The Atmospheric Remote-sensing Infrared Exoplanet Large-survey (Ariel) sensitivity and performance

Enzo Pascale[a], Andrea Bocchieri[a], Paul Eccleston[b], Lorenzo V. Mugnai[c], Giorgio Savini[d], Angèle Syty[e], Vinooja Thurairethinam[d], and Giovanna Tinetti[d]

[a]Dipartimento di Fisica, La Sapienza Università di Roma, Piazzale Aldo Moro 5, Roma 00185, Italy
[b]RAL Space, STFC Rutherford Appleton Laboratory, Didcot, Oxon, OX11 0QX, UK
[c]School of Physics and Astronomy, Cardiff University, The Parade, Cardiff, CF24 3AA, UK
[d]Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, UK
[e]Université Paris-Saclay, Chemin du Couvent 44, Gif-sur-Yvette, 91190, France

ABSTRACT

The Ariel space mission will characterize spectroscopically the atmospheres of a large and diverse sample of hundreds of exoplanets. Targets will be chosen to cover a wide range of masses, densities, equilibrium temperatures, and host stellar types to study the physical mechanisms behind the observed diversity in the population of known exoplanets. With a 1-m class telescope, Ariel will detect the atmospheric signatures from the small, $< 100\,\mathrm{ppm}$, modulation induced by exoplanets on the bright host-star signals, using transit, eclipse, and phase curve spectroscopy. Three photometric and three spectroscopic channels, with Nyquist sampled focal planes, simultaneously cover the 0.5-7.8 micron region of the electromagnetic spectrum, to maximize observing efficiency and to reduce systematics of astrophysical and instrumental origin. This contribution reviews the predicted Ariel performance as well as the design solutions implemented that will allow Ariel to reach the required sensitivity and control of systematics.

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

1. INTRODUCTION

Planets are ubiquitous in our Galaxy, with more than 5,000 exoplanets detected over the past two decades from space- and ground-based observations. Discoveries with *TESS*, *Cheops*, and soon with *Plato* are increasing the sample size, allowing robust exploration into the mechanisms of formation and evolution likely driving the observed diversity in terms of size, mass, composition, and orbital parameters. From rocky Earth-like planets to large gas giants, many of these celestial bodies are found in close proximity to their host stars. This diversity, unseen in our Solar System, highlights the need for a comprehensive understanding of the underlying physical and chemical processes. This requires a detailed and statistically significant spectroscopic survey of exoplanetary atmospheres to reveal the chemical composition and the thermodynamic properties of their atmospheres.

Ariel (Atmospheric Remote-sensing Infrared Exoplanet Large-survey)[1] aims to spectroscopically characterize the atmospheres of a large and diverse sample of exoplanets, enabling comparative studies of their physics and chemistry. By observing transits, eclipses, and phase curves, this ESA-led space mission will detect atmospheric signatures from the small ($< 100\,\mathrm{ppm}$) spectral modulations induced by exoplanets on the bright host-star signals.

The mission utilizes a 1-meter class Cassegrain telescope to cover the visible to infrared spectral range (0.5-7.8 µm) with high sensitivity. The payload comprises two instruments: the Fine Guidance System (FGS) and the *Ariel* Infra-Red Spectrometer (AIRS). FGS includes three photometers (VISPhot, 0.50-0.60 µm; FGS-1, 0.60-0.80

Further author information:
E.P.: E-mail: enzo.pascale@uniroma1.it

Space Telescopes and Instrumentation 2024: Optical, Infrared, and Millimeter Wave,
edited by Laura E. Coyle, Shuji Matsuura, Marshall D. Perrin, Proc. of SPIE Vol.
13092, 130921F · © 2024 SPIE · 0277-786X · doi: 10.1117/12.3017657

µm; FGS-2, 0.80-1.10 µm) and one spectrometer (NIRSpec, 1.10-1.95 µm, R≥ 15). AIRS has two spectrometers (AIRS-Ch0, 1.95-3.90 µm, R≥ 100; AIRS-Ch1, 3.90-7.80 µm, R≥ 30). These instruments simultaneously observe the same transit event across all channels, ensuring high observational efficiency and reducing systematics.

Ariel's orbit around the Sun-Earth Lagrange point L2 provides a photometrically and thermally stable environment for the telescope and instruments. The mission's primary requirement is to achieve sufficient photometric stability to measure atmospheric signals with a precision of 10-100 ppm relative to the stellar flux over timescales relevant to transit and eclipse observations.

The design of the *Ariel* payload incorporates lessons learned from previous exoplanetary atmosphere measurements conducted by missions such as *Spitzer* and HST, as well as from ground-based instruments. Key features enabling *Ariel*'s stable performance include simultaneous multi-wavelength observations, continuous monitoring of transit events, and a payload design that mitigates or allows for the removal of systematics in data analysis.

