# The Ariel Mission

## *A mission of the European Space Agency for the characterization of exoplanets*

Jean-Christophe Salvignol*[a], Theresa Lüftinger[a], Gonzalo Saavedra Criado[a], Salma Fahmy[a], Camille Desportes de la Fosse[a], Riccardo Rinaldi[a], Cyril Colombo[a], Lidia Icardi[a], Robert Knockaert[a], Gianfranco Sechi[a], Ludovic Puig[a], Delphine Jollet[a], Anders Svedevall[a], Thierry Tirolien[a], Raymond Fels[a], Jorge Fiebrich[a], Marie-Geneviève Perichaud[a], Anja Plitzke[a]; David Milligan[b], Claudio Mevi[b]; Catarina Alves de Oliveira[c], Giovanna Tinetti[g], Paul Eccleston[d], Christophe Gabilan[e], Ludovic Larue[e], Jacques Oubrier[e], Ahmad Qadir[f]

[a]European Space Agency, ESTEC, Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands
[b]European Space Agency, ESOC, Robert-Bosch-Str. 5, D-64293 Darmstadt, Germany
[c]European Space Agency, ESAC, Camino Bajo del Castillo s/n, 28692 Villanueva de la Cañada Madrid, Spain
[d]Rutherford Appleton Laboratory, Harwell Campus, Didcot, Oxfordshire, OX11 0QX, UK
[e]Airbus Defence and Space, 31 rue des Cosmonautes, 31402 Toulouse Cedex 4, France
[f]Airbus Defence and Space, Gunnels Wood Road, Stevenage, SG1 2AS, UK
[g]University College London, Gower Street, London C1E6BT, UK
*Ariel Project Manager, Jean-Christophe.Salvignol@esa.int, phone +31-611318619, https://www.esa.int/Science_Exploration/Space_Science/Ariel

## ABSTRACT

Ariel, part of the European Space Agency's (ESA) Cosmic Vision science program, is an innovative medium-class mission designed for atmospheric remote sensing of exoplanets. It is the first mission solely dedicated to investigating the atmospheres of more than 500 transiting exoplanets, ranging from gas giants to super-Earths, using a combination of transit photometry and spectroscopy. The mission's primary goal is to analyze these exoplanets' chemical composition and thermal structures, paving the way for large-scale, comparative planetology.

Ariel is scheduled for launch in 2029 aboard Ariane 6.2. It will operate from an orbit around the Sun-Earth system's second Lagrange point. The mission has a nominal lifetime of four years, with the potential for a two-year extension.

The spacecraft comprises two main modules: the Service Module (SVM) and the Payload Module (PLM). The SVM manages platform elements, including attitude control, power, data handling, and communication systems. The PLM incorporates an all-aluminium cryogenic telescope with two scientific instruments, the Ariel IR Spectrometer (AIRS) and the Fine Guidance System (FGS).

The Operational Ground Segment consists of ground stations and the Mission Operation Centre (MOC) located at ESOC, responsible for the operations of the spacecraft and instruments. The Science Ground Segment (SGS) consists of the Science Operation Centre (SOC), located at ESAC, along with the Instrument Operations and Science Data Centre (IOSDC) provided by the Ariel Mission Consortium (AMC). The SGS will perform the science mission planning as well as processing of the data to generate the mission data products and provision of the Ariel mission archive for the user community.

While ESA holds overall responsibility for Ariel, the Ariel Mission Consortium is responsible for the procurement of the payload units, as well as managing the IOSDC. This collaborative effort aims to unlock the mysteries of exoplanetary atmospheres and deepen our understanding of these distant worlds.

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# 1. INTRODUCTION

Ariel, the atmospheric remote-sensing infrared exoplanet large-survey, is the fourth medium class mission within ESA's Cosmic Vision science programme. Ariel is the first mission dedicated to studying the atmospheres of a statistically large and diverse sample of transiting exoplanets (≥ 500) through a combination of transit photometry and spectroscopy. Ariel aims to measure the chemical composition and thermal structures of exoplanets extending from gas giants (Jupiter or Neptune like) to super-Earths, that (currently) orbit in the very hot to warm zones of their F to M-type host stars, opening up the way to large-scale, comparative planetology and allowing to address the following fundamental questions:

- What are the physical processes shaping planetary atmospheres?
- What are exoplanets made of?
- How do planets and planetary systems form and evolve?

Ariel is due for launch in 2029 on board an Ariane 6.2 in a dual launch configuration with the Comet Interceptor mission. It will operate from an orbit around the second Lagrange point of the Sun-Earth system (L2), which offers the benefit of a stable thermal environment thanks to the constrained relative orientation of the Sun and Earth to the spacecraft. The nominal mission lifetime is 4 years, however the mission will be sized to allow a lifetime extension to 6 years.

The spacecraft is composed of the Service Module (SVM), onto which the Payload Module (PLM) is integrated. The SVM hosts all the platform elements of the spacecraft such as the attitude and orbit control, power, data handling and communications systems, as well as warm electronics units and the cryocooler of the payload. The PLM hosts the telescope and detection chain of the payload, along with so-called "V-groove" structures, which serve to thermally decouple the PLM from the SVM. The S/C will be three-axis stabilized and oriented such that the PLM is maintained in the shadow of the SVM, enabling the telescope assembly to cool passively, reaching an operating temperature <70 K. The total spacecraft wet mass is approximately 1410kg with a power budget of 1kW.

The PLM holds the telescope assembly, containing an afocal off-axis Cassegrain telescope and common optics, which direct the incoming light to the two science instruments. The instruments consist of the Ariel IR Spectrometer (AIRS), providing spectroscopy over the wavelength range 1.95 - 7.80 µm and the Fine Guidance System (FGS) instrument which contains 3 photometric channels, VISPhot (0.50-0.60 µm); FGS1 (0.60-0.80 µm) and FGS2 (0.80-1.10 µm), as well as a low-resolution spectrometer covering the waveband 1.10-1.95 µm. The FGS1 and FGS2 channels also serve as a Fine Guidance Sensor in the attitude control loop of the spacecraft, allowing to achieve the pointing stability required to meet the science objectives.

The Operational Ground Segment consists of the ground stations and the Mission Operation Centre (MOC), located at ESOC, responsible for the operations of the spacecraft and instruments. The Science Ground Segment (SGS) consists of the Science Operation Centre (SOC), located at ESAC, along with the Instrument Operations and Science Data Centre (IOSDC) provided by the Ariel Mission Consortium. The SGS will perform the science mission planning as well as processing of the data to generate the mission data products and provision of the Ariel mission archive for the user community.

The overall responsibility for the mission lies with ESA, with the Ariel Mission Consortium being responsible for the PLM and warm payload units as well as for the IOSDC.

# 2. OVERVIEW OF THE MISSION MANAGEMENT SCHEME

The overarching responsibility for all aspects of the Ariel mission rests with the Directorate of Science of the European Space Agency (ESA).

ESA is responsible for the overall Ariel mission, and in particular for:

- The development of the space segment, consisting of a spacecraft split into a service module (SVM) to be provided by ESA, and a payload module (PLM) to be provided by the Ariel Mission Consortium (AMC) and carrying the scientific instruments;
- The development of the ground segment, in particular the MOC and the Science Operation Centre (SOC, part of the SGS), as detailed in Section 6;
- The launch services procurement;
- The mission and science operations (jointly with the AMC), covering early operations, commissioning and all subsequent in-orbit operation phases, including the decommissioning and disposal of the spacecraft in the post-operations phase.

Funded by national Funding Agencies, within the remit of a Multi-Lateral Agreement (MLA), including ESA and the national Funding Agencies, the AMC is responsible for:

- Providing the payload elements, comprised of: (i) the complete PLM, carrying the scientific instruments, (ii) the warm payload units to be accommodated in the SVM; both according to the agreed interfaces and schedule;
- Contributing to the integration and tests of the payload elements at spacecraft level, in coordination with the spacecraft industrial prime contractor and under the control of ESA;
- Supporting the payload safety, maintenance and operations throughout the mission Lifetime;
- Providing contributions to the Science Ground Segment (SGS), through the Instrument Operations and Science Data Centre (IOSDC).

NASA is contributing by providing sensors for the Fine Guidance System (FGS), pursuant to the relative Memorandum of Understanding between ESA and NASA.

The Canadian Space Agency (CSA) procures the cryo-harness for the AIRS instrument and the Telescope thermal control. The Ludwig Maximilian University of Munich (Germany) and JAXA (Japan) will provide coatings of optical components in the Payload Module.

The AMC activities are overseen by the Consortium Principal Investigator (PI), Co-PIs, and Consortium Project Manager (CPM). The PI serves as the formal point of contact with ESA for science and mission-related issues, while the CPM handles programmatic and technical matters.

ESA has nominated an Ariel Project Scientist (PS), who chairs and coordinates the AST activities and is the agency's interface with the AMC for all scientific matters. The role of the AST is to provide scientific advice during the development and operations of the Ariel mission, including the review and endorsement of top-level requirements, supervision of the preparation and periodic update of the Mission Candidate Sample (MCS) list, and definition of scientific priorities for the Mission Reference Sample (MRS).

The general scientific community will be able to participate in suggesting targets for Complementary Science and the possibility to suggest targets for the Ariel Mission Candidate Sample (MCS), which are either not already included in the MCS, planned to be observed with a different priority, or using a different observational strategy. The selection of these targets will be performed through an open ESA-run call roughly a year ahead of launch, in close coordination with the Ariel Science Team to guarantee full consistency with the core survey plans.

## 3. MISSION ARCHITECTURE

### 3.1 Observation strategy

Variations in the measured signal from spatially unresolved observations of an exoplanet at different points in its orbit around its host star will be used to determine the spectrum of the planetary atmosphere and measure phase-curve modulations (see Figure 3-1).

