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The afocal telescope of the ESA ARIEL mission: analysis of the layout

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ABSTRACT

ARIEL (Atmospheric Remote-sensing Infrared Exoplanet Large-survey) is one of the three present candidates as an M4 ESA mission to be launched in 2026. During its foreseen 3.5 years operation, it will observe spectroscopically in the infrared a large population of known transiting planets in the neighborhood of the Solar System. The aim is to enable a deep understanding of the physics and chemistry of these exoplanets.

ARIEL is based on a 1-m class telescope ahead of a suite of instruments: two spectrometer channels covering the band 1.95 to 7.8 μm and four photometric channels (two wide and two narrow band) in the range 0.5 to 1.9 μm.

The ARIEL optical design is conceived as a fore-module common afocal telescope that will feed the spectrometer and photometric channels. The telescope optical design is based on an eccentric pupil two-mirror classic Cassegrain configuration coupled to a tertiary paraboloidal mirror.

The temperature of the primary mirror (M1) will be monitored and finely tuned by means of an active thermal control system based on thermistors and heaters. They will be switched on and off to maintain the M1 temperature within ±1 K thanks to a proportional–integral–derivative (PID) controller implemented within the Telescope Control Unit (TCU), a Payload electronics subsystem mainly in charge of the active thermal control of the two detectors owning to the spectrometer. TCU will collect the housekeeping data of the controlled subsystems and will forward them to the spacecraft (S/C) by means of the Instrument Control Unit (ICU), the main Payload's electronic Unit linked to the S/C On Board Computer (OBC).

Keywords: space instrumentation, telescope, optical design, exoplanetary science, thermal control, ICU

1. INTRODUCTION

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

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

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Thanks to the knowledge of the planetary ephemerides of the selected targets, ARIEL will be able to differentiate the signals coming from the planet and the host star. This enables the measurement of atmospheric signals from the planet at levels of at least 10^{-4} relative to the star. Given the bright nature of targets, the adoption of more sophisticated techniques, such as phase curve analysis and eclipse mapping, will provide a deeper insight into the nature of their atmospheres. This requires a payload with broad instantaneous wavelength coverage, to detect many molecular species, probe the thermal structure, identify clouds and monitor the stellar activity as well. To guarantee the required photometric accuracy and precision, a specifically designed stable payload and satellite platform are needed.

Transit spectroscopy means that no angular resolution is required and detailed performance studies, performed by the ARIEL Consortium, show that a telescope collecting area of 0.64 m^2 is sufficient to achieve the necessary observations on all the ARIEL targets within the mission lifetime.

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

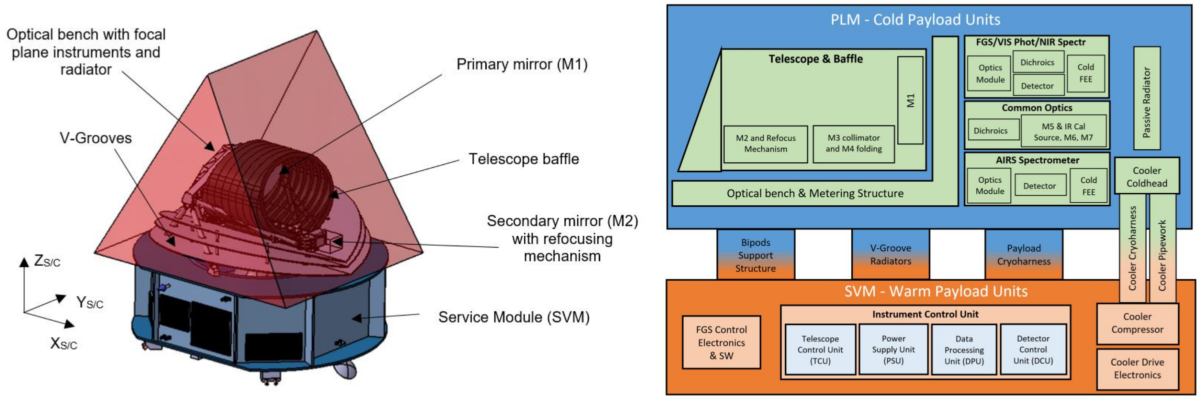
The payload is passively cooled to ~50 K by isolation from the S/C bus via a series of V-Groove radiators. The AIRS detectors are the only items that require active cooling to <42 K via an active Ne-based JT cooler.

