Publication Year	2018
Acceptance in OA	2020-10-14T10:52:02Z
Title	The optical configuration of the telescope for the ARIEL ESA mission
Authors	Da Deppo, Vania, FOCARDI, MAURO, MORGANTE, GIANLUCA, Middleton, Kevin, Pace, Emanuele, CLAUDI, Riccardo, MICELA, Giuseppina
Publisher's version (DOI)	10.1117/12.2313412
Handle	http://hdl.handle.net/20.500.12386/27801
Serie	PROCEEDINGS OF SPIE
Volume	10698

The optical configuration of the telescope for the ARIEL ESA mission

Vania Da Deppo, Mauro Focardi, Gianluca Morgante, Kevin Middleton, Emanuele Pace, et al.

Vania Da Deppo, Mauro Focardi, Gianluca Morgante, Kevin Middleton, Emanuele Pace, Riccardo Claudi, Giuseppina Micela, "The optical configuration of the telescope for the ARIEL ESA mission ," Proc. SPIE 10698, Space Telescopes and Instrumentation 2018: Optical, Infrared, and Millimeter Wave, 106984O (21 August 2018); doi: 10.1117/12.2313412

Event: SPIE Astronomical Telescopes + Instrumentation, 2018, Austin, Texas, United States

The optical configuration of the telescope for the ARIEL ESA mission

Vania Da Deppo*[a,b], Mauro Focardi[c], Gianluca Morgante[d], Kevin Middleton[e], Emanuele Pace[f],
Riccardo Claudi[b], Giuseppina Micela[g] and the ARIEL Team

[a] CNR-Istituto di Fotonica e Nanotecnologie, Padova, Via Trasea 7, 35131 Padova, Italy
[b] INAF-Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, 35122 Padova, Italy
[c] INAF-Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, 50125 Firenze, Italy
[d] INAF-Osservatorio di Astrofisica e Scienza dello spazio di Bologna, Via Piero Gobetti 93/3, 40129 Bologna, Italy
[e] RAL Space-STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot OX11 0QX, UK
[f] Dip. di Fisica ed Astronomia-Università degli Studi di Firenze, Largo E. Fermi 2, 50125 Firenze, Italy
[g] INAF-Osservatorio Astronomico di Palermo, Piazza del Parlamento 1, 90134 Palermo, Italy

ABSTRACT

The Atmospheric Remote-sensing Infrared Exoplanet Large-survey (ARIEL) has been recently selected as the next ESA medium-class mission (M4) with a foreseen launch in 2028. During its 3.5 years of scientific operations, ARIEL will observe spectroscopically in the infrared (IR) a large population of known transiting planets in the neighbourhood of the Solar System. ARIEL aims to give a breakthrough in the observation of exoplanet atmospheres and understanding of the physics and chemistry of these far-away worlds.

ARIEL is based on a 1-m class telescope feeding a collimated beam into two separate instrument modules: a spectrometer module covering the waveband between 1.95 μm and 7.80 μm; and a combined fine guidance system/visible photometer/NIR spectrometer. The primary payload is the spectrometer, whose scientific observations are supported by the fine guidance system and photometer, which is monitoring the photometric stability of the target and allowing, at the same time, the target to be properly pointed.

The telescope configuration is a classic Cassegrain layout used with an eccentric pupil and coupled to a tertiary off-axis paraboloidal mirror; the design has been conceived to satisfy all the mission requirements, and it guarantees the requested "as-built" diffraction limited performance.

To constrain the thermo-mechanically induced optical aberrations, the primary mirror (M1) temperature will be monitored and finely tuned using 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 by the Telescope Control Unit (TCU).

The TCU is a payload electronics subsystem also responsible for the thermal control of the main spectrometer detectors as well as the secondary mirror (M2) mechanism and IR calibration source management. The TCU, being a slave subsystem of the Instrument Control Unit (ICU), will collect the housekeeping data from the monitored subsystems and will forward them to the master unit. The latter will run the application software, devoted to the main spectrometer management and to the scientific data on-board processing.

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

1. INTRODUCTION

ARIEL has been selected to be the next M4 mission 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.

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

Space Telescopes and Instrumentation 2018: Optical, Infrared, and Millimeter Wave, edited by Makenzie Lystrup,
Howard A. MacEwen, Giovanni G. Fazio, Proc. of SPIE Vol. 10698, 106984O
· doi: 10.1117/12.2313412

ARIEL science goals [2] are highly complementary to those of other international facilities (such as TESS [3], to be launched in 2018) and it will build on the success of ESA exoplanet missions such as Cheops [4] and PLATO [5], which will provide an optimized target list prior to launch.

