ALTIUS ATTITUDE AND ORBIT CONTROL SYSTEM SOFTWARE AND SYSTEM-LEVEL TEST RESULTS

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ABSTRACT

The Atmospheric Limb Tracker for Investigation of the Upcoming Stratosphere (ALTIUS) project is ESA's ozone-monitoring mission developed as part of ESA's Earth Watch programme and is planned for launch in 2025. The small satellite will use a high-resolution spectral imager and limb-sounding techniques to profile the ozone and other trace gases within the upper atmosphere, while supporting weather forecasting and monitoring long-term ozone trends. The ALTIUS satellite platform and its Attitude and Orbit Control System (AOCS) software are an evolution of the ESA Project for On-Board Autonomy (PROBA) series of satellites, which have over 45 combined years of successful in-orbit experience. To complete the mission objectives, the ALTIUS AOCS software must provide the spacecraft with high agility, high autonomy, and fine pointing accuracy, requiring several AOCS software innovations compared to the previous PROBA missions. This paper focuses primarily on the following three autonomous novelties implemented for ALTIUS: Limb Looking mode, Augmented B-dot Safe mode, and thruster management with off-modulation. This paper discusses the challenges associated with their design and presents their performance based on the AOCS Software System-Level Tests (SST) results. The SST campaign was performed on a closed-loop MATLAB/Simulink simulator and was completed in January 2023.

1 INTRODUCTION

The Atmospheric Limb Tracker for Investigation of the Upcoming Stratosphere (ALTIUS) project is the European Space Agency's (ESA) ozone-monitoring mission developed as part of their Earth Watch programme and is planned for launch in 2025. The small satellite will use a high-resolution spectral imager and limb-sounding techniques to profile the ozone and other trace gases within the upper atmosphere, while supporting weather forecasting and monitoring long-term ozone trends. To carry out these mission objectives, the Attitude and Orbit Control System (AOCS) software must provide the spacecraft with high agility and fine pointing accuracy.

The ALTIUS satellite platform and its AOCS software are an evolution of the ESA Project for On-Board Autonomy (PROBA) series of satellites, which have over 45 combined years of successful in-orbit experience from PROBA-1 (October 2001) [1][2][3][4], PROBA-2 (November 2009) [5][6][7], and PROBA-V (May 2013) [8][9][10]. Building upon its PROBA predecessors, ALTIUS ensures a high-level of on-board autonomy to the spacecraft, minimizing the need of ground station commands. Each of the PROBA missions (PROBA-1, -2 and -V) are ESA projects where the prime contractor is Redwire Space (RWS), formally QinetiQ Space. Responsible for the design, implementation, and validation of the AOCS software on-board each of the PROBA missions is NGC Aerospace Ltd (NGC). The respective responsibilities are the same for the ALTIUS mission.

To complete the mission objectives, ALTIUS requires several AOCS software innovations compared to the previous PROBA missions. The autonomous novelties implemented for ALTIUS include the following:

- Limb Looking Guidance Mode
- Augmented B-dot Safe Mode
- Thruster Management with Off-Modulation
- Stellar Occultation Mode
- Occultation Event Prediction and Monitoring
- Control Using Four Reaction Wheels Simultaneously

This paper focuses on the first three innovations above, namely the Limb Looking mode, the Augmented B-dot mode, and the thruster management with off-modulation. The novelties related to stellar occultation observations are presented in [11].

This paper begins with an overview of the ALTIUS mission as well as a summary of its main mission objectives and AOCS software requirements. Next, a discussion on the ALTIUS AOCS software structure, functions, and high-level architectural design is presented, followed by a summary of the AOCS software operation modes, and the status of the development and validation process. Afterwards, an overview of each of the AOCS software novelty algorithms is presented. For each of the three novelties under focus in this paper, the challenges associated with their design are discussed, and the AOCS Software System-Level Tests (SST) results are presented to assess their performance. The SST results are generated from a closed-loop MATLAB/Simulink simulator.

2 ALTIUS MISSION OVERVIEW

This section includes a description of the ALTIUS mission and its objectives. It also presents the AOCS software requirements that drive the novelties presented in this paper.

2.1 Mission Background and Objectives

Satellites are the only way of measuring recovery and change in the ozone layer in a consistent and systematic manner. Most ozone-measuring satellites, such as the Copernicus Sentinel-5P mission, provide a value for the amount of ozone in a column of air from the ground (or just above the ground) to the top of the atmosphere. Alone, such measurements only provide a partial assessment of ozone in the atmosphere. Measurements taken in profile provide concentrations of ozone at different altitudes and complete the data obtained from air column measurements. Since the end of ESA's Envisat mission, there are only a few instruments in orbit that provide profiles of ozone, and some of these missions will end in the next few years.

The ALTIUS mission fills this important gap in the continuation of "limb" measurements for atmospheric science, by monitoring the distribution and evolution of stratospheric ozone at high vertical resolution. This will be achieved by an innovative limb sounder flying on a small spacecraft in a Sun-synchronous orbit. The payload consists of three optical channels in the ultraviolet, visual, and near-infrared spectra which can provide 2D images of the Earth's limb at specific wavelengths.