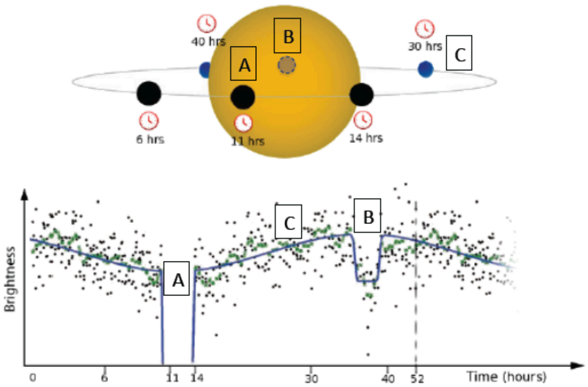


*Figure 3-1 Illustration of the orbit of an exoplanet around its host star and the resulting light curve measured from the combined star-exoplanet as a function of time (based on observations by Borucki et al (Science 2009, 325, 709) of HAT-P-7b with Kepler). Event A is referred to as a primary transit, B as occultation or a secondary eclipse and C as the orbital phase.*

The signal from both the star and exoplanet are collected simultaneously. The signal from the exoplanet, a very small fraction of the total, can be isolated by differencing observations made at various points of the exoplanet's orbit. Simultaneous collection of signals from both the star and exoplanet allows for isolation of the exoplanet's signal through differencing observations at various orbital points. Three observation sets explore distinct aspects of the exoplanetary atmosphere:

- Emission/reflection spectroscopy during eclipse/occultation unveils the dayside planetary spectrum by differencing in- and out-of-occultation observations.
- Transmission spectroscopy during transit measures absorption features in the exoplanetary atmosphere, isolating the fingerprint signal through differencing in- and out-of-transit measurements.
- Phase variation, observing changes in the visible exoplanet hemisphere during different orbital phases, reveals insights into energy redistribution and atmospheric dynamics by analyzing minute differences between observations at various points in the planetary orbit.

### 3.2 Science driven mission performance requirements

The Ariel mission architecture is strongly driven by the science requirements and programmatic constraints. Ariel's mission faces challenges as the star's emission dominates, leaving the exoplanetary signal at around $10^{-4}$. Strict engineering requirements for photometric stability and signal-to-noise ratio are crucial for effective signal isolation, necessitating precise pointing stability and noise control. Achieving science goals also requires careful calibration.

Observing one target at a time, driven by mission goals, emphasizes the need for high sky visibility (30% at any time) and mission availability exceeding 85%. Fulfilling Ariel's science objectives relies on simultaneous observations across the visible to infrared wavelength range (0.5-7.8μm) with specific spectral resolution, primarily influencing the payload design.

To summarize, the key mission performance requirements impacting achievement of the science objectives are the following:

- wavelength coverage
- spectral resolving power
- signal-to-noise ratio and noise requirements
- photometric stability / pointing stability
- sky visibility/source accessibility
- temporal resolution
- limiting targets (targets on the extremes of the target types)
- calibration
- zodiacal light and background (in turn impacting the signal to noise ratio)

Ariel aims to study a diverse set of known exoplanets for atmospheric spectra and light-curves, covering various properties. Simultaneously, specific objectives require detailed information about a chosen sub-sample. To enhance Ariel's scientific output, observations will focus on nested samples with defined spectral resolutions and signal-to-noise ratios.

| **The *Ariel* Core Sample survey** | | |
|---|---|---|
| **RECONNAISSANCE SURVEY TIER** | | |
| **Observational strategy** | **Science outcome** | **% lifetime** |
| • Low resolution spectroscopy (10 spectral resolution elements covering the 1.10 – 7.80 μm range) measurements with average SNR ≥ 7<br>• All planets in the sample<br>• Transit or eclipse | • What fraction of planets are covered by clouds?<br>• What fraction of small planets have still retained H2?<br>• Colour-colour diagrams<br>• Constraining/removing degeneracies in the interpretation of mass-radius diagrams<br>• Albedo, bulk temperature & energy balance for a subsample | ~30% (TBC) |

**DEEP SURVEY TIER**

| Observational strategy | Science outcome | % lifetime |
|---|---|---|
| • Spectroscopic measurements for a subsample (e.g. 50% of sample)<br>• R~10 for 1.10<λ<1.95μm R~50 for 1.95< λ <3.90μm R~15 for 3.90< λ <7.80μm with average SNR ≥ 7<br>• Transit and/or eclipse, and/or phase-curves | • Main atmospheric component for small planets<br>• Chemical abundances of trace gases<br>• Atmospheric thermal structure (vertical/horizontal)<br>• Cloud characterization<br>• Elemental composition | ~60% (TBC) |

**BENCHMARK/REFERENCE PLANETS TIER**

| Observational strategy | Science outcome | % lifetime |
|---|---|---|
| • Spectroscopic measurements at full R with average SNR ≥ 7<br>• Observations include transits, eclipses & phase-curves, spectral mapping etc. | • Very detailed knowledge of the planetary chemistry and dynamics<br>• Weather, spatial & temporal variability<br>• Elemental composition | ~10% (TBC) |

## 3.3 Launch trajectory, orbit and attitude constraints

Ariel is planned to be launched from Kourou (French Guiana) on board an Ariane 6.2, in a dual launch configuration with Comet-Interceptor. The launch trajectory is designed to place Ariel in a direct transfer orbit to the second Lagrange point in the Sun-Earth system (L2).

Ariel's planned operational orbit is a large, eclipse-free quasi halo orbit around the Sun-Earth L2 point, chosen for a stable thermal environment, high mission availability, and sky visibility. This orbit, free of Earth and Moon eclipses for up to 6 years, enables a simple spacecraft design, keeping the Payload Module in the shadow of the Service Module. This minimizes interruptions to science observations, meeting mission availability requirements.

Sun illumination regions for the payload are detailed in Figure 3-2, including a temporary region post-launch before safe sun-pointing acquisition. During science operations, the spacecraft has a constrained field of regard but can perform a full 360-degree rotation around its Z-axis for observations. Maintaining specific attitudes around the X and Y axes allows for extended observations of a single target without the need for spacecraft slew.

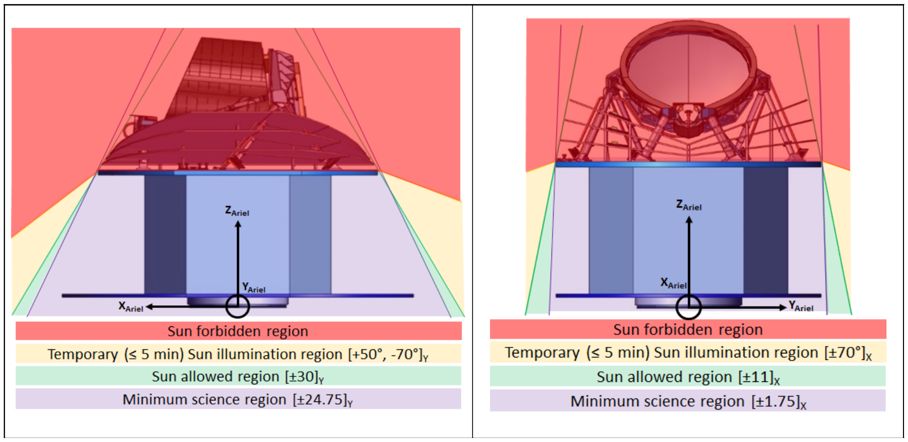


*Figure 3-2 Illustration of the Sun allowed region (green) in XZAriel plane (left, showing associated rotations around YAriel) and YZAriel plane (right, showing associated rotations around XAriel)*

### 3.4 Mission lifetime and mission phases

The spacecraft and its payload are designed for a 4-year in-orbit operational time to meet science requirements, with consumables allowing a potential 2-year mission extension. The mission encompasses Launch and Early Operations Phase, a Commissioning Phase (up to 3 months), Performance Verification Phase (up to 6 months), Nominal Science Operations Phase (minimum 3.5 years), and an Extended mission phase (if approved) for 2 years. Following routine science operations, decommissioning and post-operations phases run concurrently, each with defined activities by the Operations Ground Segment (OGS) and the Science Ground Segment, lasting 3 months (maximum) and 2 years, respectively.

### 3.5 Mission architecture

The Ariel mission architecture is structured similarly to other ESA science missions and comprises the following Mission Elements:

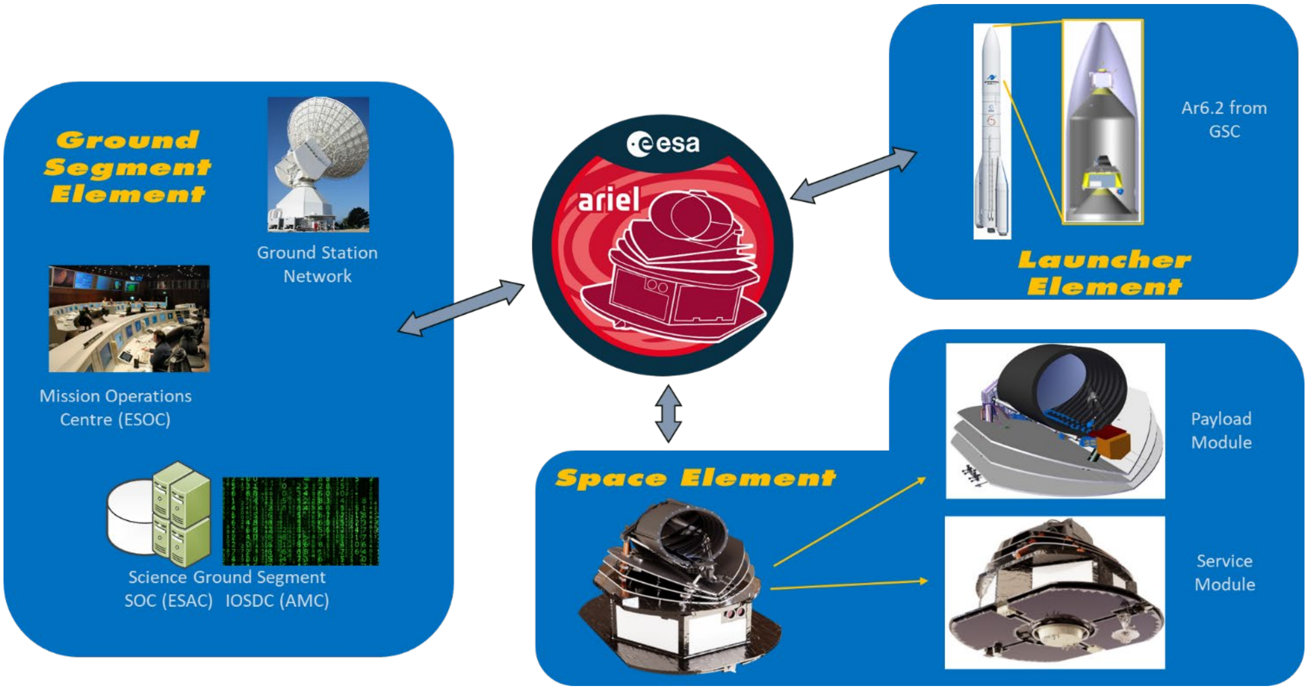


*Figure 3-3 Ariel Mission Architecture showing the Ariel Mission Elements. Each Mission Element falls under the responsibility of a distinct entity within the overall Ariel mission and is subject to a dedicated development cycle.*

## 4. OPERATIONS AND MISSION PLANNING CONCEPT

### 4.1 Overall mission concept

Ariel's operational framework is meticulously designed to facilitate its primary mission objective: observing known exoplanet-hosting stars. The nominal science operations concept outlines Ariel's approach to observing these stars, focusing on predicted transit or eclipse times. Ariel dedicates itself to observing a single target for the entire event, ensuring comprehensive coverage by co-aligning and operating both its AIRS and FGS instruments simultaneously for spectral analysis. Interruptions to this continuous sequence are minimized, limited only to essential maintenance activities. To ensure maximal science availability, Ariel's payload remains active during nominal spacecraft activities between science pointing, thereby avoiding significant thermal variations. Attitude pointing and slews are pre-planned and uploaded well in advance, allowing for at least 6 days of autonomy for on-board manoeuvres and payload configuration commands.