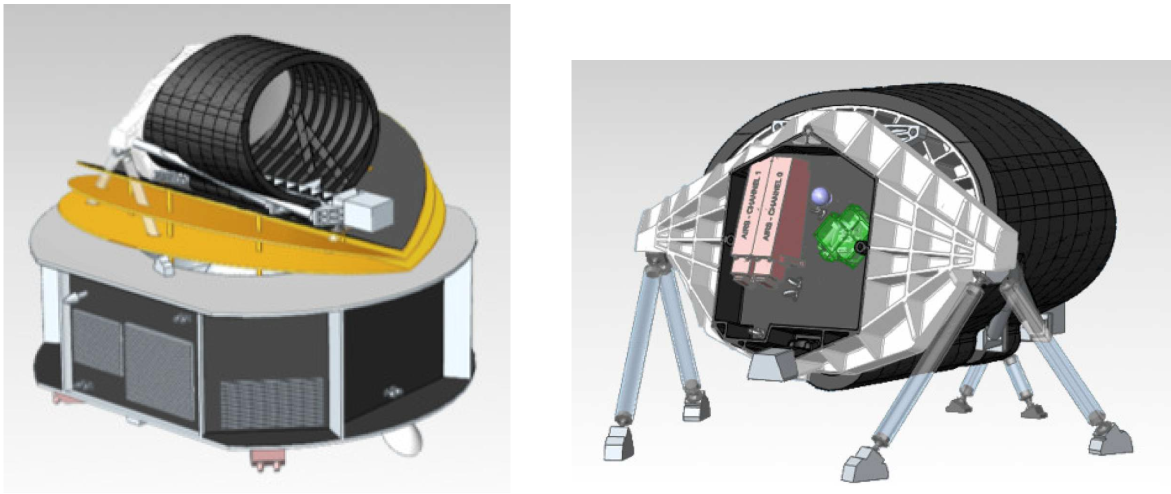
ARIEL will carry a telescope unit feeding a collimated beam into two separate modules hosted in the payload. The first, which is the main instrument, is the ARIEL IR Spectrometer (AIRS), providing variable resolving power in the range 30–180 for a waveband between 1.95 µm and 7.8 µm. The second is a 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 and a further low-resolution (R=~10) NIR spectrometer channel in the 1.2–1.95 µm waveband. The aims of this later module, often called simply FGS, are to monitor the photometric stability of the target stars, and in addition two of its 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 spacecraft (S/C) [6].

1.1 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 payload is passively cooled to ~50 K. The telescope and optical bench hosting the suite of instruments are decoupled from the service module (SVM), working at ambient temperature, by means of bipods and three V-grooves (see Figure 1a).

To constrain the thermo-mechanically induced optical aberrations, the temperature of the primary mirror will be monitored and finely tuned thanks to 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), an electronics subsystem in charge of the active thermal stabilization of the detectors assemblies belonging to AIRS and FGS, besides M1 [7] [8].



(a) (b)

Figure 1. In (a) ARIEL mechanical layout including the warm service module at the bottom and the cold telescope plus instrument unit at the top. In yellow the V-Grooves. In (b) mechanical design of the OB with highlighted in green the FGS and in pink the AIRS modules.

The AIRS detectors are the only items that require active cooling to <42 K via an active Ne-based JT cooler.

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 1b). 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 [9].

2. TELESCOPE OPTICAL DESIGN AND PERFORMANCE

2.1 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.

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 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.

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].

2.2 Telescope design characteristics

The baseline telescope design is an afocal unobscured eccentric pupil Cassegrain telescope (M1 and M2) with a recollimating off-axis parabolic tertiary mirror (M3). All the mirrors share the same optical axis. An M4 plane mirror is redirecting the exiting beam parallel to the back of M1 where the OB is located and the instrument will be mounted (see Figure 2).

