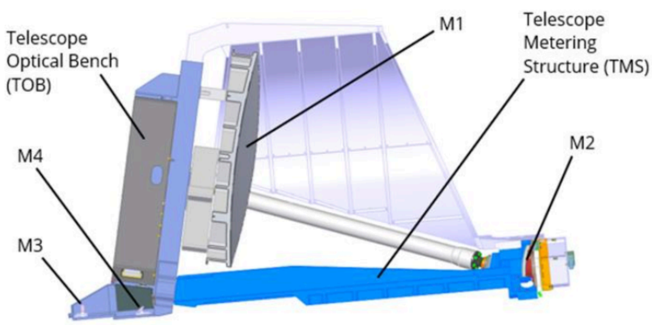


Figure 3.1: Optical elements of the TA. Source: ESA.

The Telescope Assembly features a standard afocal off-axis configuration, which is typical for infrared (IR) telescopes because allows for effective light collection [9].

The main characteristics of the TA mirrors at the operating temperature 50K are reported in Table 3.1.

Optical element	M1	M2	M3	M4
Type	Concave mirror	Convex mirror	Concave mirror	Plane mirror
Clear aperture shape	Elliptical	Elliptical	Elliptical	Circular
Clear aperture dimensions (mm)	1100 x 730	110 x 80	28 x 20	24
Mirror dimensions (mm)	1125 x 771	130 x 100	50 x 45	50
Surface roughness (nm RMS)	10	2	2	2
Mirror material	6061-T651	6061-T651	6061-T651	6061-T651
IR Reflective coating	Silver	Silver	Silver	Silver

Table 3.1: Main optical parameter values of the Telescope Assembly mirrors.

All mirrors are manufactured from the same Aluminium Alloy 6061-T651 substrate and will feature a protected silver coating on the optical surface. This choice enhances reflectivity across the Ariel spectral range, which is essential for the mission's success.

The choice of aluminium for the realization of the mirrors brings some advantages:

- **Maximizing Heat Exchange:** Since the rest of the TA is made of aluminium, the mirrors efficiently dissipate heat, crucial for maintaining optical performance in space.
- **Cost Reduction:** Aluminium is more cost-effective compared to traditional glass or ceramic mirrors.
- **Technological Advancement:** The use of aluminium substrates represents a significant step forward in mirror technology for space missions.

The primary mirror is particularly remarkable as it is a monolithic large-size cryogenic aluminium mirror, a type never before used in space missions. This makes M1 one of the highest risk activities within the Ariel program due to the challenges involved.

The first challenge is its precision manufacturing. The primary mirror must have a large collecting area with precise curvature accuracy down to tens of nanometers. This ensures that the light collected is accurately reflected to the telescope's secondary mirrors and imaging system [34].

In addition, given the considerable size of the primary mirror, it was designed to be lightweight to limit its mass. This lightweighting is a trade-off between reducing mass and maintaining the optical surface quality to meet SFE (Surface Figure Error) requirements [9].

Media Lario[1], prime contractor for the mirrors, faces the challenge of producing large aluminium mirrors that meet the stringent requirements of the space missions.

3.2 Mirror Materials

3.2.1 Aluminium Alloy Substrate

In the design of space structures a significant constraint is weight, necessitating the use of materials with the lowest possible density while maintaining other necessary properties. This drives the preference for lightweight alloys, such as aluminium alloys, and composite materials, which offer excellent structural and thermal qualities at very low densities. Notably, aluminium is the single most versatile material used in space due to its lightweight yet robust characteristics [34].

[1] Media Lario Srl, Via al Pascolo, 10, 23842 Bosisio Parini LC, Italy.

All mirrors for the Ariel telescope are fabricated from aluminium EN AW 6061 T651. This specific alloy, combined with optical quality specifications, ensures Isotropic deformations and stable performance. However, creating a mirror as large as Ariel's M1 (1.1 × 0.7 m) from aluminium for space applications has never been done before, and thus, established manufacturing processes do not exist for this application.

The production of Ariel's mirror begins with a monolithic slab of laminated aluminium 6061 T651, as this method allows for the creation of blocks larger than 1.2 meters.

In the fabrication phase, the mirror undergoes material extraction from the rear in a honeycomb pattern to reduce mass as shown in Figure 3.2. Honeycomb structures are known to have excellent mechanical performances, which are mainly due to the configurations of the unit cell [35].

Figure 3.2: Honeycomb structure of M1 for mass reduction. Source: ESA.

After rough machining, the mirror undergoes the diamond machining by LT ULTRA[2], and polishing by Media Lario.

However, the alloy produced by the rolling process has a strong presence of Si-Mg aggregates with dimensions to ~1 μm. These aggregates affect the polishing of the optical surface. Aggressive polishing to improve the shape can tear off the aggregates, leaving holes that generate a diffuse opacity over the entire surface and markedly increase the roughness value. Aggregates are generated in the alloy because the rolling procedure requires heating the raw aluminium block to 400°C before each pass in the roll. The slow temperature variation allows the elements in solution with the aluminium to re-aggregate into structures, mainly Si, Mg, and Fe [36].

[2]LT Ultra-Precision Technology GmbH, Wiesenstraße 9, 88634 Herdwangen-Schönach, Germany.

To address this intrinsic defect of the laminated alloy, a heat treatment has been developed based on recipe by NASA/Goddard Space Flight Center [37].

For larger components of the TA, such as the Telescope Optics Bench and the Telescope Metering Structure, temper T652 (solution treatment, stress-relief by compressive deformation, and artificial aging) has been selected due to the impracticality of procuring a 6061 T651 aluminium billet large enough to manufacture these elements as monolithic parts. Moreover, this option allows the telescope to remain aligned as it cools to operational temperatures since they have nearly identical Coefficients of Thermal Expansion (CTE) between room and cryogenic temperatures [38].

Using aluminium for such a large mirror has several advantages. It ensures homogeneity with the rest of the TA structure, avoiding thermal gradients that could misalign the optics. Additionally, it eliminates the need for interfaces, thereby reducing both mass and complexity [9].

3.2.2 Protected Silver Coating

The optical surfaces of telescope mirrors are usually enhanced and protected with a thin film coating to maximize reflectivity in the desired observational wavebands.

In the case of the Ariel telescope, the AMC made a strategic decision regarding the choice of metal coatings to ensure excellent reflectance in both the infrared and visible wavelengths. The options considered were aluminium, gold, and silver. Each of these metals comes with a well-documented history of use in scientific research and space applications, making them strong candidates for this purpose.

Aluminium stands out with the best overall reflectance from the ultraviolet (UV) through the far-IR, and it is less susceptible to atmospheric tarnishing than silver. Additionally, aluminium is generally more durable with regard to handling compared to both gold and silver. However, its reflectance significantly drops at wavelengths greater than 1 μm. Given that the Ariel mission will operate within the 0.5-7.8 μm range, the decrease in aluminium's IR reflectance becomes a critical factor [39]. Silver-based coatings are the optimal choice for a wide range of applications due to their superior reflectivity from the visible (VIS) to the IR spectrum. Among all metals, silver provides the highest reflectivity, making it an ideal candidate for enhancing the performance of optical systems, including ground and space telescopes [40]. Additionally, its CTE is not significantly different from that of aluminium, which is essential for ensuring robustness under thermal stress conditions (cryogenic temperatures).

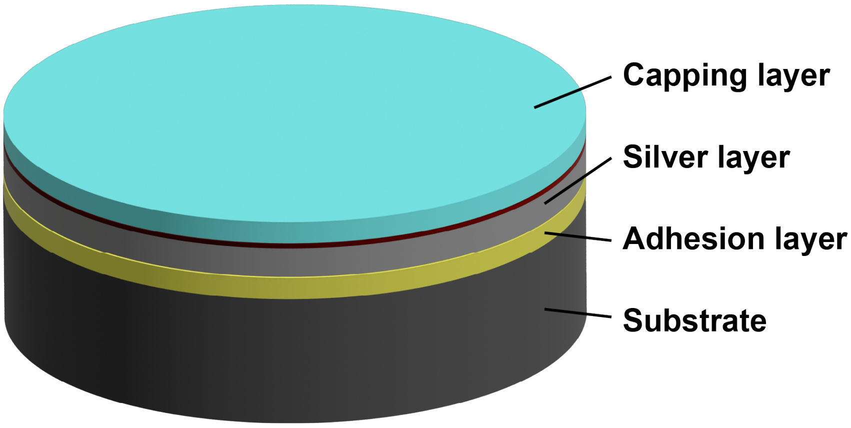


Figure 3.3: Approximate composition of the coating structure over the aluminium substrate.

The use of silver-coated aluminium mirrors in both ground-based and space telescopes is well-documented and established [41]. These mirrors have demonstrated reliable performance across various operational environments, including cryogenic temperatures. The low emissivity of silver is another critical factor contributing to its selection. Lower emissivity minimizes the thermal noise from the warm payload, thereby increasing the telescope's sensitivity and improving the quality of the signal recorded from celestial objects [42].

However, the formation of corrosion products like silver sulfide (Ag_2S) and silver chloride (AgCl) significantly reduce the reflectivity of silver mirrors. To preserve silver coatings from corrosion, transparent dielectric materials such as silicon dioxide (SiO_2) and aluminium oxide (Al_2O_3) are commonly applied as protective layers[40]. These materials are effective in creating a barrier that prevents pollutants from reaching the silver surface.

The Ariel mirrors coating structure consists of :

- **Nickel-Chromium(NiCr)**: a less than 10 nm thick adhesion layer, which enhances adhesion to aluminium and acts as a diffusion barrier.
- **Silver (AG)**: the high reflectance layer.
- **Capping layer**: a nanostructured protection layer, with a recipe develped by CILAS[3].

The overall thickness of the protected silver coating averages around 350 nm.

This combination of layers not only provides the desired reflectivity in the IR but also ensures durability and stability under the thermal cycling conditions of space.

[3] CILAS - Ariane Group, Orléans, France.

3.3 Ageing Effect

The investigation of the possible aging effect of silver coatings is driven by the characteristics of silver.

