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ORIGINAL ARTICLE

The *Ariel* ground segment and instrument operations science data centre

Organization, operation, calibration, products and pipeline

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Abstract
The ground segment for the ESA M4 *Ariel* exoplanet space mission is introduced. The ground segment encompasses the framework necessary to support the development of the *Ariel* mission to launch, in-flight operations and calibration, data processing pipeline and data handling, including user support. The structure of the ground segment and assumed responsibilities between ESA and the *Ariel* mission consortium is explained, along with their interfaces. The operational phases for the mission are introduced, including the early commissioning/verification phases, the science operations and the calibration strategy. The smooth transition of the ground segment through the various pre/post launch mission phases to nominal operations will be paramount in guaranteeing the success, scientific return and impact of the *Ariel* mission. The expected science data products are defined and a representative data processing pipeline is presented.

Keywords Ariel · Exoplanets · Ground segment

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1 Introduction

Since their initial discovery in the early 1990's [18, 35], more than 4000 exoplanets have now been revealed. Exoplanet science now stands at a threshold of a revolution, moving from the epoch of discovery to that of investigation of the physical and chemical properties of exoplanets in transiting orbits around their host stars. Such studies demand a large, unbiased spectroscopic survey of exoplanets and the *Ariel* mission has been uniquely conceived to conduct such a survey to explore the atmospheres of exoplanets shedding light on their formation and evolution.

Ariel (the Atmospheric Remote-sensing Infrared Exoplanet Large-survey) has been selected as the next medium-class science mission (M4), for the European Space Agency's (ESA) Cosmic Visions programme [31, 32]. The responsibility for the mission is split between the *Ariel* Mission Consortium (nationally funded member countries, hereafter AMC) and ESA. *Ariel* is currently in the definition study phase (Phase B1), aiming for mission adoption in November 2020 and an expected launch in 2028.

Ariel will be a metre-class telescope mission(1.1m x 0.73m elliptical primary off-axis Cassegrain), operating at optical to thermal infrared wavelengths (0.5–7.8μm) in a halo orbit around the L2 Lagrangian equilibrium point. The mission lifetime is nominally four years with a possible extension to at least six years. The *Ariel* scientific payload consists of two instruments described in Table 1 [5]. The *Ariel* InfraRed Spectrometer (AIRS) provides low/medium resolution ($R = 30 - 200$) spectroscopy between 1.95 and 7.8μm. The Fine Guidance System (FGS) instrument combines the functionality of both guidance and science channels with 3 photometric bands defined as VISPhot, FGS-1, FGS-2 and a low resolution spectrometer, NIRSpec ($R>20$).

Ariel will use the technique of differential transit/eclipse spectroscopy over this wavelength range, to determine the physical and chemical conditions of the atmospheres of a sample of around 1000+ known exoplanets, targeting primarily warm to hot transiting gas giants, Neptunes and super-Earths around a wide range of host star types. Through this detailed measurement of the spectral energy distribution and spectral features of exoplanet atmospheres, it will be possible to establish the chemical composition, energy budget, chemical abundances, thermal structure, optical albedo, and spatial and temporal variability of their atmospheric structure [32].

Table 1 The *Ariel* instrument suite

Instrument	Channel	Type	Unit
AIRS	CH0	Spectrometer	1.95 – 3.9 μm
	CH1	Spectrometer	3.9 – 7.8 μm
FGS	VISphot	Photometer	0.50 – 0.60 μm
	FGS1	Photometer	0.60 – 0.80 μm
	FGS2	Photometer	0.8 – 1.1 μm
	NIRspec	Spectrometer	1.10 – 1.95 μm

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. 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. The combination of the very broad instantaneous spectral coverage and high photometric stability of *Ariel* provides a unique opportunity to address science questions over a wide range of areas in astrophysics. The *Ariel* targets and survey strategy is discussed in detail in [6, 36].

This work describes the framework, collectively referred to as the *Ariel* Ground Segment, required to support the operations, data processing and calibration for the *Ariel* mission, as well as providing support for the *Ariel* users. The *Ariel* Ground Segment is described in detail in Section 2 defining the responsibilities of ESA and the AMC. Section 3 describes how the AMC ground segment contribution will evolve through the on-ground calibration campaign to launch. The in-flight science and calibration operations are summarised in Section 4. In Section 5, the expected science data products and science data processing pipeline are introduced. A summary is given in Section 6.

2 The *Ariel* ground segment

2.1 Overview of the *Ariel* ground segment

The *Ariel* Ground Segment (GS) provides the framework and resources with which to manage and operate the *Ariel* mission. The GS sends and receives telemetry to/from the *Ariel* satellite via telecommands. The GS will process the science telemetry via automatic pipelines. The GS will also produce, disseminate and archive the generated data products, as well as providing user support. The GS also provides a framework to support the pre-launch payload level ground testing and in-flight calibration campaigns. The responsibility for and provision of the *Ariel* GS is nominally split between ESA and the AMC.

In detail, the GS consists of the Operational Ground Segment (OGS at ESA for mission operations described in Section 2.2) and the Science Ground Segment (SGS, for science operations described in Section 2.3). Science operations are conducted by the SGS consisting of the Science Operations Centre (SOC) under the responsibility of ESA and the *Ariel* Instrument Operations Science Data Centre (IOSDC) drawn from the AMC. A component diagram of the entire GS is shown in Fig. 1.

2.2 *Ariel* Mission Operations Centre (MOC)

Ariel mission operations are conducted by the OGS. The OGS is organised and led by the Mission Operation Centre (MOC) and includes the ESA ground stations. The ground segment and operations infrastructure for the MOC will be set up by ESA at the European Space Operations Centre (ESOC) in Darmstadt, Germany. ESOC will prepare the OGS including all facilities, hardware, software, documentation, the

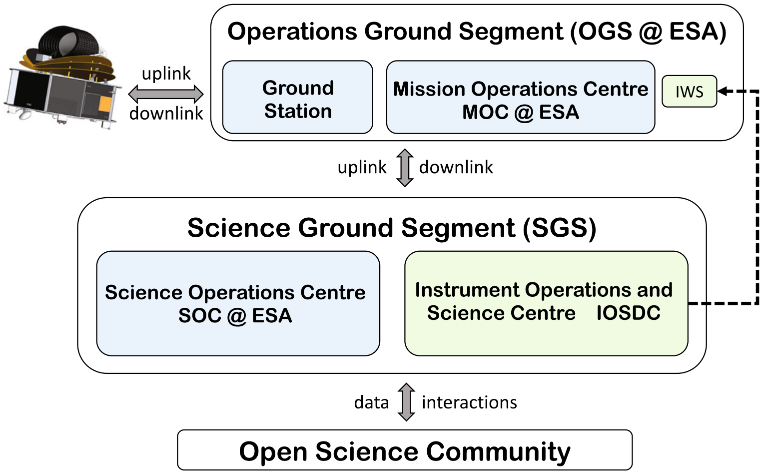


Fig. 1 The *Ariel* Ground Segment. The ESA led components are shown in *blue* and the AMC components in *green*. The SOC is the nominal point of contact to MOC during in-flight operations, with the exception of the commissioning phase and for contingency case handling. In these cases a direct link between the IOSDC and MOC can be established through the instrument workstation (IWS)

respective testing, validation and training of staff required to conduct the mission operations. The MOC will be responsible for all operations, monitoring and control of the *Ariel* platform and payload during all mission phases covering both nominal and contingency operations.

Prime MOC responsibilities include:

- Operations preparation and procedures.
- Spacecraft platform and payload monitoring and control.
- Maintaining the health and safety of both platform and payload.
- Intervention in case of anomalies
- Planning, generation and upload of all spacecraft and instrument commands (science observation commanding inputs are provided by SOC).
- Spacecraft maintenance and engineering support, e.g. on-board software maintenance.
- Flight dynamics support, including determination and control of the satellite orbit and attitude.
- Planning, scheduling and execution of the ground station contacts.
- Receipt of all telemetry including science data.
- Distribution of all relevant data (science, housekeeping and auxiliary data) to the SOC and archiving of all housekeeping data.

The MOC performs all communications with the satellite through the ground station network. The 35m ground stations of the ESA ESTRACK network comprising of the New Norcia, Cebreros and Malargüe antennas will be used for communication and precise orbit determination. Additional coverage will be provided during the Launch and Early Operations Phase (LEOP) from the small New Norcia (NNO-2) antenna to support first acquisition. All communications and tracking with *Ariel* will be done at X-Band using existing capabilities in the OGS.

In addition, a dedicated instrument workstation (IWS), provided by the IOSDC **(with input from the instrument team)** and located at the MOC, will allow the *Ariel* consortium fast access to the satellite telemetry during the in-flight commissioning phase and for payload contingency analysis support if necessary.

2.3 Science Operations Centre (SOC)

The SOC, based in ESA/ESAC in Madrid, Spain,will design, develop and operate the ESA-funded component of the *Ariel* SGS throughout all mission phases, and is leading the system engineering aspects of the complete SGS.

The SOC responsibilities include:

- Centralised scheduling system as interface to MOC to produce instrument commanding and pointing requests.
- Reception of science, housekeeping and auxiliary data from the satellite received via MOC.
- Operation of the automated data processing pipeline.
- Data quality control.
- Operational support for instrument operations.
- Mission planning and observation scheduling during in-flight operations.
- The *Ariel* data archive.
- Distribution of data products (including housekeeping, etc) to the IOSDC and community.
- User support including ESA-led community calls.

The responsibility for the design, implementation, and operation of the SOC rests with ESA. The *Ariel* data processing pipeline will be supplied by the AMC and run automatically at SOC to produce data products up to Level 2 (see Section 5). SOC will maintain the *Ariel* archive comprising of the mission data base and science data archive, and will disseminate science data to the scientific community.

2.4 *Ariel* Instrument Operations Data Science Centre (IOSDC)

The IOSDC will be provided by the AMC. The IOSDC structure will follow a distributed model, across the participating consortium countries, but will provide a single-point interface to the SOC (and also to the MOC). The IOSDC will design, develop and operate the AMC-supported element of the SGS throughout all mission phases. The main responsibilities of the IOSDC will include:

- Long term observing plan tool implementation and delivery.
- Science instrument calibration requirements and plan.
- Science data processing pipeline software (to Level 2 products).
- Calibration products delivery and maintenance
- Definition of operation observing modes.
- Execution of the in-flight Commissioning Phase plan.