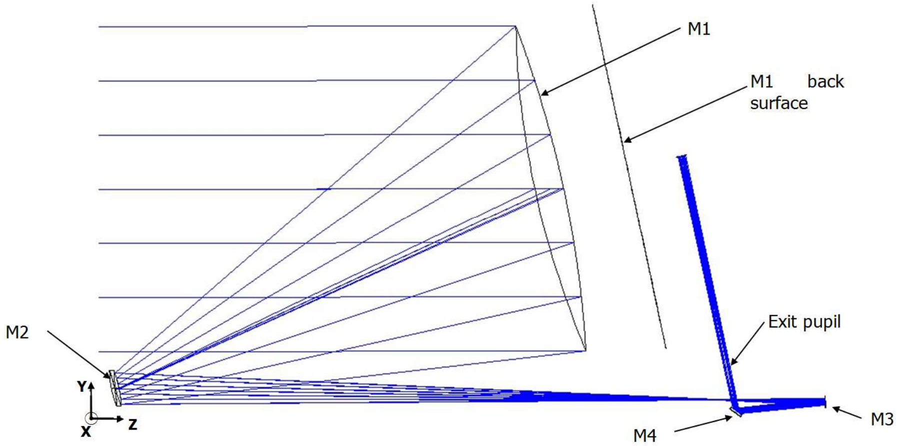


Figure 2. Scale drawing of the telescope – view in Y-Z plane.

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.

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)

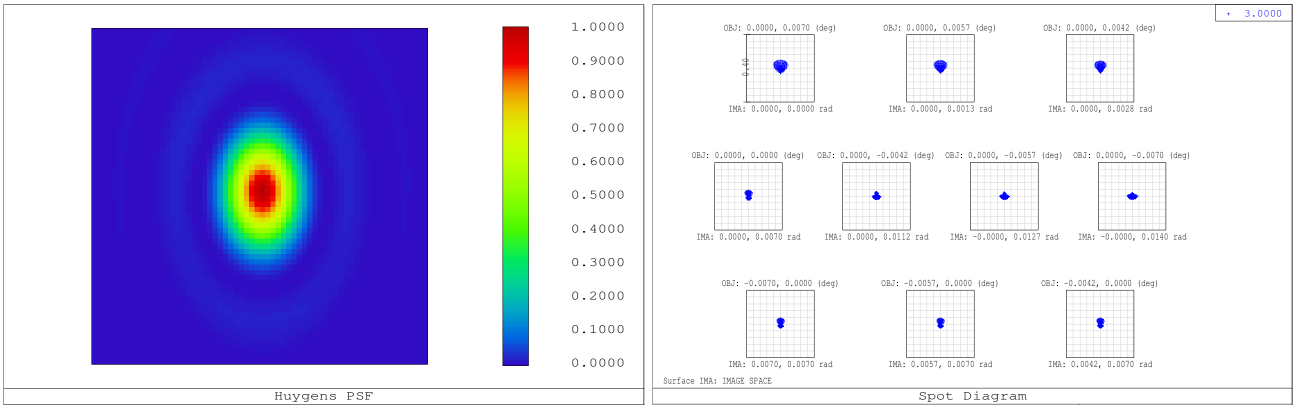
Optical element	**M1**	**M2**	**M3**
R (mm)	-2319.5	-239.0	-491.5
k	-1	-1.4	-1
Off-axis (mm) (y direction)	500	50	20
Clear Aperture Radius (mm)	Elliptical, 550 (x) by 365 (y)	Elliptical, 56 (x) by 40 (y)	Elliptical, 15 (x) by 11 (y)
Type	Concave mirror	Convex mirror	Concave mirror