ARIEL is highly complementary to other international facilities (such as TESS [4], to be launched in 2018) and will build on the success of ESA exoplanet missions such as Cheops [5] and PLATO [6], which will provide an optimized target list prior to launch.

2. SPACECRAFT AND SCIENCE PAYLOAD

2.1 Spacecraft architecture

A “horizontal” configuration, with respect to the Service Module (SVM) cylinder, has been adopted as baseline for the spacecraft architecture (see Figure 1a). The X axis of the ARIEL mechanical reference system corresponds with the telescope mirrors optical axis, the Z axis is the launch vehicle symmetry axis (“vertical”) and Y axis completes the right-handed set.



(a) (b)

Figure 1. In (a) schematics of ARIEL spacecraft baseline configuration: main components and S/C reference system are highlighted; the red cover shows the minimum allowable volume with respect to the Sun vector. In (b) ARIEL baseline payload block diagram architecture.

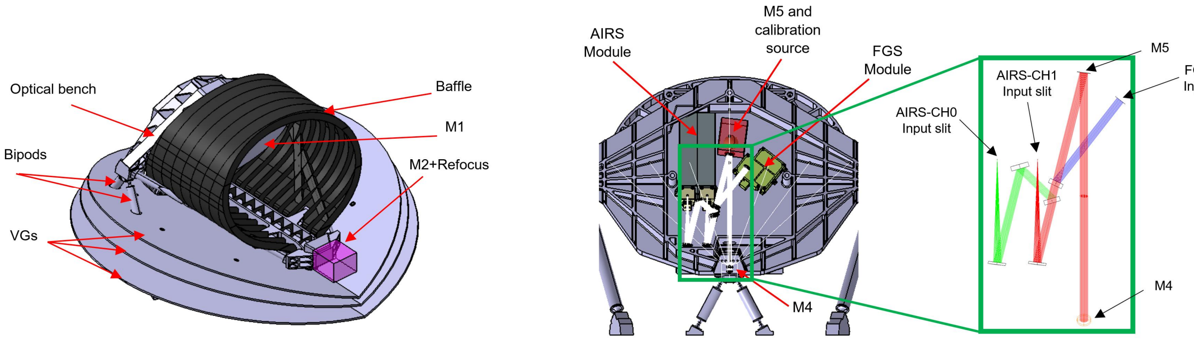
The spacecraft (S/C) can be considered as composed of a cold Payload Module (PLM), containing the telescope and the instruments with their thermo-mechanical hardware, and a warm Service Module (SVM) that includes all the mission supporting systems together with the PLM and cryogenic control units [7]. The PLM will interface to the SVM via a set of thermally isolating support struts, or bipods, and will be radiatively shielded from the SVM and the solar input loads by a set of 3 V-Grooves (VGs). A block diagram of the overall payload architecture, including the subsystems, is shown in Figure 1b.

The Sun is located below the platform (i.e. $-Z_{S/C}$). The V-Grooves and volumes are designed to accommodate a ±6° angle and a ±30° angle clearance respectively around the X axis and the Y axis with respect to the Sun vector.

2.2 Payload module

The spacecraft carries a single dedicated payload conceived to achieve the ARIEL primary science objectives. The ARIEL cold PLM consists of an integrated suite of telescope, spectrometers and FGS/photometers along with the necessary supporting hardware and services (such as optical bench, cryogenic harnessing, thermal isolation structures, active thermal stabilization control, i.e. heaters and thermistors, etc.).