The ALTIUS mission objectives are split into:

- primary objectives: to observe the global distribution of stratospheric ozone at high vertical resolution in support to operational services in near-real time and to contribute to stratospheric ozone long term monitoring,
- secondary objectives: addressing mesospheric ozone and other atmospheric constituents, temperature, and ozone tomography, for scientific studies related to ozone chemistry, climate change and atmospheric dynamics.

The foreseen operational orbit for ALTIUS is a 668 km circular polar quasi Sun-synchronous frozen orbit, with a Local Time of the Descending Node (LTDN) of 10:30 AM at launch time. The orbital parameters at injection have been optimized to limit the LTDN variation, due to orbital plane's drift, within 30 minutes, during the 5-year (extended) mission lifetime, with a minimal need for orbit maintenance.

2.2 Limb Looking and Stellar Occultation AOCS Pointing Performance Requirements

The stringency of the requirements specified for the ALTIUS spacecraft are derived from the mission scientific needs and the instrument imaging requirements. They are requested to be applicable for each imaging session and for all observation geometries and diverse pointing profiles.

The system-level requirements are transformed into different sets of subsystem requirements ensuring the critical pointing performance to be satisfied by the platform while imaging in the different AOCS modes. For the AOCS software, the most stringent of pointing requirements are for Limb Looking and Stellar Occultation modes and are listed below:

- Attitude Knowledge Error (AKE): 5 arcseconds (95% confidence level)
- Absolute Performance Error (APE): 25 arcseconds (95% confidence level)
- Relative Performance Error (RPE): 3 arcseconds over 1 s (95% confidence level)

The stringency of the requirements is considered to be within the reach of the achievable performance, as proven in the frame of the previous PROBA missions experiences.

2.3 Augmented B-dot Mode Performance Requirements

The Augmented B-dot mode serves as a fallback in case of anomalies. The main tasks of the Augmented B-dot mode are: Damp out the spacecraft residual angular rates with respect to the magnetic field, roughly align the spacecraft angular momentum along the orbit normal, and roughly control a User-specified body-fixed vector to align with the Earth's magnetic field (to ensure sufficient incoming solar power).

For the AOCS software, the performance requirements in Augmented B-dot mode are:

- The spacecraft angular momentum shall be maintained within an angle of 20 degrees with respect to the orbit normal for 95% of the time.
- The angle between the User-specified vector and the Earth's magnetic field should be below 125 degrees.

2.4 AOCS Pointing Performance Requirements During Propulsion

The ALTIUS spacecraft is equipped with a propulsion system so it can satisfy the mission's debris mitigation (end-of-life disposal/de-orbiting) requirements and the mission's extended lifetime's orbit maintenance and collision-avoidance needs.

For the AOCS software, the pointing performance during propulsive manoeuvres are the following:

- AKE: 0.25 deg (95% confidence level)
- APE: 1 deg (95% confidence level)
- RPE: 0.5 deg over 5 s (95% confidence level)

3 ALTIUS AOCS SOFTWARE OVERVIEW

This section provides a high-level breakdown of the ALTIUS AOCS software functions, and the architecture of the high-fidelity simulator developed by NGC that is used to perform the Software System-Level Tests. Also included is a discussion on the different operational AOCS modes, the AOCS development process, and a summary of the current development status of the AOCS software for ALTIUS.

3.1 Software Structure and Function Level Breakdown

The ALTIUS AOCS software and its development environment are similar to those of their PROBA ancestors in that the top-level functional breakdown consists of the Real-World Software (RWSW), System (SYS) and the AOCS software (AOCSSW) [10]. A functional diagram showing the interaction between the three software modules and their respective child functions is provided in Figure 1. However, one difference of the ALTIUS AOCS software and simulator compared to its PROBA-1, PROBA-2, PROBA-V predecessors is that it is developed in MATLAB/Simulink whereas the other PROBA projects were developed in MATRIXx/SystemBuild. In both cases, the flight AOCS software is obtained by automatic generation of C code from the models.