2.3 Telescope theoretical 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.

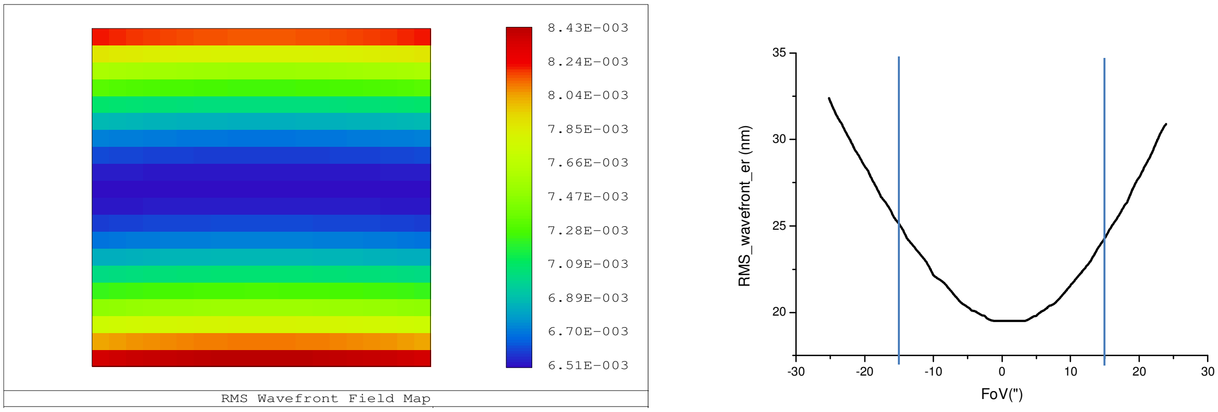
The nominal diffraction PSF at 3 μm wavelength has an Airy radius respectively of 0.2 mrad and 0.29 mrad in the X and Y directions. A picture of the expected theoretical PSF is depicted in Figure 3a; in Figure 3b for comparison the spot diagram all over the 50" unobstructed telescope FoV are drawn and 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 4); this value is well below the telescope diffraction limit at 3 μm, i.e. 220 nm.



(a) (b)

Figure 3. 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 4. 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.

A material trade study for the telescope mirrors, specifically for M1, and structure has been carried out during the ARIEL assessment phase and the result is that the ARIEL consortium considers as the optimum solution a telescope with mirrors and structure made from aluminum 6061 T651 alloy. To support this conclusion, the viability of using aluminum as the baseline material for the telescope mirrors has been assessed during the phase A by producing a pathfinder M1 mirror [11].

2.4 Telescope tolerance analysis and "as built" performance

The ARIEL telescope will be realized on-ground, at 1 g and room temperature environmental conditions, but it shall operate in space at about 50 K. For this reason, a detailed tolerance analysis was performed to assess that the all-aluminum design for the telescope is able to guarantee the expected as-built optical performance during its operation in flight [12] [13].

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).

For the manufacturing, integration and alignment phase optical element standard manufacturing and mounting tolerances have been considered. The mirrors are foreseen to be equipped with a reference cube, or reference surfaces, and, with respect to these references, the mirror local axis will be measured with high precision (~10/20 microns in position and 2/4" in rotation). If after manufacturing, M1 will be measured and found to be out of the specifications, to avoid the time consuming process of re-working a 1 meter diameter mirror, the possibility of re-optimize M2 will be considered. The total impact of the manufacturing, integration and alignment process on the RMS WFE is expected to be of the order of 40 nm.

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

A preliminary thermoelastic analysis has been performed to verify the deformation of the primary mirror, and the telescope structure, during the cooling phase from ambient, 293 K, to the operating temperature. The considered operating temperature map is the one calculated using the thermal model for the reference worst case condition, i.e. COLD case (see Section 3 and [9]). The variation of the distance between the centers of primary and secondary mirrors is of about 20 μm along the X direction, about 600 μm and 4.7 mm respectively in the Y and Z ones. These numbers are in line with the expected displacements, in fact the mean Al6061 coefficient of thermal expansion (CTE) in the considered temperature range is about 17 μm/K/m.

Choosing some reference points (nodes) on the primary and secondary mirrors and comparing the node expected positions, calculated with the simple scaling of the design, with the ones derived by the thermoelastic analysis, the residual deformations of the telescope have been derived. The telescope results to be rotated approximately 4' around the X axis, the distance between M1 and M2 is about 200 μm more than expected and the estimated variation for the shape of the primary mirror is about 20 μm PTV. The first effect can be recovered re-orienting the whole S/C, the second, and partly the third, by moving M2 via the refocusing mechanism. The residual WFE after refocusing is expected to be of the order of 200 nm.

For the stability in-flight, at present, the foreseen seasonal changes are estimated to be less than 1 K corresponding to an expected RMS WFE of about 130 nm. Anyway, if considered necessary, the M2 refocusing mechanism can be used from time to time to recover the WFE changes. During one single exposure, i.e. up to 10 hours, the temperature variation is negligible of the order of a few mK. The induced boresight errors will be recovered by using the FGS.

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

3. 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 5) 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. This configuration will help in filtering out all potential instabilities with periods of the order of 10–100 s originated in the PLM.