The ARIEL telescope consists of three mirrors (M1, M2 and M3) having optical power plus a plane mirror (M4) used to redirect the collimated beam towards the optical bench (OB) located on the back of M1 (see Figure 2a and Figure 3). The secondary mirror is located at the end of a metering structure (beam) departing from the OB and it will be equipped, as a baseline, with a refocusing and tip/tilt mechanism. There will be also an eccentric baffle around M1, internal vanes between M1 and M2, M2 and M3, field and Lyot stops to control and limit both the out-of-field and in-field scattered straylight.



(a) (b)

Figure 2. In (a) ARIEL telescope mechanical layout. In (b) mechanical design of the OB with highlighted the optical path to the FGS and AIRS modules; in the inset there is a zoom on the common optics region.

The primary science payload is the spectrometer, whose scientific observations are supported by the FGS/photometers, which is monitoring the photometric stability of the target and allowing, at the same time, the target to be properly pointed. Both the spectrometer and FGS modules will be mounted on the common OB (see Figure 2b).

2.2.1 FGS and its objectives

The FGS main task is to ensure the correct pointing of the satellite, in order to guarantee that the target star is well centred on the spectrometer slit during all the observation sessions. It will also provide high precision astrometry, photometry and spectro-photometry of the target for complementary science. In particular, the data from the FGS will be used for de-trending and data analysis on ground. The sensor uses star light coming through the optical path of the telescope to determine the changes in the line of sight of the ARIEL instrument. The attitude measurement is then merged with the information from the star trackers, and used as input for the control loop stabilizing the spacecraft through high performance gyros.

To meet the goals for guiding and photometry, four spectral bands are defined:

- FGS 1: 0.8–1.0 μm,
- FGS 2: 1.05–1.2 μm,
- VIS-Phot: 0.50–0.55 μm,
- NIR-Spec: 1.25–1.90 μm including a prism element with low spectral resolution greater than 10.

The spectral bands are selected from the incoming light using dichroic filters. The information from all the channels is used as a stellar monitor and to provide photometric information to constrain the VIS/NIR portion of the exoplanet spectra. The instrument has two detectors: one is shared by the FGS1 and VIS-Phot channels and the other one by the FGS2 and NIR-Spec channels.

2.2.2 ARIEL IR Spectrometer (AIRS)

AIRS is a broadband, low-resolution NIR and MIR spectrometer operating between 1.95 μm and 7.8 μm. This module can be properly split into multiple channels avoiding loosing wavelengths with key spectral features.

The baseline design foresees two spectrometers with independent optical channels and detectors: the first one (CH0) covering the shorter waveband (1.95–3.9 μm), the second (CH1) the longer waveband (3.9–7.8 μm). As dispersive element, prisms have been considered in the present design [8].

The spectrometer detectors are expected to require active cooling managed by a thermal control system (TCS) operated by the TCU, providing a nominal operating temperature of ~36 K, to reach both the requirement and goal performance with the chosen baseline sensors [9].

3. TELESCOPE OPTICAL DESIGN

3.1 Telescope design requirements

The telescope has been designed in order to provide the optical requirements reported in Table 1. The requirement on the collecting area of at least 0.6 m^2 implies an entrance pupil of the order of 1 m in diameter. The collecting area is related with the minimum intensity (magnitude) of the observable targets.

The design performance is driven by the requirement that the final as-built quality of the telescope system has to be diffraction limited at 3 μm over a FoV of 30", i.e. equivalent to an RMS wavefront error (WFE) of 220 nm.

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

Table 1. Summary of the telescope optical requirements.

Parameter	**Value**
Collecting area	>0.6 m^2
FoV	30" with diffraction limited performance 41" with optical quality TBD allowing FGS centroiding 50" unvignetted
WFE	Diffraction limited @ 3 μm
Wavelength range	0.55–8 μm
Throughput	Minimum >0.78 Average >0.82
Output beam dimension	20 mm x 13.3 mm

The wavelength coverage and the global FoV of the telescope are determined by the requirements on the instruments following the telescope, i.e. the FGS and the AIRS [10].