- Provision and maintenance of the IWS at MOC.
- Health monitoring and trend analysis system and quick look analysis tools.
- Level 3 data product production and delivery to SOC

The structure of the IOSDC will be dynamic in nature and is expected to evolve throughout the various mission phases. Functionally, the IOSDC will be organised into dedicated teams, summarised in Fig. 2, independently managed and reporting to the IOSDC manager.

An Instrument Team, initially autonomous from the IOSDC during the payload development phase will undertake ground testing, instrument software development and the initial in-flight commissioning. This team will be fully absorbed into the IOSDC after launch, during the Performance Verification phase. The Calibration Team will provide support for the on-ground science calibration and the calibration plan for flight operations. An IWS team will be responsible for the provision of the Instrument Work Station and will initially be split between the IOSDC and elements of the instrument teams, to be fully absorbed within the IOSDC after in-orbit commissioning. An Operations Team will be responsible for operational procedures and interactions for the instruments (logging, health monitoring and trend analysis). A Software Team is responsible for the production of the data analysis pipelines and Quick Look Analysis (QLA) tools. An Observations Team will be created towards launch and will provide an interface between the instrument and software teams with the *Ariel* science, including science observations planning before launch and science

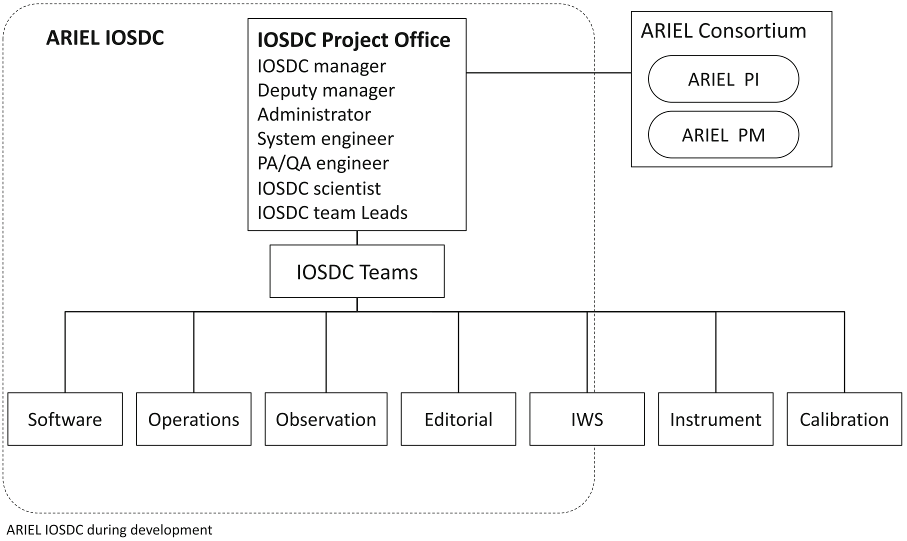


Fig. 2 Functional structure of the IOSDC. The *dotted box* denotes the IOSDC during the development phase of the *Ariel* mission and assumes the calibration and instrument teams will be semi-autonomous and include payload, instrument and AIV engineers, etc. During flight operations it is expected that these teams will be absorbed into the general IOSDC structure. The IWS (Instrument Work Station) team is lead by the IOSDC with input from the instrument team. The IOSDC project office interacts with the rest of the AMC, including the *Ariel*-PI and project manager via the IOSDC manager

validation of observations. Finally, an Editorial Team will take the responsibility for all documentation for the IOSDC including the transfer of knowledge between the instrument teams to the IOSDC before launch.

3 The smooth transition philosophy

3.1 Definition

Throughout all *Ariel* mission phases a smooth transition approach, similar to that employed for the ESA *Herschel* mission [22, 24] will be adopted. The smooth transition approach will incrementally develop a single framework that evolves to support all mission phases, ensuring a familiar environment as much as possible from initial instrument level testing, through launch and flight operations, to post operations. This philosophy facilitates the transfer of knowledge and procedures and reduces conversion efforts and transitional errors. Under the smooth transition philosophy, the initial ground level testing should closely resemble the final operational environment and the set-up should subsequently smoothly adapt into the in-flight phase operations environment.

3.2 Ground calibration campaign

The ground calibration campaign of the *Ariel* payload is designed to ensure that it meets specification and will address parameters and associated accuracy not easily accessible once in flight. The campaign will be the responsibility of the AMC including the IOSDC. The ground campaign will follow a hierarchical strategy, implementing as many tests as possible at the lower levels to avoid complication further down the signal chain at either the instrument or spacecraft levels. The instrument/calibration teams shall conduct tests at the *Component Level* (e.g. detectors, cold front end electronics (CFEE), dichroics, etc), the *Unit Level* (e.g. FGS and AIRS detector systems) and the *Subsystem Level / Instrument Level Testing* (AIRS instrument, FGS instrument, Instrument Control Unit, etc). The IOSDC will participate at the *Payload Module* Level, with the integrated instruments and telescope payload (proto-flight model, PFM). This will include the payload functional/performance tests in order to understand the stability and throughput of the overall system, including the full end to end optical test of telescope + payload module integrated system test.

The IOSDC will develop a suite of QLA software, initially for use in the payload level tests, to enable visualisation of test data. The typical functionality of the QLA tool is analysis of the housekeeping and science data at the pixel level in order to check the correct detector behaviour and the expected data content and format. Under the smooth transition philosophy, these QLA tools will be run on the Instrument WorkStation (IWS, see Fig. 1) to support ARIEL testing on-ground and then in-flight commissioning on the IWS at MOC for the validation of observational data during flight operations. The QLA/IWS is not expected to be necessary during nominal operations, except in the case of any contingency.

A dedicated Electronic Ground System Equipment (EGSE) environment will be developed by the AMC for the purposes of all ground testing and calibration. At the component/unit test level, the individual instrument teams will develop their own EGSE. Under the smooth transition philosophy, the EGSE from the instrument level testing to the payload level integrated system test will enable the same software to be used for all mission phases including the IWS. A schematic overview of the smooth transition of the envisaged EGSE is shown Fig. 3. In addition, similar Optical Ground System Equipment (OGSE, including a telescope simulator) will provide a collimated beam to the *Ariel* primary mirror and calibration source(s) covering the full wavelength range from 0.5-7.8 μm.

Finally, full end-to-end tests of the entire Ground Segment will involve taking data using standard observational modes and processing data both on-board and on the ground (via the data processing pipeline).

4 *Ariel* flight operations

4.1 Operation phases

The *Ariel* mission operational phases are defined, from ~1 year prior to launch, as:

- Pre-launch phase (including launch campaign)
- Launch and Early Operations Phase (LEOP, ~days)
- Commissioning Phase (CP, ~3months)
- Performance Verification Phase (PVP, ~2months)
- Science Demonstration Phase (SDP, ~1month)
- Nominal Science Operations Phase (NSP, 3.5 years))
- (possible) Extended Science Operations Phase (ESOP, 2 years)
- Post-Operations Phase including 3 months Decommissioning (POP, 2 years)

LEOP shall be from launch to the end of the first trajectory correction manoeuvre and is expected to last <48 hours. *Ariel* will be launched on an Ariane 62 rocket into an eclipse-free (Earth and Moon), large amplitude halo orbit around the Sun-Earth L2 point.This orbit offers a very stable thermal and radiation environment, combined with a very large instantaneous field of regard.

CP is the responsibility of the instrument and payload teams and refers to low level instrument/payload functional commissioning. At this point, following the smooth transition philosophy, the necessary elements of the instrument and payload teams (including the IWS) will have been fully absorbed into the IOSDC.

PVP will include dedicated calibration observations in order to characterise and verify the instrument performance, i.e. that the performance measured on the ground is still valid in flight. Once the operational science readiness of the mission has been confirmed, science (survey) observations can begin.

SDP will be the execution of a tailored survey, optimized for demonstrating the scientific capabilities of the mission. The SDP produces the first scientific results and will transition to the Nominal Science Phase (NSP).