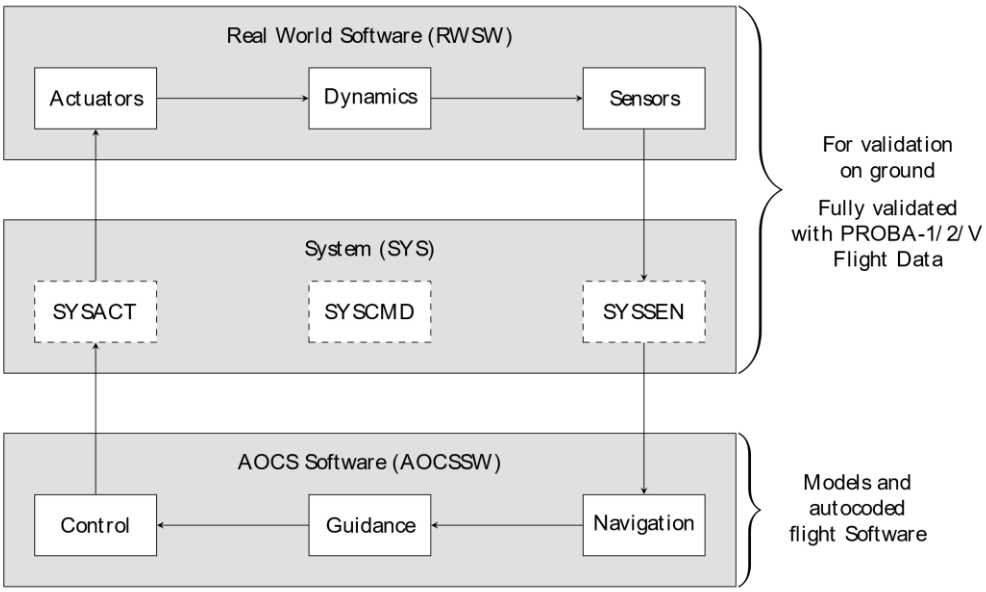


Figure 1. High Level Architecture of the AOCS Software and Simulator

As stated in Figure 1, both the RWSW and System functions are used for validation on ground only, whereas the AOCS software is the piece of flight software under validation. The AOCS software is validated against the RWSW model, which includes dynamic models of the actuators, the sensors, the spacecraft and the relevant environmental perturbations and phenomena that affect the spacecraft dynamics (i.e., orbit, attitude, Sun ephemeris, Earth dynamics, time, etc.). The System function is constructed of all the functions outside the AOCS software. It includes the on-board data handling functions and the ground segment functions. These functions are emulated to the extent required for the AOCS software validation. System also provides commands and sensor measurements to the

AOCS software, while the AOCS software sends actuator commands and AOCS status information to System.

The AOCS software provides the following top-level functions:

Navigation:

Navigation consists in the determination of the current dynamical state (orbit, attitude) of the spacecraft from measurements. It also includes functions for measurement pre-processing, determination of Earth and Sun ephemerides, events and occultation prediction as well as the determination and management of on-board time.

Guidance:

Guidance consists in the computation of the desired or reference dynamical state of the spacecraft. The Guidance function also includes the computation of the difference between the desired dynamical state and the current dynamical state provided by the navigation function. This difference is called the control error.

Control:

Control consists in the determination and execution of the necessary control commands that will bring the current dynamical state of the spacecraft to the desired state, i.e., the actions that bring the control error to zero. The control function also includes angular momentum management (for wheel desaturation) and actuator management, including the determination of the required thruster commands during propulsive manoeuvres.

Failure Detection and Identification:

The failure detection and identification function consists in monitoring the input, internal and output variables, and parameters of the AOCS software and testing them for their numerical and/or physical validity. This function also includes the identification of the cause and origin of any non-valid data that are detected.

3.2 Operational Modes

The ALTIUS satellite has 12 AOCS operational modes: three safe (magnetic-based) modes, one quiescent mode, and eight different fine pointing modes. A brief description of each operational mode and their respective latest flight heritage (if applicable) are provided as follows.

Quiescent (PROBA-2, PROBA-V):

The Quiescent mode is used between each mode transition. All control outputs are zero.

B-dot (PROBA-2, PROBA-V):

The B-dot mode uses the B-dot algorithm to actuate the spacecraft magnetic torque rods to interact with the magnetic field to reduce the angular rate and serves as the main rate reduction mode to remove the excess angular rate imparted to the spacecraft at launcher separation. As was the case on PROBA-2 and PROBA-V, the momentum bias generated by maintaining the reaction wheels at a constant speed is used to roughly align the spacecraft angular momentum axis along the orbit normal.

Augmented B-dot (Developed for ALTIUS):

Augmented B-dot mode is very similar to the previously described B-dot mode. The classic B-dot algorithm determines the magnetic dipole needed to reduce the angular rate of the spacecraft, and the reaction wheel momentum bias aligns the spacecraft angular momentum axis with the orbit normal. Once the rate of the spacecraft has been sufficiently reduced, the “augmented” portion of the mode will command the magnetic torque rods to align a user-commanded vector that is perpendicular to reaction wheel momentum vector with the local magnetic field, thus providing an extra degree of freedom of control about that momentum axis.

Magnetic (PROBA-V):

The Magnetic mode provides three-axis control using magnetometer measurements, magnetorquer actuation with the reaction wheels held at constant speed, and spacecraft position provided either by Two Line Elements (TLE) or GPS. The mode points the momentum bias axis towards the orbit normal and controls the orientation around this axis to point a given spacecraft axis to Earth.

Inertial (PROBA-V):

The Inertial mode is the mode in which the spacecraft attitude is controlled with respect to the Inertial frame, using reaction wheel actuation. User-commanded fixed angular rate manoeuvres are also executed in this mode.

Sun (Developed for another project but no flight heritage):

The Sun mode is the mode in which the spacecraft attitude is controlled to point the solar panel of the spacecraft in an optimal manner toward the Sun and to maximize the Earth exclusion angle of the star trackers.

Orbital (PROBA-2, PROBA-V):

The Orbital mode is the mode in which the spacecraft attitude is controlled for nadir pointing.

Earth Target (PROBA-2, PROBA-V):

The Earth Target mode is the mode in which the spacecraft attitude is controlled to point to a fixed target on Earth.