3.2 Telescope design characteristics

The baseline telescope design is an afocal unobscured eccentric pupil Cassegrain telescope (M1 and M2) with a recollimating off-axis parabolic tertiary mirror (M3). All the mirrors share the same optical axis. An M4 plane mirror is redirecting the exiting beam parallel to the back of M1 where the OB is located and the instrument will be mounted (see Figure 3).

The telescope is accommodated horizontally with its optical axis (Z) along the S/C X axis. The centre of the FoV of the telescope is inclined of 0.1° in the YZ plane with respect to the optical axis of the telescope defined by the mirrors common optical axis.

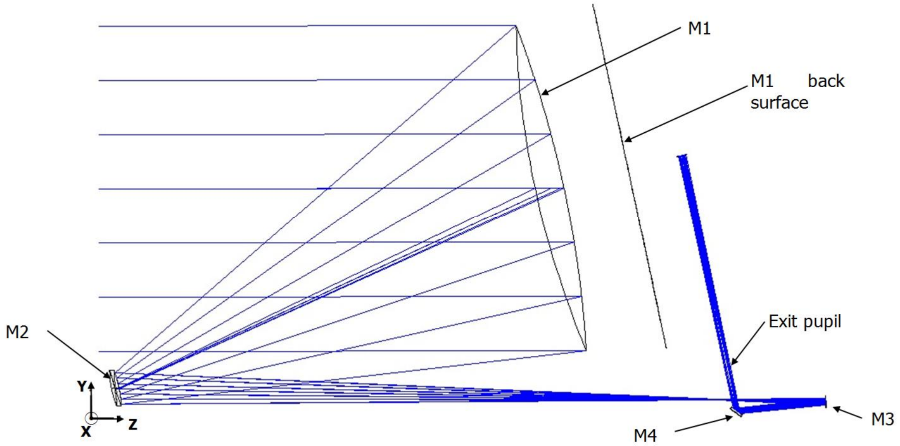


Figure 3. Scale drawing of the telescope – view in Y-Z plane.

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

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

(a)

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

(b)

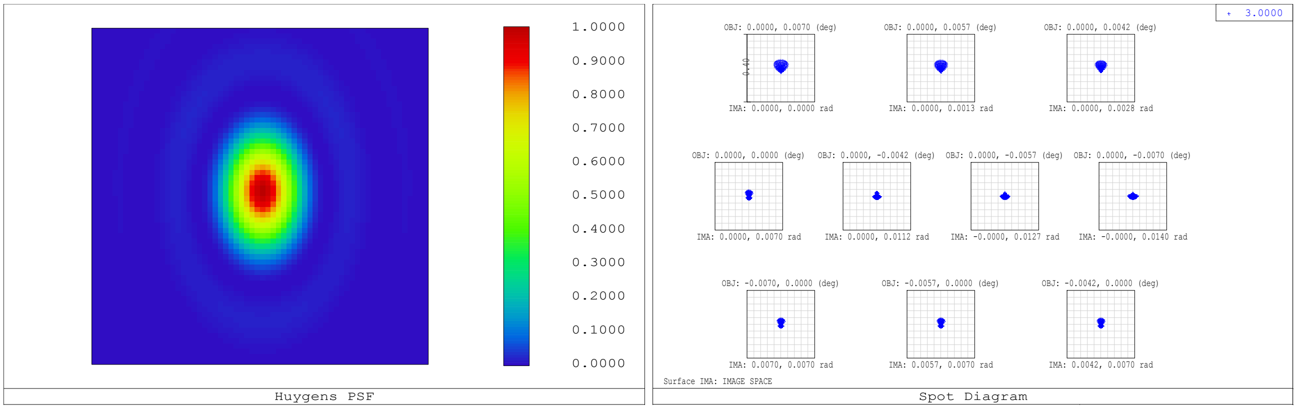
Optical element	M1	M2	M3
R (mm)	-2319.5	-239.0	-491.5
k	-1	-1.4	-1
Off-axis (mm) (y direction)	500	50	20
Clear Aperture Radius (mm)	Elliptical, 550 (x) by 365 (y)	Elliptical, 56 (x) by 40 (y)	Elliptical, 15 (x) by 11 (y)
Type	Concave mirror	Convex mirror	Concave mirror

