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An integrated payload design for the Atmospheric Remote-sensing Infrared Exoplanet Large-survey (ARIEL): results from phase A and forward look to phase B1

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ABSTRACT

ARIEL (the Atmospheric Remote-sensing Infrared Exoplanet Large-survey) has been selected by ESA as the next medium-class science mission (M4), expected to be launched in 2028. The mission will be devoted to observing spectroscopically in the infrared a large population of warm and hot transiting exoplanets (temperatures from ~500 K to ~3000 K) in our nearby Galactic neighborhood, opening a new discovery space in the field of extrasolar planets and enabling the understanding of the physics and chemistry of these far away worlds. ARIEL was selected for implementation by ESA in March 2018 from three candidate missions that underwent parallel phase A studies. This paper gives an overview of the design at the end of phase A and discusses plans for its evolution during phase B1, in the run-up to mission adoption.

ARIEL is based on a 1 m class telescope feeding two instruments: a moderate resolution spectrometer covering the wavelengths from 1.95 to 7.8 microns; and a three-channel photometer (which also acts as a fine guidance sensor) with bands between 0.5 and 1.2 microns combined with a low resolution spectrometer covering 1.25 to 1.9 microns. During its 3.5 years of operation from an L2 orbit, ARIEL will continuously observe exoplanets transiting their host star.

This paper presents an overall view of the integrated design of the payload proposed for this mission. The design tightly integrates the various payload elements in order to allow the exacting photometric stability targets to be met, while providing simultaneous spectral and photometric data from the visible to the mid-infrared. We identify and discuss the key requirements and technical challenges for the payload and describe the trade-offs that were assessed during phase A, culminating in the baseline design for phase B1. We show how the design will be taken forward to produce a fully integrated and calibrated payload for ARIEL that can be built within the mission and programmatic constraints and will meet the challenging scientific performance required for transit spectroscopy.

Keywords: Astronomy, Instrumentation, Exoplanets, Spectroscopy, Space, Transit, Telescope, Atmosphere

1. INTRODUCTION

This paper gives an overview of the ARIEL design at the end of phase A and discusses plans for its evolution during phase B1, in the run-up to mission adoption. The design of AIRS (the ARIEL infrared spectrometer) – the spectrometer at the core of the payload is described.

1.1 Payload overview and mission design

The ARIEL payload consists of a Cassigrain telescope with a 0.7 x 1.1 m elliptical primary mirror feeding both a moderate resolution spectrometer covering the wavelengths from 1.95 to 7.8 microns, and a mulit-channel photometer and low resolution spectrometer (which also acts as a Fine Guidance Sensor) with bands between 0.55 and 1.90 microns. The various payload elements are functionally tightly integrated in order to allow the exacting photometric stability requirements of the mission to be met. The key performance improvement that ARIEL will allow over other existing facilities and data-sets is to provide extremely high photometric stability data simultaneously across a very broad wavelength range for a large number of exoplanet targets. For further discussion of the science case for ARIEL see Tinetti et al [1]. The mission is based on a L2 orbit, reached via a dedicated launch which is currently assumed to be on an Ariane 6-2 in 2028. For further details of the mission design and concept see Puig et al, 2016 [2].

1.2 Scientific and technical requirements for the ARIEL payload

The key requirements for the payload for ARIEL are to provide high stability spectroscopy simultaneously in wavelengths from 1.95 to 7.8 micron at a resolving power of $R \geq 100$ at wavelengths below 3.95 microns, and a resolving power of $R \geq 30$ above this. Additionally, three photometric channels at wavelengths between 0.5 and 1.2 microns and a low resolution spectrometer ($R \geq 10$) are also included. Two of the photometer channels also act as fine guidance sensors to provide the necessary pointing stability. The noise requirements are set such that the photometric stability of the data produced by payload must be $<10^{-4}$ for periods of a transit (which range between 5 minutes and 10 hours).

1.3 Payload modularity and responsibilities

Although the functions of the payload are highly integrated, the programmatic necessities of such a large endeavor and the nationally funded nature of ESA science mission payloads lead to a need for some level of modularity in the design. This is done by defining a few major subsystems within the payload for which different nations within the consortium are responsible. The architecture for the payload is shown, along with the national responsibilities as currently defined, in Figure 1 below.