Geodetic (PROBA-V):

The Geodetic mode is the mode in which the spacecraft attitude is controlled for geodetic Earth normal pointing. This mode can be used with or without yaw steering. Yaw steering is a guidance law that generates a small rotation around the pointing axis such that a spacecraft axis is oriented perpendicular to the tangent of the ground trace at every moment.

Flight (PROBA-2):

The Flight mode is the mode in which the spacecraft attitude is controlled with respect to the Flight frame, i.e., with respect to the spacecraft velocity vector and orbit anti-normal vector.

Limb Looking (Developed for ALTIUS):

The Limb Looking mode is the mode in which the spacecraft attitude is controlled to align the payload to a desired point tangent to the Earth limb at a fixed altitude above the Earth surface. The desired tangent point is selected depending on the Limb Looking sub-mode, which is described in more detail in Section 4.1.

Stellar Occultation (Developed for ALTIUS):

This mode includes 2 sub-modes: Standby and Tracking. In the Tracking sub-mode, the spacecraft attitude is controlled to point to the apparent position of a targeted celestial object during an occultation event. The targeted object may be the Sun, the Moon, stars, or planets. In the Standby sub-mode, the payload is pointed at the Earth’s horizon and has a fixed azimuth angle with respect to the orbital plane corresponding to the expected location of the target at the start of the next occultation event.

3.3 Development Process and Status

The ALTIUS project follows the classic V-shape development process. The V-shape process along with the ALTIUS AOCS software development status is summarized in Figure 2.

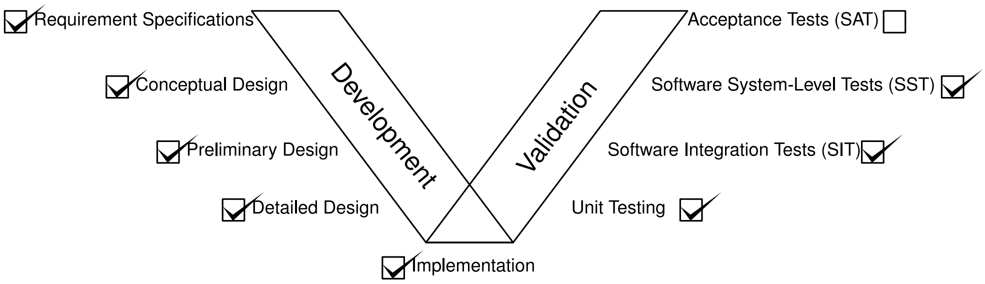


Figure 2. Development Process of the ALTIUS AOCS Software

The ALTIUS AOCS software requirement specifications were defined by Redwire Space. NGC then completed the design and implementation of the software to fulfil the requirements defined. Next, NGC conducted the validation testing, beginning with unit testing of individual functions, followed by Software Integration Tests (SIT) to validate the integration of the software functions. More recently, NGC completed the Software System-Level Tests to validate the performance and robustness of the software as well as demonstrate compliance to the requirements. At the time of writing this paper, the SST campaign is completed by NGC and the final System Acceptance Tests (SAT) will be starting soon by Redwire Space.

4 ALTIUS AOCS SOFTWARE NOVELTIES

To carry out the ALTIUS mission, six new algorithms compared to ALTIUS's in-flight PROBA predecessors were implemented for the ALTIUS AOCS software. A description of each new algorithm design and a discussion on why it is required for the mission follows.

4.1 Limb Looking Mode

The Limb Looking mode is required to point the payload to the Earth limb in order to observe profiles of ozone and other trace gases in the upper atmosphere. The Limb Looking mode guidance function autonomously generates the reference spacecraft attitude profile, angular rate profile and angular acceleration profile necessary to align the spacecraft body frame towards the Limb Looking frame, of which the z-axis points from the spacecraft to the Earth limb (i.e., a tangent point at a specified altitude above the Earth surface).

For a given spacecraft position, there are infinite tangent points around the spacecraft. A specific tangent point can be fully defined by specifying a reference vector and a commanded yaw rotation angle. The types of reference vector (e.g., velocity vector, North pole direction vector, etc.) and the commanded angle define the different Limb Looking sub-modes:

- Backward Limb Looking (BLL), Left Limb Looking (LLL), Forward Limb Looking (FLL), and Right Limb Looking (RLL): The tangent point is defined by specifying the spacecraft anti-velocity vector, with commanded yaw angle of 0 deg, 90 deg, 180 deg, or 270 deg, respectively.
- Pole Limb Looking (PLL): The tangent point is in the plane that is formed by the Earth-satellite direction vector and the North or South pole direction vector.

- Optimal Limb Looking (OLL): The tangent point is in the plane that is formed by the Earth-satellite direction vector and the Earth-Sun direction vector, in the direction of the Sun.
- Tomography (TOM): The tangent point is defined by specifying the spacecraft anti-velocity vector and the commanded yaw angle is a precomputed angle profile (and an associated angular rate profile) that is a function of the argument of latitude of the spacecraft.