3.3 Telescope optical performance

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

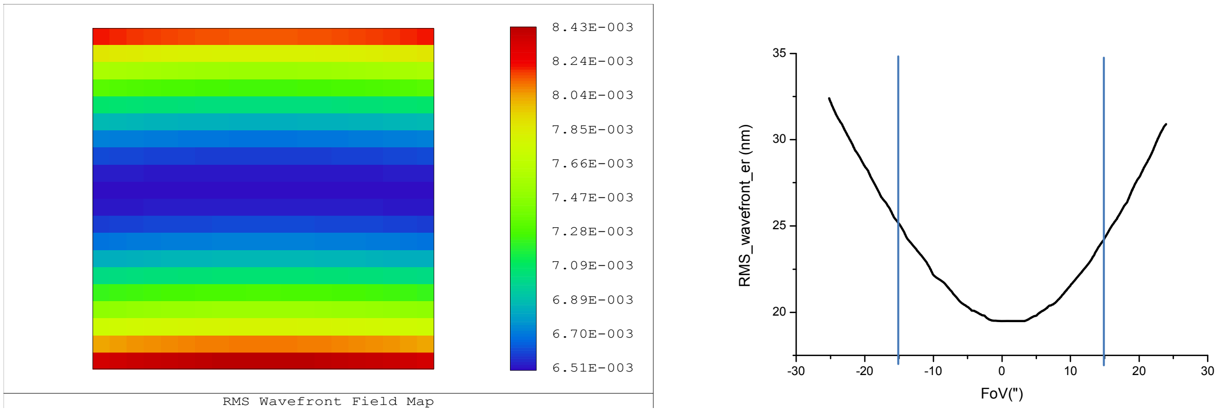
The nominal diffraction PSF at 3 μm wavelength has an Airy radius respectively of 0.2 mrad and 0.29 mrad in the X and Y directions. A picture of the expected theoretical PSF is depicted in Figure 4a; in Figure 4b for comparison the spot diagram all over the 50" unobstructed telescope FoV are drawn and compared with a box of 0.4 mrad size, so to show that telescope design is diffraction limited at the 3 μm primary wavelength.

The telescope RMS wavefront error is always less than 26 nm over the 30" nominal telescope FoV (see Figure 5); this value is well below the telescope diffraction limit at 3 μm, i.e. 220 nm.



(a) (b)

Figure 4. In (a) PSF calculated at the telescope FoV centre for a wavelength of 3 µm depicted over a 1 mrad square box. In (b) Spot Diagrams in the afocal space; the scale (box) is 0.4 mrad.



(a) (b)

Figure 5. In (a) RMS wavefront error field map calculated for the 3 µm wavelength over the 30" nominal telescope FoV. Units are λ. In (b) cross section along the Y direction of the RMS wavefront error expressed in nm; in the X direction the wavefront error is constant.

To assess the final performance of the as-built telescope and its variation during the operation in flight, a tolerance analysis has been done [11] [12]. The tolerance analysis has taken into account the different parts of the realization and life of the instrument:

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

The results show that the telescope, thermally stable after cooldown and refocused via M2 mechanism, will have a wavefront error of the order of the required 220 nm RMS. The total RMS wavefront error in flight, including the stability, will be within 250 nm, which is perfectly suitable to achieve the scientific purpose of the instrument.

4. TELESCOPE THERMAL CONTROL

The telescope is passively cooled to ≤70 K and its thermal control is based on a passive/active approach. A high efficiency thermal shielding system (see Figure 6) based on a multiple radiators configuration can provide stable temperature stages down to 50-60 K in the L2 orbit environment.

The telescope baffle provides a large radiator area with a good view to deep space; this provides sufficient radiative cooling to dump the parasitic loads from the PLM support struts, cryoharnesses and radiative load from the final VG. Temperature control of the mirrors is achieved by partial thermal decoupling from PLM units: each mirror is mounted on its supporting structure by insulating struts with a total conductance of less than 0.1 W/K.