Silver is the prime candidate for high-performance applications in both visible and infrared mirror technology due to its exceptional properties: high reflectivity, low emissivity, and the lowest polarization splitting of all metals [43].

However, silver's susceptibility to tarnishing and corrosion poses significant challenges. The presence of common atmospheric pollutants such as humidity, sulfur, and chlorine can initiate degradation processes, leading to a deterioration in reflectivity and an increase in scatter, thereby significantly compromising its optical performance. This vulnerability to pollutants is particularly concerning, as such contaminants are present even in controlled cleanroom settings [44].

The samples used to study if the aging effect is present are presented in the next section.

The aging effect studies involves periodic testing of the samples stored in ISO6 cleanroom conditions at CNR-IFN. These tests are designed to monitor any morphological and performance variations over time, providing valuable data on the long-term stability and durability of the silver coatings.

3.3.1 Samples

The samples employed for testing the ageing effect are the same samples used for the qualification campaign of the protected silver coating. The disks are made of EN AW 6061-T651, each with a diameter of 25 mm and a thickness of 6 mm.

A picture of one representative sample can be seen in Figure 3.4.

All samples were cut from the same plate of rolled EN AW 6061-T651, initially used in the fabrication of the prototype for the primary mirror. As previously described, the protected silver coating consists of a stack with three layers: an adhesion layer of NiCr, a reflective Ag layer, and capping layer [43].

After the successful conclusion of the qualification process, the samples have been stored in cleanroom conditions. They are periodically tested to monitor any morphological or performance variations, characterizing the aging process of the coating. This ongoing testing ensures that the coating maintains its integrity and performance over time.

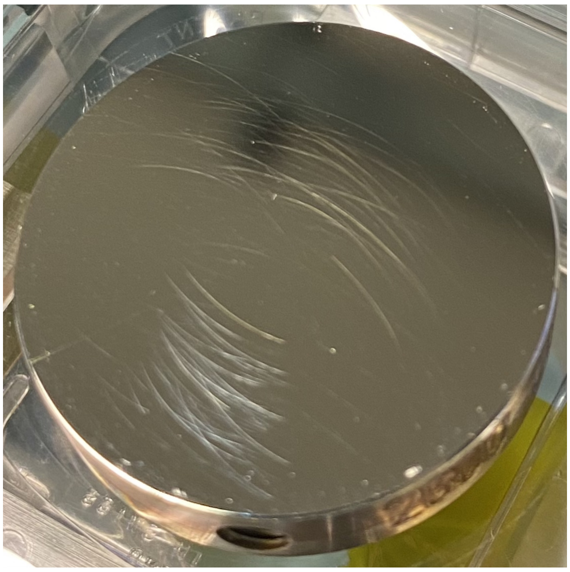


Figure 3.4: High resolution photograph of a reference sample (SN02M) of EN AW 6061-T651 with a diameter of 25 mm and a thickness of 6 mm.

Before the delivery to CILAS for coating application, the samples were polished and cleaned by MediaLario, who also conducted a subset of the qualification tests. .

CILAS performed the coating deposition and most of the qualification tests. The rigorous qualification campaign was designed to ensure the coating would meet the end-of-life requirements of the instrument without significant performance degradation, adhering to the ECSS Q-ST-70-17C [45] standard.

The qualification tests have been crucial to verify the coating's durability and performance under conditions simulating the operational environment of the Ariel telescope.

For ageing analysis, five of the qualification samples have been selected as representative as shown in Figure 3.5, while the others are detailed in the Annex. These representative samples underwent different tests to verify the quality of the coating run and its consistency with the qualification campaign requirements.

Sample SN1 is part of the first deposition run conducted on April 3rd, 2019 by CILAS.

Samples SN02M(L02), SN04M(L04), SN06M(L06), SN08M(L08) are from the qualification run carried out on December 12th, 2019 by CILAS.

	Humidity	Thermal	Adhesion Level 2	Cryotest	Cleaning	Abrasion
SN1			✓	✓	✓	
SN02M(L02)			✓			
SN04M(L04)	✓		✓			
SN06M(L06)			✓	✓		
SN08M(L08)	✓	✓	✓	✓	✓	✓

*all samples have undergone visual inspection and spectral relative reflectivity

Figure 3.5: Tests conducted on each representative sample.

The specification of the test are the following:

- **Visual inspection:** conducted according to ISO 9211-4 Annex C.
- **Spectral measurement:** AOI = 20° Wavelength 500-2500 nm by step of 5nm, AOI = 8° Wavelength 500-2500 nm by step of 5nm.
- **Humidity:** ISo 9022-2, Method #12 Severity 06, test duration of 24h, exposed to 90 % humidity environment, 55‡3 °C (no condensation).
- **Thermal:** temperature cycling at ambient pressure according to ISO 9022-2. T. range: -40 °C / +70 °C, T. change rate: 2°C/min, Dwell time: 15 min, Nr of cycles: 30.
- **Adhesion level 2:** ISO 9211-4 Method #2 Severity 02.
- **Cryotest:** ten cryogenic cycles as described in ECSS-O-ST-70-04C. T. range: 54 K / 293 K, T. change rate: 5°C/min, Dwell time: 15 min, Vacuum: $< 10^{-4}$ mbar.
- **Cleaning and solvent compatibility:** Manual cleaning with solution and optical wipe at room temperature, 5 times.
- **Abrasion resistance:** realized according to ISO 9211-4 Method #1 Severity 01.

3.4 Methods

3.4.1 Atomic Force Microscopy

The atomic force microscope (AFM) was introduced by Binnig, Quate, and Gerber in 1986, as an atomic-scale surface imaging technique

AFM operates by scanning a cantilever with a silicon tip over the surface of a sample. This cantilever is moved by a piezoelectric ceramic driver that precisely controls the lateral and vertical positions of the probe. Depending on the imaging mode, the interaction forces between the tip and the sample either introduce a static deflection of the cantilever or, in dynamic AFM modes, alter the frequency, amplitude, or phase of the cantilever's oscillation [46].

In Figure 3.6 a schematic representation of the type of tip-interaction forces based on the distance between them.

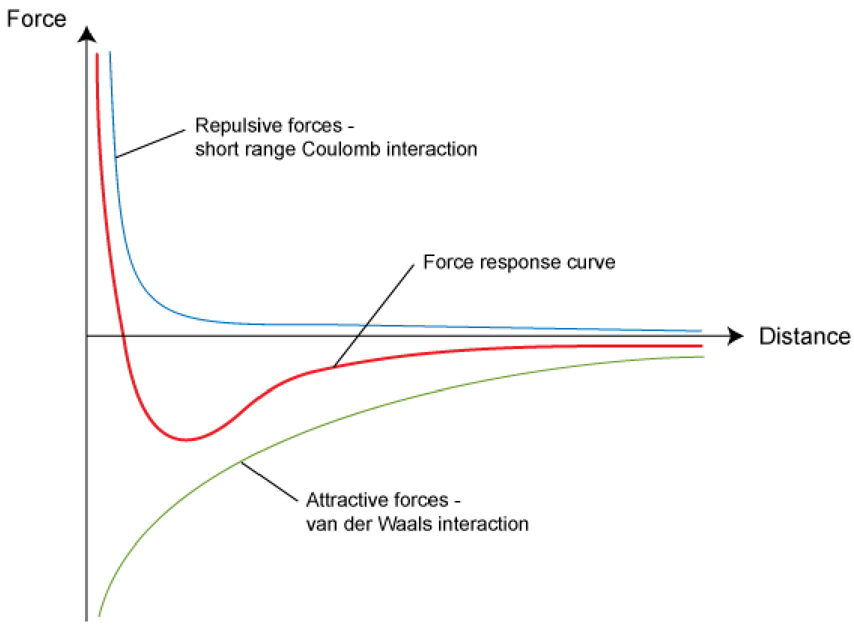


Figure 3.6: Representation of tip-surface interaction forces. Source: University of Cambridge.

In contact mode, the tip maintains direct contact with the sample surface, and repulsive short-range interatomic forces cause the cantilever to deflect. As the tip scans the surface, these local repulsive forces induce deflections, which are then used to map the surface topography with nanometer-scale precision. However, the strong vertical and lateral forces applied by the scanning tip can cause surface deformation or removal of weakly bound and defective layers [47].

In non-contact mode, the cantilever is oscillated at or near its resonance frequency with a small amplitude (1 nm or less) while being kept a few nanometers way from the sample surface. This mode measures surface topography based on attractive van der Waals forces without the tip making direct contact with the sample, thereby preventing damage. When the probe senses a force, the oscillating frequency changes due to changes in the system's spring constant. These changes in frequency or phase are measured to provide topographic information [48].

AFM is highly sensitive to surface contamination, especially in environments exposed to ambient air. Contaminants can significantly impact the precision and accuracy of AFM imaging. One critical issue is capillary forces pulling contaminants up the probe, which can drag particles across the sample surface during scanning [48]. This contamination can distort images and compromise data integrity, making interpretation challenging. In such cases, replacing the AFM tip may be the only solution.

AFM's capability to provide high-resolution surface analysis makes it an important tool for characterizing the protective silver coatings on the Ariel telescope mirrors.

Instrumentation

All of the samples have been analyses with a Park System XE-Series 70 microscope, with scans conducted over an area of 10 µm x 10 µm, 256^2 pixels and processed with XEI, the provided proprietary software.

Then, the selected representative samples SN02M(L02), SN04M(L04), SN06M(L06) , SN08M(L08) were analyzed again with the more recent Park NX10 microscope, with scans of 5 µm x 5 µm, 256^2 pixels and processed with XEI.

To assess any morphology variation, the required criteria for M1 is to maintain surface roughness below 10 nm RMS.

3.4.2 Fourier-transform infrared spectroscopy

Fourier Transform Infrared Spectroscopy (FTIR) Analysis, also known as FTIR Spectroscopy, is a powerful technique used to study the interaction of infrared radiation with molecular vibrations. This method is applicable to a wide range of samples across various temperatures and physical states [49]. FTIR is particularly valuable in analyzing thin coatings on telescope mirrors, such as those used in the Ariel mission, to ensure they meet performance standards.