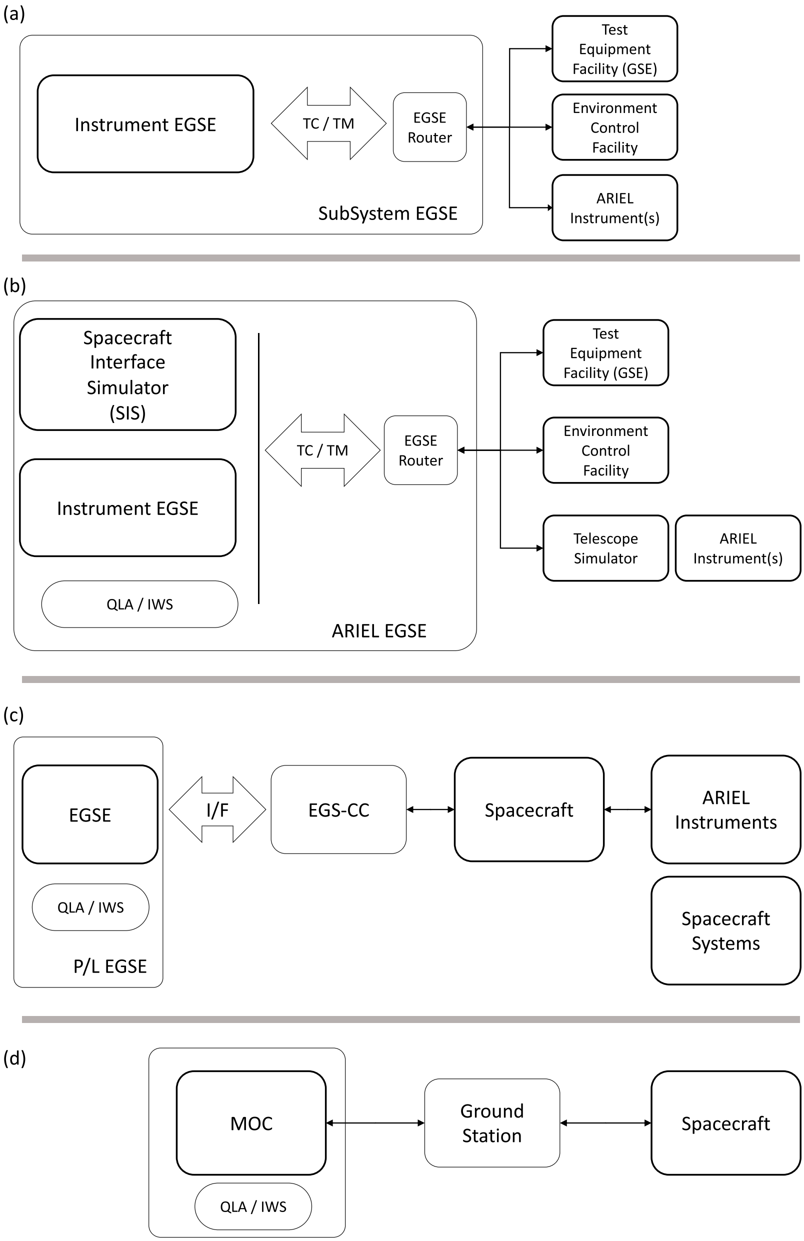


Fig. 3 Schematic overview of the EGSE set up for the *Ariel* ground test campaign. *Panel a:* the EGSE set up during component and unit tests including the EGSE router to handle both tele-commands (TC) and telemetry (TM). *Panel b:* EGSE setup during Instrument Level Testing (ILT) of the entire AIRS and FGS instruments. At the ILT level, both a spacecraft interafce simulator (SIS) and telescope simulator will be required. The IOSDC **together with the instrument teams** will also develop the QLA/IWS at this test level. *Panel c:* Payload (P/L) and spacecraft integrated system tests (IST) of the entire system. *Panel d:* under the smooth transition philosophy, the EGSE evolves from lowest test level through to in-flight operations

It is expected that NSP will be conducted in cycles of 6 months for the purposes of the data release of observations (see Fig. 4). All data will be released after processing, consolidation and quality control are completed. Note that the general astronomical community may have the opportunity to propose complementary science through ESA open time calls.

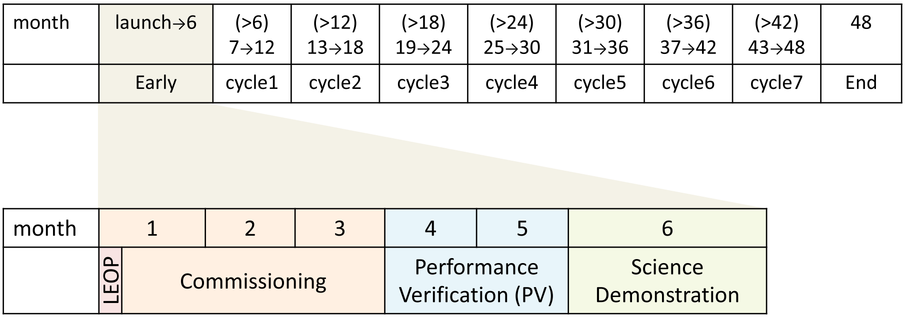
Routine calibration observations will also be made during the NSP, amounting to a maximum of 7 hours/week (4.2% of the mission time).

At the end of routine science operations (including any mission extensions), the spacecraft decommissioning and post-operations phases start. Both are running in parallel with decommissioning performed by Operations Ground Segment (OGS) and post- operations by the SGS with durations of 3 months (maximum) and 2 years, respectively.

4.2 Observation scheduling

Over 4000 extra-solar planets have been discovered to date. Additionally, the *Transiting Exoplanet Survey Satellite* (*TESS*, launched 2018) is expected to detect over 4500 planets around bright stars and more than 10,000 giant planets around fainter stars [1]. Moreover, ground-based surveys and future missions such as *PLATO* [27] shall add more new planets. [6] have used the list of known exoplanets plus the predicted TESS targets from [1], to create a list of potential targets for *Ariel*.

This list was then analysed using the *Ariel* radiometric model (ArielRad; [21]), which provides realistic noise models for all planets. These noise models were used to create a new list of potential detectable targets, based on the expected performance of *Ariel*. This master list is referred to as the *Mission Candidate Sample* (MCS). The MCS forms the basis for the *Ariel* scheduling exercise, to produce a subset of the MCS referred to as the *Mission Reference Sample* (MRS). This MRS provides the content for the mission long-term observation plan.



month	launch→6	(>6) 7→12	(>12) 13→18	(>18) 19→24	(>24) 25→30	(>30) 31→36	(>36) 37→42	(>42) 43→48	48
	Early	cycle1	cycle2	cycle3	cycle4	cycle5	cycle6	cycle7	End

month	1	2	3	4	5	6
	LEOP Commissioning			Performance Verification (PV)		Science Demonstration

Fig. 4 *Ariel* Operations Phase Overview. The performances of spacecraft and payload are designed for a in-flight operational time of 4 years, consisting of a maximum of 6 months combined for Launch and Early Operations Phase (LEOP), Commissioning, Performance Verification, and Science Demonstration Phases, and a minimum of 3.5 years for Nominal Science Operations(NSP). NSP will be conducted in cycles of 6 months for the purposes of the data release from observations

To achieve a high scheduling efficiency, an optimisation process based on a figure-of-merit for maximizing the scientific return as an integral part of a long-term planning tool will be used. Two independent algorithms based on an AI genetic algorithm optimisation technique [9, 20] and a classical "greedy" iterative approach [19] have been tested to demonstrate the feasibility and performance of the *Ariel* core survey under the current MCS described above. These independent simulations of the mission planning demonstrate that about 950 exoplanets could be observed, subsuming a total of ∼90-92% of the science observation time (including science targets and calibration time).

The IOSDC is responsible for performing the scientific mission planning activity before launch and delivery of the long-term planning tool, including training to SOC. SOC will then carry out the long-term planning exercise during operations.

4.3 Science observations

The *Ariel* mission aims to explore around 1000 targets (star transiting planet(s)) using a hierarchical 4-tier survey structure [6] comprising of:

Tier 1 Reconnaissance Survey: (∼ 30% lifetime) All planets will be observed at low spectral resolution in order to obtain a signal-to-noise ratio, SNR=7 in 6 selected spectral bands.

Tier 2 Deep Survey: (∼ 60% lifetime) Atmospheric characterisation of a subsample of ∼400+ planets observed with a spectral resolution of R=50 below 3.9μm and R=15 above 3.9μm, to the same SNR as the Tier 1 survey.

Tier 3 Benchmark Planets: (∼ 10% lifetime) A detailed survey of 50+ of the best planets orbiting very bright stars observed at the maximum spectral resolution to a high SNR>7.

Tier 4 Phase Curves and Bespoke Observations: Phase-curves, eclipse mapping, bespoke observations with multi-band photometry/spectroscopy (SNR>7) for a small number (10+) of targets.

Tier 1 will provide the sample for selecting Tier 2 planets, which in turn will inform the selection of Tier 3 targets.

A typical observation sequence for a science target during normal operations will follow the procedure: acquire science target, observe target for a minimum of 2.5x the transit duration, proceed to next target.

The data flow for a single transit *observation* (star + planet) is described in Fig. 5. Charge is accumulated up the detector ramps until a detector reset is performed, forming a single *exposure*. The detector pixel clock drives the cadence at which the detectors are read. The signal up each ramp can be read out as Non-Destructive Reads (NDR) at a given cadence. All NDRs are read and passed to the on-board Data Control Unit (DCU). In principle, due to the correlated nature of the astronomical signal, not all NDRs are required, therefore to remain within the telemetry budget limits, the DCU will provide a level of preliminary processing, e.g. decimation (similar to the MULTIACCUM readout scheme described in [28]). The output from the DCU is referred to as a *Science Frame* (SF) and forms the basic data packet. The time stamp assigned by the DCU is the time from the on-board clock corresponding to the reset

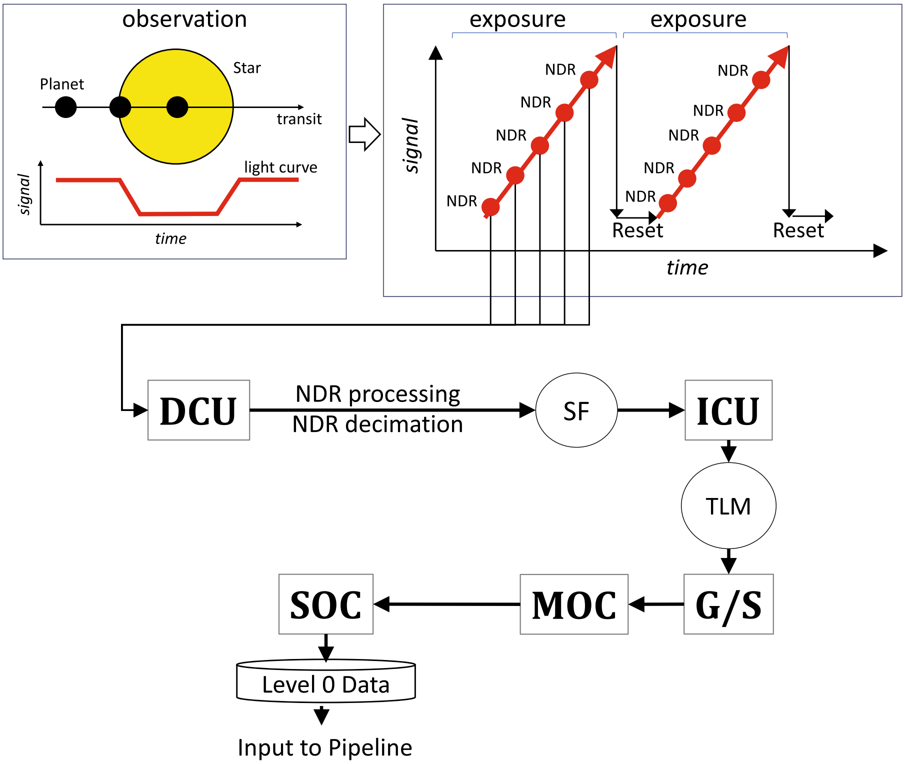


Fig. 5 The data flow of the signals produced by the *Ariel* detectors for a transit observation. Detectors accumulate charge up a ramp until a detector reset. The ramps are periodically read-out as Non-Destructive Reads (NDR) by the detector cold front end electronics (CFEE) and delivered to the data Control Unit (DCU). The DCU may process and decimate these data to form telemetry science frames (SF) to be compressed by the Instrument Control Unit (ICU). The ICU stores the compressed frames in the payload science data storage, and sends them as telemetry when a telemetry window opens from the spacecraft ICU to MOC via the ground station (G/S). The data is then sent from MOC to SOC to form the basis of the Level 0 data as input to the *Ariel* data processing pipeline

of the first pixel in the array. The science frames are then passed to the Instrument Control Unit (ICU, [7]) which sends the data telemetry (TLM) to the ground station. This is received by the MOC and passed on to SOC. This data forms the basis of the Level 0 products, the starting point for the *Ariel* data processing pipeline as shown in Fig. 11.