The most significant disturbances of astrophysical and instrumental origin are listed in Table 1, along with the strategies employed to mitigate their impact on detection and photometric stability.

Table 1. Summary of noise sources and systematic errors (from 2).

Uncertainty type	**Source**	**Mitigation strategy**
Detector noise	Dark current Readout noise	Choice of low-noise, cryogenic detectors
	Gain instability	Temperature controlled focal planes, calibration, data-analysis.
Thermal noise	Emission from telescope, all optical elements and enclosures	Negligible due to cryogenic temperatures.
	Temperature fluctuations	Negligible by design.
Astrophysical noise	Target photon noise	Fundamental noise limit, choice of telescope aperture size.
	Photon noise from Zodiacal light	Negligible over *Ariel* bands
	Target star activity	Multi-wavelength stellar monitoring, post-processing detrending
Pointing jitter	AOCS stability, detector intra/inter pixel response	High AOCS stability and post-processing detrending
	Slit losses	Choice of slit-less prism spectrometers

2. PERFORMANCE MODELLING

The *Ariel* performance is estimated using a family of radiometric and time-domain software simulators developed by the Ariel Mission Consortium (AMC).

ArielRad,[3] a radiometric simulator, addresses the challenges in optimizing the *Ariel* payload design and ensures compliance with the science requirements. Based on ExoRad2.0,[4] a generic radiometric simulator for point source photometry and spectroscopy, ArielRad uses a parametric description of the instrument design, the target, and the observing parameters to estimate optical efficiency and the magnitude of the signal at the focal planes. It further estimates noise, breaking it down into its components (photon noise, detector noise, etc.) based on a noise model described in the next section.

ExoSim2[5*], a generic time-domain simulator of spectro-photometric observations of transiting exoplanets developed by the AMC, can simulate an entire *Ariel* observation as a function of time using a parametric description of the payload. This enables detailed performance studies during all mission phases. The simulated observations consist of photometric and spectral images vs. time, sampled in NDR up-the-ramp. It is a particularly powerful tool to study the details of systematics that can introduce time-correlated nuisances. ExoSim2 expands upon the capabilities of ExoSim[6] and EchoSim.[7]

Ariel is diffraction-limited at wavelengths above 3 µm and operates as a light-bucket at shorter wavelengths. It relies on geometric aberrations to ensure that shorter wavelength focal planes are critically sampled, including the three photometers and NIRSpec. A common input of both the radiometric and time-domain simulators is a detailed description of the optical wavefront that propagates from the payload input pupil to the six focal planes. The point spread functions are estimated using PAOS, a generic Physical Optics Propagation tool purpose-developed by the AMC for *Ariel* and publicly available[†].

All input parameters characterizing the subsystems needed by the simulators to define the instrument properties are maintained in a version-controlled database. The database collects requirements, design current best estimates, and measurements as they become available. This allows tracing the performance estimates as the mission design and construction proceeds in its expected development.

3. RADIOMETRIC NOISE MODEL

The radiometric modeling of expected uncertainties is described in the equation below, which also accounts for the disturbances listed in Table 1. It allows estimating the relative noise on the signal average S at the time scale T.

$$\frac{\mathrm{Var(S)}}{S^2} = \begin{cases} & \sigma_G^2 \times \frac{1}{T} & + & \text{(gain)} \\ + & g_\gamma (1+X) \frac{1 + k\eta_{opt}\eta_{qe} f A_{tel} \Omega_* / \lambda^2}{k \eta_{qe} N_0} \times \frac{1}{T} & + & \text{(photon noise)} \\ + & \frac{N_{pix} I_D + N_{pix} \sigma_{rd}^2 / \Delta t}{(k\eta_{qe} N_0)^2} \frac{1}{T} & + & \text{(dark current and readout noise)} \\ + & p_0 & + & \text{(stability term)} \end{cases} \tag{1}$$

Here, the number of incoming photons per unit time at the focal planes in the photometric or spectral bin with spectral width $\Delta\lambda$ is $N_0 = A_{tel}\eta_{opt}\frac{\lambda}{hc}F(\lambda)\Delta\lambda$, where A_{tel} is the telescope collecting area, η_{opt} is the optical efficiency, $F(\lambda)$ is the target spectral irradiance, and h and c are the Planck constant and the speed of light in a vacuum, respectively.