Attitude control is another critical aspect of Ariel's operations. The spacecraft autonomously adjusts its attitude to meet stringent pointing requirements, either following ground-commanded attitudes or utilizing uplinked target quaternions or ground-computed attitude profile timelines. This autonomy is essential for avoiding sun exclusion and restricted zones, ensuring safe operations. Even in cases where the Attitude and Orbit Control System (AOCS) is directed to an unsafe position, onboard autonomy (FDIR) prevents dangerous attitudes, thus maintaining the spacecraft's integrity.

Autonomy is paramount for Ariel, given its limited ground station passes and the need for high availability to minimize science interruptions. The spacecraft is equipped with autonomy features ensuring at least 6 days of autonomy for nominal science operations and the capability for 7 days in safe mode triggered by anomalies. Standard PUS services, such as the Mission Timeline (MTL) and On-Board Control Procedures (OBCPs), are employed to facilitate autonomous parameter checks and reactions. Additionally, the On-Board Monitoring (OBM) service continuously monitors parameters and triggers actions, while the Event-Action service initiates actions based on specific Event TM packets.

Payload operations and calibration are managed by the Instrument Operations and Science Data Centre (IOSDC), which oversees instrument operations requests and calibration activities. The IOSDC collaborates closely with the Science Operations Centre (SOC) to generate payload command requests and ensure smooth transitions during mission phases. Observation scheduling, under SOC responsibility, involves generating uplink request products for Mission Operations Centre (MOC) compliance, covering the next month of planned observations. Scientific mission planning involves long-term observation planning, incorporating calibration observations and mission constraints to maximize scientific return.

Finally, decommissioning and disposal procedures ensure the safe termination of Ariel's mission, including passivation, heliocentric disposal maneuvers, and Jacobi constant raising to minimize return probabilities, adhering to debris mitigation protocols.

## 4.2 From launch till start of survey

The 4-year mission, with a possible 2-year extension, will commence with a launch from the ESA Kourou Space Centre using an Ariane 6. After a transfer phase of approximately one month, the spacecraft will reach its final orbit around the L2 point. The launcher will place the spacecraft on a direct transfer orbit, with three planned transfer control manoeuvres—the first typically occurring within 1 day, and no later than 2 days, after separation from the launcher. No insertion manoeuvre is expected to be needed to reach the final large halo orbit around L2. The platform and payload commissioning and calibration phase will span 6 months following launcher separation. This phase includes the initial month during the transfer and the subsequent 5 months at the L2 orbit.

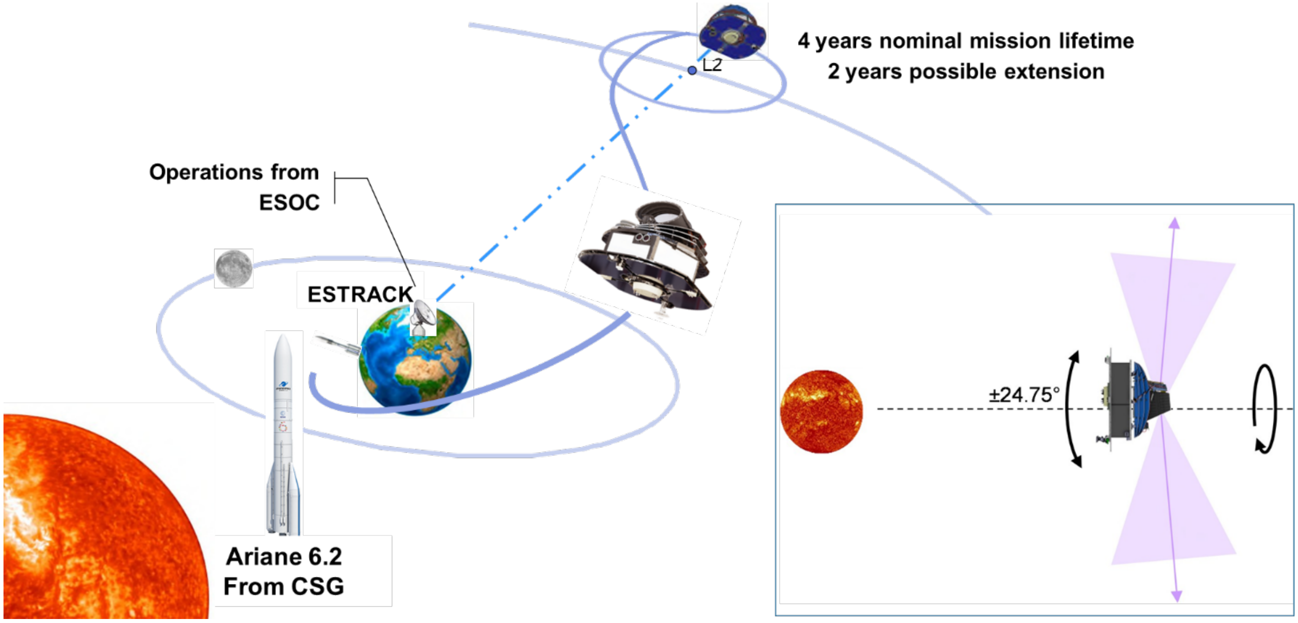


Figure 4-1From launch in Kourou to operations at L2

## 4.3 Overview of the science operation plan

Once in L2, the availability of the spacecraft for science observation is very high. The main interruptions are:

- Every 28 days, less than 2 hours are allocated for Station-Keeping Maneuvers
- Every 2-4 days, pointing of the high gain antenna to Earth and transmission of science data in < 1.5h
- Between observation of 2 successive targets, pointing maneuvers and stability convergence in < 20min

Science observation slots last typically in average 7.7 hours and a maximum of 3 days for each target.

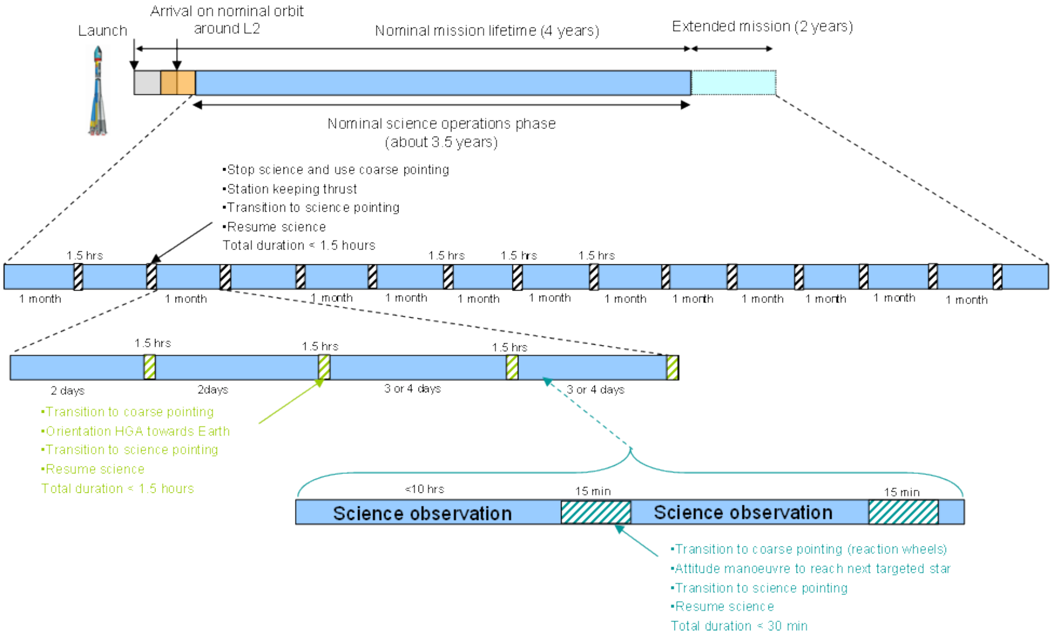


*Figure 4-2 Overall Science operation plan and interruptions*

# 5. THE ARIEL SPACECRAFT

## 5.1 Ariel Spacecraft design overview

The Ariel spacecraft is a three-axis stabilized spacecraft that consists of two modules integrated together:

- Service Module (SVM) hosting all S/C platform equipment as well as payload “warm electronics” units as well as the payload Active Cooling System units;
- The Payload Module (PLM) consisting of the Ariel telescope, including all optics and the two scientific instruments along with their “cold front end” read out electronics. In addition, the PLM includes the V-Groove assembly.

## 5.2 Ariel Spacecraft Platform

### 5.2.1. Overview

The Ariel spacecraft is designed to offer deep space thermal environment to the Ariel telescope. The radiative interface with the service module (SVM) is limited to the interface plane to the payload module (PLM). The SVM top floor does not exceed this area and fills it completely to provide to the PLM the required sun shadowing function that guarantees that the sun never enters in the shadow cone depicted in Figure 3-2. No SVM hardware extends out of the SVM allocated cone to ensure that no SVM hardware is in direct sight of any PLM part.

The spacecraft configuration is characterized by a highly modular configuration enabling parallel development and integration of its main sub-assemblies.

The PLM composed of the telescope assembly with its bipods and the V-grooves is a module whose integration is made easy by the flat top floor fully dedicated to the PLM interface.

The modular concept is used for the solar array mounted below the bottom panel. The propulsion configuration is an independent module with a mechanical interface for its structure on the bottom floor of the SVM. The additional thruster located on the -X side of the spacecraft is installed on a shear wall. The communications units are all accommodated on a single panel. The bare panel is delivered to the communications module supplier for integration of the subsystem and full validation. The module is then delivered to spacecraft AIT without need to revalidate internal interfaces. Similarly, the units of the payload cryocooler system are all accommodated on a single panel for AIT simplification.