Ground contacts are currently planned at 14hrs/week corresponding to the allocated average data rate of maximum 236 Gbit/week assuming a compression factor of ~ 2.5 for the telemetry data. This contact time will be divided into 3 contact periods per week with Daily Telemetry Communications Periods (DTCP) of 2 × 4hrs and 1 × 6hrs. During all active mission phases, *Ariel* shall be able to operate without ground contact for a period of 5 days without interrupting mission product generation with data being stored on the instrument mass memory, for up to 2 missed contacts (i.e. up to 5 days without ground contact).

For the brightest targets i.e. short saturation time (e.g. HD 219134 Kmag $<$ 3.5), a Correlated Double Sampling (CDS), readout scheme will be used, where the DCU produces only two science frames corresponding to the first and last NDR in the exposure at a cadence equal to the saturation time of the detector array.

4.4 In-flight calibration strategy

The measurements to be made by *Ariel* require that the stability of the system is either maintained, or monitored to allow removal of variations in the system performance, to around 10-100 ppm (parts per million) over the duration of a transit (up to 10 hours). This will require both a highly optimised design for the spacecraft and instruments, and a calibration scheme capable of monitoring the system performance to within the specified limits. In order to achieve these requirements the instruments must be calibrated both before launch on the ground and in-flight. The smooth transition philosophy, described in Section 3 ensures the necessary self-supporting and efficient calibration scheme.

Effects requiring calibration (or correction using calibration products) can be grouped into 3 broad categories:

Instrumental Effects: These are mainly linked to the detection process and the associated detection chain and includes calibration and correcting of effects such as dark current, pixel response / uniformity, offsets and crosstalk, etc.

Spacecraft Effects: These are associated with changes in the stability of the spacecraft, e.g. telescope temperature, pointing performance and stability, mechanical vibration and variations in stray light, etc

Astrophysical Effects: These are associated with the observing "scene" and require dedicated measurement and monitoring schemes as they are outside of the design parameters of the mission, e.g. effects of the L2 environment such as glitches or scattered light, the stellar signal in general or contamination by the background stars in the target field.

After launch, the 6 month CP/PVP/SDP period (see Section 4.1) is used to fully characterise the satellite and verify that the performance measured on the ground is still valid. Following this, there will be regular calibration observations during nominal science operations (i.e. routine calibration phase). It is expected that calibration products will be periodically updated during the operational phase.

The routine in-flight calibration phase will consist of a combination of long term observations to monitor stability on the duration of a transit (6 hours), to shorter observations (minutes - $<$1 hour) to correct for instrument effects. The required calibration measurements and corresponding calibrators are summarised in Table 2. The calibration observations will then be used to populate the Calibration Products in Table 4 as required by the *Ariel* Data Reduction Pipeline (ADaRP).

An internal calibration source may be implemented in order to monitoring trends in the detector systems, particularly for the flat-fielding of the detector arrays. An integrating sphere will be mounted behind the *Ariel* M5 mirror with the calibration signal injected through the output port of the sphere and a small hole in the mirror, a method which results in a negligible loss of throughput. For the AIRS and NIRSpec

Table 2 *Ariel* in-flight calibration procedures

Calibration	Calibrator
Detector Dark Current	Detector dark pixels or dark sky
Pixel Deglitching	Detector dark pixels or dark sky
Detector Gain Variation	Calibration stars
Non-linearity	Calibration stars
Persistence	Calibration stars
Pixel Crosstalk	Detector dark pixels or dark sky
Flat Fielding	stars / On-board calibration source
Variations in Thermal Background	Dark Sky
Instrument Performance Ageing	Calibration stars
Straylight variation	Calibration stars
Absolute Pointing Performance	Calibration stars
Pointing Stability	Calibration stars
Optical Distortion	Calibration stars
Optically Stability	Calibration stars
Optimisation of PSF	Calibration stars
Absolute Photometric Calibration	Calibration stars
Relative Photometric Calibration	Calibration stars
Wavelength Calibration	Calibration stars / Planetary nebulae

channels operating in the near-mid-infrared with an input slit, the baseline solution is to use a thermal tungsten filament source corresponding to a blackbody at 1100 K (utilising *JWST*-MIRI heritage [12]). However, this does not provide sufficient optical power to illuminate the FGS photometric channels. Therefore, in addition, 3 LEDs are also included feeding the same sphere. LEDs emitting in the visible and NIR are routinely used at cryogenic temperatures in a similar environment to that of *Ariel*. The flashes produced by the calibration source are spatially reproducible in time (i.e producing a repeatable normalised illumination pattern on any of the detector arrays) and will be used during CP and PVP. The calibrator may also be used during science operations if required for the purposes of flat fielding.

The wavelength scale of the *Ariel* spectrometers will be calibrated before launch and only minor changes are expected in-flight. A requirement of 1/3 of the spectral resolution is necessary and any additional wavelength calibration will be carried out using astronomical sources, e.g. evolved stars and planetary nebulae (PNe). Suitable targets for these observations are provided from the *ISO*-SWS catalogue and the brighter targets observed by the *Spitzer* IRS [8, 26, 34]. Any source seen with ISO-SWS is likely to be suitable for *Ariel* to observe with a high SNR.

The absolute flux calibration for *Ariel* will use visible/NIR stellar standards. Although absolute flux calibration is not a critical constraint for *Ariel*, previous MIR missions have achieved calibration accuracies in the few percent range (e.g. [15]). Existing databases from the *WISE*, *Spitzer*, *MSX* and *AKARI* missions [14, 15, 25] will be utilised to identify both the core calibration stars and those with uncalibrated MIR excesses in order to remove them from the standard calibration list.

Dark sky observations are likely to be required for detector dark current measurements and pixel deglitching if the detector dark pixels are not sufficient. In addition, dark sky observations may be required during the operation of any on-board calibration source in order to avoid contamination of the flat field by stellar objects. Any selected dark sky observations need to be made in areas of high visibility. Most space missions have utilised the North Ecliptic Pole (NEP) region. For example, the *Spitzer*-IRAC instrument dark sky was located at 17^h40^m, $+69^d$ (J2000), very near the NEP [16].

For the planetary transit measurements, a relative photometric calibration accuracy of 10-100 ppm over 10 hours is required. A network of G stars has been selected as stellar calibrators on the basis of their photometric stability and will be used to monitor the stability and evolution of the system response. They will be observed just like the science targets and then fed through the data processing pipeline (Section 5.1). Both short calibration and long calibration observations of G stars will be made. Short calibration observations of a duration of 1h will be made typically every ∼36h, to monitor systematics (e.g. wavelength variation, drifts, etc). Long duration calibration observations of ∼ 6h will be made approximately every 30 days, to monitor stability on the timescale of a typical transit. [4] has shown that 70% of G dwarfs are stable in the visible to better than 10ppm over periods of 30 days and that there are over 500 in the solar neighbourhood brighter than K=5 (See Fig. 6 *left-panel*). These are uniformly distributed over the *Ariel* sky and have a comparable brightness distribution to the stars in the *Ariel* target sample. This will allow high signal-to-noise observations to determine accurately the slow variation with time of the instrument response and detector performance. Ideally, a catalogue of G stars covering a magnitude range matching the range of target magnitudes will be required (down to 8-9 magnitude).

There have been several studies following [4], in particular, [11] analysed the noise properties of four years of *Kepler* data finding that there are many Kepler solar-like stars that are as quiet as the quiet Sun. Although, the abundance of very quiet G stars might be smaller than the initial study by [4], after careful selection of targets, these could be used as standard calibrators for *Ariel*. As a test case, 40 main sequence G

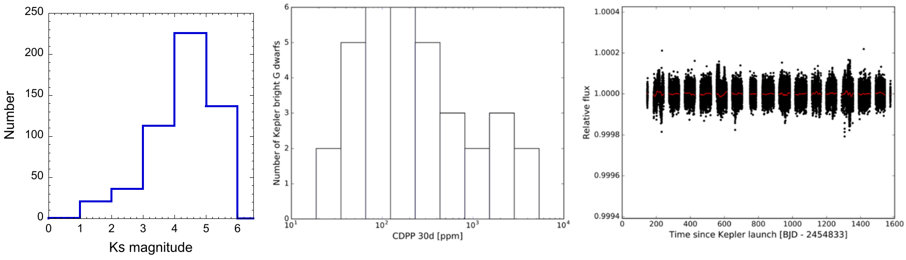


Fig. 6 *Left-Panel*: Ks magnitude histogram for close and bright G stars selected by (0.2 < J-H <0.45) (Ks < 5.5) colours as potential calibration sources for *Ariel*. *Middle-Panel*: stability histogram of 40 *Kepler* selected bright (K>8) G stars. horizontal axis is variability index in parts per million. *Right-Panel*: variability over four years of *Kepler* data of the star TYC 3565-1235-1 (KeplerID= 11719930, K=7.98). Red line represents a mean noise level of 36 ppm

stars brighter than magnitude K=8 were identified in the *Kepler* data. Their variability over a time scale lower than 30 days was analysed using years of data. The *middle-panel* of Fig. 6 shows the histogram of their variability index, indicating the fraction of stars more stable than 100 ppm is 31±9%. For *Ariel* calibration purposes, the three stars within the sample that are more stable than 50 ppm over four years are BD+41 3338, HD 177412 and TYC 3565-1235-1. As an illustration in Fig. 6 (*right-panel*), the relative flux over a four year period for the star TYC 3565-1235-1 (KeplerID= 11719930) is shown. Over the course of the *Ariel* mission lifetime the star has an average noise level of 36 ppm.

Before launch, a systematic survey will be conducted from the ground by the AMC to study the properties of a sample of G dwarfs using activity indicators (CaII H & K, X-Ray) in order to carefully select the lowest activity stars to become the calibrators.