4.2 Augmented B-dot Mode

The Augmented B-dot mode is an experimental magnetic-based contingency mode for the spacecraft. Although the mode uses only magnetorquer actuation, some of the spacecraft's reaction wheels are held at non-zero constant speeds to provide a net momentum bias vector. Its purpose is to continue to point the solar arrays of the spacecraft (which are not articulated) towards the Sun during commissioning or during a contingency by coarsely aligning a User-specified direction vector (that is perpendicular to the reaction wheel momentum bias axis) with the Earth's magnetic field. This mode has the advantage of providing an additional degree of freedom of control over the classic B-dot algorithm while not requiring spacecraft position information, like the Magnetic mode.

As the name implies, this mode uses an enhanced form of the B-dot detumbling control law, allowing the spacecraft to align a reference vector with the local magnetic field vector.

Let $\vec{a}$ be the reference unit vector that will be aligned with the local magnetic field and $\vec{B}$ be the local magnetic field vector. The axis about which the spacecraft must rotate to align $\vec{a}$ with $\vec{B}$ is $\vec{n} = \frac{\vec{a}\times\vec{B}}{||\vec{a}\times\vec{B}||}$ and the angle between the two axes is $\tan\Omega = \frac{||\vec{a}\times\vec{B}||}{\vec{a}\cdot\vec{B}}$. To reduce the angle $\Omega,$ an angular velocity about $\vec{n}$ needs to be realized.

It is known from the classic B-dot law, that the magnetic dipole to reduce the rate of the spacecraft is $\vec{m} = -k\dot{\vec{B}} = -k\vec{\omega}\times\vec{B}$, where $k > 0$ is a tuning gain and $\vec{\omega}$ is the angular velocity of the spacecraft. The same equation can therefore be used to determine the magnetic dipole needed to realize a rotation about the axis $\vec{n}$. Let $\vec{\omega}_{ref} = k\Omega\vec{n}$, then the magnetic dipole needed to achieve this rotation is $\vec{m} = -\vec{\omega}_{ref}\times\vec{B}$. This constitutes the augmentation to the classic B-dot control law.

In order for this augmentation to not act counter to the nominal B-dot detumbling law, the reference vector $\vec{a}$ must be judiciously selected. The ALTIUS spacecraft is in a near-polar orbit, so the B-dot detumbling law by itself will align the remaining angular momentum of the spacecraft in the direction of the orbit normal, i.e., perpendicular to the magnetic field. If $\vec{a}$ is not to interfere with the nominal B-dot control action, it must therefore be perpendicular to the spacecraft's total angular momentum.

This enhancement is not suitable for reducing the angular velocity of the spacecraft and can only be used when the component of the spacecraft's angular velocity that is perpendicular to the magnetic field is small. To avoid this issue, the AOCS software implements a logic to combine this augmentation with the standard B-dot law.

4.3 Thruster Management with Off-Modulation

The ALTIUS spacecraft has a four-thruster quadrilateral configuration where all the thrusters have the same orientation. For delta-V manoeuvres under nominal operation, all four thrusters are used. In case of a thruster failure, a two-thruster configuration is used as a fallback.

The rationale for the off-modulation functionality is to allow for the execution of larger delta-V manoeuvres, since without off-modulation, the reaction wheels could quickly saturate during long delta-V manoeuvres. Through off-modulation of a combination of thrusters, the thrusters absorb the portion of the control torque about the thrusters' torque axes, thus the control torque sent to the reaction wheels is reduced, delaying the saturation of the reaction wheels momentum capacity.

The main algorithm features are:

- Computation of the desired thruster control torque based on the attitude control torque while compensating for the thruster disturbance torques;
- Selection of the optimal thruster pair (for four-thruster configuration) or optimal thruster (for two-thruster configuration) for off-modulation to realise the desired thruster control torque;
- Mapping of the thruster control torque into duty cycle commands, considering thruster operational constraints.

4.4 Stellar Occultation Mode

The Stellar Occultation mode is required to point the high-resolution spectral imager towards a celestial target during an occultation event. An occultation is defined as the event during which a given celestial target is located between -10 km and +100 km tangent altitude above Earth's horizon. This mode is required for the ALTIUS mission to observe spectral data from different celestial bodies as it passes through the Earth's atmosphere, in order to analyse the ozone content of the atmosphere.

There are two sub-modes within the Stellar Occultation mode: the Tracking sub-mode, used during an occultation event to track the celestial body, and the Standby sub-mode, used during long periods of time between two stellar occultation events to prepare for the next occultation event, while also avoiding blinding of the star trackers. The typical schedule for the Stellar Occultation mode is to observe the Sun occultation while the spacecraft is entering eclipse, then observe the occultation events of 5 to 10 celestial bodies during the eclipse period and then to observe a second Sun occultation event as the spacecraft exits eclipse.

The design and performance assessment of the Stellar Occultation mode are described and discussed in [11].

4.5 Occultation Event Prediction and Monitoring

The accuracy of the occultation event prediction and scheduling is of critical importance to the ALTIUS mission. As a result, the AOCS software provides prediction and monitoring of up to 11 occultation targets, as a service, to allow the User to schedule the celestial targets and occultation events in Stellar Occultation mode.