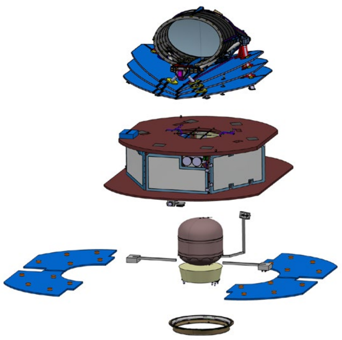


*Figure 5-1 Ariel modular configuration*

### 5.2.2. Mechanical design

The SVM structure is a hybrid CFRP and Aluminium sandwich panel structure.

The primary structure is composed of a core structure providing the required structural strength and stiffness. It is composed of the following items: Top panel (CFRP sandwich panel), Bottom panel (CFRP sandwich panel), 6 shear walls (CFRP sandwich panels) and Launcher Interface Ring (LIR) in Aluminium. 6 Lateral panels in Aluminium sandwich construction where dissipative units are installed also serve as thermal radiators. The secondary structure is composed of cleats, support structure for appendages, connector brackets, etc.

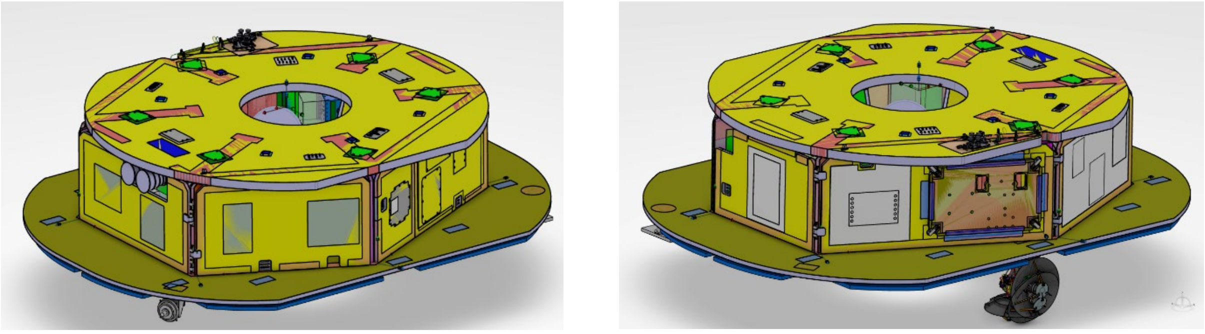


*Figure 5-2 – Ariel SVM structure overview*

The 6 shear walls provide an irregular hexagonal shape to the SVM main structure as their location and orientation is driven by the PLM Bipod interfaces. The core structure elements are linked together through Titanium cleats and brackets, which also provide the required strength and stiffness on the critical interface locations.

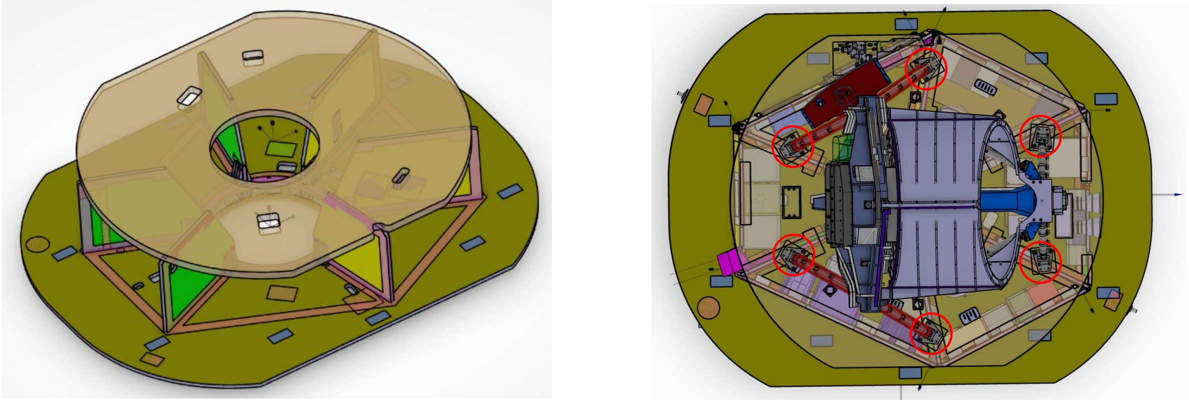


*Figure 5-3 – Ariel core structure*

The main structural load path is provided by the assembly of the LIR, shear walls, top panel and bottom panel. The LIR interfaces with the bottom panel, while pairs of Titanium shear brackets directly join the shear walls to the LIR.

The telescope is attached to the SVM by means of three pairs of bipods (6 interfaces). Considering the mass of the PLM (in the range of 350kg) these interfaces are deemed the major payload interfaces. In order to be able to sustain the mechanical loads, these interfaces rest over the structure top panel directly above the shear walls. Reinforced cleats joining the shear walls to the top panel on the bipod interface locations ensure the adequate strength and stiffness to the assembly. Together with the core structure design logic this architecture allows for a very direct load path between the telescope interfaces and the LIR. The bipods are interfaced to the top panel through Titanium fittings that engage the studs present on the top panel.

The propulsion module is attached to the lower side of the bottom panel through an Aluminium interface ring, which provides support for the main tank through a dedicated tank support cone. An equipment deck underneath the tank (attached to the interface ring through intermediate brackets) serves as support for the various equipment (pressure transducers, latch valves, -Z thrusters, etc.).

### 5.2.3. Electrical and Data Handling Architecture

The electrical architecture consists of:

- A data handling subsystem comprising the On-Board Computer (OBC) and Remote Interface Unit (RIU)
- A power subsystem comprising the Power Conditioning and Distribution Unit (PCDU), one Battery and body mounted Solar Array
- A communications subsystem comprising two X-band transponders, two Solid State Power Amplifiers (SSPA) two Low Gain Antennas (LGA), one steerable Medium Gain Antenna (MGA) and the associated RF distribution network (RFDN)
- An AOCS subsystem comprising two Star Trackers, two Acceleration Measurement Units (AMU), two Rate Measurement Units (RMU) and three Fine Sun Sensors (FSS). It also includes 4 Reaction Wheels and sends commands to a mono-propellant propulsion system for attitude / manoeuvres control.
- A “warm units” payload subsystem comprising the ICU, ADCU, TCU, FCU and ACS electronics (Figure 5-5).

The Data Handling Architecture is crafted to provide the necessary flexibility and connectivity for efficient data management in both payload and platform operations. It consists of two units:

- On-board Computer: This unit hosts processing and memory resources for on-board software, along with hardware control functions, SHP command drivers, MIL-STD-1553B and CAN bus interfaces. It facilitates SpaceWire links to Payload instruments and is sized to store both scientific and housekeeping data. The OBC also hosts the spacecraft Central Software, managing memory functions, telemetry, telecommands, time management, and system reconfigurations. It communicates with spacecraft units for receiving telemetry or sending telecommands via MIL-STD-1553, CAN, or SpaceWire links. Additionally, it interfaces with the X-Band transponder for telecommand reception and telemetry transmission.

- Remote Interface Unit: This unit hosts tailored interfaces for Platform equipment. The RIU manages discrete telemetry and telecommands, providing numerous interfaces and making them accessible to the OBC via the MIL-STD-1553 bus.

### 5.2.4. Attitude and Orbit Control

The Attitude and Orbit Control subsystem design uses the following set of equipments:

- RMU: 3-axis gyros for acquisition/safe mode/FDIR
- FSS Fine Sun sensors for acquisition/safe mode/FDIR
- STR: Star tracker for normal mode
- FGS: Fine Guidance System #1 & #2 (built into the instrument focal plane) for fine pointing mode
- AMU: Accelerometers
- CPS: Thrusters to perform trajectory correction and station keeping manoeuvres, angular momentum management, and attitude control for acquisition/safe mode
- RW: Reaction wheels, which can only exchange angular momentum with the spacecraft, for short-term attitude control and fine pointing. The wheels contain local speed loops to reduce the impact of friction torque jumps.

Ariel AOCS is organised around four modes:

- SAM (Sun Acquisition Modes) for initial acquisition and subsequent safe-hold modes.
- NOM-O (Offloading/Orbit) for thruster-based nominal operations: trajectory corrections in LEOP, station keeping, offloading of angular momentum, end-of-life disposal.
- NOM-C (Coarse), for wheel-based nominal operations outside of science observations and slew manoeuvres
- NOM-F (Fine), for fine pointing with FGS in the loop during science operations

The NOM-O, NOM-C and NOM-F are seen as separate AOCS normal modes (used for normal operations) but share most of their functions and algorithms, thanks to the modular architecture retained.

The design is meant to be simple (for operations) and versatile (for limiting constraints on the payload), involving as few modes and units as possible. Some of the design features are listed below:

- The normal modes operate without a gyro and need only one STR optical head.
- A single NOM-O mode takes care of trajectory corrections, station keeping and RW offloading
- A single NOM-C mode can perform attitude slews, routine operations and FGS target star acquisition
- To simplify operations, the normal modes are able to compute and perform attitude slews and offloading manoeuvres autonomously.
- Safe/Acquisition Modes (SAM) share common implementation at AOCS level.

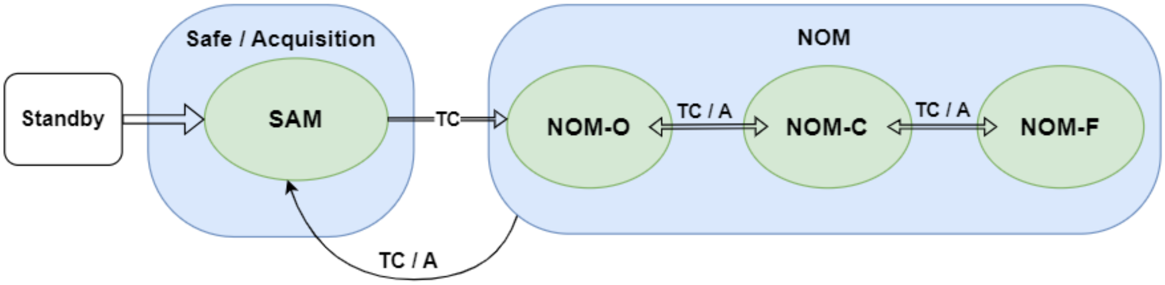


*Figure 5-4: AOCS Modes and transitions*

### 5.2.5. Telecommunications

The Communication subsystem is responsible for maintaining the spacecraft command uplink and telemetry downlink communications through all stages of the mission.

The Communication subsystem working in X-band (7190 – 7235 MHz for uplink and 8450 – 8500 MHz for downlink) comprises two Transponders, two Solid-State Power Amplifiers (SSPA), two Low Gain Antennas (LGA), one Medium Gain Antenna and its pointing mechanism (MGAMA) and the RF Distribution Assembly (RFDA) made of diplexer filters for isolation between Rx and Tx paths, RF switches for cross-strapping, one 3dB hybrid coupler for LGA combination and the RF coaxial cables.

