Ariel - AOCS overview, Safe Mode and Normal Mode design

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ABSTRACT

Ariel (Atmospheric Remote-sensing Infrared Exoplanet Large-survey) is an ESA scientific mission whose mission is to measure the atmospheric spectrum of a large population of known transiting planets in our galaxy. To achieve this, it has a large telescope and an infra-red spectrometer payload.

The main driving requirements for AOCS are sun angle exclusion zone requirements, which apply from launcher separation, and the fine pointing mode requirements for the observation phase at the sun-earth Lagrange L2 orbit. Fine pointing requires reaction wheels with built-in speed controllers, and using payload Fine Guidance Sensors in the AOCS loop.

This paper presents an overview of the Ariel mission and the AOCS design, particularly the safe mode and fine pointing mode.

1 INTRODUCTION

Ariel, the atmospheric remote-sensing infrared exoplanet large-survey, is the fourth medium class mission within ESA's Cosmic Vision science programme. Ariel is the first mission dedicated to studying the atmospheres of a statistically large and diverse sample of transiting exoplanets (≥ 500) through a combination of transit photometry and spectroscopy. Ariel aims to measure the chemical composition and thermal structures of exoplanets extending from gas giants (Jupiter or Neptune like) to super-Earths, that (currently) orbit in the very hot to warm zones of their F to M-type host stars, opening up the way to large-scale, comparative planetology [1].

Ariel is due for launch in 2029 on board an Ariane 6.2 in a dual launch configuration with the Comet Interceptor mission. Ariel will be injected into a direct transfer to L2. It will operate from an orbit around the second Lagrange point of the Sun-Earth system (L2), which offers the benefit of a stable thermal environment thanks to the constrained relative orientation of the Sun and Earth to the spacecraft. The injection will be biased low so that correction delta-v for launcher dispersion will be required only in the direction outwards from the sun.

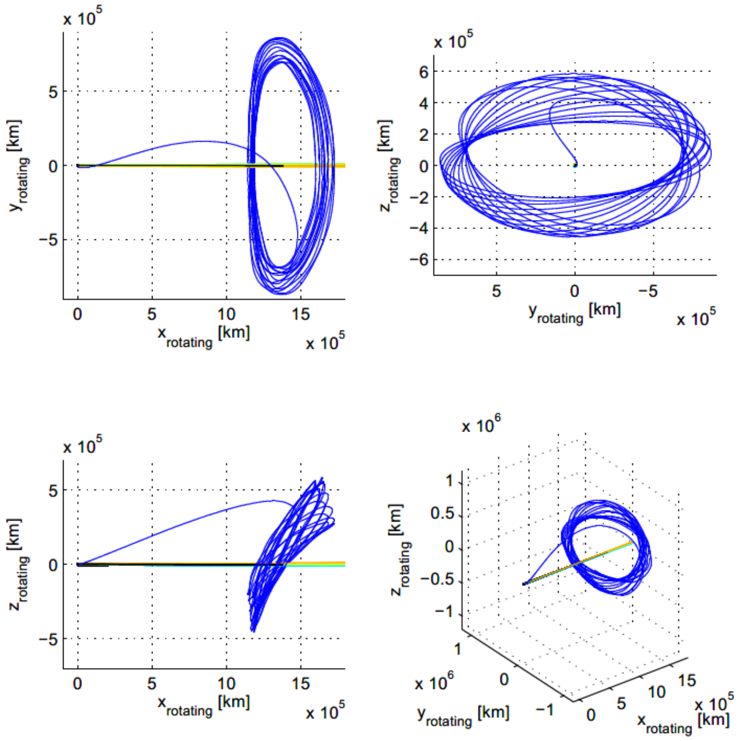

Figure 1 Example of transfer to L2 and halo orbit around sun-earth-L2 in rotating frame, origin at earth

Ariel will operate within a narrow range of sun-referenced attitudes, keeping the payload module within the shadow of its solar array, enabling suitably cold conditions for the infra-red optics and detectors.