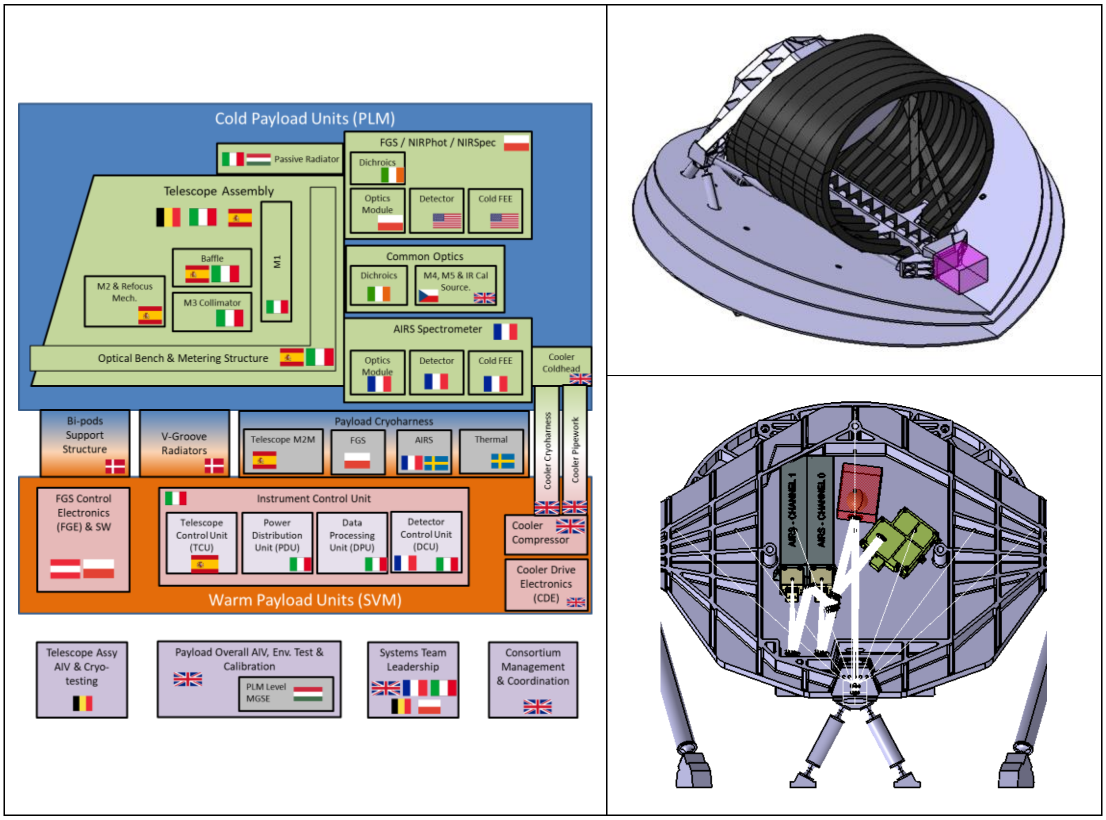

Figure 1: Payload architecture, modularity and responsibilities (left). Mechanical layout (right)

The baseline architecture splits the payload into two major sections, the cold payload module (PLM) and the items of the payload that mount within the spacecraft service module (SVM). The major items are:

- Cold PLM:
    - Telescope system, incorporating M1, M2, M3 and M4 mirrors, a re-focusing mechanism on the M2 mirror, the telescope structure and baffles.
    - An optical bench / metering structure onto which both the telescope items and the other instruments are mounted.
    - A set of common optics including the dichroics to split the fine guidance sensor and spectrometer light, formatting optics to inject the light into the spectrometer correctly, and potentially a common calibration source for the payload.
    - The ARIEL IR Spectrometer (AIRS), including all optics and structure plus detector and cold front end electronics (cFEE).
    - The Fine Guidance Sensor / Near-IR Photometer (FGS/NIR-Phot), including all optics and dichroics to split into 4 separate channels, prime and redundant detectors and cold front end electronics.
    - Thermal hardware: active cooler coldhead for Neon JT cooler, passive radiator for cooling of FGS detectors and all cFEE, V-grooves and support structure to isolate the cold PLM from the warmer SVM and solar thermal loads.
- Warm SVM mounted units:
    - Instrument Control Unit (ICU) incorporating the AIRS warm front end electronics (wFEE), and the telescope control unit for mechanism (M2 refocusing and tip-tilt) control and thermal monitoring and control of the telescope.
    - FGS Electronics incorporating the FGS/NIR-Phot wFEE, the control and processing electronics and software for determining the pointing from the FSG data and transmitting this information to the spacecraft.
    - Active cooler system:
        - Cooler control electronics