Infrared spectroscopy examines how electromagnetic radiation interacts with the sample's surface. Depending on the surface characteristics and its environment, the light may undergo three types of reflection: internal reflection, specular reflection, and diffuse reflection [1]. In practice, all three types of reflections can occur simultaneously, although with varying contributions. In Figure 3.7 the three types of reflections are illustrated.

Specular Reflection occurs when light is reflected from a smooth surface, such as a mirror, at a definite angle. This type of reflection is ideal for FTIR analysis because it provides clear and precise reflection measurements.

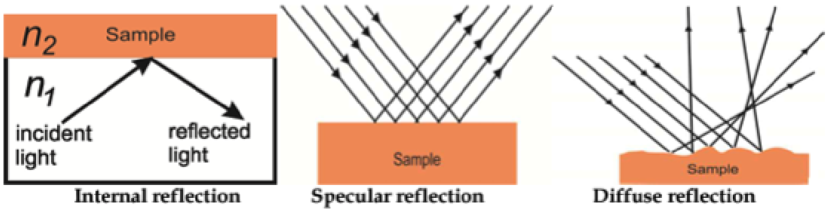


Figure 3.7: Schematic illustration of reflection types. Source [1].

Specular reflectance provides a non-destructive method for measuring thin coatings on smooth, selective substrates without requiring sample preparation. This method is particularly beneficial for analyzing the protective silver coatings on the Ariel telescope mirrors and verifying the reflectance performance.

In general, the samples area needs to be homogeneous and 'optically thick' to avoid back-surface reflected or diffuse radiation. The samples used for the coating qualification meet the criteria for FTIR spectroscopy, making them perfect candidates for the type of study of specular reflection. This analysis will provide reliable data on the coating's performance.

Instrumentation and Experimental Procedure

The IR spectra reported were all recorded by a Nicolet i5s FTIR spectrometer interfaced to a '10Spec' specular reflectivity accessory by Pike Technologies shown in Figure 3.8.

The 10Spec is an accessory for near-normal sample reflectivity measurements, using a collimated beam fixed at 10 degrees.

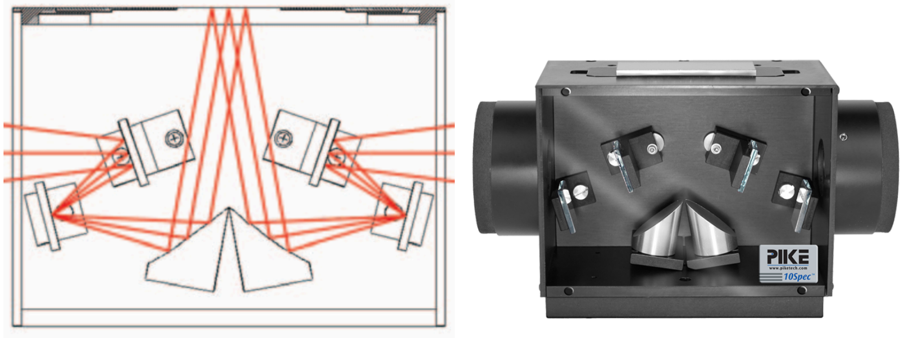


Figure 3.8: '10 spec' accessory by Pike Technology and beam path in the accessory. Source: Pike Technology.

The FTIR instrument in reflectance mode is frequently employed qualitatively for material identification. However, for this study, quantitative measurements were required.

Initially, measurements were taken using a gold sample provided by the supplier. These initial measurements were conducted without strict control over the timing between sample placements. Later, it was discovered that time was a crucial parameter for the success of the analyses. Measurements were taken over two days, with 40 readings each day. These results were inconsistent, showing significant variations in reflectance.

It was hypothesized that introducing air into the instrument when raising the sample affected the reflectance. Infrared measurements are highly sensitive because air contains absorption lines, especially from water vapor and carbon dioxide, which can interfere with the readings. For this type of measurement, controlling the working conditions is essential, including temperature, air quality, and humidity. Ensuring a stable environment minimizes external variables and enhances the accuracy and reliability of the results.

Consequently, a methodology incorporating specific timing protocols was developed. The most suitable timings involved a 30-minute pause from the placement of the sample to the measurement using the instrument's software, and an additional 30-minute pause when switching samples. Moreover the instrument was placed in a ISO6 cleanroom. These conditions secure a reproducible setup, ensuring that external variables are minimized and the results are reliable.

Using this modality, reflectance measurements for the gold sample at a representative wavelength of 10 µm are provided in Figure 3.9, showing the error margin band.

Once the setup was verified, measurements for the samples of Ariel mirrors were conducted over the course of two days. For each set of measurements, the same background was used. More specifically, for these baseline measurements, a calibrated aluminium sample (ALREF-

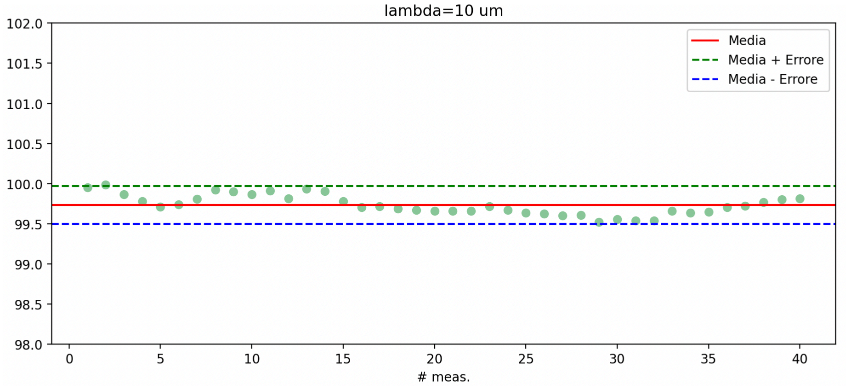


Figure 3.9: Reflectance measurements at 10 µm of the gold sample used to establish the setup.

21017) from Filmetrics [4] was employed. Reflectance standards are crucial for establishing a spectrometer baseline. Starting from calibrated curves initially provided by the manufacturer within a narrow range (0.165 µm to 2.2 µm), a set of optical constants needed to be determined to best characterize the optical properties of the reference sample over a wider range of interest. Essentially, the Filmetrics sample's behavior was extrapolated for the wavelengths not originally provided.

Three sets of optical constants (n, k) for aluminium from experimental data available in the relevant range, were considered:

- Ordal et al. 1988, with values of n, k in the 0.667-200 µm range [50].
- Rakić 1995, with values of n, k in the 0.000124-200 µm range [51].
- Hagenmann et al. 1974, with values of n, k in the 0.0000103-1240 µm range [52].

Among these, the measurements using Rakić's constants closely represented the reflectance of the Filmetrics aluminium sample, as shown in Figure 3.10. Thus, the curve obtained from Rakić's constants was used to normalize the representative Ariel's samples for wavelengths beyond 2.2 µm.

Using the same method described earlier, FTIR measurements were taken for five aluminium and protected silver samples (SN1, SN02M(LO2), SN04M(LO4), SN06M(LO6), SN08M(LO8)).

Subsequently, the reflectance data were normalized to the reference aluminum sample from Filmetrics.

[4] Filmetrics, inc., 10655 Roselle St. San Diego, CA 92121, USA.

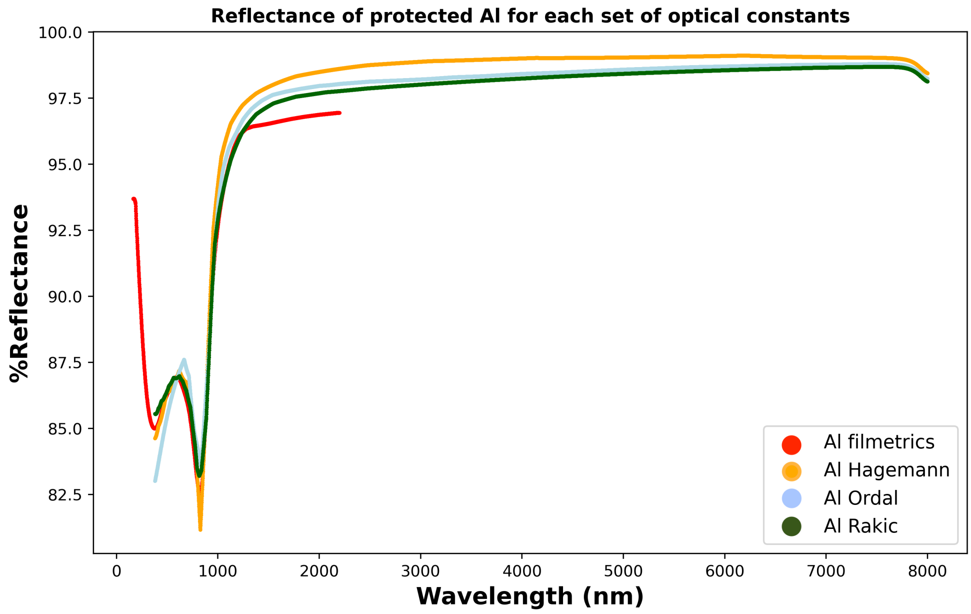


Figure 3.10: Curves of aluminium relfectance using different sets of optical constants.

3.5 Results

The samples don't present signs of degradation observed after the storage period and all results align with the established criteria for acceptable performance, as presented in the following sections.

3.5.1 AFM Roughness Results

The AFM scans were performed to provide a qualitative assessment of surface morphology variations. The sampling location for the AFM has been chosen to be approximately at the central area of each sample, as the previously analysis conducted at CNR-IFN in 2022. However, the measurements do not capture the exact same portion of the surface because the microscope lacks the functionality to precisely relocate the previous scanning area.

For each sample, both the morphological representation and the 3D representation are reported. Additionally, the roughness parameters of two linear profiles for each sample are presented. The results of sample SN02M(L02) are presented in Figures 3.11 and 3.12. For sample

SN04M(L04) the results are shown in Figures 3.13 and 3.14, for sample SN06M(L06) in Figures 3.15 and 3.16 and finally, for sample SN08M(L08) in Figures 3.17 and 3.18.