The design and performance assessment of the occultation event prediction and monitoring functions are described and discussed in [11].

4.6 Control Using Four Reaction Wheels Simultaneously

Another ALTIUS AOCS innovation that is not a part of the PROBA-1, -2, and -V flight heritage is performing attitude control using four reaction wheels simultaneously. The baseline operation for ALTIUS, as per the previous PROBA missions, remains to be to use three reaction wheels in-the-loop, with a fourth wheel redundant. However, the option to use four reaction wheels in-the-loop is available on ALTIUS. This option is set up to use the null space of the matrix of reaction wheels spin axes [13] to control the reaction wheel speeds to half of their linear range of operation, thereby maximizing the margin until saturation and zero speed crossings. This also increases the agility capacity of the spacecraft by reducing the slew duration of large-angle manoeuvres.

5 LIMB LOOKING MODE RESULTS

This section first describes the challenges encountered with the Limb Looking mode design and how they were addressed. Then, the SST results are presented to demonstrate the final Limb Looking mode performance after the problems were resolved.

In order to meet the stringent pointing requirements in Limb Looking mode, especially the AKE accuracy of 5 arcseconds (95% confidence level), the AOCS software implements an on-board perturbation estimation function, based on a Nonlinear Disturbance Observer (NDO) [12]. During the Software Integration Test (SIT) campaign, it was found that when in the Pole Limb Looking (PLL) and Optimal Limb Looking (OLL) sub-modes, there is a degradation in attitude knowledge performance when passing in the polar region and the equatorial region, respectively. This is due to an increase in the spacecraft angular rates, as required to track the pole direction (when in PLL) and the Sun direction (when in OLL). Large angular rates degrade the NDO's ability to estimate the perturbing torques, and thus degrade the spacecraft attitude estimation performance. At high rates, the internal NDO states tend to diverge, resulting in a long convergence time after returning to lower rates. Prior to the SST campaign, the perturbation estimation function was retuned, resulting in improved attitude estimation performance, as observed in the SST results.

The Tomography (TOM) sub-mode is used to align the payload towards the tangent points observed during the previous orbit. In TOM, the tangent point is fully defined by specifying the velocity vector as the reference vector, and a commanded angle with respect to the reference vector. The commanded angle and its rate are functions of the spacecraft position on the orbit, and are provided from ground via lookup tables. During the early stages of the SST campaign, a degradation in TOM performance was observed, in comparison with the other Limb Looking sub-modes, due to an incoherence between the angle profile and the angular rate profile provided in the lookup tables, i.e., the rate profile did not completely correspond to the time derivative of the angle profile. These initial SST results demonstrated the impact of the lookup table data on the TOM pointing performance, highlighting the importance of generating coherent data in the lookup tables. Consequently, for robustness, an option was added to the AOCS software guidance function, to compute the angular rate profile on-board rather than use the lookup table data. Subsequent tests demonstrate that this option provides improved TOM performance, and is thus enabled by default in the baseline design.

The Limb Looking mode pointing performance was assessed in the SST campaign, performed in the MATLAB/Simulink high-fidelity closed-loop simulator developed by NGC for AOCS software validation, with a Monte Carlo simulation of 200 runs with various dispersions of the test conditions. The following test conditions were dispersed with a uniform distribution: the spacecraft mass, centre of mass and inertia (MCI) properties between beginning and end of life, the spacecraft MCI knowledge errors, the initial attitude in any inertial orientation, the initial spacecraft velocity up to 0.2 deg/sec in any direction of the body frame, the initial wheel speeds up to 500 rad/sec in either direction, noise seeds and unit selection for sensor and actuator models, the spacecraft residual magnetic moment and the time slopes of the various on-board clocks.

A summary of the Limb Looking mode pointing performance is presented in Table 1, showing the performance metrics at 95% of the time, over the 200 runs. All the Limb Looking mode pointing performance requirements are met for all the sub-modes, except in the RLL sub-mode, the AKE requirement is slightly exceeded. Due to the nature of the Sun-synchronous orbit, the star tracker configuration and the RLL attitude, the spacecraft experiences blinding of the star trackers more frequently in the RLL sub-mode. When considering only the periods where at least two (of the three) star trackers are providing valid data (i.e., up to one star tracker blinded), then the RLL AKE performance is 2.21 arcsec, meeting the requirement. Overall, the AOCS software performs as required to meet the mission objectives.

Table 1: Limb Looking Mode Pointing Performance Summary

	AKE (arcsec)	**APE (arcsec)**	**RPE over 1 s (arcsec)**
Requirement (95% confidence level)	**5**	**25**	**3**
BLL	2.26	3.12	0.129
FLL	3.07	3.61	0.144
RLL	**5.80**	6.08	0.237
LLL	3.05	3.78	0.145
PLL (North pole)	3.57	10.71	0.270
PLL (South pole)	4.37	9.30	0.278
OLL	2.20	4.02	0.195
TOM	2.30	2.65	0.164

6 AUGMENTED B-DOT SAFE MODE RESULTS

In Augmented B-dot mode, the AOCS software shall ensure that the spacecraft momentum vector is maintained within 20 deg with respect to the orbit normal for 95% of the time, and the User-specified vector is within 125 deg with respect to the Earth's magnetic field. The Augmented B-dot mode performance was assessed in the SST campaign with a Monte Carlo simulation of over 200 runs. In an example run, with the spacecraft initial angular rate at 5.7 deg/s, Figure 3 shows the true spacecraft rate, demonstrating the Augmented B-dot mode's capability to detumble the spacecraft down to around 0.2 deg/s, which takes around 7.2 hours in this run. In this figure, the yellow curve is the true total spacecraft rate, whereas the blue curve is the spacecraft rate as estimated by the AOCS software, i.e., the spacecraft rate with respect to the magnetic field, which does not include the spacecraft angular velocity component along the magnetic field.