5 The *Ariel* science data products and pipeline

5.1 Overview

The *Ariel* Data Reduction Pipeline (ADaRP) will be provided by the IOSDC in order to process and analyse the data obtained from the scientific observations taken with *Ariel*. The Level 0 to Level 2 components of the pipeline will be delivered to SOC, possibly as virtual machines or containers. The pipeline itself will then be automatically and systematically run at SOC on all observational data from *Ariel*, with the data products populating the *Ariel* science archive also located at SOC.

The *Ariel* pipeline will have natural break points corresponding to milestones in the data processing. These milestones, correspond to the specific data product levels described in Section 5.2. Following the data processing to a given level, the corresponding products are ingested into the *Ariel* science archive, and made available to the science community via appropriate timed data releases.

Following the data flow from an *Ariel* observation described in Fig. 5 , the SOC will receive consolidated raw telemetry data from MOC in the form of Level 0 data. The instrument specific software pipelines (delivered by the IOSDC) will be automatically run at SOC for the extraction of the Level 1, Level 1.5 and Level 2 data products. The Level 3 data products will be produced independently using specialised tools by the IOSDC. The Level 3 data will then be ingested into the *Ariel* archive at SOC when ready.

5.2 *Ariel* science data products

The results of the *Ariel* science observations will be released as official science data products produced by a dedicated data processing pipeline described in Section 5.3. These science data products are defined by a specific data processing level and are listed in Table 3.

The Level 0 Products are the lowest level telemetry data received on the ground by MOC and consist of time ordered raw telemetry still in a compressed form that MOC receives from the spacecraft which are then sent from MOC to SOC.

Table 3 *Ariel* science data product levels

Level	Description	Source
Level 0	Raw data Spectroscopic and photometric channels: Raw compressed data files derived from TLM, delivered from MOC to SOC	MOC
Level 1	Raw photometric or spectral images Unpacked, uncompressed, time-ordered, uncalibrated, meta-data enriched, raw data cubes of target, containing the science frames for each exposure taken during an observation. Spectroscopic channels: raw data spectral image time stamped 3D cube of which each slice is a Science Frame: – spectral pixel (pixel number) – spatial pixel (pixel number) – integrated signal value in ADU Photometric channels: raw data image time stamped 3D cube of which each slice is a Science Frame: – spatial pixel (pixel number) – spatial pixel (pixel number) – integrated signal value in ADU	SOC
Level 1.5	Calibrated photometric or spectral images Time-ordered data cubes, meta-data enriched, calibrated, background subtracted, with instrument artefacts removed/corrected fitted ramps of exposures of the observation of a target. Spectroscopic channels: time stamped spectral image 3D cube of which each slice is an array of fitted ramps: – spectral pixel (microns) – spatial pixel (pixel number) – signal (slope or time averaged CDS in the case of brightest targets) (in e$^-$/s) Photometric channels: time stamped image 3D cube of which each slice is an array of fitted ramps: – spatial pixel (pixel number) – spatial pixel (pixel number) – signal (slope or time averaged CDS for brightest targets) (e$^-$/s)	SOC
Level 2	Spectrally resolved light-curves of the target. Spectroscopic channels: wavelength binned 2D set of light curves of the target: – time axis (s) – wavelength axis (microns) – intensity signal (e$^-$/s or Wm^{-2})	SOC

Table 3 (continued)

Level	Description	Source
	Photometric channels: one broad-band light curve per channel of the target: – time axis (s) – photometric band – intensity signal (e^-/s or Wm^{-2})	
Level 3	Exoplanet broad-band spectra. Spectroscopic and photometric channels: Individual planet(s) spectrum (e.g.: ppm vs wavelength) for each observation Co-added planet(s) spectrum (e.g.: ppm vs wavelength) for all observation Stellar properties Legacy: e.g.: planet spectrum averaged over multiple transits	IOSDC

Science products for the spectroscopic (NIRspec, AIRS) and photometric (VISphot, FGS1, FGS2) channels are shown with a brief description of the contents and data structure. Level 0 products are delivered from MOC to SOC and form the basis of the input to the automatic pipeline run at SOC. Level 1, Level 1.5, Level 2 products are produced by SOC. Level 3 products will be produced externally by the IOSDC

The Level 1 Products are raw, time stamped uncalibrated data cubes, composed of all *science frames* contained in each *exposure* for the entire *observation*. Each slice corresponds to a *science frame* with axes of spatial pixel number, spectral pixel number for spectroscopic channels and spatial pixel number, spatial pixel number for photometric channels and integrated signal in ADU. Figure 7 shows a representative temporal slice of an *Ariel* Level 1 Product for the AIRS CH1 spectroscopic channel. The product was created using simulated data from the *ExoSim Ariel* instrument simulator [23, 30] processed through the pipeline. The Level 1 Data Products are the lowest scientific data produced by the pipeline. Like Level 0, Level 1 Products are considered as raw data and will not be reproduced with newer versions of the pipeline unless absolutely necessary.

The Level 1.5 Products are the calibrated (spectral or photometric) images for each *exposure*. The Level 1.5 Products are created from the Level 1 Products, after processing to remove all known instrument signatures/artefacts, except for some instrument related time dependencies. Level 1.5 Products are created by fitting the ramps between the *science frames* from the same *exposure* to calculate a slope, i.e. the rate of change of the integrated counts. Signal levels are expressed in e^-/s. A wavelength calibration solution is included in the metadata of the product. Figure 8 shows a single temporal slice (corresponding to a single *exposure*) of an *Ariel* Level 1.5 Product, for the AIRS CH1 spectroscopic channel, created by the current version of the pipeline using simulated data. Level 1.5 Products will be reproduced by

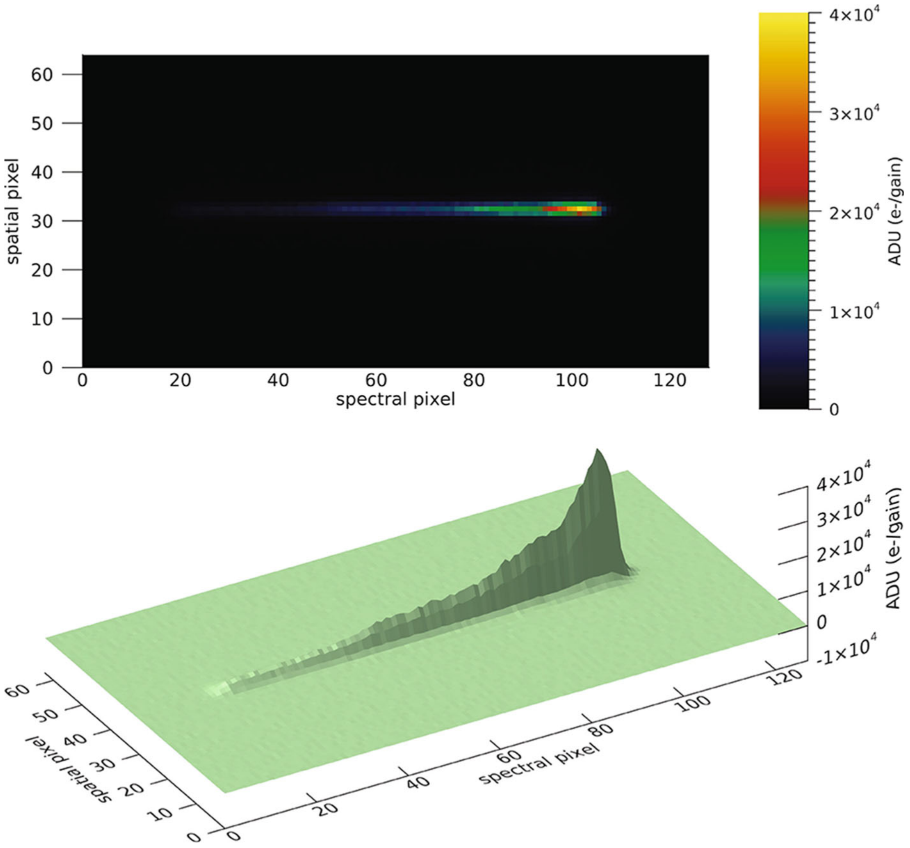


Fig. 7 Possible representation of one temporal slice (i.e.:one science frame) of an *Ariel* Level 1 Product (described in Table 3), for the spectroscopic AIRS CH1 channel. Signal units (colour-bar/z axis) are in ADU (images are produced from simulated data, and given the currently unknown gain values, the reported quantities are in units of e-/gain)

running an updated version of the pipeline on the Level 1 Products every 6 months, including new calibration products if necessary.

The Level 2 Products are the final science data products produced by the pipeline at SOC. They contain the target light curves (star + planet(s)) for one entire *observation*. Level 2 Products consist of the intensity calibrated 2D arrays along the re-binned wavelength (according to the resolution of the observing tier, see Section 4.3) and time axes. Figure 9 shows a possible example of a Level 2 Product for the AIRS CH1 spectroscopic channel. The overall Level 2 array (Fig. 9 *top-panel*) can be sliced along a selected time bin to show the measured spectrum (Fig. 9 *bottom-left-panel*), or selected spectral bin to show the measured light curve (Fig. 9 *bottom-right-panel*).