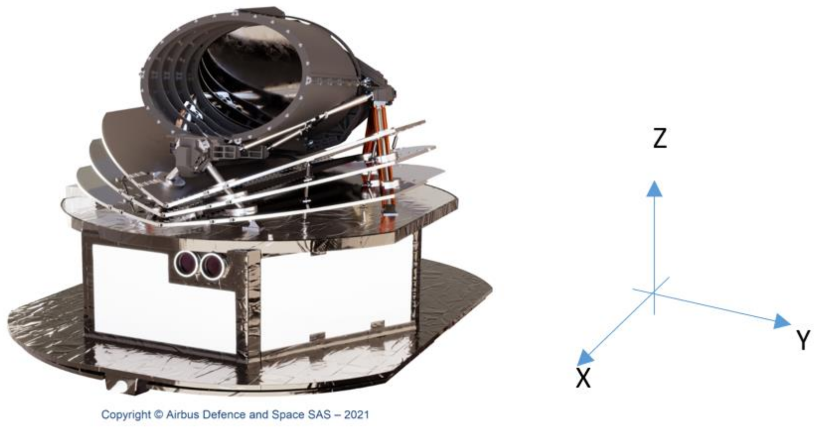

Figure 2 Ariel co-ordinate frame

At the time of writing the project is in phase B2, working towards PDR in late 2023.

2 REQUIREMENTS

The AOCS performs the following main functions:

- Rate reduction and sun acquisition after separation from launcher, or for safe mode
- Slews to science targets and to delta-v attitudes
- Momentum off-loading and delta-v
- Fine pointing for science observations

Sun acquisition from separation has some unusual features. The sun is required to stay within a narrow region centred on the sun, with only temporary excursions into a larger region permitted for a max of 5 minutes, in order that the telescope LOS is kept away from sun-pointing, and the V-groove sides of the payload module do not experience prolonged sun exposure.

The spacecraft geometry is such that the telescope LOS is approximately 90 deg to the launcher vertical axis. The nominal separation attitude has therefore been chosen to be with the vertical axis close to the anti-sun direction, which means that the solar array side of the spacecraft, which hosts the sun sensors, is initially in the shadow of the upper stage at separation time.

Sun acquisition and safe mode must meet time and angle limits on sun exposure shown in Figure 3. The permitted range of +/-Y rotations is asymmetric to favour keeping the telescope LOS far from the sun, which leads to the choice of nominal separation attitude described later.