Other terms in the noise equation: g_γ is a photon noise boost that is equal to 1 when detectors are processed using correlated double sampling;[8] k is the aperture correction; η_{qe} is the detector pixel quantum efficiency; $f = 1/[\exp(hc/kT_*\lambda) - 1]$ is the Bose-Einstein distribution for thermal radiation at the target star temperature T_*; Ω_* is the solid angle subtended by the target star; N_{pix} is the number of pixels in the aperture used for signal extraction; I_D is the detector dark current; σ_{rd} is the detector readout noise on each non-destructive read (NDR); Δt is the detector exposure; p_0 is a stability term modeling long time scale Brownian processes.

The first term models disturbances that have a multiplicative effect on signal detection. The gain variance σ_G^2 has units of time and models effects such as electronic gain variations and stellar activity. The photon noise term has two components: the first is the photon shot noise term, and the second is the wave noise term accounting for photon correlations.[9] The latter is negligible as the star solid angle Ω_* is small.

The most important parameters are the gain stability term allocated to be $\sigma_G \simeq 40\,\mathrm{ppm}\sqrt{\mathrm{hour}}$, and a required $1/f$ noise knee at a timescale longer than 10 hours. These two parameters translate into a stability term $p_0 = 20\,\mathrm{ppm}$. This term is conservative, as Ariel is expected to perform better: there is currently no known source of instability at the $\sigma_G \simeq 40\,\mathrm{ppm}\sqrt{\mathrm{hour}}$ level, nor at timescales longer than 10 hours. The payload is designed so that all noise components are small or negligible relative to the photon noise of the target. Therefore, the term $X = 40\%$ is used as an overall margin to account for unexpected measurement or data analysis instabilities.

---

[*] https://exosim2-public.readthedocs.io/

[†] https://paos.readthedocs.io/

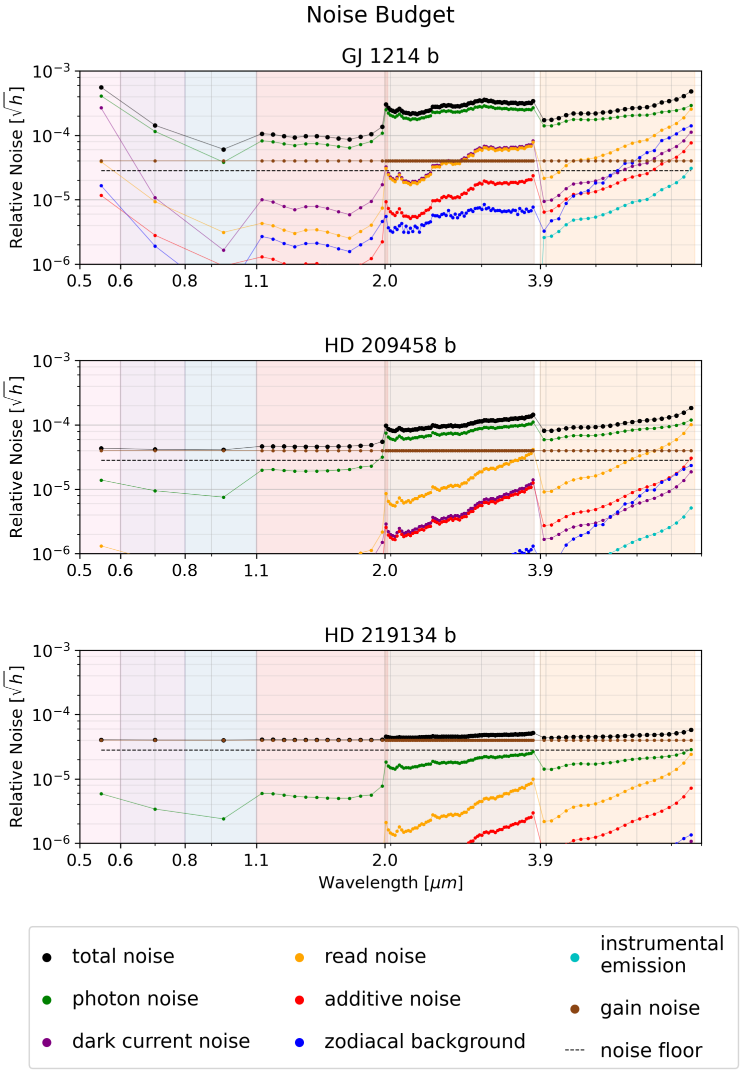

Figure 1. Noise budget for the three sizing planets with channel bands highlighted. The total noise is the sum in quadrature of all noise sources, where the target photon noise has been scaled up by a factor of $1 + X$. The noise floor is the sum in quadrature of the true noise floor and jitter noise; it has no units as it does not integrate down with time. The Noise floor is not included in the total noise.