- Cooler compressors
- Cooler gas handling panel incorporating fill connections, filtering etc.

2. DETAILED PAYLOAD DESIGN

The telescope is a Cassegrain design (parabolic primary and hyperbolic secondary) with a third mirror used to re-collimate the beam. Further details are in section 3.1 and in Da Deppo et al [3]. The aperture stop, located at the primary mirror, M1, defines the elliptical entrance pupil, of size 1100 mm x 730 mm. The entrance baffle, a cylinder extending the length of the optical bench, limits M1's view of the sky. In combination with placing the stop at the first optical surface (M1), this provides the first line of defence to block out-of-field light.

M2 has a refocus mechanism with three degrees of freedom: focus and tip/tilt. The purpose is to correct for one-off movements due to launch loads and cool-down. The Cassegrain focus after M2 provides the possibility of inserting a field stop to aid stray-light rejection.

After the Cassegrain focus, the beam is recollimated by M3, resulting in a recollimated beam of size 20 mm x 13.3 mm. The first dichroic, D1, is used to split light between the FGS and AIRS, with a transition at about 2 um. The dichroics operate at around 10° to 15° and preliminary designs have been produced by vendors for all of them.

The short wave beam from D1 passes to the FGS, which provides prime and redundant guiding channels along with one photometric band and a low resolution (R=10) spectrometer from 1.25 µm to 1.9 µm.

The long wave beam from D1 is further split by D2 into two wavebands, of one octave each. Each of these two paths is focused onto the spectrometer entrance slit by a set of input optics, the function of which is to deliver the correct input f-numbers. The two spectrometers have independent optical channels. Channel 0 gives R=100 over the shorter waveband (1.95 – 3.9 um) while channel 1 gives R=30 over the longer waveband (3.9 – 7.8 um). The design has evolved considerably since the start of the phase A study with the original grating solution being replaced with a prism. Further details of the AIRS design can be found in section 3.2 and in Beaulieu et al [4].

An additional item being considered in the common optics is the provision of an internal calibration source for the instruments. The calibration light is injected into the optical path through a small (c. 1mm diameter) hole in one of the mirrors on the optical bench (such as M5). Two different type of calibration sources are being considered. One is an integrating sphere (a few cm diameter max) with thermal broadband sources. An alternative solution would be provided by a series of LED feeding the integrating sphere.

2.1 AIRS: The ARIEL infrared spectrometer

AIRS is the ARIEL scientific instrument providing low-resolution spectroscopy in 2-IR channels (called Channel 0 CH0 for the [1.95-3.90] µm band and CH1 for the [3.90-7.80] µm band). It is located at the intermediate focal plane of the telescope and common optical system. The AIRS instrument is composed of three main architectural blocks (Figure 2):

- AIRS Optical Bench (AIRS-OB)
- AIRS Focal Plane Assembly for Channel 0 and 1 (AIRS-FPA-0 and AIRS-FPA-1)
- AIRS Detector Control Unit (AIRS-DCU)

The AIRS-OB and AIRS-FPA 1 & 2 are located on the cold section of the PLM, while the AIRS-DCU is located in the warm part of the SVM.