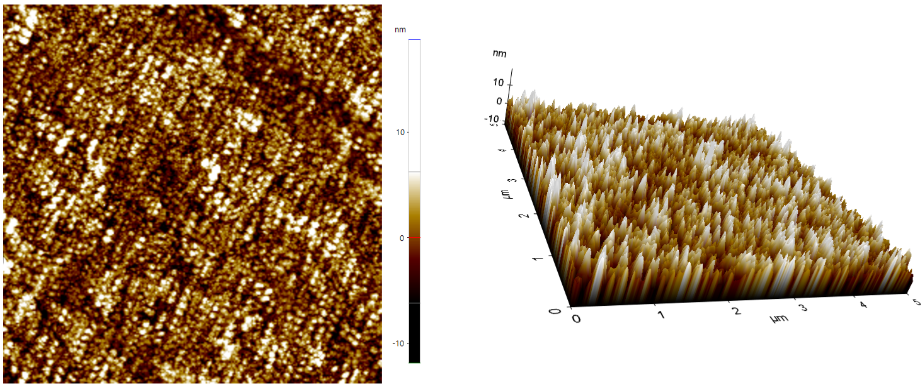
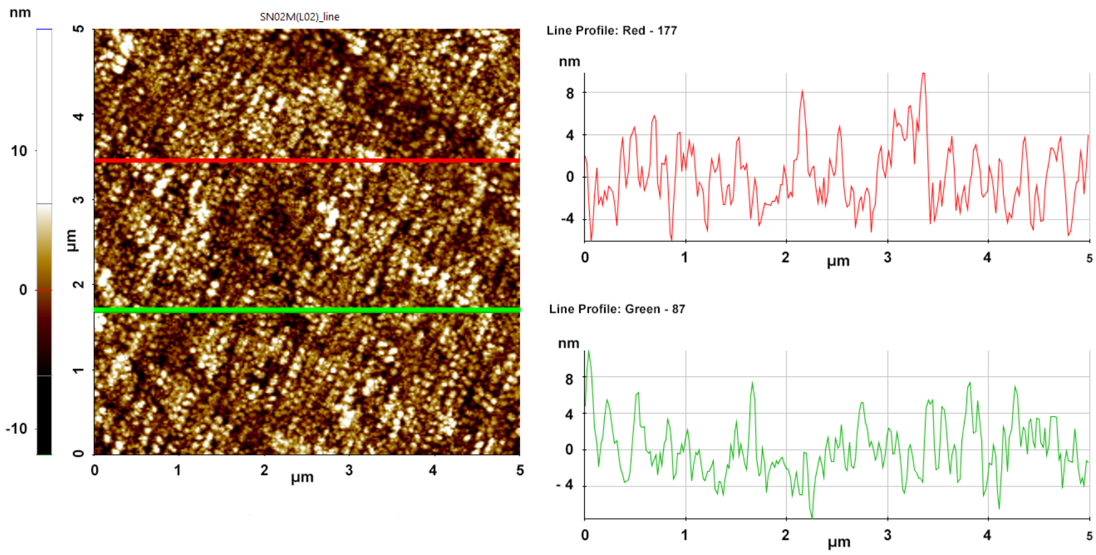


Figure 3.11: Height map of sample SN02M(L02) and its 3D representation.



Statistics

Line	Min(nm)	Max(nm)	Mid(nm)	Mean(nm)	Rpv(nm)	Rq(nm)	Ra(nm)	Rz(nm)	Rsk	Rku
Red	-6.079	9.827	1.874	0.000	15.906	3.003	2.414	12.216	0.563	3.186
Green	-7.593	10.866	1.636	0.000	18.459	3.073	2.434	13.532	0.549	3.274

Figure 3.12: Two linear profiles of sample SN02M(L02).

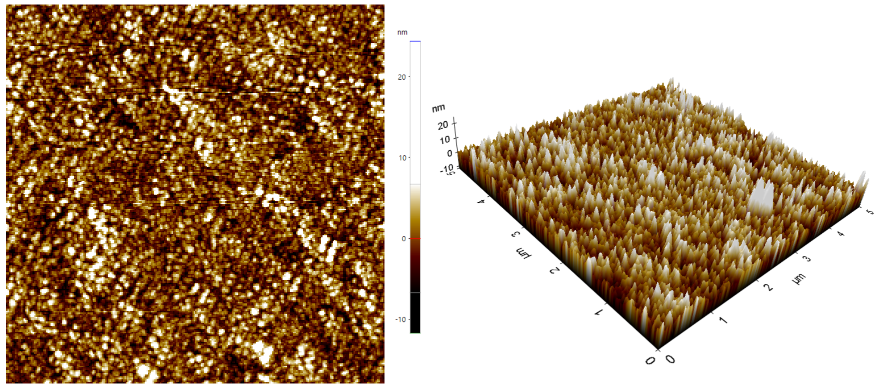
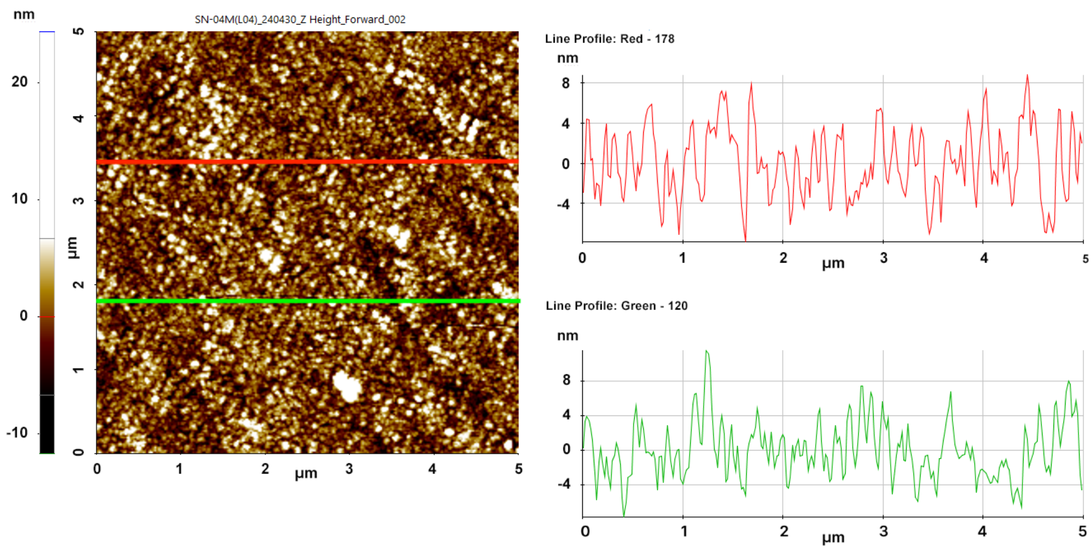


Figure 3.13: Height map of sample SN04M(L04) and its 3D representation.



Statistics

Line	Min(nm)	Max(nm)	Mid(nm)	Mean(nm)	Rpv(nm)	Rq(nm)	Ra(nm)	Rz(nm)	Rsk	Rku
Red	-7.830	8.770	0.470	0.000	16.600	3.462	2.875	14.442	0.111	2.396
Green	-7.715	11.485	1.885	0.000	19.200	3.328	2.608	14.094	0.555	3.370

Figure 3.14: Two linear profiles of sample SN04M(L04).

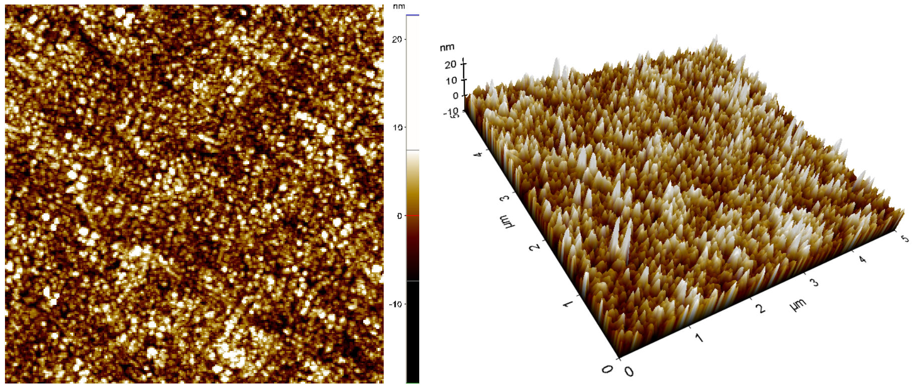
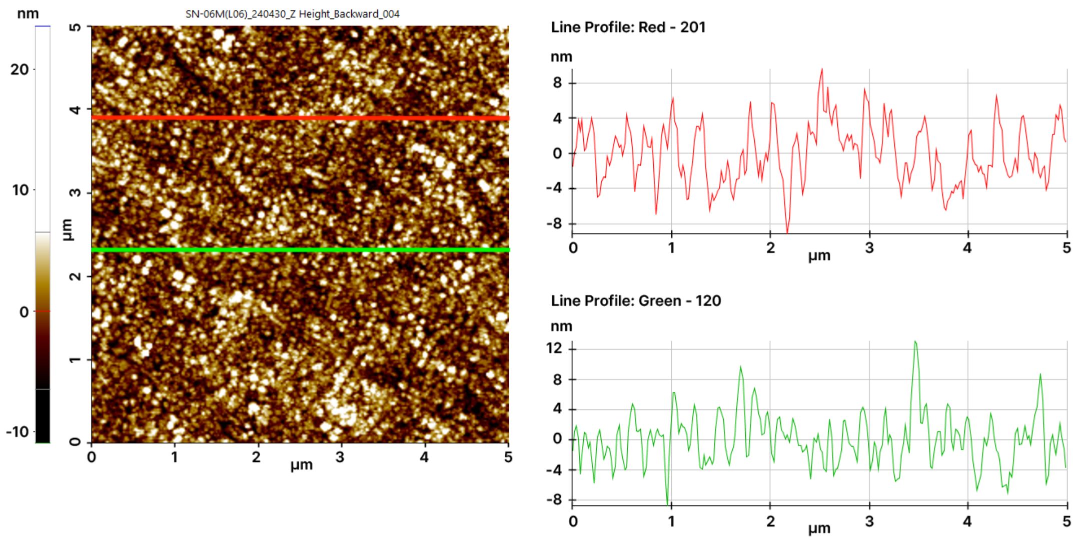


Figure 3.15: Height map of sample SN06M(L06) and its 3D representation.