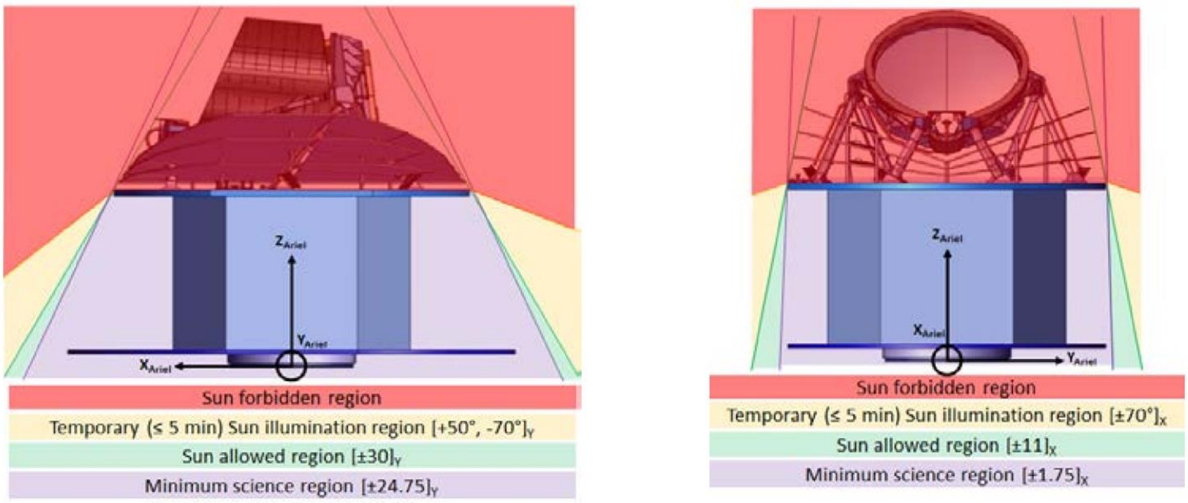

Figure 3 Sun allowed region (green), Temporary Sun Illumination region (yellow) [2] and Science Region (magenta), in XZ plane (left, showing associated rotations around Y) and YZ plane (right, showing associated rotations around X).
The sun is not allowed within the forbidden region (red), even after a failure, or even within the temporary region (yellow) after the first sun acquisition.

Ariel has fine pointing requirements for the across LOS axes perpendicular to the telescope LOS, shown in the tables below for bright and faint target stars (the requirements for the relatively coarse around LOS axis are not shown). Ariel RPE, RPE_MPE and PDE are typically expressed in milli-arcsec, mas.

Table 1 : Pointing and stability requirements in fine mode, bright targets

Fine mode, bright targets			
APE	RPE$_{0.1s}$	RPE_MPE (90s,0.1s)	PDE$_{\infty}$
1000 mas	180 mas	130 mas	70 mas

Table 2 : Pointing and stability requirements in fine mode, faint targets

Fine mode, faint targets			
APE	RPE$_{0.1s}$	RPE_MPE (300s,0.1s)	PDE$_{\infty}$
1000 mas	280 mas	280 mas	300 mas

RPE_MPE is the Relative Pointing Error of the Mean Pointing Error

The PDE has windows of duration 90s or 300s, respectively for bright and faint targets, which can be as far as 10 hours apart.

3 AOCS Architecture

Ariel AOCS is organised around five AOCS modes:

- L-SAM and SAM (Sun Acquisition Modes) for initial acquisition and subsequent safe-hold modes. L-SAM (L for launch) is dedicated to the launcher separation sequence
- NOM-O (Offloading/Orbit) for thruster-based nominal operations: trajectory corrections in LEOP, station keeping, offloading of angular momentum, end-of-life disposal.
- NOM-C (Coarse), for wheel-based nominal operations outside of science observations and especially slew manoeuvres
- NOM-F (Fine), for fine pointing with payload in the loop (using Fine Guidance Sensor (FGS) and Reaction Wheels) during science operations

The NOM-O, NOM-C and NOM-F are seen as separate AOCS normal modes (used for normal operations) but share most of their functions and algorithms, thanks to the modular architecture retained.

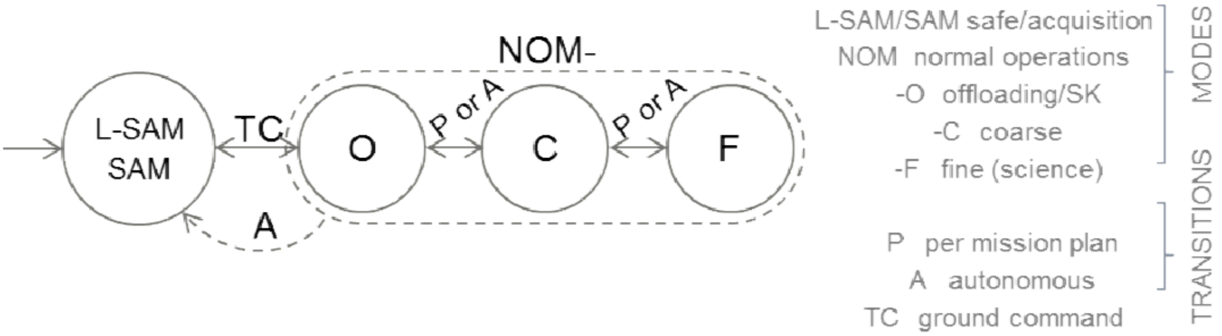

Figure 4 Ariel AOCS modes and mode transitions

The AOCS equipment is tabulated below.