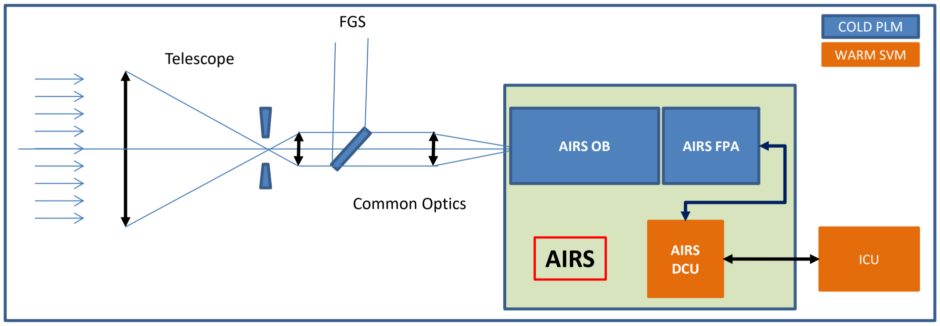

Figure 2: Architectural block diagram of the ARIEL Infra-Red Spectrometer.

After an extensive phase A trade-off, which included consideration of both prism and grating options, the following design solution was settled on:

- A collimator that collimates the incoming f#=18 beam on the prism
- A prism which is the dispersive element
- A camera which function is to re-image the beam on the detector
- A focal plane array detector with reference pixel pitch is 18 µm (sensitivity to pixel size is given section 3.3.1 of AIRS optical design trade-off analysis ARIEL-CEA-INST-DD-001).

The main expected advantage of this baseline is a better SNR because of the capability to circularise the PSF through the prism anamorphism, and to have an enhanced transmission compared to estimated efficiencies of the grating, despite the variable resolution inherent to the prism. The prism design with relatively modest size elements is also lower risk, particularly from the point of view of straylight.

The main drawback associated to the proposed baseline with prism is the larger dynamics of flux because the PSF is circularised at λmin and the throughput is more important compared to the grating. The dynamics of signal goes approximately from 100 to 250 000 e-/s/pixels in the prism design while it covers 100 to 100 000 e-/s/pixels in the grating design.

Following the trade-off analysis and its outcome recommendation for a prism system baseline, a detailed implementation of the design has been performed under Zemax for further analysis. The implementation is made at operational temperature of 55 K and the indexes of refraction are defined at this temperature. The selected material for the prism is CaF2, which has heritage from previous IR space missions.

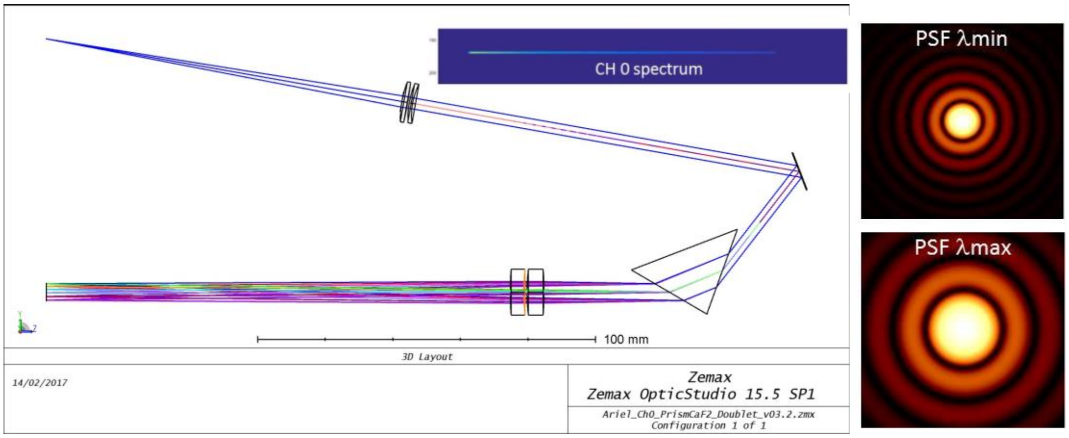

Figure 3: Zemax implementation of Channel 0 spectrometer.