The Level 3 Products are not produced with the automatic pipeline at SOC but rather by the IOSDC, via dedicated pipelines, and delivered to SOC, to be ingested into the *Ariel* science archive. Level 3 Products consist, of the planet(s) spectrum, in fractional transit depth as a function of wavelength, for each *observation*. Figure 10

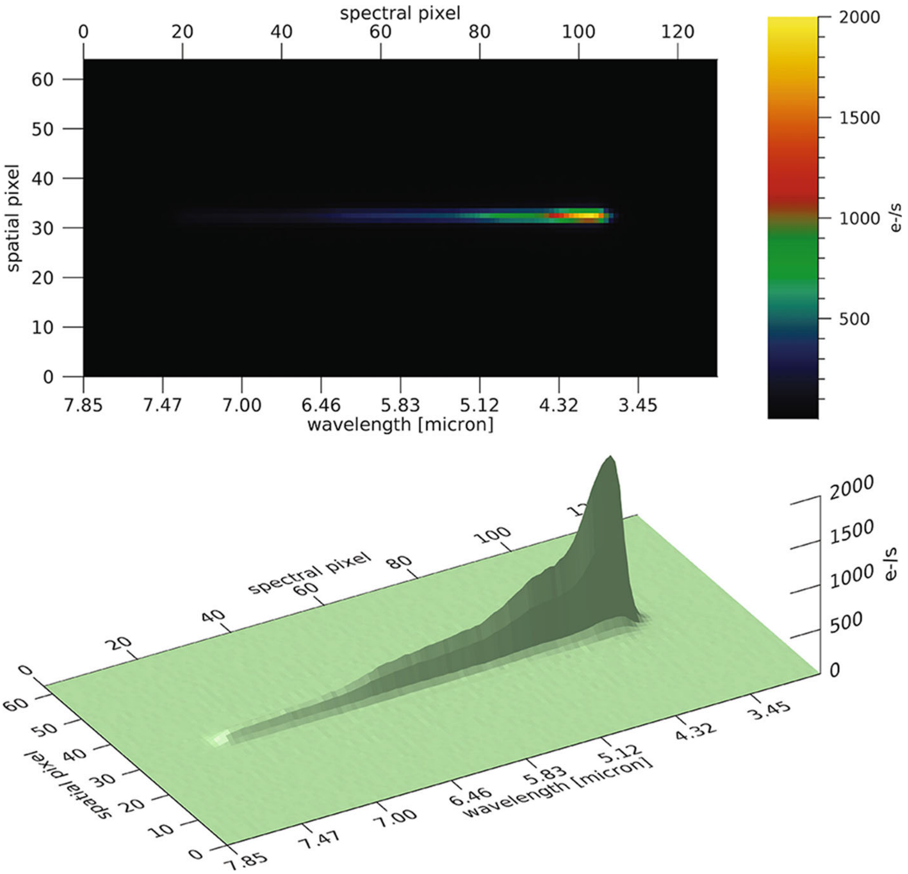


Fig. 8 :Possible representation of a single temporal slice (corresponding to a single exposure) of an *Ariel* Level 1.5 Product (described in Table 3), for the spectroscopic AIRS CH1 channel

shows a possible representation of a Level 3 Product created by the current version of the pipeline derived from simulated data. In addition to the individual planet spectra for each observation, Legacy Level 3 Products will also be produced, that contain the stacked planet spectra created from all observations during the mission lifetime, plus information on the stellar properties of the target stars.

All data products will be ingested into the *Ariel* science archive at SOC. The data processing time estimation based on the current version of ADaRP plus conservative projections, is that around 1 month of processing time shall be needed to analyse 6 months of data from Level 0 to Level 2. Assuming a 4 year mission lifetime, and including a final reprocessing 6 months after the end of mission, the expected data volume budget is estimated to be approximately 90TB.

Data processing up to Level 2 and archive ingestion is made continuously throughout the mission. All data will be released after processing, consolidation and quality control are completed, approximately 1-2 months after the last required observation

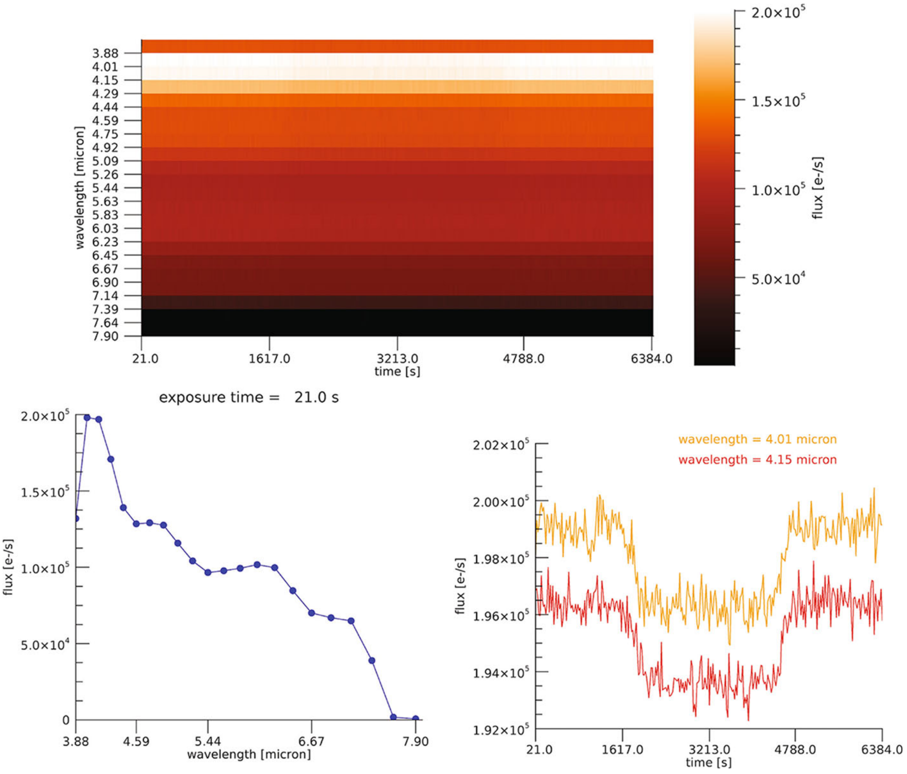


Fig. 9 Possible representation of *Ariel* Level 2 Product (described in Table 3) for the spectroscopic AIRS CH1 channel. The overall Level 2 data array (top panel) can be “sliced” along the x-axis to show the measured spectrum for a selected time bin (bottom left panel), or along the y-axis to show the measured light curve for selected spectral bins (bottom right panel)

for a target is taken, with all data being accessible from the *Ariel* Science Archive interface. A fraction of Tier 2 or 3 targets, will be observed and Level 2 Products released, as part of SDP. The current policy will be to release data products up to and including Level 2 products after each cycle (see Fig. 4) when the required SNR and spectral resolution for a particular target requiring multiple observations has been achieved. The data release up to Level 2 during the routine mission phase is currently (at the time of writing) envisioned as:

Tier 1 data public immediately after quality control is completed;
Tier 2 data public 6 months after quality control is completed;
Tier 3 data public 6 months after quality control is completed;
Tier 4 data public 1 year after quality control is completed.

Since the Level 3 data products will not be produced automatically by the processing pipeline (see Section 5.3.4), it is estimated to provide the Level 3 products at least on an annual basis, and sooner/more frequently when the knowledge to produce them is

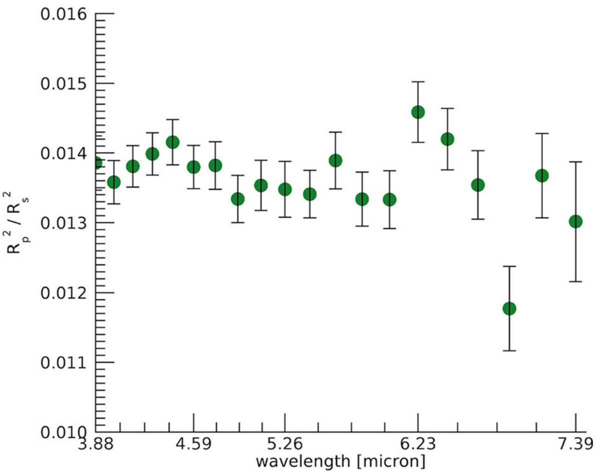


Fig. 10 Possible representation of an *Ariel* Level 3 Product. An observation, of the planet(s) spectrum, shown in fractional transit depth, where R_p and R_s are the radius of the planet and the star, respectively, as a function of wavelength

fully understood, after their acceptation for publication. The *Ariel* data rights policy will be made available in the *Ariel* Science Management Plan (SMP).

5.3 The *Ariel* Data Reduction Pipeline (ADaRP)

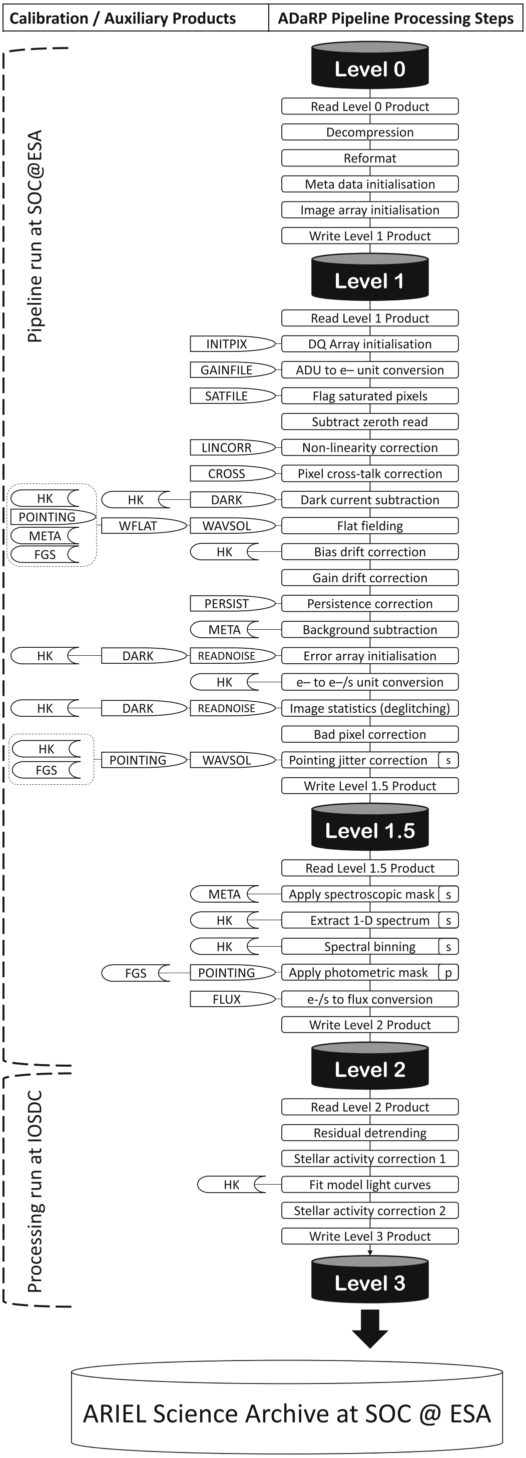
The *Ariel* consortium, via the IOSDC will facilitate data processing pipelines, collectively referred to as the *Ariel* Data reduction Pipeline (ADaRP).