Table 3 Ariel AOCS sensors and actuators

Unit	Number of units	Redundancy
Sun sensor CSS	2	Internally redundant
Gyro RMU	2	Hot redundant
Star tracker STR	2	Hot redundant
Wheels RW	4	3 from 4 hot redundancy
Fine guidance FGS	2	Cold redundant
Accelerometer AMU	2	Hot redundant
4N thruster	5 x 2 branches	Cold redundant

The FGS and its simulation model are provided by the Ariel payload consortium. The FGS measurements are used within the AOCS fine pointing mode.

4 SUN ACQUISITION

After extensive analysis in previous phases, a 3-axis separation has been selected. The inertia matrix is not suitable for spin stabilisation. The spacecraft separates from the launcher in a 3-axes stabilised mode, with a nominal attitude with the Sun near -Zsc, and with azimuth about the sun that maximises separation of the payload LOS from the earth direction. The target state for the first SAM is –Zsc to the sun with nominally zero rates about all 3-axes (in particular zero mean rate about Zsc, so that the payload does not scan over the earth).

After the separation there is a minimum time before the AOCS can perform attitude control on the spacecraft, due to safety distance constraints from the launcher. At the expiry of the wait time (20s imposed by launcher), the AOCS in Launch Sun Acquisition Mode / Safe Mode (L-SAM) starts damping the tip-off rates imparted by the separation mechanism to the spacecraft. Both thruster branches are pre-heated in the launcher, such that the FDIR could command a direct switchover between the prime and redundant branches in case of failure.

At separation time the CSS will be in the shadow of the upper stage. For this unique phase of the mission, L-SAM is used. Sensing during the shadow phase is purely from the gyros, until the CSS is available. Attitude monitoring in L-SAM is provided as a delta-SAA computed by integration of the gyro measurements.

Once the rates are damped and the Sun is acquired by the CSS, the solar arrays can generate enough power to support all operations and it is then up to ground to decide when to command transition to higher AOCS modes.

Overall, this initial acquisition is the most critical part of the mission from the point of view of ensuring that the Sun exclusion zone requirement is fulfilled, due to the potentially high tip-off rates imparted by the separation system to the spacecraft (leading to a time criticality of all operations performed in this phase).

Note that the Sun is expected to always lie within the field of view of the CSS (except during a possible short shadowing from the launcher), even in case of failure. Nonetheless, if a non-Sun pointing attitude occurred due to multiple failures in the system, there is a scanning strategy to recover Sun pointing whilst minimising the chance of pointing the telescope to the sun.