Statistics

Line	Min(nm)	Max(nm)	Mid(nm)	Mean(nm)	Rpv(nm)	Rq(nm)	Ra(nm)	Rz(nm)	Rsk	Rku
Red	-9.152	9.551	0.200	0.000	18.703	3.313	2.748	13.911	0.093	2.622
Green	-8.802	13.090	2.144	0.000	21.892	3.397	2.584	15.738	0.596	4.232

Figure 3.16: Two linear profiles of sample SN06M(L06).

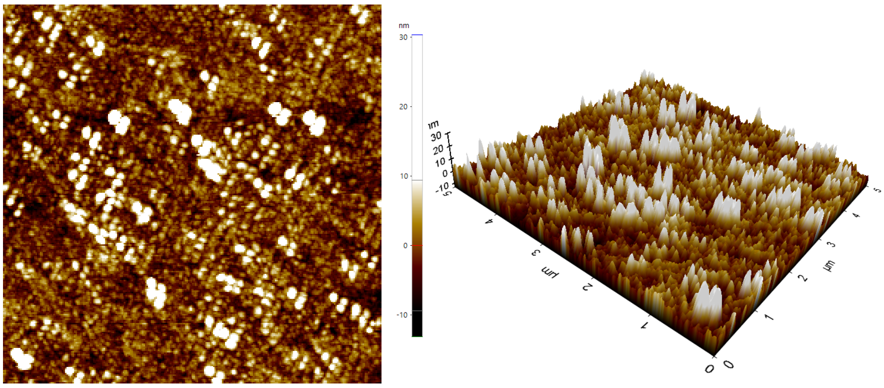
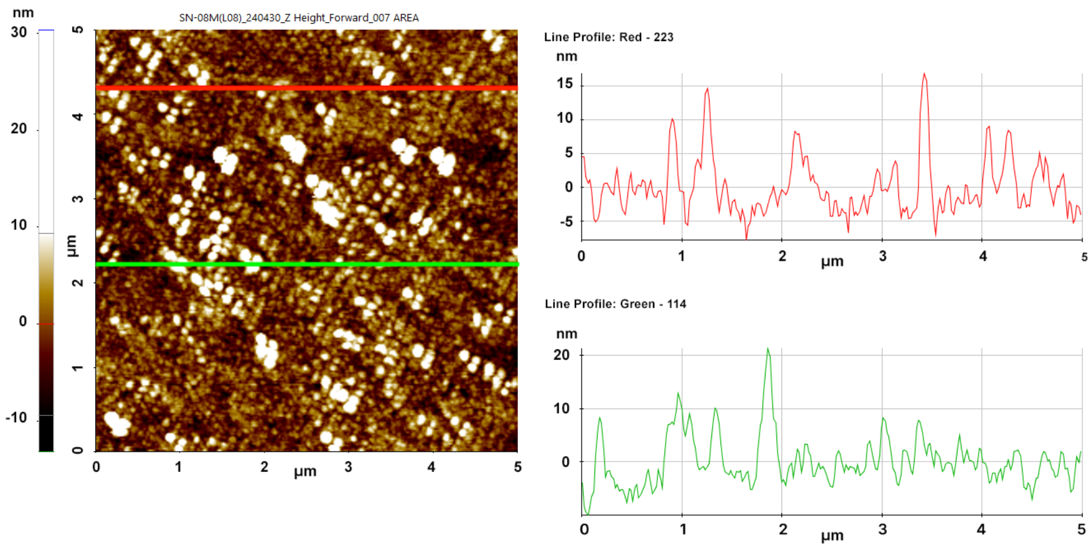


Figure 3.17: Height map of sample SN08M(L08) and its 3D representation.



Statistics

Line	Min(nm)	Max(nm)	Mid(nm)	Mean(nm)	Rpv(nm)	Rq(nm)	Ra(nm)	Rz(nm)	Rsk	Rku
Red	-7.771	16.827	4.528	0.000	24.599	4.204	3.060	18.312	1.457	5.605
Green	-9.995	21.208	5.607	0.000	31.203	4.739	3.504	19.277	1.264	5.723

Figure 3.18: Two linear profiles of sample SN08M(L08).

Roughness measurements are reported in Figure 3.19 in terms of Rq (nm) for the line profiles, with the data representing the average of four profiles taken from each sample.

Roughness is also reported in Figure 3.20 as Sq to measure the area roughness.

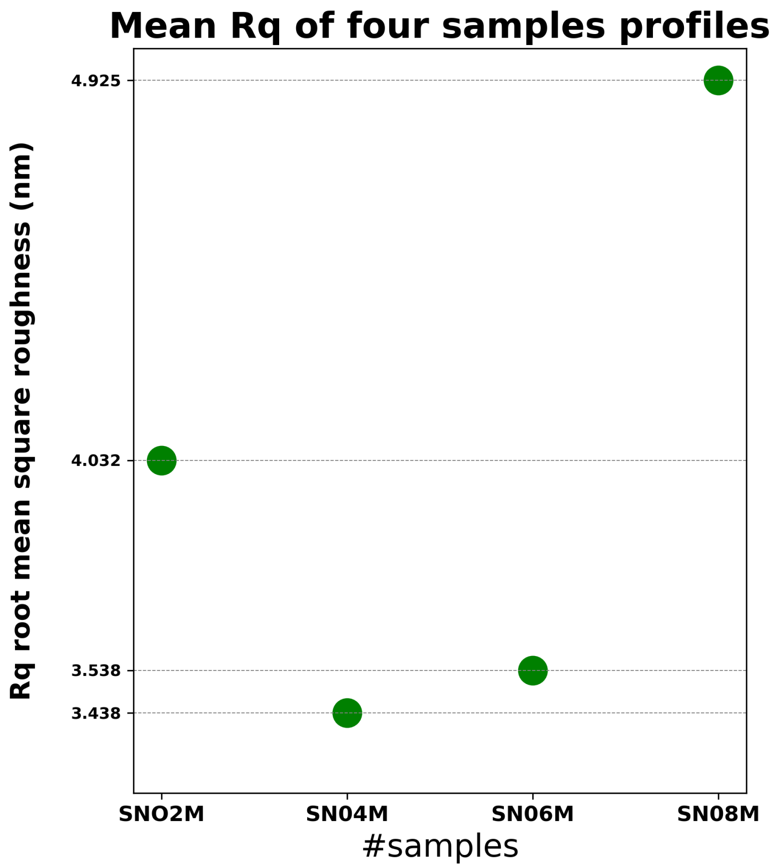


Figure 3.19: Roughness Rq graph of selected samples.

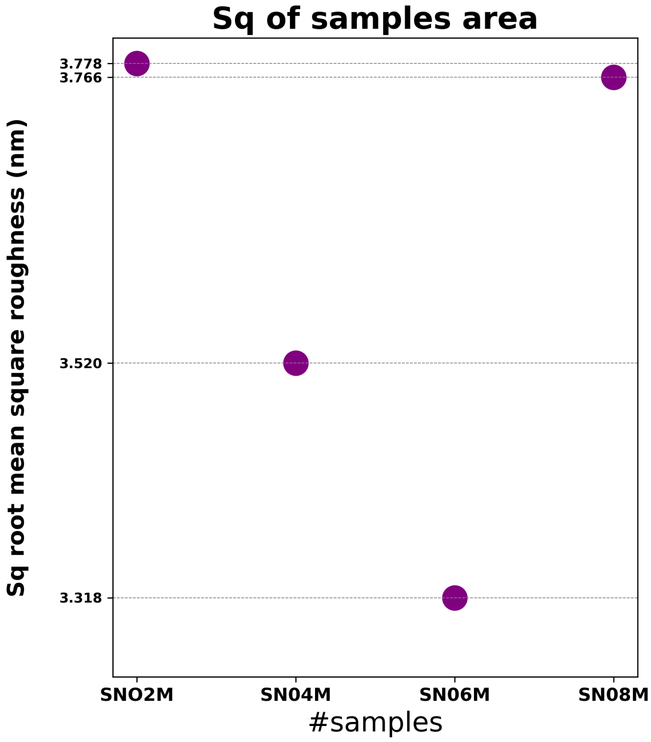


Figure 3.20: Roughness area Sq graph of selected samples.

Figures 3.19 and 3.20 show that the roughness of the samples is in the range 3.3-4.9 nm.

The results show that the surface topology remains qualitatively consistent, with surface roughness below the required 10 nm RMS.

The AFM measurements indicate that the surface roughness is within ±1 nm of the previous measurements conducted at CNR-IFN in April 2022.

3.5.2 Reflectance results

The results of reflectance measurements are displayed in the graph in Figure 3.21. The spectra of the samples within the 3 µm to 8 µm range, consistently remain above the acceptable threshold of 90%.

A notable drop around 4.2 µm is observed, which can be attributed to the fact that the FTIR measurements were conducted in an environment that was not fully isolated from air. The drop corresponds to the fundamental vibrational transitions of the CO_2 molecule, indicating absorption of infrared light by CO_2 in the atmosphere.