The Level 0 to Level 2 processing components of the full ADaRP pipeline, form the automatic pipelines delivered to SOC. The pipeline processes sequentially, with the data level at each previous stage being used as the input to the next processing stage. As discussed in Section 5.2, the Level 2 to Level 3 processing will be executed independently by the IOSDC, since the final extraction of the planet spectra will require sophisticated and interactive procedures.

Figure 11 provides a schematic overview of ADaRP from the raw Level 0 data through to the final Level 3 products. The pipeline will be able to mitigate any instrumental effects and calibrate the data in order to provide an optimal estimate of the wavelength dependent planet-star contrast ratio, and an estimate of the noise error. Note that ADaRP has been designed to be modular such that the order of some of the steps in Fig. 11 are provisional and may be rearranged in the future as the pipeline is shaped by further characterisation of the instruments. The current version uses the ExoSim simulations [23, 30] as a testbed to generate synthetic data with noise and systematics that can be used for the pre-flight validation of the pipeline.

ADaRP will require various calibration products, shown in Fig. 11, in order to process the scientific data. These products will initially be created during the

Fig. 11 Overview of the *Ariel* Data Reduction Pipeline (ADaRP). Level 0 to Level 2 pipeline and data products at SOC. Level 3 processing and products will be produced by IOSDC. All data products will be ingested into the *Ariel* Science Archive at SOC. The ADaRP processing steps are shown as sequential rectangles as steps between each science data product level. The steps are representative at this stage and the order may evolve. Processing steps used solely for the spectroscopic channels are marked with an "S" and steps used solely for the photometric channels are marked with a "P". Also shown on the left of the pipeline are the required calibration (listed in Table 4) and auxiliary products. Auxiliary products can be from the satellite housekeeping (HK) data, the FGS pointing timeline (FGS) or from metadata produced by the pipeline itself (META)



on-ground calibration campaign (see Section 3.2) and updated in-flight (see Section 4.4). The calibration products are listed in Table 4 together with the corresponding ADaRP step that requires them.

It is expected that ADaRP will be updated regularly during the nominal mission lifetime. The current projection for updated versions of the pipeline is 6 months. Therefore at 6 month intervals, it is expected that the entire current science archive will be reprocessed (starting from the Level 1 products). This reprocessing will also incorporate any relevant and necessary updates to the calibration products as the mission progresses.

5.3.1 Pipeline processing from Level 0 to Level 1

The processing steps from Level 0 to Level 1 are outlined below:

Read Level 0 Product Raw telemetry files read from the archive.

Table 4 *Ariel* Calibration Products required by the *Ariel* Data Reduction Pipeline (ADaRP)

Product	Pipeline Step	Description
INITPIX	DQ array initialiastion	Initial pixel data quality flags
SATFILE	Flag staurated pixels	Pixel saturation thresholds
GAINFILE	ADU to e- unit converstion	ADU to electron gain per pixel
LINCORR	Non-linearity correction	Non-linearity model coefficients per pixel
CROSS	Pixel crosstalk correction	Crosstalk model coefficients per pixel
DARK	Dark subtraction Error array initialisation Image Statistics (deglitching)	Dark image array
WAVSOL	Flat fielding Apply spectral mask Extract 1D spectrum Spetcral binning	Wavelength solution model
WFLAT	Flat fielding	Wavelength-dependent QE per pixel
PERSIST	Persistance correction	Persistence model coefficients per pixel
READNOISE	Error array initialisation Image Statistics (deglitching)	Read noise per pixel
POINTING	Flat fielding Jitter correction Apply photometric mask	Converts FGS pointing timeline to channel-specific x and y offsets
FLUX	e-/s to flux conversion	Flux to e/s conversion factor

Initial versions of these products will be populated during the ground test campaign and then updated in flight where necessary. The pipeline step that uses each calibration product refers to the pipeline in Fig. 11

Decompression Data in the archive is in the format as received from MOC as compressed *Science Frames* (SF). This step decompresses and expands the *Science Frames*.

Reformat Identifies, extracts and re-orders data into the separate channels in preparation for the Level 1 Product.

Metadata initialisation The metadata contains information that is relevant for the data processing of the science data. This can include simple housekeeping information (timing of each SF, FGS pointing timeline, temperature timeline etc) and other identifying information (e.g. object, position, etc.) associated with the given observation.

Image array initialisation Extracts individual SFs from the reformatted Level 0 data, reconstituting them into 2-D images, and then ordering them into a 3-D (spectral/photometric) data cube as a function of time.

Write Level 1 Product Write the Level 1 Product to the archive. The product will also be populated with extensions and headers that provide information about the observation and the SFs (e.g. timing, observational parameters used, object information etc.), obtained from the metadata.

The format of the Level 1 Product is described in Table 3 and visualised in Fig. 7.

5.3.2 Pipeline processing from Level 1 to Level 1.5

The processing steps from Level 1 to Level 1.5 of ADaRP in its current form are outlined below:

Read Level 1 Product Reconstitute the image array and associated metadata are from the Level 1 Product.

DQ Array initialisation A data quality (DQ) array will be populated by a number of flags that identify the quality of each pixel in each SF. Initial values for the DQ array are provided by the INITPIX calibration product. The Level 1 Product itself is not changed by this pipeline step.

ADU to e^- unit conversion Conversion from ADU to electrons. The GAINFILE calibration product contains the necessary multiplicative values with which to convert the existing ADU values for each pixel into electron counts.

Flag saturated pixels Each pixel will have defined full-well capacity in units of electrons. The full well is defined typically as the charge level when the end-to-end non-linear response (photon-to-measured electrons) is 5% deviated from linear [3]. A detector pixel is considered saturated if it reaches the full well capacity.

Saturation of pixels will cause prolonged after-images (persistence) and bleeding of charge into neighbouring pixels. To remain in the linear regime and avoid saturation, a lower limit may be used to define an effective saturation limit, e.g. 80% of the full well. Different pixels may have slightly different saturation limits based on their individual response. The SATFILE calibration product is needed to define the electron counts for each pixel at which saturation occurs. Saturated pixels are then flagged in the DQ array.

Subtract zeroth read Subtracts the zeroth SF from all SFs in an exposure in order to normalise the integration ramp to the same initial level for each exposure.

Non-linearity correction Infrared detectors are inherently non-linear as there is a variation in the detector capacitance during the integration time [33]. The full signal chain will have an end-to-end' non-linearity, i.e. photon to measured electron count, and it is this combined response that is corrected by this step. The LINCORR calibration product contains polynomial coefficients for each pixel that are applied to the signals to replace the previous counts in each SF.

Pixel cross-talk correction Electrical crosstalk can occur due to parasitic capacitative coupling after charge collection and can be particularly problematic after a cosmic ray hit (glitch). Such interpixel electrical cross talk has been studied for *JWST*-MIRI, [29] and NIRSpec [10]. The existence of any electrical crosstalk will be established during the ground calibration campaign and will be corrected by using the CROSS calibration product using a multiplicative correction matrix.

Dark current subtraction Dark current is the residual current in the absence of any illumination on the detectors. It is the result of the random production of electron-hole pairs in the depletion region. Electrons (or holes) can be thermally exited into the conduction band to produce a dark current. The dark current results in an excess on the final pixel count over that of the target signal. If this excess is not removed it can lead to an inaccurate determination of the planet transit depth. To reduce the dark current, the detector is therefore operated at low temperature. Any residual dark current is then removed by applying the DARK calibration product that contains dark images taken at different integration times. Depending on the integration time of each SF (calculated from the satellite housekeeping data), a matching dark image is found. The dark image counts are then subtracted from the SF counts.

Flat fielding Pixel to pixel variation in the quantum efficiency response of the number of electrons generated to the number of incident photons is referred to as the photon-response non-uniformity (PRNU). For the spectroscopic channels this is also a function of the different wavelengths falling on different pixels. Flat fielding is the process that removes the PRNU from the image. Flat fielding is necessary to recover the correct relative signal between pixels, to mitigate any fixed pattern or Poisson noise and to reduce the effects of noise due to pointing jitter. To apply an effective flat field, the relative variation is needed at each wavelength for each pixel. For each SF, the exact wavelength falling on each pixel is calculated using the WAVESOL calibration product. WAVSOL models the wavelength dependency with spatial position on the detector array. Since this will depend on the x and y pointing offsets from pointing jitter corresponding to each SF, reference is made to the Housekeeping data, the FGS pointing timeline and the POINTING calibration product (to convert the FGS pointing timeline into pointing offsets for each channel). Having calculated the wavelength per pixel per SF, the WFLAT calibration product is used to implement the flat field. WFLAT contains a 3-D matrix of x pixel vs y pixel vs wavelength, and encodes the wavelength-dependent quantum efficiency of each pixel. The reference wavelength of each pixel is then used to find the corresponding relative quantum efficiency. The pixel value is then divided by this.

Bias drift correction This step removes the common mode noise resulting from bias voltage fluctuations during the observation. The common mode noise refers to the correlated readout from multiple pixels. A timeline of bias voltage variations due to common mode noise is processed from the reference pixels counts (stored in the metadata). The satellite housekeeping data provides the start and end times for each SF, and the timeline for the SFs, needed to apply the correction.

Gain drift correction Gain variations during the course of an observation due to any temperature-dependency are expected to manifest themselves as drifts in the signal timeline that are out of band with the science signal and therefore can be corrected estimating the effect directly from the data. It is envisaged that ground testing will characterise gain variations, such that a parametric model of gain variation can be constructed and applied in this step if necessary.

Persistence correction In infra-red detectors, persistence is an “afterglow” from earlier exposures. The basis of persistence are ’charge traps’. Various models have been produced to model the persistence behaviour in IR detectors, notably the “ramp” systematic that occurs on the Hubble WFC3 IR detector, has been modelled [2]. Persistence may be correctable using a parametric model based on measurements derived during the ground calibration campaign. The PERSIST calibration product will contain, for each pixel, the coefficients required for defining the parametric correction model.

Background subtraction Background light from incident photons may arise from sources other than the target system: e.g. zodiacal light, emission from optical surfaces, and stray light (diffuse sources). The background subtraction step samples the science frame in a peripheral region to measure the background contribution to the signal. This contribution is then subtracted from the full image. The background count per x pixel coordinate per SF is saved as a 2D array in the metadata.