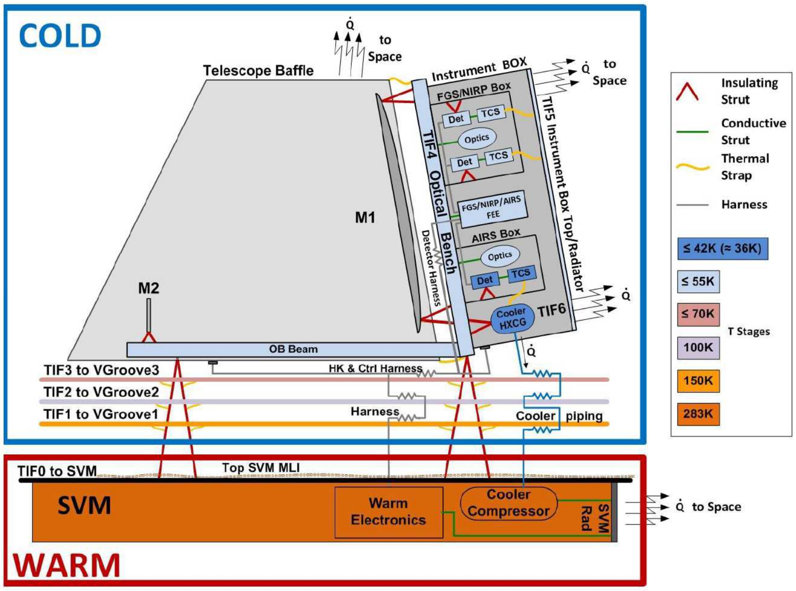


Figure 5. PLM thermal architecture scheme.

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 Proportion-Integral-Derivative (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. A preliminary 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.

A thermal analysis has been performed at PLM level. Both steady state and transient studies have been carried out for different boundary conditions on the SVM top plate and SVM radiative shield. The expected steady-state temperatures in the nominal operating conditions, corresponding to the S/C orbiting around the Sun-Earth L2 point, have been calculated as well as transients induced by an abrupt change of the boundary conditions. Also the cooldown from ambient temperature to the operative condition in orbit, calculated over a 30 days period, has been simulated [14].

4. INSTRUMENT AND TELESCOPE CONTROL UNITS

The ARIEL Instrument Control Unit (ICU) [15] 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 (refer to Figure 6).

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 save mass and power and to simplify the unit electrical architecture as well, designed at this stage to be flexible in order to interface classical (SIDECAR ASIC) and customized Cold Front-End Electronics (CFEE), operating at cryogenic temperatures.

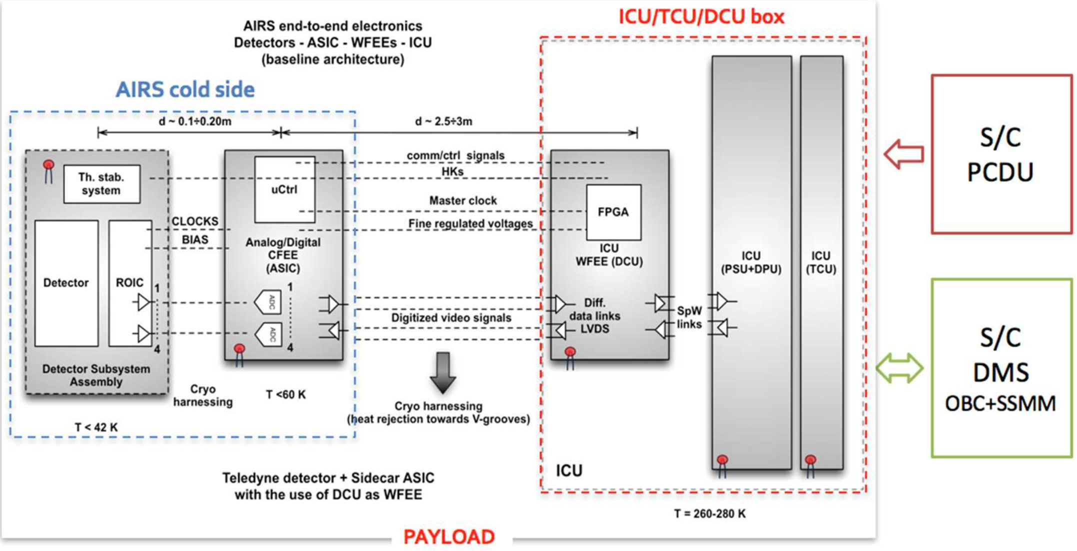


Figure 6. On-board electronics architecture.