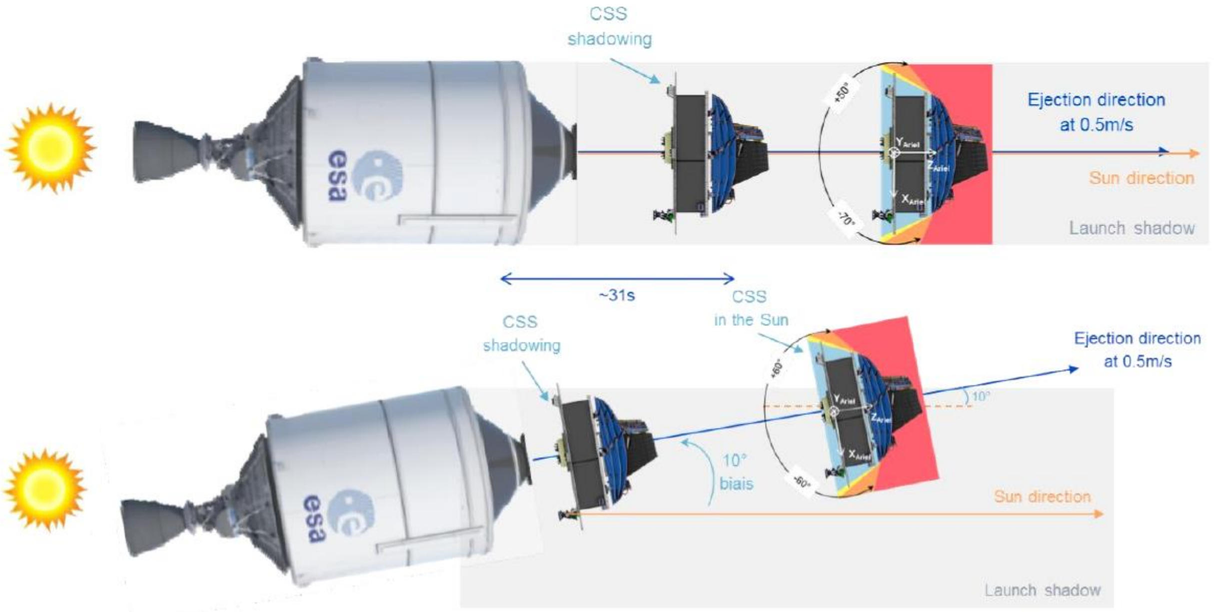

Figure 5 Two different separation attitude options, no bias (top), and biased (bottom)
The chosen upper stage separation attitude biases the telescope LOS away from the sun to provide equal margins for +Y or –Y rotations with respect to their asymmetric constraints for the sun forbidden zone, and to provide a quick exit from the shadow of the upper stage

Study of separation conditions showed that in order to have an acceptable time within the temporary illumination zone, larger thrusters than European 1N are required. IHI Aerospace (Japan) 4N thrusters have been selected.

The robustness of the system to protect the payload from direct illumination after any single failure (e.g. sensor or thruster) requires special attention for the FDIR design. This is currently an active area of study.

