DOI: 10.13009/EUCASS2019-902

Euclid AOCS - Highest pointing stability for Dark Universe Investigation

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Abstract

Euclid is the second medium class (M2) mission from the Cosmic Vision 2015-2025 programme, of the ESA's long-term planning for space science, and is dedicated to the investigation of the properties of the dark energy and dark matter.
The scientific objectives of this mission impose very challenging requirements on image quality driving outstanding pointing stability for the AOCS, but still ensuring frequent and fast repointing capabilities of multiple types and sizes, with fast access to distant observation targets. The Euclid AOCS uses high-end sensors and actuators within an elaborated Science Observation mode, which guarantee the achievement of those demanding objectives.

1. Introduction

ESA scientific programme is currently implementing the Euclid Mission, dedicated to the investigation of the properties of the dark energy and dark matter. Euclid is the second medium class (M2) mission from the Cosmic Vision 2015-2025 programme, which responds to the ESA's long-term planning for space science missions.

Within the Euclid Spacecraft, the Attitude and Orbit Control System (AOCS) is the system dedicated to acquire the desired pointing for the Spacecraft, to maintain that pointing with the required pointing evolution and stability, and to reorient the telescope to the different target directions necessary for the desired scientific observations. The system includes sensors, actuators, logic, data, software, etc., necessary for the achievement of those functions. For the Euclid AOCS the quality of the science observations requires an outstanding pointing stability, such demanding that the conventional AOCS equipment and design would not be enough for its achievement. Additionally, a high pointing accuracy has to be obtained for accurate target acquisition and for sky coverage gaps and without unnecessary overlaps. Finally, a significant pointing agility must be combined with fast and very deterministic reorientations.

The Euclid AOCS uses sensors and actuators with outstanding performance necessary to achieve such objectives, including a dedicated Fine Guidance Sensor (FGS) and a set of low-noise cold-gas Micro-Propulsion System (MPS) thrusters. The data from very high performance gyroscopes are also fused together with the FGS measurements and with MPS control commands in a state-of-the-art Kalman filter to deliver a very accurate and continuous attitude estimate. Additionally, the AOCS has to avoid, manage and compensate any dynamic disturbance, either from the AOCS actuators or from other elements in the spacecraft or from the external environmental disturbances. This applies also to the vibrations introduced by the Reactions Wheels (RWL) and the dynamic disturbance caused by the motion of the Filter and Grism Wheel Mechanisms in the NISP payload.
In a different technology area, the AOCS development involves a quite integrated configuration of components which are implemented in common Hardware (centralised computer), and Software. The flight software integrates the AOCS Application Software (AASW) with the Central Application SW (CASW) to be loaded in the Central Data Management Unit (CDMU). SW auto-coding techniques have been introduced and applied to develop the AOCS flight software and simulator in particular for all the AOCS control modes.

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After having passed the Critical Design review, EUCLID is currently undergoing Phase D under the lead of the European Space Technology Centre (ESTEC, Noordwijk, NL). The Euclid industrial development is led by Thales Alenia Space in Torino, Italy (TAS-I) as Prime Contractor for the construction of the satellite and the Service Module (SVM), while the Payload Module(PLM) is under the responsibility of Airbus Defence and Space in France. As part of the SVM, SENER is the overall responsible and prime contractor of the Euclid AOCS, with Airbus Defence and Space Netherlands as main partner, while more than seven additional direct subcontractors are contributing with different components of the subsystem.

2. Euclid Mission and Spacecraft

2.1 Science Observation and Mission

In a major step towards the understanding of the origin and evolution of the Universe, the principal objectives of the Euclid mission is the characterisation of the so-called dark energy and dark matter which should explain the accelerating expansion of the Universe. Cosmological models predict a Dark Energy content around 75% of the energy content of the Universe, and jointly with the dark matter, they dominate the Universes matter-energy content. Neither of them are directly observable, since they do not interact “directly” with light and electromagnetic radiation, however, they can be characterised by the other (e.g. gravitational) effects that they generate. Characterisation should serve to establish the realism of the concept as “energy/matter”, or its consideration as constants in the models or as anomalies/deviations from the cosmological models.

Several means and techniques will be applied for the investigation[1], which include the Weak Gravitational Lensing (WL) and the Galaxy Clustering(GC), the latter encompassing the Baryonic Acoustic Oscillations (BAO) and the Redshift Space Distortion, which combination would probe the effects of the dark energy and dark matter(see Figure1). While the WL will be obtained from the shape and shear of the galaxies detected by the visual (VIS) and Near-Infrared(NIR) photometric observations, the Galaxy Clustering would be obtained by the evaluation of the redshift of 3500 galaxies per deg2, when using the NIR spectrometric observations. In consequence, careful sequential and simultaneous observations with the two instruments will be required.