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 6.

The Telescope Control Unit (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. Indeed, the TCU is designed as 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.

5. CONCLUSIONS

In this paper, an introduction about the design, goals and payload of the next ESA medium class mission (M4) ARIEL has been briefly given. A fundamental element of the ARIEL payload is the front collecting telescope, thus its afocal layout solution has been illustrated and also the different requirements and characteristics have been discussed.

The chosen telescope configuration is an un-obscured eccentric pupil Cassegrain plus a collimating off-axis paraboloidal mirror followed by a plane folding mirror. As baseline, the entire system, i.e. mirrors, telescope structure and optical bench, will be realized in aluminum. The theoretical performance, i.e. spot diagrams, PSF and wavefront error, of the baseline telescope layout has been shown together with the expected performance in flight derived through a tolerance analysis carried out taking into account the different phases of the mission.

A preliminary study on the passive/active thermal control of the instrument has been given. In fact, 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, finely tuned and stabilized mainly by means of the thermal control subsystem working in a feedback closed-loop configuration.

Finally, the end-to-end detection and data processing system, up to the Instrument and Telescope Control Units and S/C main electrical subsystems as well, have been described.

ACKNOWLEDGMENTS

This activity has been realized under an Agenzia Spaziale Italiana (ASI) contract, ARIEL 2015-038-R.0, to the Istituto Nazionale di Astrofisica (INAF) with the support of Leonardo S.p.A. (Campi di Bisenzio, Firenze – Italy) and MediaLario S.r.l. (Bosisio Parini, Lecco – Italy).

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

REFERENCES

[1] Puig, L., Pilbratt, G. L., Heske, A., Escudero Sanz, I., and Crouze, P.-E., "ESA M4 mission candidate ARIEL", Proc. SPIE 9904, 99041W (2016).

[2] Tinetti, G., et al., "The science of ARIEL (Atmospheric Remote-sensing Infrared Exoplanet Large-survey)", Proc. SPIE 9904, 99041X (2016).

[3] Ricker, G. R., et al., "The Transiting Exoplanet Survey Satellite (TESS): discovering exoplanets in the solar neighborhood", to be published in Proc. SPIE 9904, 9904-2B (2016).

[4] Fortier, A., et al., "CHEOPS: a space telescope for ultra-high precision photometry of exoplanet transits", Proc. SPIE 9143, 91432J (2014).

[5] Ragazzoni, R., et al., "PLATO: a multiple telescope spacecraft for exo-planets hunting", Proc. SPIE 9904, 990428 (2016).

[6] Eccleston, P., et al., "An integrated payload design for the Atmospheric Remote-sensing Infrared Exoplanet Large-survey (ARIEL)", Proc. SPIE 9904, 990433 (2016).

[7] Focardi, M., et al., "The Atmospheric Remote-sensing Infrared Exoplanets Large-survey (ARIEL) payload electronic subsystems", Proc. SPIE 9904, 990436 (2016).

[8] Focardi, M., et al., "Design of the Instrument and Telescope Control Units integrated subsystem of the ESA-ARIEL payload", Proc. SPIE 10698, 10698-162 (2018).

[9] Da Deppo, V., et al., "An afocal telescope configuration for the ESA ARIEL mission", CEAS Space J. (2017).

[10] Da Deppo, V., et al., "Design of an afocal telescope for the ARIEL mission", Proc. SPIE 9904, 990434 (2016).
[11] Da Deppo, V., et al., "A prototype for the primary mirror of the ESA ARIEL mission: design and development of an off-axis 1-m diameter aluminum mirror for infrared space applications", Proc. SPIE 10706, 10706-110 (2018).
[12] Da Deppo, V., et al., "The afocal telescope optical design and tolerance analysis for the ESA ARIEL Mission", Proc. SPIE 10590, 105901P (2017).
[13] Sierra Roig, C., et al., "The ARIEL ESA mission on-board metrology", IEEE Workshop on Aerospace Metrology, Padova (Italy), 21-23 June 2017 (2017).
[14] Morgante, G., et al., "Thermal architecture of the ESA ARIEL payload”, Proc. SPIE 10698, 10698-154 (2018).
[15] Focardi, M., et al., "The ARIEL Instrument Control Unit design for the M4 Mission Selection Review of the ESA’s Cosmic Vision Program", to be published in Special Issue on ARIEL, Exp. Astron. (2017).