### 5.2.6. System budgets

| | |
|---|---|
| **Lifetime** | 4 years nominal + 2 years extension |
| **Spacecraft Dimensions** | ~3.5 x 2.7 x 2.6 m (L x l x h) |
| **Mass** | 1410 kg (S/C)<br>610 kg (Payload) |
| **Propellant** | 195 kg |
| **Power** | 1 kW EoL |
| **Science data** | 236 Gbits/week |
| **Mass Memory** | 330 Gbits (EoL) |
| **RF power** | 14 W (EoL) |
| **Link rate** | 5.4 Mbits/s (downlink)<br>16 kbits/s (uplink) |

| | |
|---|---|
| **Pointing accuracy (99.7% conf. level)** | 1 arcsec absolute |
| **Pointing stability (99.7% conf. level)** | 180 mas over 0.1 s<br>230 mas over 90s<br>70 mas from 90s to 10 hours |
| **Agility** | 70° in 15 minutes |
| **Reliability** | > 90% |
| **Availability** | > 89% |

## 5.3 The Ariel Payload

### 5.3.1 Overview

The integrated payload comprises an off-axis Cassegrain telescope made entirely of aluminum, directing a collimated beam into two distinct instrument modules. Operating in the visible to infrared, the Fine Guidance System (FGS) features three photometry channels spanning from 0.50 µm to 1.1 µm. Among these channels, two serve as a redundant system, ensuring guidance and closed-loop control for the AOCS. Additionally, this module houses a low-resolution spectrometer (R = ~15) operating within the 1.1 µm – 1.95 µm waveband.

A second instrument module, named the Ariel IR Spectrometer (AIRS), offers spectral resolutions ranging from 30 to 100 across a waveband from 1.95 µm to 7.8 µm. To maintain operational temperatures, the payload module employs passive cooling techniques, reaching approximately 55 K through isolation from the spacecraft bus, facilitated by V-Groove radiators and isolating Bipods. The only components requiring active cooling are the detectors for the AIRS instrument, which are cooled to below 42 K using an active Ne JT cooler. The design of the payload and its associated instruments is depicted below.

### 5.3.2 Payload architecture

The payload is composed of two major sections, the cold payload module (PLM) and the payload warm items that are mounted within the spacecraft service module (SVM).

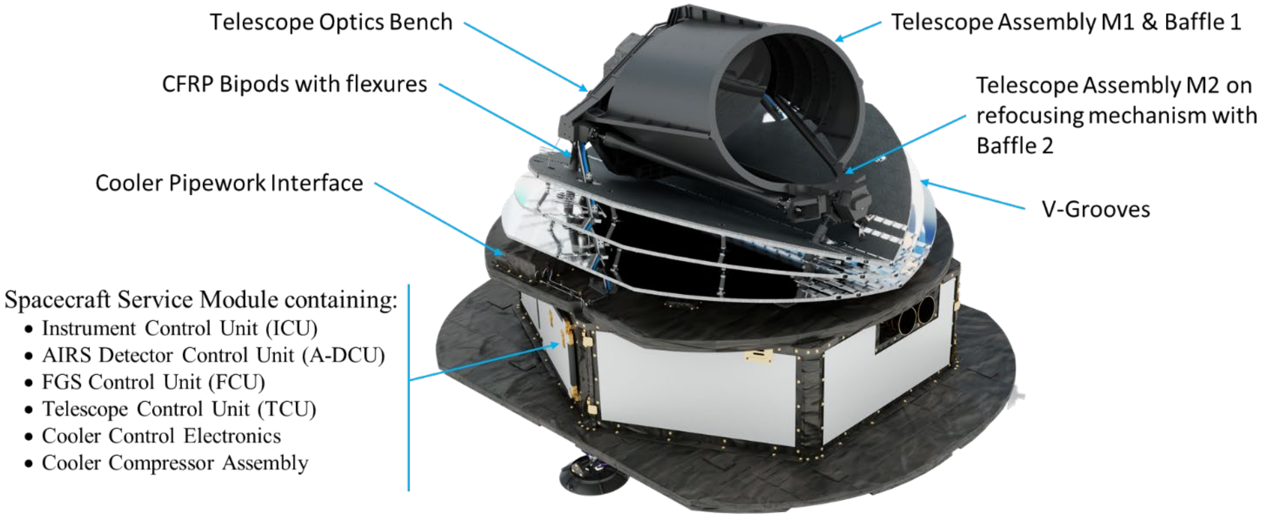


Figure 5-5: Illustration of the Ariel PLM and SVM

The major items, as shown above in Figure 5-5 and below in Figure 5-6 and Figure 5-7 are:

- **Cold PLM:**
  - The Telescope Assembly (TA) is based on an optical off-axis Cassegrain telescope system that consists of the Telescope Optical Bench (TOB) and the Metering Structure (TMS), of the primary mirror M1,

secondary mirror at prime focus M2 with a re-focusing mechanism on the M2 mirror (M2M), the M3 and M4 beams to collimate the beam and direct it towards the optical bench, and of the TA Baffle.

- A set of common optics to split the incoming beam between the AIRS and FGS instruments including the M5 mirror to direct the incoming beam, the dichroics to split the FGS and spectrometer light, and formatting optics to inject the light into the spectrometer correctly.
- The Ariel IR Spectrometer (AIRS) to use the light focused by the telescope to perform the high resolution spectroscopy extended into the far infrared, including all optics and structure plus detectors, cold front-end electronics (cFEE), and interface to the AIRS DCU.
- Fine Guidance Sensor / Visible Photometer / Near-IR Spectrometer (FGS/VISPhot/NIRSpec), including all optics and dichroics to split into the 4 separate channels, prime and redundant detectors and cold front end electronics (cFEE).
- Thermal hardware: active cooler cold head for Neon JT cooler, passive radiator for cooling of FGS detectors and cFEEs, V-grooves and Bipods to isolate the cold PLM from the warmer SVM.

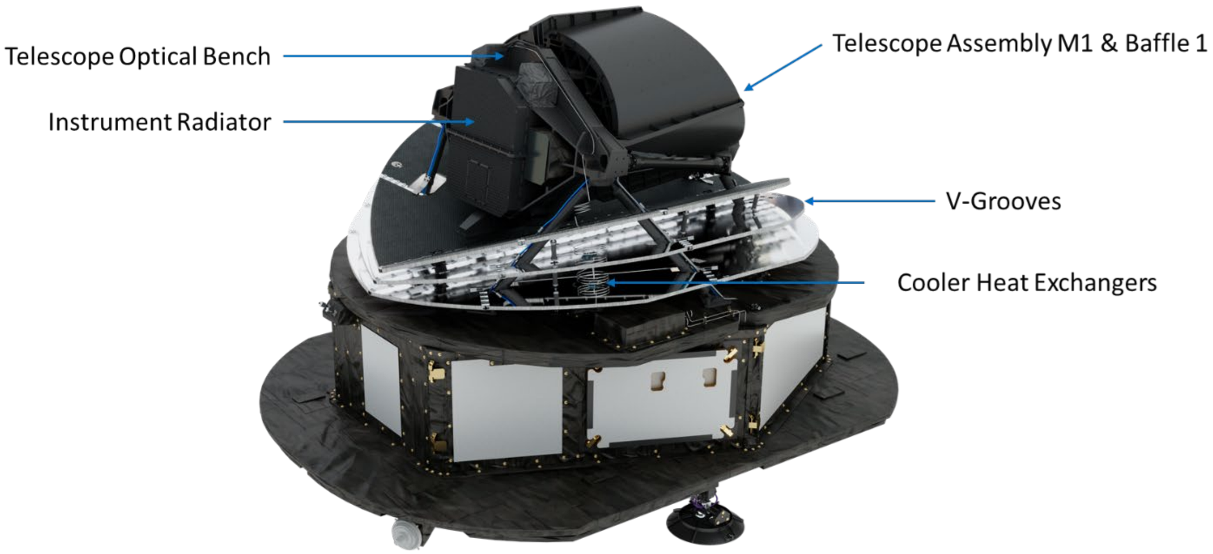


*Figure 5-6: Illustration of the rear of the Ariel PLM*

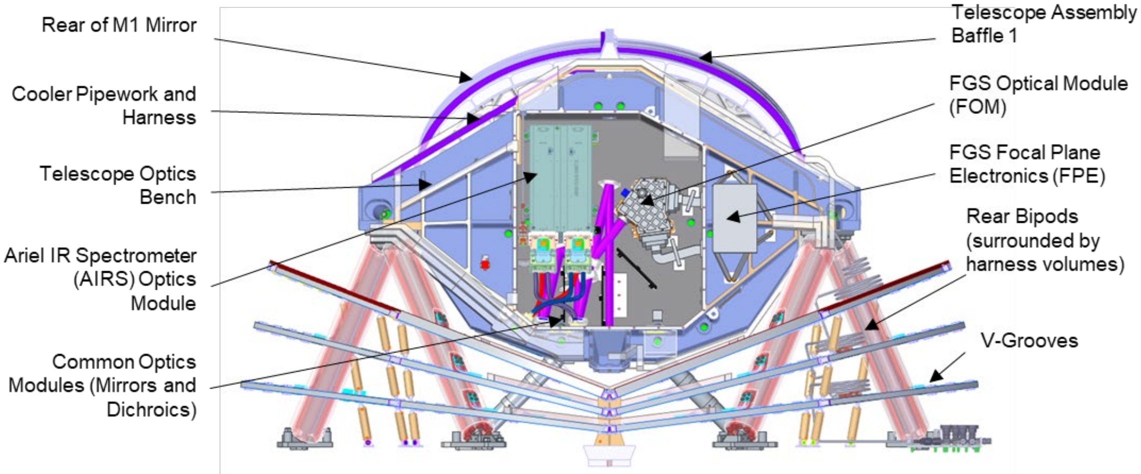


*Figure 5-7: Illustration of the accommodation on the Ariel PLM Optical Bench*

- **Warm SVM mounted units:**
    - Instrument Control Unit (ICU) housing the central data processing unit (DPU) for the spectrometer data, a power supply unit (PSU), communication and interface to the A-DCU and TCU, and a Commanding and Data Processing Unit (CDPU).
    - AIRS Detector Control Unit (A-DCU) which includes a power and data interface to the ICU, housekeeping & central logic, biasing, data acquisition & pre-processing for the spectrometer and thermal control and monitoring for AIRS.
    - Telescope Control Unit (TCU) with power and data interface to the ICU, power distribution & central logic, M2M mechanism control, and thermal monitoring and control of the telescope.
    - FGS Control Unit (FCU) electronics incorporating the FGS/VISPhot/NIRSpec wFEE, the control and processing electronics and software for determining the pointing from the FGS data and transmitting this information to the spacecraft.
    - Active Cooler System (ACS):
        - Cooler Control Electronics (CCE), including power and conditioned signals to the cooler compressor, monitoring of cooler housekeeping data, and stabilization of cold head temperatures (if necessary).
        - Cooler ComPressors Assembly (CPA)
        - Cooler gas handling panel incorporating fill connections, filtering etc., the Cooler Ancillary Panel (CAP)

### 5.3.3 Payload responsibilities

The overall architecture for the Ariel payload is depicted in Figure 5-8.