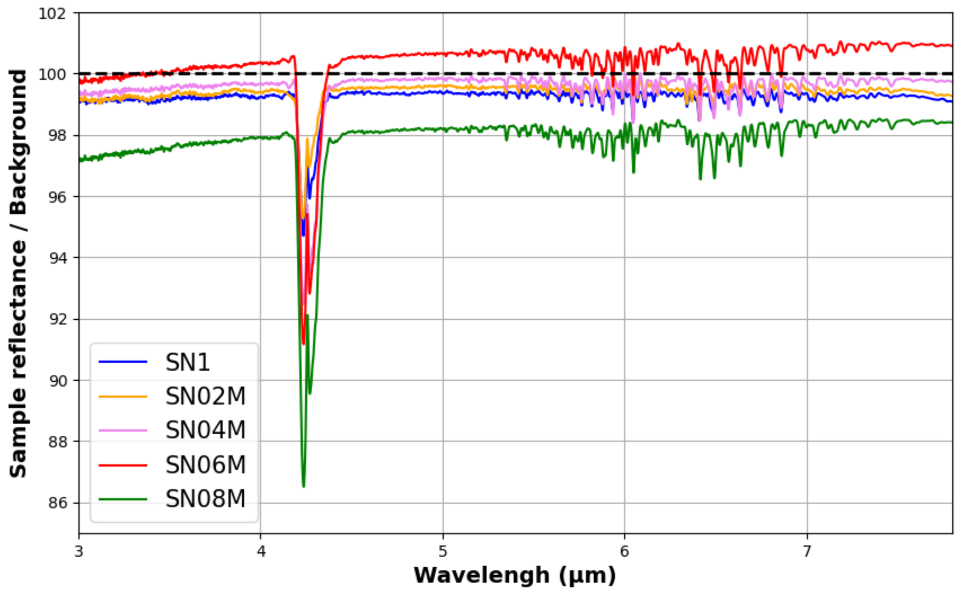


Figure 3.21: Reflectance measurements of selected samples.

	3 µm	5 µm	7,8 µm
SN1 Refletance by CILAS	98,416	99,610	99,768
SN1 Reflectance by CNR-IFN	99,210	99,345	99,084

Figure 3.22: Reflectance measurements of SN1 provided by CILAS and CNR-IFN at representative wavelenght.

In the case of sample SN06M, the spectra exceed the 100% line, likely due to background noise and external interferences affecting the reflectance data. A thorough analysis of these errors is programmed for the near future. Additionally, future measurements will be improved by isolating the measurement environment with a nitrogen flow.

While reflectance measurements of samples SN02M, SN04M, SN06M, and SN08M were conducted for the first time at CNR-IFN, for sample SN1 reflectance has been already measured by CILAS.

Table 3.22 presents a comparison of these data with the reflectance measurements taken at CNR-IFN for SN1, showing a difference of ±1%.

4
Conclusion

This thesis work presents Ariel (Atmospheric Remote-sensing Infrared Exoplanet Large-survey), ESA's fourth medium-class mission in the 'Cosmic Vision' programme, set to launch in 2029.

After a general introduction to the European context of the Ariel mission within the 'Cosmic Vision' programme, the mission's objectives were analyzed. Ariel is the first space mission dedicated to measuring the chemical composition and thermal structures of exoplanets, which are planets outside our Solar System. This will help establish a clear link between the characteristics of exoplanets and their parent stars.

The complex subdivision and management of the payload within the Ariel Mission Consortium were described, with a specific focus on the telescope assembly. The mission's milestones were also outlined.

Moreover, it presents the role of a Product Assurance Manager (PAM) within a space project, emphasizing their responsibility in ensuring the safety and success of all mission components.

Specifically, several key documents essential for PA/QA work were discussed. Among these, the Critical Items List (CIL) serves as a comprehensive inventory of items and processes within a space project considered critical to the mission's success and safety. One of these critical elements is the primary mirror of the Ariel telescope, constructed from a monolithic piece of aluminium, with stringent requirements for opto-mechanical performance.

To improve the reflectance performance of the mirrors, a protected silver coating was applied. Samples of this coating on the aluminium substrate were examined to assess potential ageing effects. This assessment was conducted using Atomic Force Microscopy (AFM), and the results were compared with previous data. Additionally, Fourier Transform Infrared (FTIR) spectroscopy analysis was performed for the first time at CNR-IFN and will be used as a reference for future comparisons.

In conclusion, the tests revealed no significant changes in optical performance or deterioration of the coating. At this stage, the ageing effect does not pose critical issues. These findings will require ongoing monitoring and confirmation through future analyses.

In the coming years, the team at CNR-IFN will contribute to the completion of the payload Critical Design Review, thanks to the AIV/AIT activities and PA responsibilities at the Telescope Assembly level and its subsystems.

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5
Annex

This annex presents additional results regarding the AFM morphological characterization.

Scans were recorded with a Park System XE-Series 70 microscope, presenting a resolution of 10 μm x 10 μm with 256^2 pixels. The samples are divided into two sets, corresponding to two coating runs and testing phases.

Samples SN1 and SN12 belong to the first deposition run conducted on April 3rd, 2019, by CILAS. Further tests were interrupted due to issues that occurred during the humidity test. These samples underwent the tests shown in Figure 5.1.

Samples SN01(L01),SN07M(L07), SN09(L09), SN10(L10) are part of the set used for the qualification of the coating, with the coating deposited on December 12th, 2019, by CILAS. These samples also underwent the tests presented in Figure 5.2.

The test specification are the same as described in Chapter 3, section 3.3.1.

The following Figures show the topography and roughness measurement of the samples.

	Humidity	Thermal	Adhesion Level 2	Cryotest	Cleaning	Abrasion
SN1						
SN12				✓	✓	✓

*all samples have undergone visual inspection and spectral relative reflectivity

Figure 5.1: Qualification tests to which the samples of run#1 have been subjected.

	Humidity	Thermal	Adhesion Level 2	Cryotest	Cleaning	Abrasion
SN01M(L01)						
SN07M(L07)	✓	✓	✓	✓		
SN09M(L09)					✓	✓
SN10M(L10)					✓	✓

*all samples have undergone visual inspection and spectral relative reflectivity

Figure 5.2: Qualification tests to which the samples of run#2 have been subjected.

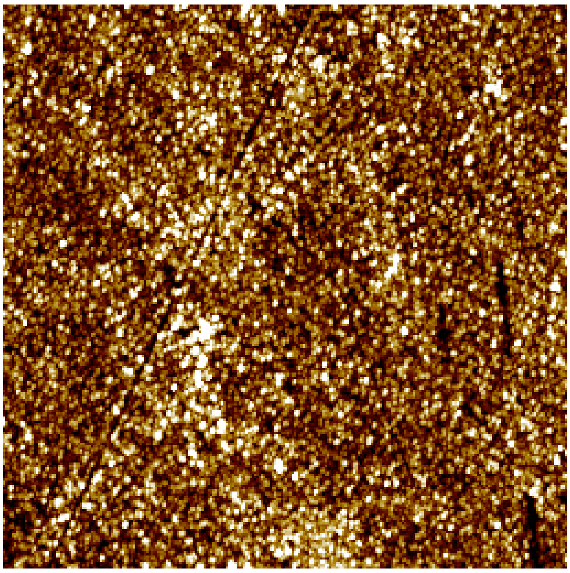
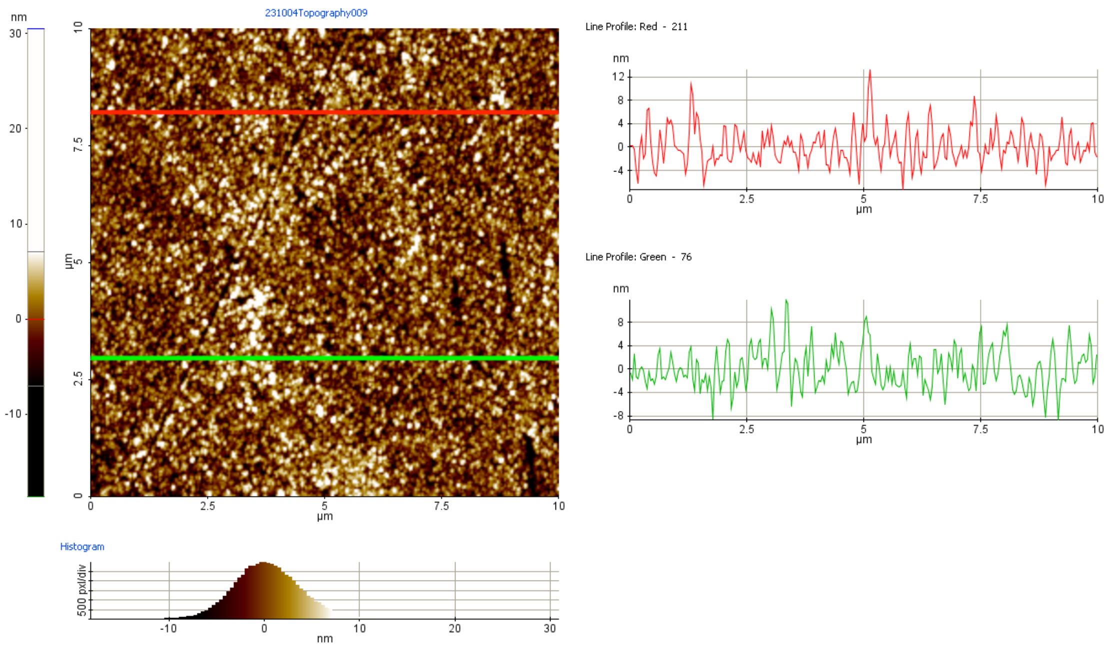


Figure 5.3: Two-dimensional representation of AFM measurement of sample SN1.



Statistics

Line	Min(nm)	Max(nm)	Mid(nm)	Mean(nm)	Rpv(nm)	Rq(nm)	Ra(nm)	Rz(nm)	Rsk	Rku
Red	-7.264	13.184	2.960	0.000	20.448	3.106	2.372	15.794	-0.823	4.521
Green	-8.685	11.752	1.533	0.000	20.437	3.453	2.767	16.827	-0.503	3.441

Figure 5.4: Roughness parameters of two linear profiles of sample SN1.