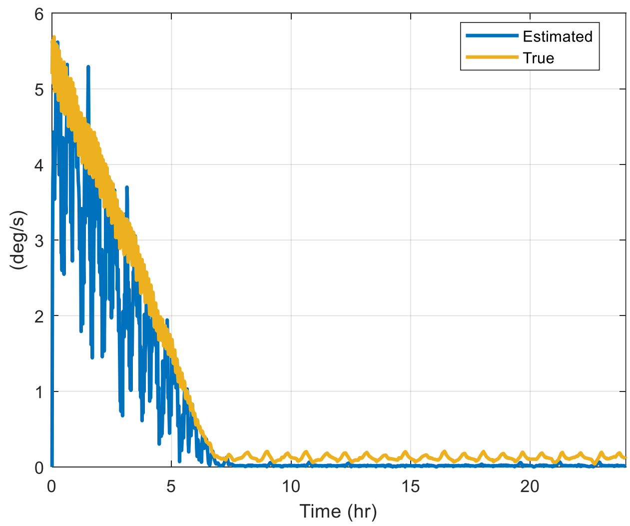
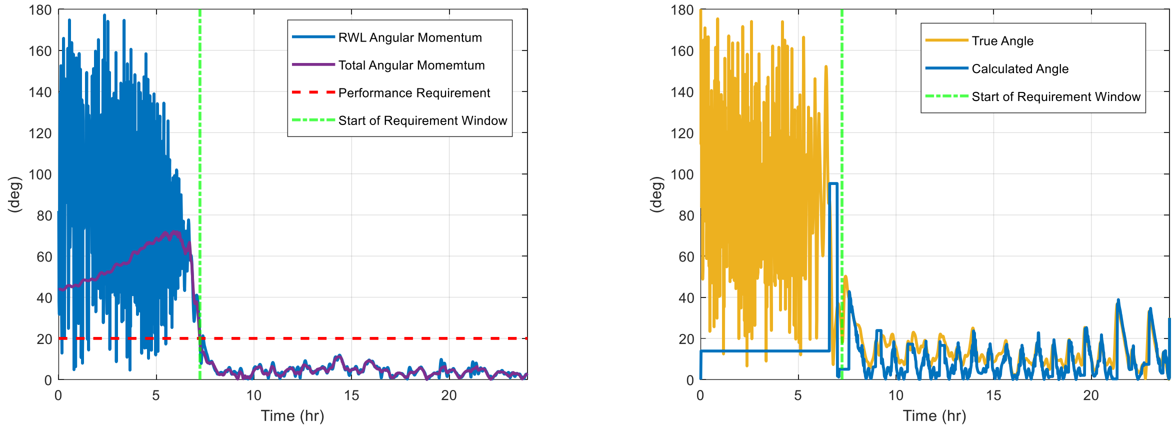


Figure 3. Spacecraft Angular Rate, for Example Run in Augmented B-dot Mode

For the same example run, Figure 4(a) shows the angle between the angular momentum vector and the orbit normal. Once the spacecraft is detumbled at around 7.2 hours, as indicated by the green vertical line, the angle remains within the requirement of 20 deg.

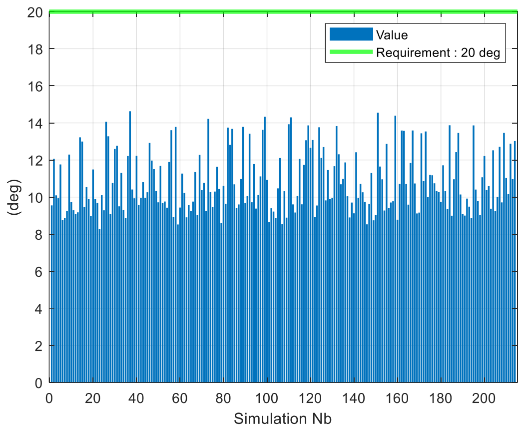
Figure 4(b) shows the angle between the User-specified vector and the Earth's magnetic field. The yellow curve is the true angle (from real-world dynamics), whereas the blue curve is the calculated angle as determined on-board by the AOCS software. In the first 7.2 hours when the spacecraft rate is large, only the classic B-dot detumbling law is operational; the angle between the User-specified vector and the magnetic field is not controlled, as demonstrated by Figure 4(b), where the "calculated angle" is a default value. Once the spacecraft is detumbled, the "augmented" portion of the mode operates and successfully maintains the true angle between the User-specified vector and the magnetic field within the required 125 deg.