This diagram also shows the nationalities of the members of the payload consortium who are taking responsibility for each element.

NASA (US) is involved in supplying the Focal Plane Modules, including the Sensor Chip Assemblies and associated Cold Front-End Electronics, for both detectors within the Fine Guidance System (FGS).

CCSA (Canada) will provide the cryoharness for the AIRS instrument and for the Telescope thermal control system.

JAXA (Japan) contribution in Ariel is confirmed and is in the process of formalization for the provision of optics and coating for the AIRS instrument. NAOJ is further contributing to Ariel scientific and ground segment activities (target preparation).

For more details, see SPIE paper 13092-48 "The Ariel payload design post-PDR".

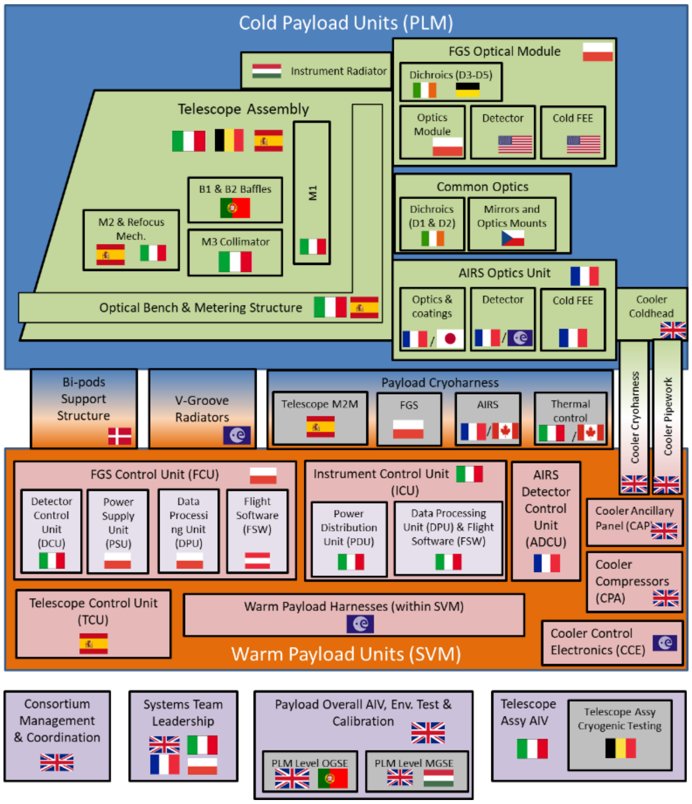


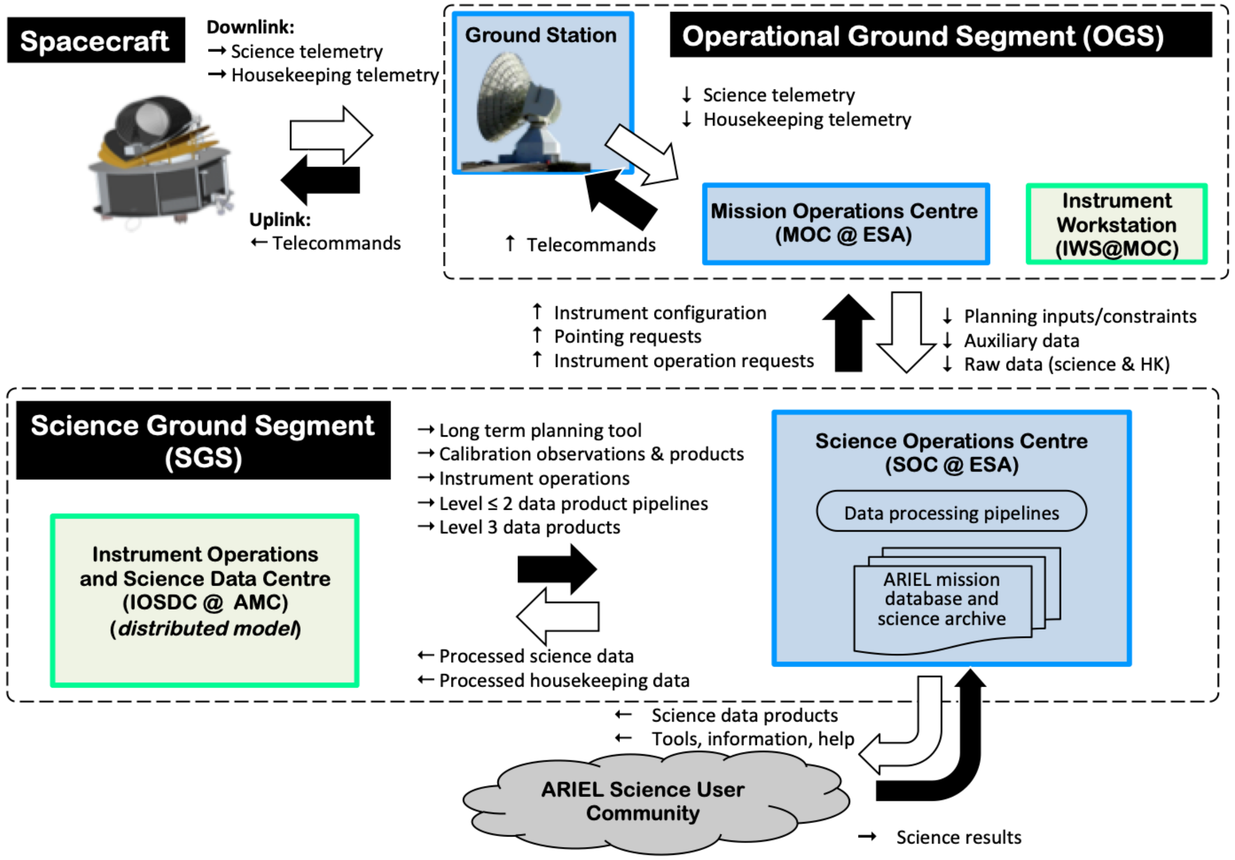
*Figure 5-8 Ariel Payload Schematic and Responsibilities*

# 6. THE ARIEL GROUND SEGMENT

The Ariel Ground Segment consists of two main components:

- The **Operational Ground Segment**, located at ESA/ESOC in Darmstadt, Germany, includes the Mission Operations Centre and the ESTRACK ground station network. It is responsible for spacecraft command and control, data downlink, and distribution to the Science Ground Segment.
- The **Science Ground Segment** comprises the Science Operations Centre based at ESA/ESAC in Villafranca del Castillo, Spain, and the Instrument Operations and Science Data Centre (IOSDC) provided by the Ariel Mission Consortium. This segment handles science operations planning, processing and archiving of science data products, payload performance monitoring, calibration, and manages the Ariel mission archive while interacting with the scientific community.

The ground segment architecture follows the typical structure of ESA science missions, utilizing multi-mission infrastructure and applications, particularly at the Mission Operations Centre (MOC) and Science Operations Centre (SOC):



## 6.1 The Operational Ground Segment (OGS)

The Mission Operations Centre (MOC) oversees Ariel spacecraft operations, ensuring safety, health monitoring, flight dynamics support, and intervention during anomalies. It handles downlinking raw telemetry to the Science Operations Centre (SOC) for further processing. Ground station scheduling, including Ariel's stations in ESA's tracking network, is managed by the MOC, coordinated with the Network Operations Centre (NOC) at ESOC. The telemetry, tracking, and command subsystem adhere to ESA Ground Segment standards and utilize the ESA tracking station network. ESA/ESOC is responsible for designing, implementing, and operating the MOC.

ESA's ESTRACK 35m antenna ground stations will be used for all mission phases, with 14 hours of weekly contacts during the nominal phase. Three passes per week are spaced regularly, compensating for missed contacts in the next pass. Additional coverage is planned for LEOP and commissioning phases. The 35m antennas will also perform ranging and Doppler measurements for orbit determination.

### 6.2 The Science Ground Segment (SGS)

As mentioned above, the responsibility for the SGS tasks and activities are distributed and shared between the SOC and the IOSDC. These comprise the SGS architecture, mission planning, instrument operations and calibration, data processing, archiving and community support.

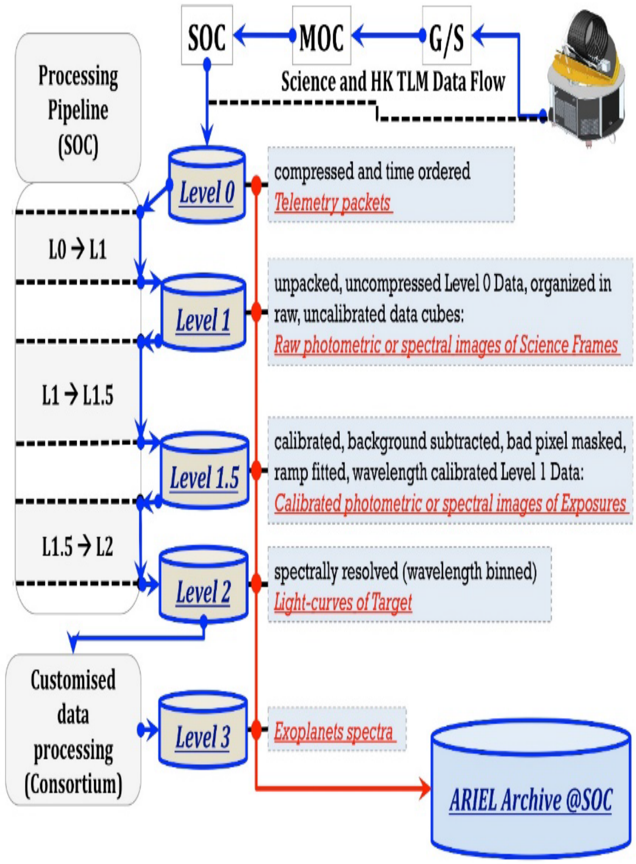
The Science Operations Centre (SOC) at ESAC in Spain oversees scientific mission planning, data product generation, validation, archival, and distribution. The Ariel Data Reduction Pipeline, managed by the IOSDC, is automatically run at SOC, producing Data Products up to Level 2, ingested into the Ariel science archive. SOC also develops and operates the Ariel Mission Archive, serving as the hub for storing and distributing mission products to the scientific community. ESAC, responsible for SOC, benefits from common tools and cross-mission support.