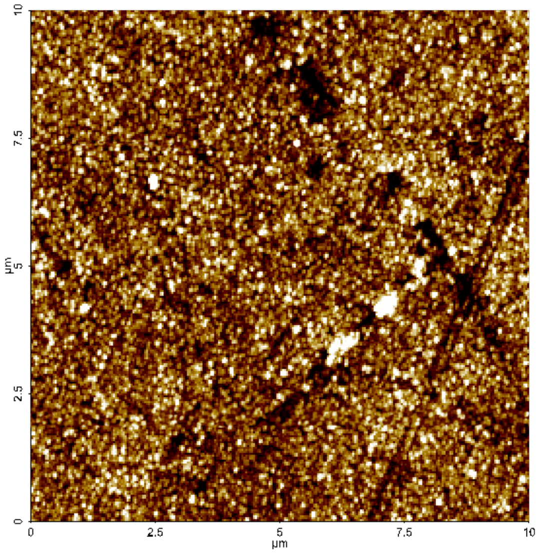
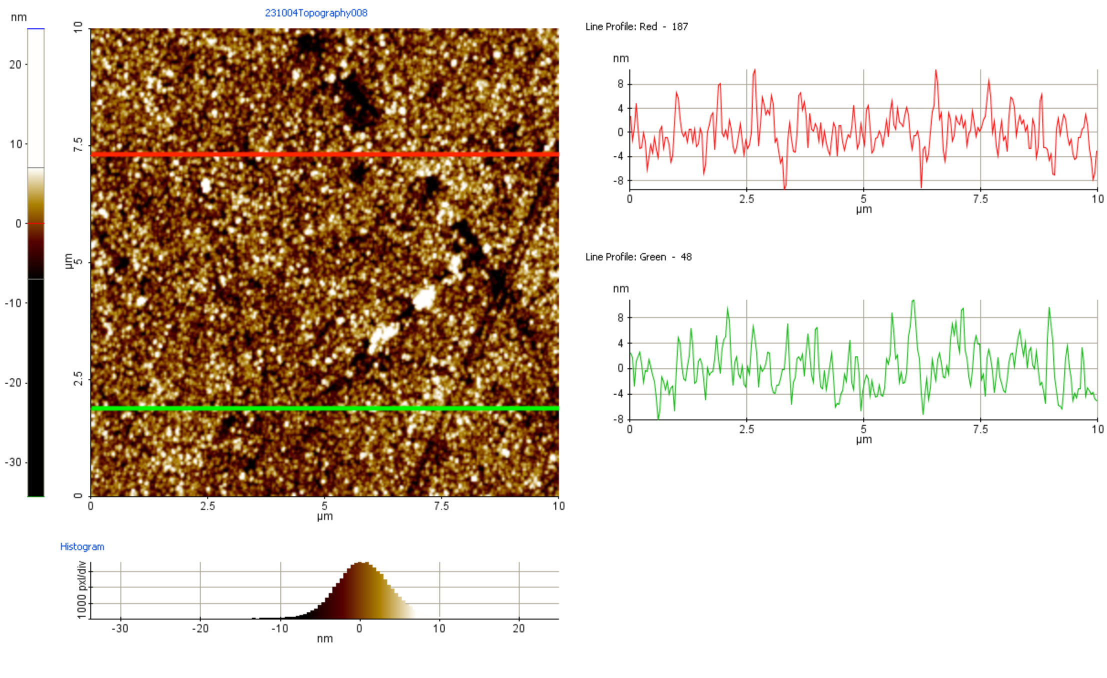


Figure 5.5: Two-dimensional representation of AFM measurement of sample SN012.



Line	Min(nm)	Max(nm)	Mid(nm)	Mean(nm)	Rpv(nm)	Rq(nm)	Ra(nm)	Rz(nm)	Rsk	Rku
Red	-9.483	10.383	0.450	0.000	19.866	3.352	2.589	16.893	-0.251	3.629
Green	-8.030	10.730	1.350	0.000	18.760	3.622	2.923	16.534	-0.491	2.992

Figure 5.6: Roughness parameters of two linear profiles of sample SN12.

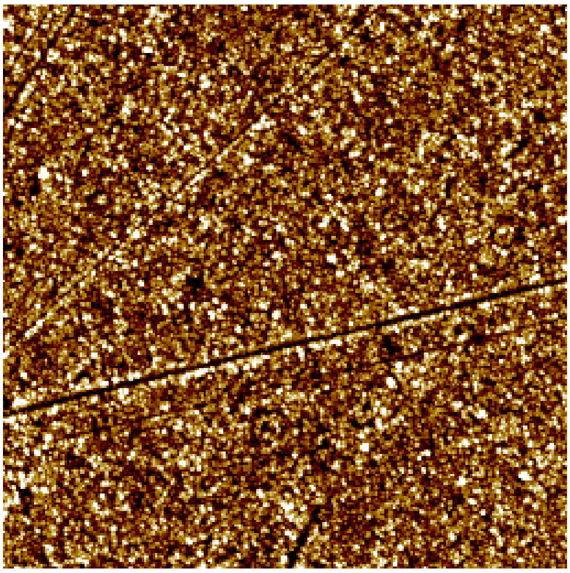
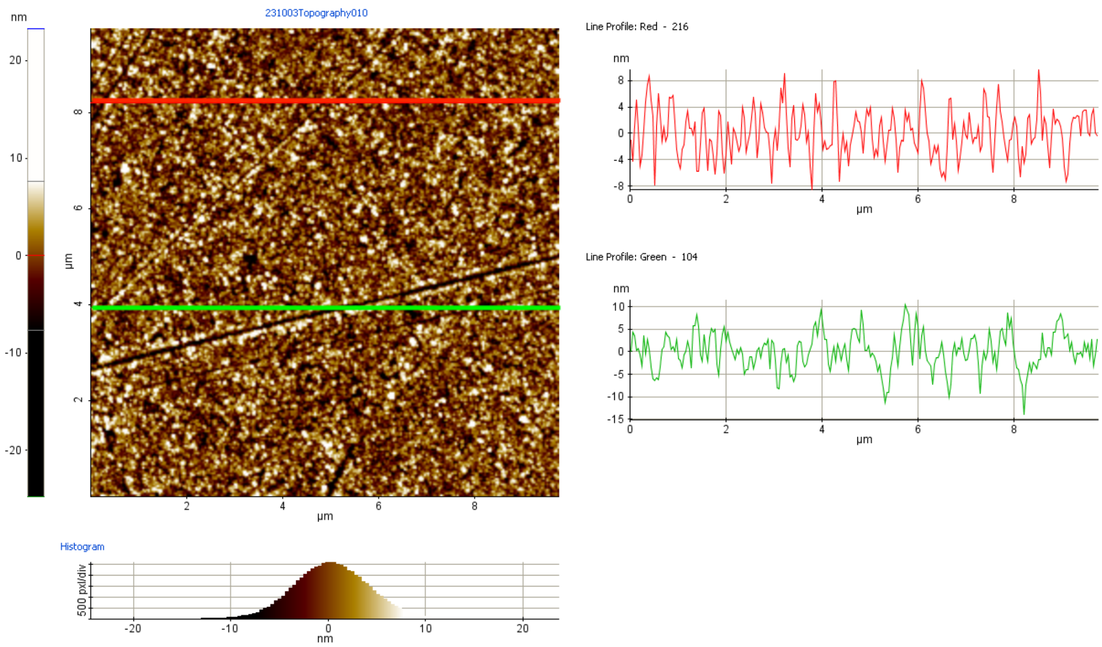


Figure 5.7: Two-dimensional representation of AFM measurement of sample SN01M(L01).



Line	Min(nm)	Max(nm)	Mid(nm)	Mean(nm)	Rpv(nm)	Rq(nm)	Ra(nm)	Rz(nm)	Rsk	Rku
Red	-8.553	9.659	0.553	0.000	18.211	3.536	2.848	16.364	-0.108	2.800
Green	-14.062	10.352	-1.855	0.000	24.414	4.067	3.158	19.782	0.180	3.298

Figure 5.8: Roughness parameters of two linear profiles of sample SN01M(L01).

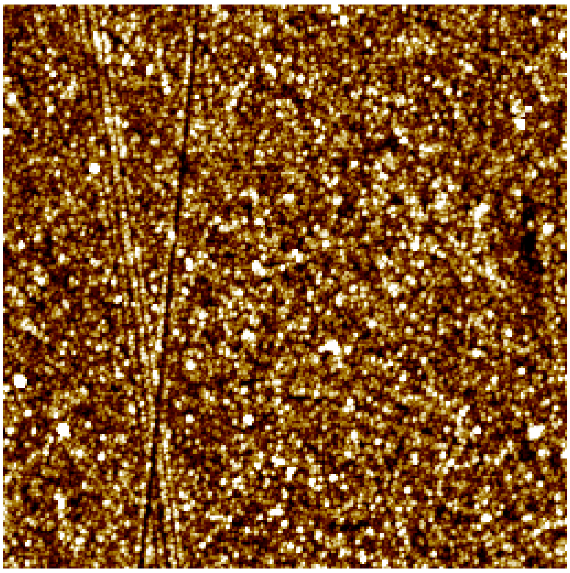
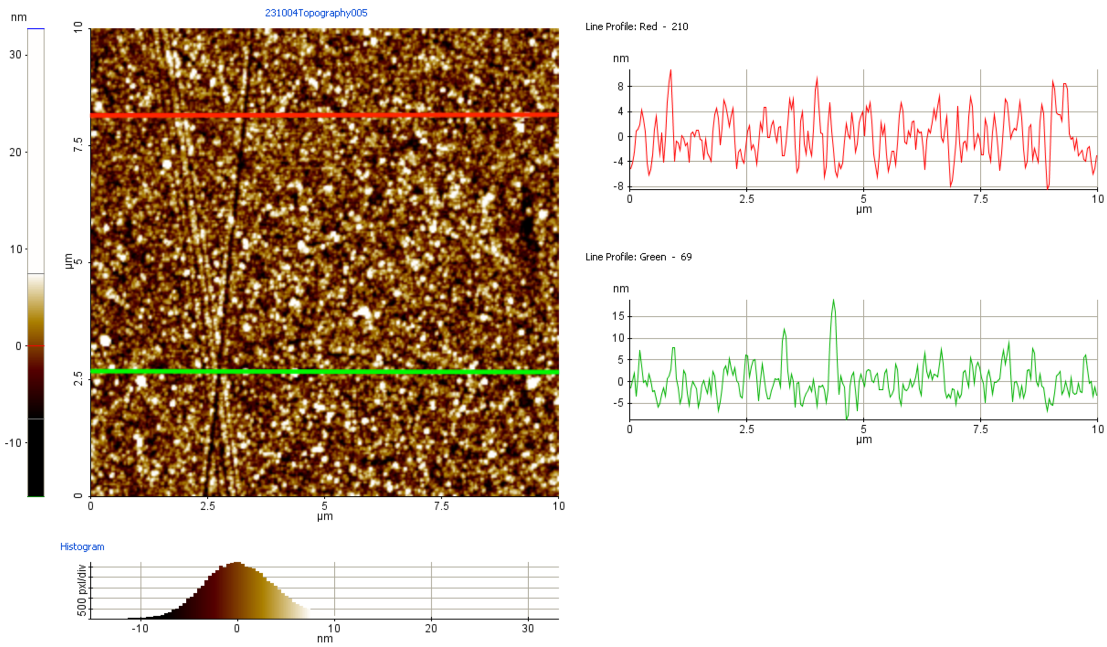


Figure 5.9: Two-dimensional representation of AFM measurement of sample SN07M(L07).