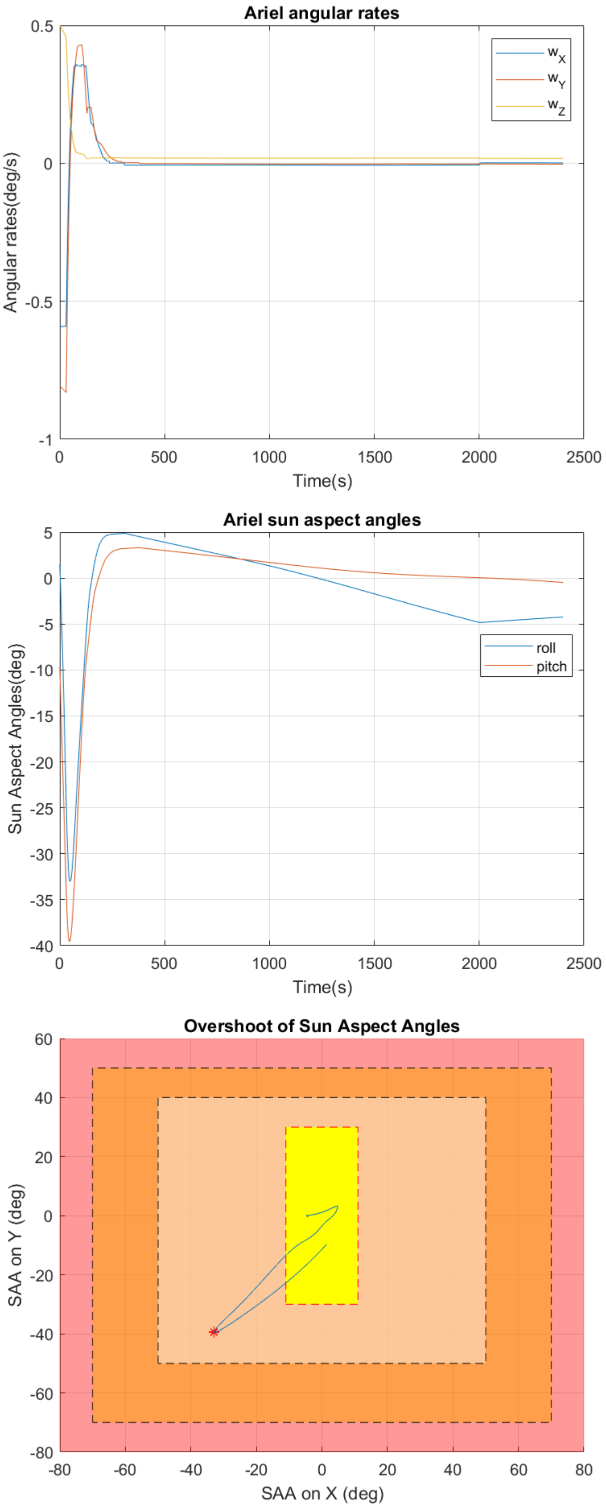

Figure 6 Simulation of SAM, example case with max tip-off rates from launcher plus anomalous OBC reboot delaying the start time of control.
The sun briefly goes into the temporary illumination zone (peach), for an acceptably short time, before settling in the sun allowed region (yellow)

5 FINE POINTING

NOM-F is the central AOCS mode for science operations, where the FGS is used in tracking mode to provide 2-axes attitude measurements, and the STR along LoS is used for the third axis measurement (roll attitude).

The FGS uses a beam splitter to project a part of the telescope light onto prime and redundant detectors, optimised for adjacent wavebands. The FGS has a FOV of a few arcsec, and consequently tracks only the target star, providing 2D measurements in a local sensor frame. The same small FOV size means that during commissioning, a raster scan sequence (using STR and NOM-C) is required to locate the first target star and calibrate the relative STR-FGS alignment.

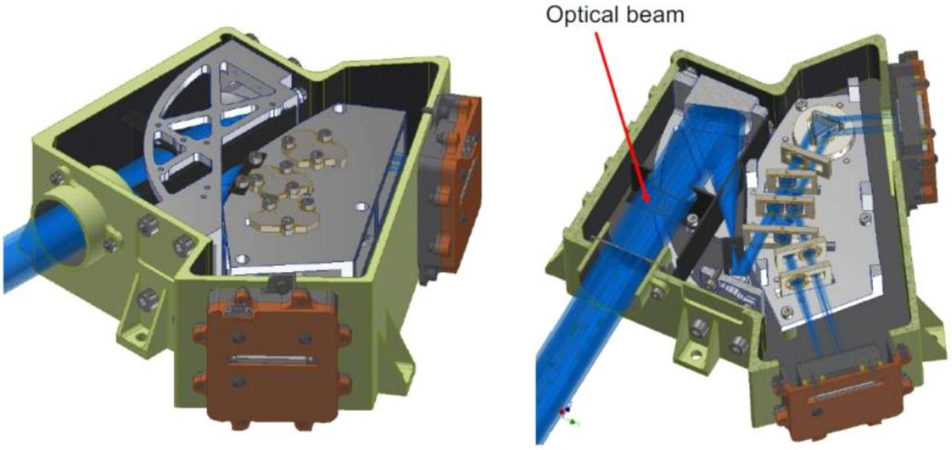

Figure 7 Two views of the FGS, showing light path to the detectors (images by AMC)

The FGS performances are shown below. The FGS tracking mode outputs measurements at 10 Hz, whilst AOCS runs at 8 Hz, causing a variable measurement delay at AOCS.

Table 4 FGS 1 and 2 predicted noise performance for tracking mode (derived from [3])

FGS #	Target	Mode	Sigma X, mas	Sigma Y, mas
FGS1	faint	tracking	54.95	64.58
	bright	tracking	1.75	2.80
FGS2	faint	tracking	4.52	2.21
	bright	tracking	1.51	0.85

The RW have internal wheel speed control loops. The speed loops provide low torque noise, enabling the NOM-F loop to be tuned to a low bandwidth with acceptably small sensor noise transmission.