3.1 Mission performance

The top-level science requirement is a mission design capable of observing a large and diverse sample of about 1,000 exoplanet atmospheres within the allocated mission lifetime. This includes observing exoplanets with different spectral resolving power and signal-to-noise ratios. The mission follows a multi-tier observing approach as described in [**?**,1] and is captured in possible observing programs as detailed in [10,11].

The noise budgets for three sizing stellar targets estimated from ArielRad simulations are presented in Figure 1. GJ 1214 is a faint target star of spectral type M5V with a k-band magnitude of $m_k = 8.8$. HD 219134, a spectral type K3V star with $m_k = 3.25$, represents the brightest target observable by *Ariel*. HD 209458, a G0V star with $m_k = 6.3$, is about ten times fainter than HD 219134 and represents the average bright target *Ariel* will observe.

The *Ariel* mission is compliant with the top-level science requirements provided that observations of targets similar to GJ 1214 are limited only by the target photon noise. As shown in the figure, radiative backgrounds are negligible compared to the signal of the targets, and detection is always target photon noise limited. The gain noise of $\sigma_G \simeq 40\,\mathrm{ppm}\sqrt{\mathrm{hour}}$, which dominates the noise budgets for targets as bright as or brighter than HD 209458, has been allocated to be the largest compatible with science requirements.

Photometric uncertainties arising from the jitter of the telescope line-of-sight are evaluated with ExoSim2 and included in the noise floor term p_0, as stated in the caption.

4. CONCLUSIONS

The *Ariel* mission is designed to meet its top-level science requirements by utilizing advanced radiometric and time-domain simulators to optimize payload design and performance. Through meticulous modeling of various noise components and leveraging a stable orbit around the Sun-Earth Lagrange point L2, *Ariel* ensures that the observations are predominantly limited by target photon noise, even for faint targets like GJ 1214. The mission's approach of multi-tier observations and stringent noise control allows it to achieve the necessary photometric precision, paving the way for groundbreaking studies of exoplanetary atmospheres.

REFERENCES

[1] Tinetti, G., Drossart, P., Eccleston, P., and et al., "A chemical survey of exoplanets with ARIEL," *Experimental Astronomy* **46**, 135–209 (Nov. 2018).

[2] Tinetti, G., Eccleston, P., Haswell, C., and et al., "Ariel: Enabling planetary science across light-years," *arXiv e-prints* , arXiv:2104.04824 (Apr. 2021).

[3] Mugnai, L. V., Pascale, E., Edwards, B., Papageorgiou, A., and Sarkar, S., "ArielRad: the Ariel radiometric model," *Experimental Astronomy* **50**, 303–328 (Oct. 2020).

[4] Mugnai, L. V., Bocchieri, A., and Pascale, E., "ExoRad 2.0: The generic point source radiometric model," *The Journal of Open Source Software* **8**, 5348 (Sept. 2023).

[5] Mugnai, L. V., Pascale, E., Al-Refaie, A. F., Bocchieri, A., Papageorgiou, A., and Sarkar, S., "ExoSim 2. The new time-domain simulator applied to the Ariel space mission," in [*European Planetary Science Congress*], EPSC2022–370 (Sept. 2022).

[6] Sarkar, S., Pascale, E., Papageorgiou, A., and et al., "ExoSim: the Exoplanet Observation Simulator," *Experimental Astronomy* **51**, 287–317 (Apr. 2021).

[7] Pascale, E., Waldmann, I. P., MacTavish, C. J., Papageorgiou, A., Amaral-Rogers, A., Varley, R., Coudé du Foresto, V., Griffin, M. J., Ollivier, M., Sarkar, S., Spencer, L., Swinyard, B. M., Tessenyi, M., and Tinetti, G., "EChOSim: The Exoplanet Characterisation Observatory software simulator," *Experimental Astronomy* **40**, 601–619 (Dec. 2015).

[8] Rauscher, B. J., Fox, O., Ferruit, P., and et al., "Detectors for the James Webb Space Telescope Near-Infrared Spectrograph. I. Readout Mode, Noise Model, and Calibration Considerations," *Publ. Astron. Soc. Pac.* **119**, 768–786 (July 2007).

[9] Lamarre, J. M., "Photon noise in photometric instruments at far-infrared and submillimeter wavelengths," *Appl. Opt.* **25**, 870–876 (Mar. 1986).

[10] Edwards, B., Mugnai, L., Tinetti, G., Pascale, E., and Sarkar, S., "An Updated Study of Potential Targets for Ariel," *Astron. J.* **157**, 242 (June 2019).

[11] Edwards, B. and Tinetti, G., "The Ariel Target List: The Impact of TESS and the Potential for Characterizing Multiple Planets within a System," *Astron. J.* **164**, 15 (July 2022).