Statistics

Line	Min(nm)	Max(nm)	Mid(nm)	Mean(nm)	Rpv(nm)	Rq(nm)	Ra(nm)	Rz(nm)	Rsk	Rku
Red	-8.497	10.711	1.107	0.000	19.208	3.611	2.938	15.898	-0.249	2.735
Green	-8.812	18.769	4.978	0.000	27.581	3.893	2.874	18.039	-1.205	6.268

Figure 5.10: Roughness parameters of two linear profiles of sample SN07M(L07).

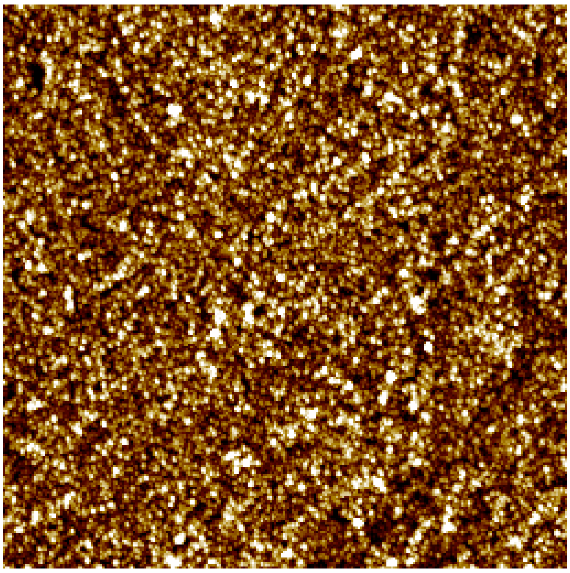
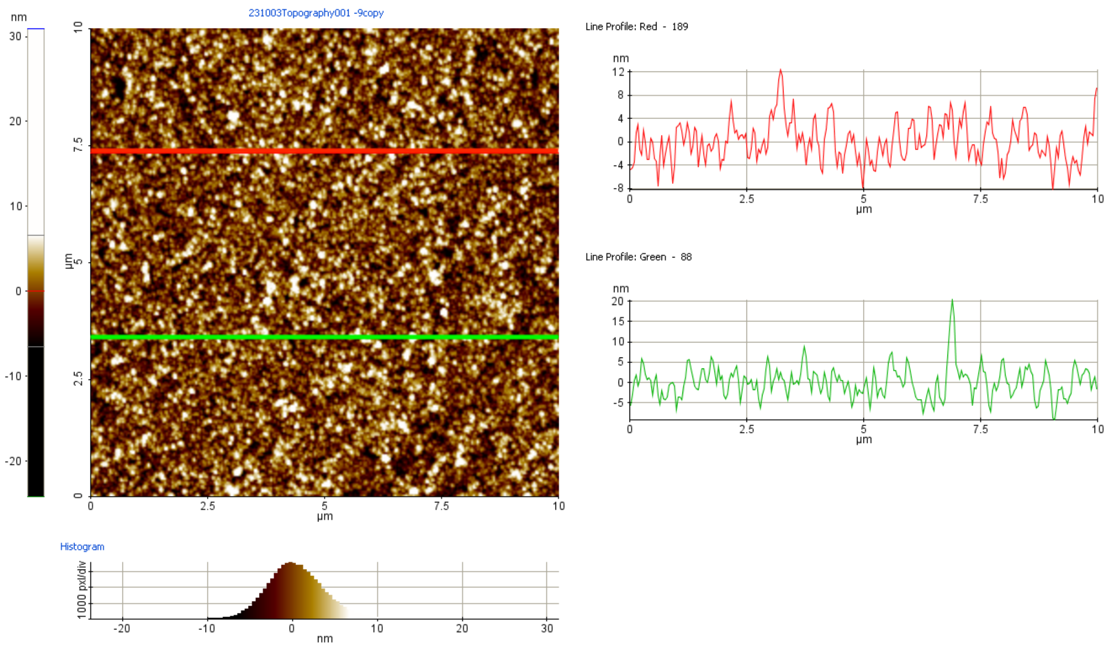


Figure 5.11: Two-dimensional representation of AFM measurement of sample SN09M(L09).



Statistics

Line	Min(nm)	Max(nm)	Mid(nm)	Mean(nm)	Rpv(nm)	Rq(nm)	Ra(nm)	Rz(nm)	Rsk	Rku
Red	-8.221	12.349	2.064	0.000	20.569	3.490	2.758	15.589	-0.443	3.430
Green	-9.166	20.254	5.544	0.000	29.421	3.864	2.887	17.415	-1.011	6.923

Figure 5.12: Roughness parameters of two linear profiles of sample SN09M(L09).

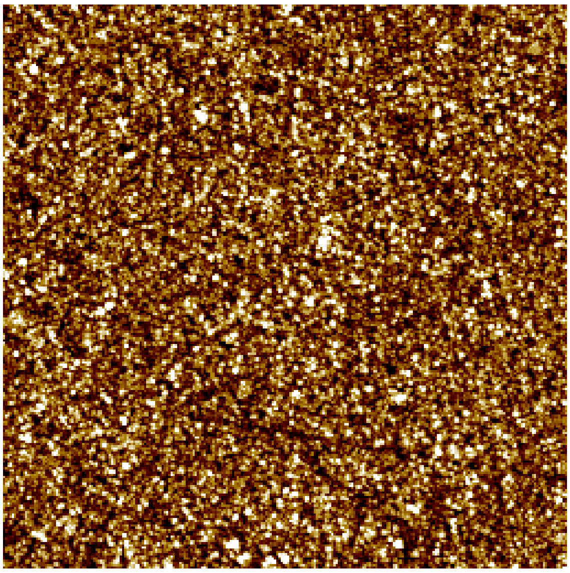
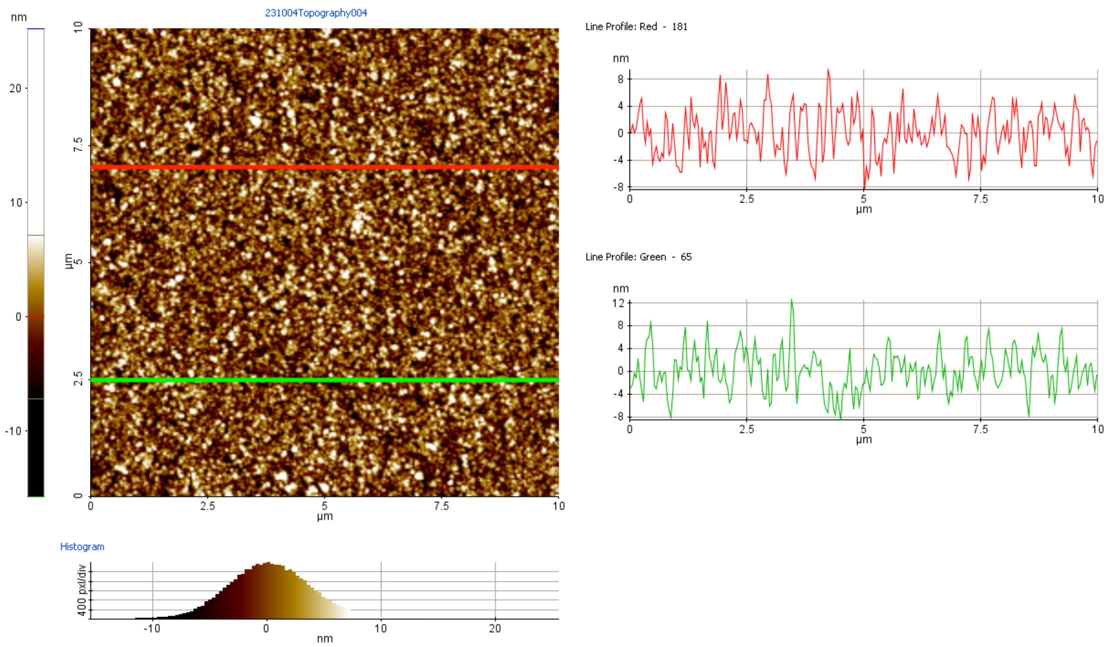


Figure 5.13: Two-dimensional representation of AFM measurement of sample SN10M(L10)



Statistics

Line	Min(nm)	Max(nm)	Mid(nm)	Mean(nm)	Rpv(nm)	Rq(nm)	Ra(nm)	Rz(nm)	Rsk	Rku
Red	-8.365	9.363	0.499	0.000	17.728	3.357	2.708	15.115	-0.047	2.629
Green	-8.513	12.485	1.986	0.000	20.998	3.608	2.860	16.828	-0.224	3.128

Figure 5.14: Roughness parameters of two linear profiles of sample SN10M(L10).