Error array initialisation An error array of the same dimensions as the image array is created (and modified within the Level 1 - Level 1.5 pipeline). The uncertainty is based on a model that includes the photon noise, read noise, dark current and background counts. The READNOISE and DARK calibration products are used to calculate the read noise and dark current signal respectively. The background noise is derived from the previous pipeline step. Housekeeping data is required to identify the start and end times of each SF.

e^- to e^-/s unit conversion This step takes the SFs of each exposure and generates a single image per exposure of fitted ramps. The houskeeping data is used to find the start and end times for the integration of each SF. For all but the brightest targets, up-the-ramp fitting (modified from [28]) is performed by fitting a straight line using a least-squares algorithm to the ramp of signal values (NDRs, see Section 4.3) for each pixel. The gradient of the line gives the new pixel value in e^-/s. For the brightest targets, correlated doubling sampling (CDS) is performed, by subtracting the first SF of each exposure from the last, the difference signal counts being divided by the CDS time. The image array is resized in the time axis, now containing 2-D exposure images in e^-/s vs time as shown in Fig. 8. The ramp fitting also provides an opportunity for potential initial deglitching due to the impact of cosmic rays (glitches) on the detectors. Cosmic ray hits will either produce an excessively high gradient for the measured slope or produce a poorly fitting slope with large errors. The DQ array is updated if glitches are detected and a flag assigned.

Image statistics (deglitching) This step provides a second stage cosmic ray detection method, by checking for pixels in exposures that have counts that differ greatly from the mean count of that pixel. A histogram is produced for each pixel based on its count rate over all exposures. Any exposures that generate a count in excess of the chosen sigma cut off from the mean value of the pixel will be discovered, and the DQ array corresponding to that pixel and exposure will be flagged as a cosmic ray hit. The error on each ramp fit is calculated and incorporated into the ERR array using the READNOISE and DARK calibration products and associated metadata.

Bad pixel correction Although all baseline bad (inoperable) pixels are expected to be pre-flagged in the INITPIX calibration product, there will be additional bad pixels, identified through the pipeline, due to saturation, cosmic ray hits, etc. Those pixels with poor data quality flags are identified and either eliminated from the data or corrected using a method such as 2D interpolation.

Pointing jitter correction Spacecraft pointing errors can result in ’jitter’ of the spectrum or photometric image in the 2-D detector plane. Various factors cause jitter such as centroid error in the fine guidance system and spacecraft internal vibrations. These jitter movements can result in signal noise. Jitter noise is complex, time-correlated with multiple contributing factors, including the signal, exposure time, the goodness of the flat field, sizing of the spectral bins, and the size and placement accuracy of any aperture mask in the data processing. Jitter noise in the spectroscopic channels can be divided into spectral and spatial jitter noise. De-correlation requires a two step process: a measurement of the relative x and y offsets between image frames and the shifting of the images on each frame to correct these offsets. The relative offsets can be estimated using image cross-correlation where a reference exposure image is chosen (e.g. the first) and offsets measured relative to this reference. Alternatively, the FGS timeline, coupled with conversion information in the POINTING calibration product can be used to find an average x and y offset for each exposure (with start and end times identified from the housekeeping data). To make the image shift, each exposure can be interpolated to a subpixel grid using 2-D cubic interpolation. This is then re-sampled at the positions corresponding to the offsets obtained in the previous step, giving the shifted image. Alternatively, a 2-D Fourier transform can be used where each exposure image is shifted in phase in Fourier space, and then inverse Fourier transformed back. The reference pointing offsets to which the images have been dejittered, are used in conjunction with the WAVSOL calibration product to update the wavelength map $\lambda(x,y)$ for the dejittered exposures. A single wavelength map is produced for all the exposures and stored as a 2-D array in the metadata associated with the observation.

Write Level 1.5 Product This step generates the final Level 1.5 Product consisting of the image, quality and error arrays with the wavelength map produced in the pointing jitter correction step serving as the wavelength assignment for the image array. The format of the Level 1.5 Product is described in Table 3 and visualised in Fig. 8

5.3.3 Pipeline processing from Level 1.5 to Level 2

The processing steps from Level 1.5 to Level 2 of ADaRP in its current form are outlined below:

Read Level 1.5 Product Reconstitute the image/DQ array and metadata from the Level 1.5 Product.

Apply spectroscopic mask Applying an aperture mask limits the number of pixels contributing background and associated noise from dark current as well as telescope and instrument emission and zodiacal foregrounds. A geometric correction is needed if there is a difference in wavelength dispersion with pixel row. The signal in each row can be interpolated with the wavelength map in the metadata to produce a new grid of virtual pixels, to which the aperture mask can be applied. The wavelength map in the metadata is also updated. An aperture mask is then applied over the spectral image in each exposure. The width of the mask may be wavelength-dependent (varying with each x pixel column) to maximise the SNR. Note that alternative methods such as optimal extraction may not require aperture mask placement

Extract 1-D spectrum The 2-D spectral image is collapsed in the spatial direction to produce a 1-D spectrum, i.e. a series of light curves, for each exposure. Simple column count integration can be used, or alternative methods such as optimal extraction [13].

Spectral binning A polynomial approximation of the wavelength map in the metadata is used to find the positions of spectral bin edges such that each bin is sized according to the required resolving power. The 1-D spectra are then subdivided into the bins. The central wavelength of each spectral bin is then calculated from the wavelength map. Note that the binning is performed for each of the different *Ariel* survey tier resolutions described in Section 4.3. Therefore, in practice there are effectively three parallel pathways running for spectroscopic channels, one for each tier.

Apply photometric mask This step acts to decorrelate any jitter in the photometric channels by applying a circular aperture over the maximum of the signal in each image. The size of the aperture will be chosen to maximise the SNR. A 2-D Gaussian model is fitted over each photometric image and a circular aperture is centred at the peak of the Gaussian. Alternatively the FGS pointing timeline and the POINTING calibration product can be used to derive the relative offsets of each image and dejittered in a manner akin to the spectroscopic channel jitter correction described in Section 5.3.2. A circular aperture mask is then fit to the same position in each dejittered image. The result in both cases is a single light curve per photometric channel.

e^-/s to flux conversion Although the nominal Level 2 Product signal will be in units of e^-/s, to give end-users the option of working in astronomical flux (physical) units a conversion factor is applied to the data using the FLUX calibration product. The conversion factor is stored in the metadata and written to the Level 2 Product

Write Level 2 Product This step generates the final Level 2 Product consisting of the image, quality and error arrays, with the wavelength maps and flux conversion factors in the metadata. The format of the Level 2 Product is described in Table 3 and visualised in Fig. 9.

5.3.4 Pipeline processing from Level 2 to Level 3

Level 2 to Level 3 data processing will involve dedicated, sophisticated procedures most likely requiring an interactive pipeline in order to extract the final planet spectrum. Since the processing to Level 3 will includes some decision on the scientific interpretation, it is likely that users may prefer to use their own analysis tools / pipelines. Therefore, the IOSDC does not have responsibility to provide tools / pipelines for this stage of the processing to the community. The Level 3 data products will be produced internally by the IOSDC and subsequently ingested into the *Ariel* science data archive at SOC for dissemination to the community (with the appropriate documentation). The Level 3 Pipeline(s) may include the following (but not exhaustive) steps:

Read Level 2 Product Reconstitute the image array and metadata from the Level 2 Product.

Residual detrending Further detrending of the light curves as a result of instrument systematics that could not be removed by pipeline steps prior to the production of the Level 2 product may be required. Possible blind correction methods include co-trending with another target, use of PCA, Gaussian methods or other advanced detrending algorithms.

Stellar activity correction 1 Star spots and faculae can result in dark and bright regions on the stellar surface respectively. When the planet transits the star, these can result in distortions to the expected light curve [30]. If a spot is crossed, the transit depth is reduced (or increased for faculae) compared to a spot-free star. This can result in an underestimation of the true transit depth at that wavelength (after fitting a model curve). Correction algorithms for spot and faculae are currently under study by the AMC.

Fit model light curves The light curve arrays from the spectroscopic channels (using the wavelength maps from the metadata) and photometric channels (with wavelength information from the housekeeping) are processed to extract the transit depth for each light curve. The output will be an array of fractional transit depth vs wavelength with associated uncertainties by fitting a transit model (e.g. [17]).

Stellar activity correction 2 This step will address any stellar activity effects that may be best removed at the level of the planet spectrum (e.g. a wavelength dependent bias from unocculted spots).

Write Level 3 Product The Level 3 Product is produced with associated metadata. The Level 3 Products are then sent from the IOSDC to SOC to be ingested into the *Ariel* Science Archive. The format of the Level 3 Product is described in Table 3 and visualised in Fig. 10.

6 Summary

Ariel promises to deliver unique science from the observations of a large (1000+), carefully selected, diverse and well characterised sample of transiting exoplanets around bright stars. The survey will reveal the composition of the atmospheres of preferentially warm to hot gas- and ice- giants down to super-Earth-sized planets. The required sensitivity and in particular stability (better than 100 parts-per-million in the signal from the target star) and state of the art procedures for extraction of the final exoplanet spectra, demand sensitive calibration and robust data processing techniques. In order to achieve these requirements, the *Ariel* scientific payload must be calibrated both before launch and in-flight and the data processed with the necessary pipeline and tools. This framework and infrastructure is collectively referred to as the *Ariel* Ground Segment.

In this work, we have provided an overview of the entire ground segment, divided between ESA responsibility and the AMC, primarily concentrating on the consortium contribution through the IOSDC.

We have emphasised the necessity for the *Ariel* ground segment to adhere to the smooth transition philosophy throughout all mission phases. In such a scenario, the initial ground test environment (including EGSE), software tools and IOSDC team structure evolve seamlessly from component level testing to the full end-to-end test of the payload, through to launch and flight operations.

The groundwork for the data pipeline processing software (ADaRP) and tools has already been laid, so as to be employed at the earliest stage in the test campaign. Similarly any QLA system employed in the early mission stages will evolve into an IWS for in-flight performance verification, calibration and operations. The science products for the *Ariel* mission have been clearly defined and the ADaRP processing steps have been tested on simulated data.

In this way, instrumental and computational expertise is captured at an early stage, maintained and projected forwards, ensuring the maximum scientific return for the global astronomy community from the *Ariel* exoplanet mission.

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Compliance with Ethical Standards

Conflict of interests The authors declare that they have no conflict of interest.

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