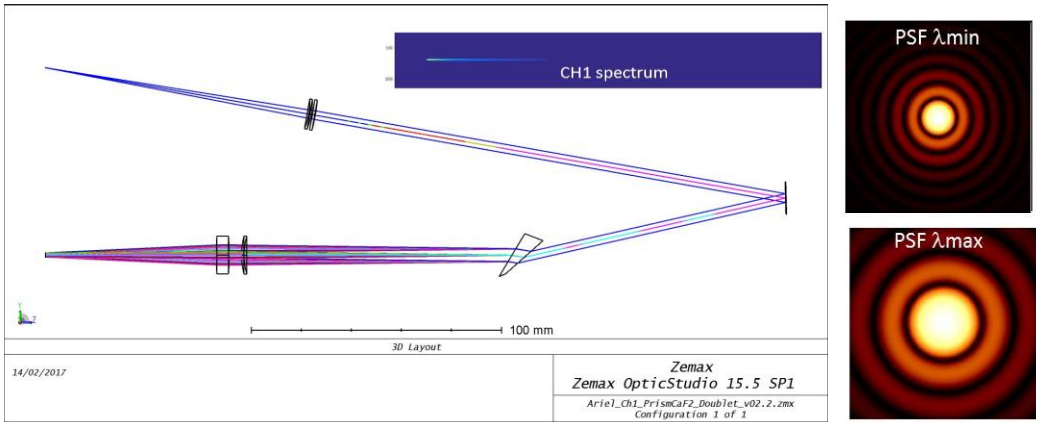

Figure 4: Zemax implementation of Channel 0 and Channel 1 spectrometer.

The detailed Zemax model introduces doublets systems for the Camera (CaF2/Sapphire) and the Collimator (CaF2/ZnSe) in order to control the chromatic aberrations. With this correction the system is diffraction limited over the useful wavelength range.

A fold mirror is inserted in the optical path following between the collimator and the prism in order to allow having both channel entrance planes and exit plane (detector plane) collocated and to optimize the location of the exit focal plane above the entrance slit. This solution improves the volume implementation of the overall instrument on PLM Thermal Optical Bench (TOB) and limit the distance from the AIRS-FPA to the SVM for cryo-cooler harnesses. The approach for the mechanical design at that stage is to have two independent spectrometer half-boxes, each containing one channel, that are ultimately assembled together.

Figure 5 shows the mechanical design of AIRS.

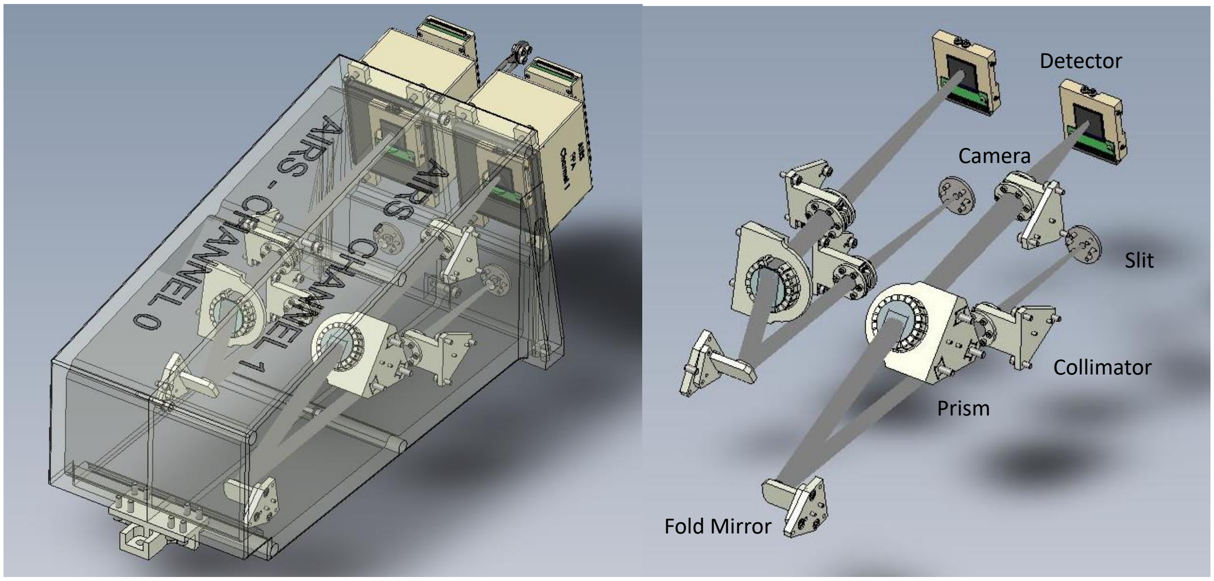

Figure 5: Implementation of optical design into the allocated volume: baseline case with 2 detectors.

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