The FGS has two operating modes, acquisition and tracking, with different effective FOV size, sampling time and performance. Each slew to a new target star uses the STR, and the new inertial attitude will sample a different spatial bias of the STR. As this bias is large relative to fine pointing requirements, a sequence is used to calibrate and then correct for the local STR bias, using FGS acquisition mode, whilst controlling the attitude using STR, before commanding FGS into its tracking mode (with narrower FOV) and AOCS mode to NOM-F, which uses FGS / tracking mode in the loop. Figure 8 below depicts this sequence.

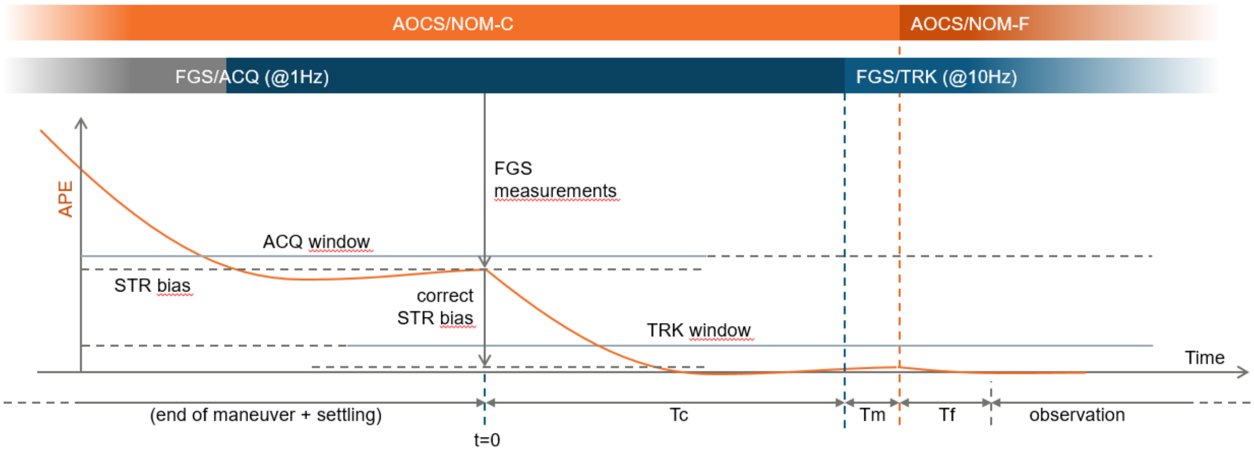

Figure 8 FGS acquisition sequence and NOM-C to NOM-F transition

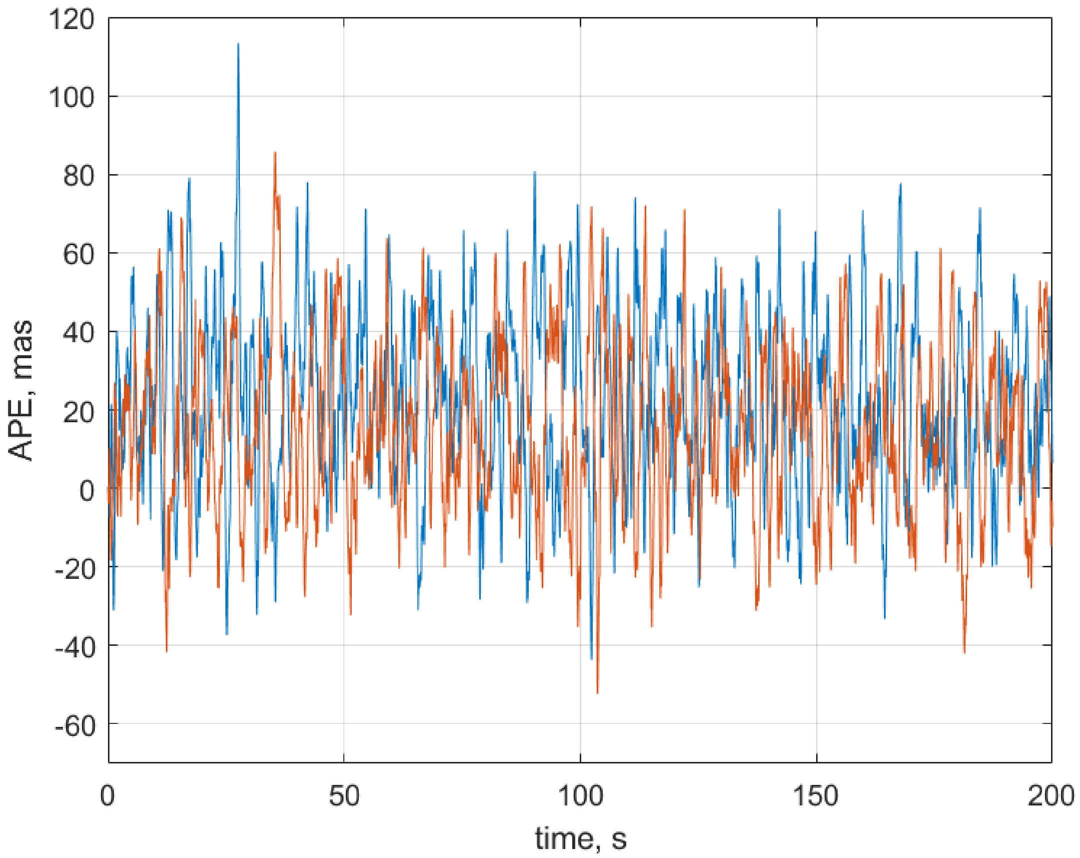

Figure 9 NOM-F fine pointing simulation of steady state, Across LOS 2d APE (AOCS simulation without micro-vibs)

Airbus has generated high time-resolution (kHz) time series of pointing (AOCS and micro vibrations) to the payload consortium to allow the science community to assess expected pointing performance.

An example fine pointing budget is shown below, with AOCS (LF) and micro-vibrations (HF) (from the Phase A).

Table 5 Pointing and stability performance in fine pointing mode – bright stars

Frequency Range	half-cone, 99.7%, temporal	APE$_{yz}$ (mas)	RPE$_{yz\,0.1s}$ (mas)	PDE$_{yz}$ 90s to 10h (mas)