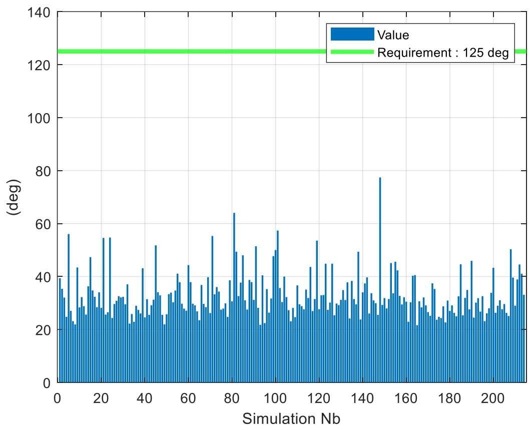
(a) (b)

Figure 4. Augmented B-dot Mode Performance in Example Run:
(a) Angle between Angular Momentum and Orbit Normal,
(b) Angle between User-Specified Vector and Earth's Magnetic Field

A summary of the Augmented B-dot mode performance results for the Monte Carlo campaign is presented in the bar graphs of Figure 5, showing the performance metric of each simulation run. Note that the performance metric is captured for the 95% of the duration of the simulation after detumbling is completed. Clearly, the Augmented B-dot performance requirements are met.



(a)



(b)

Figure 5. Bar Graph of Augmented B-dot Mode Monte Carlo Results:
(a) Angle between Angular Momentum and Orbit Normal;
(b) Angle between User-Specified Vector and Earth's Magnetic Field

7 ATTITUDE MAINTENANCE DURING PROPULSION RESULTS

Outside of propulsive manoeuvres, the attitude control is completely realised by the reaction wheels. However, during a propulsive manoeuvre, the thruster disturbance torques are large enough to quickly cause saturation of the reaction wheels. Thus, during propulsive manoeuvres, a portion of the attitude control torque will be realised by off-modulation of the thrusters, to prevent/delay reaction wheel saturation.

A torque distribution function is implemented to distribute the attitude control torque between the thrusters and the reaction wheels during propulsive manoeuvres. Since the thrusters and the wheels have different levels of torque authority, the challenge faced in the design is in finding an appropriate tuning for the parameter that weighs the torque distribution between the thrusters and the wheels. If too little of the control torque is allocated to the thrusters, then the wheels are used to realise most of the attitude control (including the rejection of the thruster disturbance torques), which can quickly lead to wheel saturation. On the other hand, all four thrusters are aligned in the same direction, thus, at minimum, the portion of the control torque about the thrust direction must be allocated to the wheels. Additionally, from the thruster configuration, there is an upper limit on the thruster torque that can be obtained by off-modulation. As the torque distribution weighing parameter has an impact on the attitude control performance during propulsion, an adequate tuning was determined through simulations, while taking into account the above-mentioned constraints.

In the SST campaign, pointing performance during propulsive manoeuvres was assessed with a Monte Carlo simulation of 200 runs. In each run, four propulsive manoeuvres are simulated: a short (5 mm/s) and long (500 mm/s) out-of-plane delta-V manoeuvre (thrust along the orbit normal), a short (5 mm/s) and long (500 mm/s) in-plane delta-V manoeuvre (thrust along the spacecraft velocity/flight direction). A summary of the pointing performance during 95% of the delta-V duration of each manoeuvre is presented in Table 2. The pointing performance requirements during propulsive manoeuvres are met.

Table 2: Pointing Performance During Propulsive Manoeuvre Summary

	AKE (deg)	APE (deg)	RPE over 5 s (deg)
Requirement (95% confidence level)	**0.25**	**1**	**0.5**
Short out-of-plane manoeuvre	0.104	0.160	0.033
Long out-of-plane manoeuvre	0.205	0.345	0.109
Short in-plane manoeuvre	0.135	0.203	0.047
Long in-plane manoeuvre	0.228	0.414	0.127

8 CONCLUSION

This paper presented the ALTIUS mission, objectives, and a summary of the AOCS software requirements driving the need for innovations in ALTIUS with respect to its PROBA predecessors. Next it presented an overview of the AOCS software, the simulator used to validate it, and the different operational modes provided by the AOCS software. The description and rationale for the latest software innovations designed for the ALTIUS mission were provided, including:

- Limb Looking Mode
- Augmented B-dot Safe Mode
- Thruster Management with Off-Modulation
- Stellar Occultation Mode
- Occultation Event Prediction and Monitoring
- Control Using Four Reaction Wheels Simultaneously

For each of the first three listed AOCS software novelties, some challenges associated with their design was discussed. The Software System-Level Test results were presented, demonstrating that these AOCS software additions meet the stringent pointing requirements needed in the Limb Looking mode, the performance requirements needed in the Augmented B-dot mode, and the pointing requirements during propulsive manoeuvres.

The ALTIUS SST tests were concluded in January 2023. Next, the acceptance tests will be performed on a System simulator. ALTIUS is planned for launch in 2025 at which time the AOCS software and its various innovative algorithms presented in this paper will be validated in flight.

9 ACKNOWLEDGEMENT

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