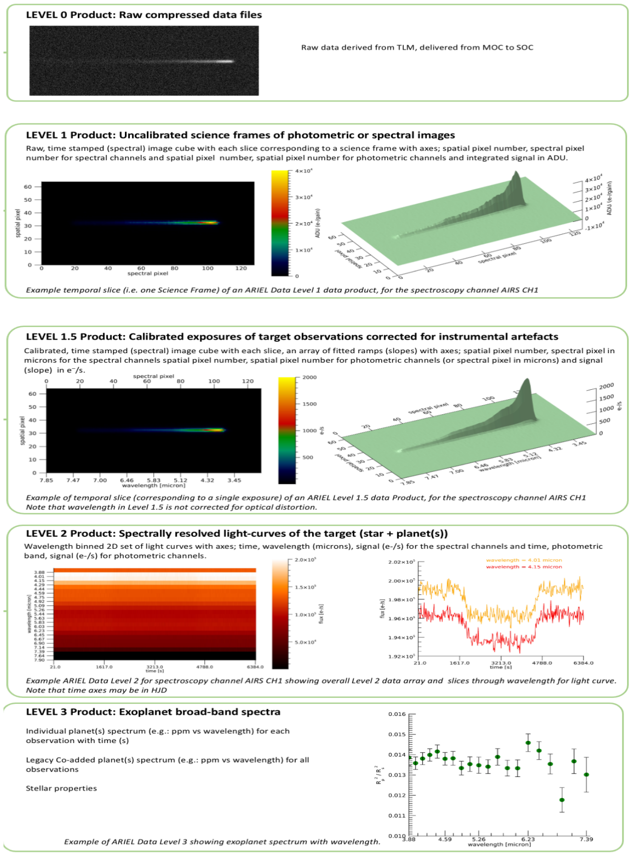
During operations, SOC is the primary contact with the MOC for uplink and downlink activities. Exceptions include contingency cases and the commissioning phase, where direct contact between IOSDC and MOC occurs. SOC acts as the central hub for Ariel data, encompassing both operational and science data.

The Instrument Operations and Science Data Centre (IOSDC), part of the AMC, manages instrument operations and contributes to SGS tasks. The IOSDC is distributed across institutes, with activities funded nationally. Functionally organized into teams, including instrument, calibration, software, operations, observations, and editorial teams, each led by a team leader, they form the management team. The smooth transition philosophy guides ground testing and calibration, ensuring a seamless shift to the final operational environment. SOC personnel collaborate with team leaders for SOC tasks and activities throughout mission phases.

### 6.3 Data products

Science data from Ariel is classified into a range of data product levels, depending on their level of processing. These are depicted in the figures below.





**LEVEL 0 Product: Raw compressed data files**

Raw data derived from TLM, delivered from MOC to SOC

**LEVEL 1 Product: Uncalibrated science frames of photometric or spectral images**

Raw, time stamped (spectral) image cube with each slice corresponding to a science frame with axes; spatial pixel number, spectral pixel number for spectral channels and spatial pixel number, spatial pixel number for photometric channels and integrated signal in ADU.

*Example temporal slice (i.e. one Science Frame) of an ARIEL Data Level 1 data product, for the spectroscopy channel AIRS CH1*

**LEVEL 1.5 Product: Calibrated exposures of target observations corrected for instrumental artefacts**

Calibrated, time stamped (spectral) image cube with each slice, an array of fitted ramps (slopes) with axes; spatial pixel number, spectral pixel in microns for the spectral channels spatial pixel number, spatial pixel number for photometric channels (or spectral pixel in microns) and signal (slope) in $e^-$/s.

*Example of temporal slice (corresponding to a single exposure) of an ARIEL Level 1.5 data Product, for the spectroscopy channel AIRS CH1*
*Note that wavelength in Level 1.5 is not corrected for optical distortion.*

**LEVEL 2 Product: Spectrally resolved light-curves of the target (star + planet(s))**

Wavelength binned 2D set of light curves with axes; time, wavelength (microns), signal (e-/s) for the spectral channels and time, photometric band, signal (e-/s) for photometric channels.

*Example ARIEL Data Level 2 for spectroscopy channel AIRS CH1 showing overall Level 2 data array and slices through wavelength for light curve.*
*Note that time axes may be in HJD*

**LEVEL 3 Product: Exoplanet broad-band spectra**

Individual planet(s) spectrum (e.g.: ppm vs wavelength) for each observation with time (s)

Legacy Co-added planet(s) spectrum (e.g.: ppm vs wavelength) for all observations

Stellar properties

*Example of ARIEL Data Level 3 showing exoplanet spectrum with wavelength.*

### 6.4 On-ground data processing and archiving

Under the responsibility of AMC/IOSDC, the Quick Look Analysis (QLA) tool, initially designed for on-ground testing and EGSE, serves as a visualization and analysis tool for promptly examining received science and housekeeping telemetry during payload and spacecraft-level tests, commissioning, performance verification, routine science operations, and contingencies.

The Health Monitoring System (HMS) ensures rapid feedback on science data and instrument health during in-flight operations. Initially interactive during commissioning, it transitions to automatic mode, analyzing pixel-level data and validating completeness. Reports from HMS, managed by AMC/IOSDC, guide SOC's monthly planning. Additionally, SOC needs a meta-data health monitoring feature for observation execution feedback and trend monitoring for long-term performance assessment.

SOC will receive the consolidated raw telemetry from MOC in form of Level 0 data. All Level 0 data will be stored in the archive and made available to the pipeline processing. From this data processing level onwards, there are currently three science data processing pipelines foreseen from level 0 to 1, from level 1 to 2 and from level 2 to 3.

The pipelines development, testing and maintenance are under responsibility of the AMC/IOSDC. The first and second pipeline (up to Level 2) is run at SOC, while the third pipeline to generate the Level 3 data products is executed at IOSDC.

Ariel will have a single archive, the “Ariel mission archive”, under ESA (SOC) responsibility. The Ariel Mission Archive will contain all Ariel data and is intended to be used as main data repository by the science ground segment. Throughout all mission phases it serves the purpose of storing and distributing mission products to the scientific community. After completion of the post-operations phase, the archive becomes the legacy Ariel mission archive. The Ariel archive will be fully in line with the scope of all science mission archives hosted at ESAC.

## 7. THE ARIEL LAUNCHER

Ariel is set to embark aboard an Ariane 6.2 rocket, sharing the journey in a dual launch scenario alongside the Comet Interceptor mission. The two spacecrafts will be housed independently on the launch vehicle, each occupying distinct locations without any direct connections in terms of mechanics, electronics, or thermal systems. This dual launch configuration is made possible through the implementation of a Dual Launch Structure (DLS), with Ariel nestled within it and Comet-I positioned atop.

## 8. PROGRAMMATIC STATUS

### 8.1 Project schedule overview

In November 2020, the mission was formally adopted, and the Invitation to Tender (ITT) for spacecraft procurement was issued in early December of the same year. Following a competitive process, Airbus Defence and Space was awarded the contract as the main contractor in November 2021. This milestone significantly propelled the mission's development, facilitating intensive co-engineering sessions with the AMC to progress on interface matters.

The spacecraft underwent its System Requirements Review (SRR) in May 2022, where system requirements, plans, and interfaces were examined and approved. Subsequently, the Preliminary Design Review (PDR) was successfully concluded in December 2023, marking the consolidation of the spacecraft's preliminary design. Meanwhile, the payload embarked on its own journey, commencing with the SRR in April 2020 and culminating with the PDR in November 2022. This strategic approach ensured the consolidation of all technologies prior to industrialization activities.

Regarding the ground segment, the first review occurs in May-June 2024 with the Ground Segment Requirements Review (GS-RQR). Subsequent reviews include the Ground Segment Design Review (GS-DR) in mid-2026, the Ground Segment Implementation Review (GS-IR) in 2028, and the Ground Segment Readiness Review (GS-RR) preceding the launch.

Mission reviews form an integral part of the overall development plan, aiming to validate the progress of the entire project, encompassing the spacecraft and its payload, the operational and scientific ground segments, and the launcher. The Mission

Requirements Consolidation Review (M-RCR) was successfully conducted in April 2023 and will be followed by the Mission Design Review (M-DR) slated for the second half of Q4 2026.

Scheduled before the end of 2029, the launch will be succeeded by a three-month commissioning period, concluding with the Mission Commissioning Readiness Review (M-CRR), which signifies the transition from the commissioning phase to the operational phase of the Ariel mission. At this juncture, the responsibility for the mission shifts from the Project Manager to the Mission Manager.

## 8.2 Spacecraft development status

### *8.2.1 Development plan Overview*

The model philosophy balances efficiency, risk and schedule with key test campaigns validating the Spacecraft design: for the structure with the Structural Model (SM) and for the avionics with the functional validation on the Avionics Verification Model (AVM). These campaigns allow early verification, before the complete workmanship and environmental qualification achieved on the Spacecraft Proto-Flight Model (PFM).

- The Structural Model provides de-risking of the PLM to SVM mechanical interfaces.
- The Spacecraft avionics design is validated on a 2D representative Spacecraft Avionics Verification Model (AVM) that allows an early functional verification and AIT sequence preparation. It includes representative Engineering Models of each flight unit.
- The Spacecraft qualification is achieved on the Spacecraft Proto-Flight Model (PFM). Collocation of the AVM and the Spacecraft PFM AIT team allows efficient support to AIT troubleshooting.

The development and verification process makes also use of other benches or simulators.

- The Functional AOCS Multi-Purpose Environment (FAME) bench is the test configuration model used for the AOCS Performance Verification campaign,
- The Numerical Software Validation Facility (NSVF) dedicated to the Central Software Verification campaign,
- The X-band RF Suitcase dedicated to verify the Spacecraft X band RF interface compatibility to the ground segment,
- The SimAIT model is based on the NSVF facility, including additional GSE numerical models and coupled with the CCS. This model allows preparing and validating the AIT test sequences and procedures ahead of the test campaign on AVM and on Spacecraft PFM.