LF	GLOBAL AOCS	77	11	45
LF	GLOBAL AOCS (incl. RW spike alloc.)	237	91	45
LF + HF	GLOBAL (inc. RW spike alloc, µvib, cryo µvib)	295	197	45
LF	REQUIREMENT	1000 mas	180 mas	70 mas
LF + HF			230 mas	

The pointing performance is predicted to comply to the requirements.

6 CONCLUSION

The Ariel AOCS design answers unusual challenges with customised solutions.

The sun exclusion zone requirements for Ariel require some special features for the sun acquisition mode, namely separation in the shadow of the upper stage with initial control using gyros. The FDIR is designed to detect failures early enough that the SAM recovery path stays within the attitude range which is safe for the payload.

Ariel’s observing performance requires a fine guidance sensor in the AOCS loop and actuators with low torque noise. The selected reaction wheel contains a built-in speed control loop that provides fast local compensation for any friction torque variation.

Ariel is on track to pioneer a survey of a large population of exoplanets, taking detailed spectroscopic measurements of planetary transits to investigate alien worlds.

7 REFERENCES

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[2] ESA-ARIEL-SC-RS-001 v3.0 Ariel Spacecraft Systems Requirements Document

[3] ARIEL-UVIE-PL-TN-002, Mathematical Model for ARIEL FGS