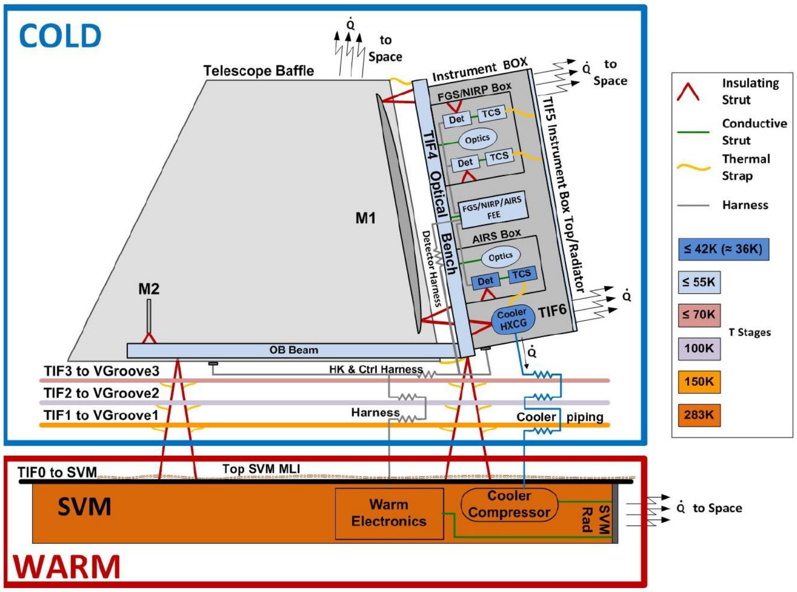


Figure 6. PLM thermal architecture scheme.

This configuration will help in filtering out all potential instabilities with periods of the order of 10–100 s originated in the PLM and longer than the expected single exposure times.

For the primary mirror, the high thermal capacitance, due to its mass, will allow a higher level of passive filtering, damping instabilities at lower frequencies, i.e. with periods of the order of few hours. The slower fluctuations, with periods of the order of several hours or longer, that could be transmitted to the optics will be smoothed by the active control system based on a PID type feed-back loop.

The telescope will also incorporate contamination control heaters on the M1 and M2 mirrors and on the PLM optical bench. These heaters will be active during the early orbit operations to ensure that the sensitive optical surfaces remain warmer than the support structure through the critical parts of cooldown. A temperature delta of ~40 K will be maintained between the baffle, which will act as a contamination getter for water and other contaminants being off-gassed by the PLM, and the optical surfaces. An initial calculation of the power required to maintain this temperature gradient shows that approximately 100 W of heater power is required during this phase. This would hold the sensitive surfaces at 200 K while the baffle cools below 160 K where the H_2O will freeze out.

5. TELESCOPE CONTROL UNIT

The ARIEL Instrument Control Unit (ICU) [13] is the main electronic subsystem designed for scientific data pre-processing and to implement the commanding and control of the AIRS Spectrometer. The ICU is interfaced on one side with the instrument and on the other side, i.e. S/C side, with the Data Management System (DMS) and the Power Conditioning and Distribution Unit (PCDU), both belonging to the hosting platform.

The DMS is composed of the On-Board Computer (OBC) and the Solid State Mass Memory (SSMM) operating as the main buffering memory for scientific data and HK telemetries before sending them to ground. For this reason, the ICU internal memories are basically conceived and designed for temporary local buffering and to support a reduced data handling as the AIRS scientific data, once properly pre-processed, are delivered to the SSMM.

This characteristic is exploited to simplify the unit electrical design, saving mass and power, for both the ICU architectures (baseline and alternative) designed at this stage to be interfaced respectively to US detectors or EU detectors by means of their customized Cold Front-End Electronics (CFEE), operating at cryogenic temperatures.

As the ICU is hosted by a warm electronic box, it will be located inside the S/C SVM and connected to the AIRS CFEE by means of cryogenic harness. The ICU subsystem acting as interface to the cryogenic harness is a warm FEE (WFEE), called Detector Control Unit (DCU), as shown in Figure 7.