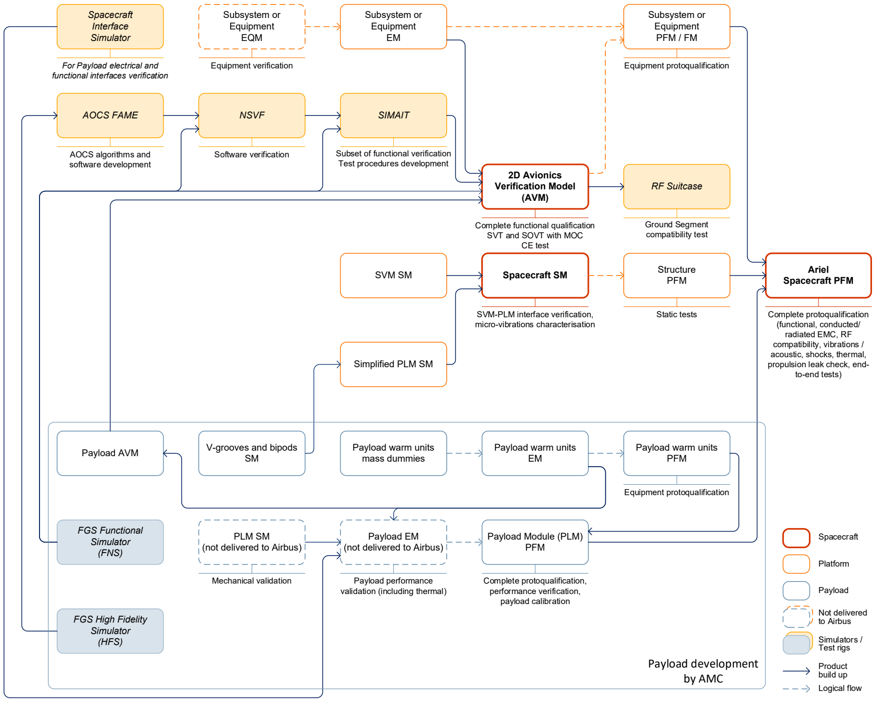


*Figure 8-1: Model Philosophy overview*

### 8.2.2 *Procurement Status*

Airbus Defence and Space SAS in Toulouse is the prime contractor vis a vis ESA. The Airbus Defence and Space SAS Toulouse team is responsible for the overall management of the development of the platform and integration of the spacecraft. They are managing Product Assurance, spacecraft engineering, mechanical engineering, thermal engineering, propulsion engineering and AIT activities.

Airbus Defence and Space Ltd Stevenage complements the core team. They are managing electrical engineering, RF engineering and functional avionic engineering.

In order to achieve upfront geographical return in critical countries, several pre-selected subcontractors were incorporated in the industrial team: 2 subsystems, 8 providers of equipment and 1 service provider.

After the Kick Off of prime activities the selection of the remaining subcontractors has been initiated. The selection process adhered to ESA's Best Practices guidelines, prioritizing compliance with geographical requirements and identifying the most suitable candidates.

Figure below shows the status of the Prime industrial consortium as per April 2024.

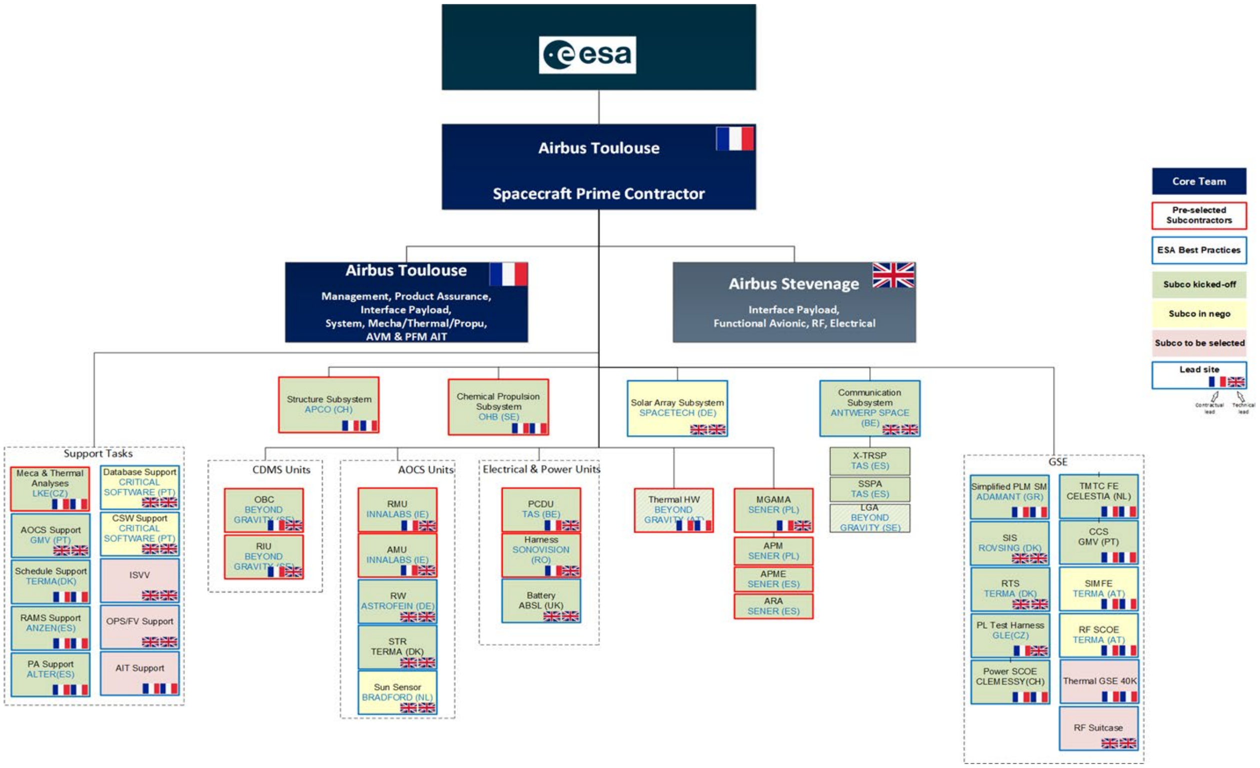


*Figure 8-2: Prime consortium at current stage (April 2024)*

### 8.2.3 *Schedule and current activities overview*

The master schedule is of 90 months duration, from Kick-off up to launch.

The 26 months Phase B2 is balanced between a first 10 months dedicated to Payload preliminary design and interfaces consolidation through close co-engineering with ESA and AMC up to the Payload PDR, and a 16-month S/C preliminary design consolidation up to the S/C PDR. The Industrial consortium is consolidated only after the Payload PDR to ensure a solid interface definition between the platform and the payload.

The Spacecraft CDR is planned for Q1 2026, once the S/C SM test campaign is completed and the S/C AVM test campaign well advanced.

The spacecraft PFM is developed and qualified in 55 months, from PDR to Flight Acceptance Review (FAR), with a spacecraft PFM AIT campaign split in two steps, first a Platform AIT over of 9 months, then a S/C AIT after the Payload PFM delivery over 12 months with a 3-month margin.

The components of the structure of the SM spacecraft are under manufacturing in Switzerland. The assembled platform structure is expected to be delivered to Airbus Toulouse in August'24 for its mating with a Simplified PLM SM. The environment tests are expected to be completed by the end of the year.

In parallel, the Avionics models (AVMs) and the EGSE are under development with the objective to start the S/C AVM test campaign Q2 2025.

## 8.3 Payload development status

### 8.3.1 Development plan Overview

The Ariel Payload Module (PLM) adopts a Proto Flight Model (PFM) approach for overall qualification. While certain major design aspects are mitigated early in the program using prior models, formal environmental qualification of the complete payload module only occurs with the PFM Payload Module.

The primary philosophy is to address critical interfaces, environmental requirements, and functionality as early as possible during phases B/C/D to minimize risk in the proto flight model program. This approach applies to all levels of payload and system construction. The development and verification of the payload adheres to the project requirements and the guidance provided in applicable ECSS standards.

To facilitate early risk mitigation, an initial Payload Structural Model (pSM) of the Payload Module (PLM) will undergo mechanical environmental testing later on this year. This will be succeeded by an Engineering Model (EM) of the PLM, which will incorporate some components of the pSM and integrate with the payload warm units (ICU, A-DCU, TCU, FCU, and Cooler units). The EM PLM will be form, fit, and functionally compliant, but there is no requirement for the units within it to undergo mechanical environmental testing to qualification level. Instead, this model will be subjected to operational temperatures to de-risk the cryogenic performance of the system. It is not intended for delivery to spacecraft level. By following this approach rather than committing to a full qualification model, flexibility in the schedule is maintained, as the program is not contingent on the completion of all unit qualification programs to commence interface and performance verification activities at the Payload level.

At the subsystem level, various qualification approaches are pursued. Some subsystems (such as the cooler & the M2M) have dedicated qualification models that undergo a full suite of environmental testing (including lifetime testing) prior to the FM builds.

### 8.3.2 Schedule and current activities overview

The Payload SRR and PDR were successfully concluded respectively April 2020 and November 2022.

The components of the Payload Structural Model (pSM) and of the Engineering Model (pEM) are under manufacturing. The large aluminium M1 mirror for the pEM is in particular polished and coated, ready for integration on the rest of the telescope. The objective is to assemble and test the pSM by the year-end and the pEM by Q3 2025.

The Payload CDR is planned to start as soon as the pSM and pEM test campaigns are completed to provide valuable input to this key review.

The Avionics Models (AVM) of the payload will be delivered to the Spacecraft AVM in 2025 to allow the development of the avionics including software.

The system integration of the flight hardware will start mid 2026 for a completion Q4 2026. The Payload FM will then go through an intensive environmental test campaign up to its delivery to the Prime Q4 2027.

# 9. CONCLUSIONS

The Ariel mission, under the lead of the Science Department of the European Space Agency, extends beyond the pioneering efforts made so far to discover new exoplanets: it is about unraveling their mysteries. We are shifting our focus from discovery to a deeper understanding of exoplanets, exploring their composition, origins, and transformations on a grand scale. What sets Ariel apart is its holistic approach, employing the very same observatory in the same environment (e.g. temperatures, micro-vibrations) to ensure consistent measurements across a wide spectrum of wavelengths, spanning from visible to infrared.

This straightforward strategy distinguishes Ariel as a mission of exceptional significance. With a planned launch in 2029, we are making significant progress in development. Airbus Defence and Space leads a robust industrial consortium tasked with platform development and the overall spacecraft system verification, while the Ariel Mission Consortium works presently to manufacture and test the various elements of the payload. These collective efforts pave the way for Ariel to revolutionize our understanding of exoplanets.

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