The Telescope Control Unit (TCU) is indeed considered an ICU slave subsystem and for its complexity and required volume is located in an independent box, with stacked drawers to the unit main box. The TCU will host the main logic board called Thermal Stabilizer (for the primary mirror Thermal Control System) & IR Calibrator (TSIRC), the M2 mirror mechanism (M2M) drivers and the needed power section to properly feed its subsystems.

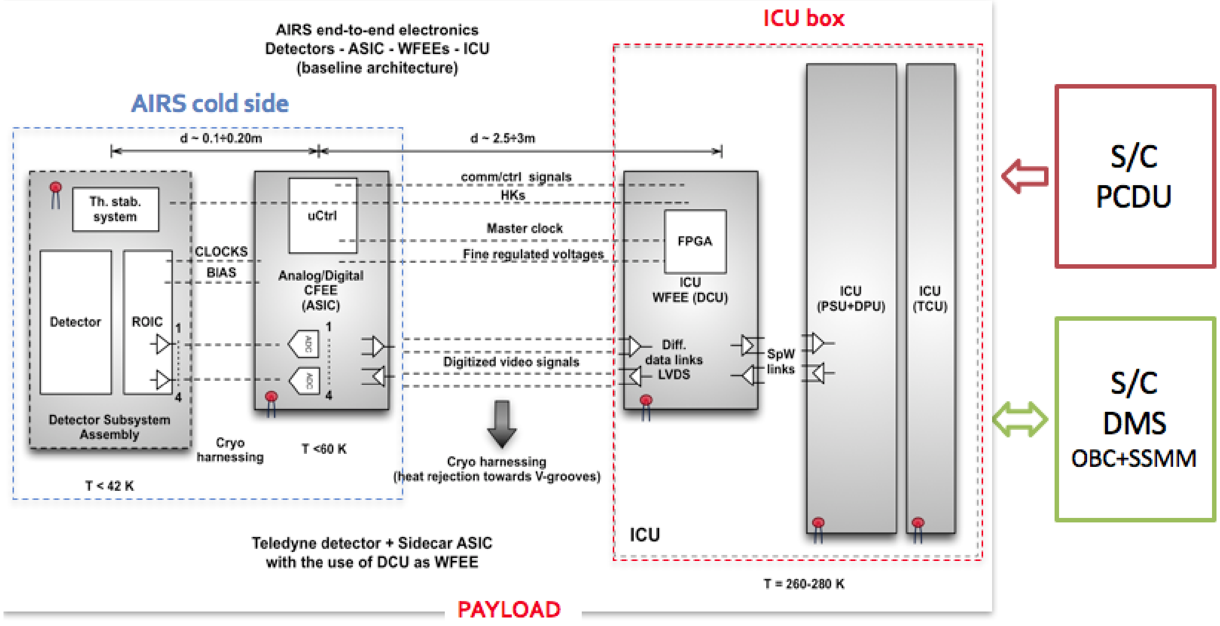


Figure 7. On-board electronics architecture.

6. CONCLUSIONS

In this paper an introduction on the ARIEL mission design and goals has been given together with a description of the various elements composing the spacecraft and the payload. A fundamental element of the payload is the front collecting telescope; its afocal layout solution has been described and the different requirements and characteristics have been discussed.

The theoretical performance, i.e. spot diagrams, PSF and wavefront error, of the baseline telescope layout has been shown. The chosen configuration is an un-obscured eccentric pupil Cassegrain plus a collimating off-axis paraboloidal mirror followed by a plane folding mirror.

A preliminary study on the passive/active thermal control of the instrument has been given. The telescope is passively cooled at an operating temperature of about 50 K.

The optical bench operating temperatures, as well as those of some subsystems, will be monitored and fine tuned/stabilized mainly by means of the thermal control subsystem working in feedback closed-loop.

Finally, the end-to-end detection and data processing system, up to the Instrument Control Unit (ICU) and S/C main electrical subsystems, have been described.

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