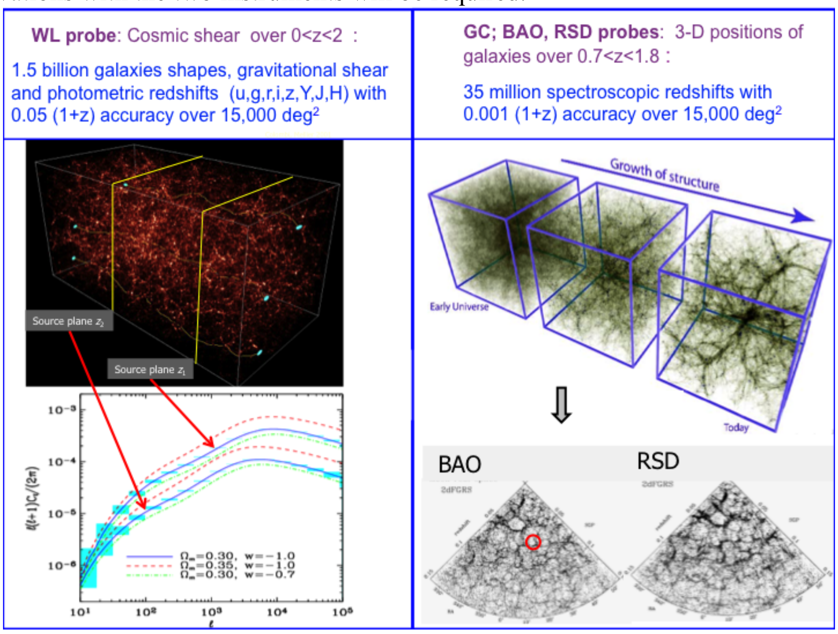

Figure 1: Euclid Science mechanisms (source Euclid consortium) [1]

Euclid will perform a mapping of large scale structures in the Universe along a cosmic time of 10 billion years in the past, for which purpose a large part of the extra-galactic sky will be surveyed. Additionally, certain regions of the sky will be observed in depth, with repeated observations along the mission duration, dimensioned to not exceed 6.25 years. Those types of observations are characterised as [1]:

1) Wide Extragalactic Survey (WES), includes 15,000 deg^2 of the dark part of the sky (excluding galactic and ecliptic plane), which is free of contamination by light from our Galaxy, and Limiting magnitudes: AB_{VIS} =24.5 (10-σ, extended); $AB_{Y,J,H}$=24.0 (5-σ, point-like)

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2) Deep Survey(DS), with 3 different fields, covering around 40 deg^2, to be observed in repeated visits along the mission and 3 different fields, selection of field location completed, and Limiting magnitudes: AB_{VIS} =26.0 (10-σ, extended); $AB_{Y,J,H}$=24.0 (5-σ, point-like).

The complete survey represents hundreds of thousands images. About 10 billion sources will be observed by Euclid out of which more than 1 billion will be used for weak lensing and several tens of million galaxy redshifts will be also measured and used for galaxy clustering. The scientific analysis and interpretation of these data is led by the scientists of the Euclid Consortium.

The Euclid spacecraft will operate in a large amplitude (~0.9 x 106 km) Quasi-Halo, and eclipse free orbit around the Sun-Earth Lagrangian point L2 about 1.5 million km away from the Earth. A direct transfer orbit will be obtained by a Soyuz 2-1b rocket from Kourou. After the launch, orbit manoeuvres will correct the launch vehicle dispersion and enable to directly reach the final orbit around L2. No large injection manoeuver will be necessary, but once the target orbit is acquired, the orbital evolution will need to be corrected approximately once per month.

Euclid is equipped with a 1.2 m diameter mirror telescope with a high resolution (0.1 arcsec). The Euclid Consortium (EC), bringing together scientific institutes in all of Europe, is responsible for the definition of the scientific goals and provides the two focal plane instruments:

1) The visible imager (VIS), including 36 CCDs (550-900nm) with 0.2arcsec resolution
2) The near-infrared spectrometer and photometer (NISP) instruments, mounts 16 HgCdTe near-infrared (NIR) detectors (920-2000nm).
   NISP allows selection of the band for photometry with the usage of the Filter Wheel Assembly (FWA), and the selection of the dispersing elements for the spectrometry with the Grism Wheel Assembly (GWA)

Every science observation is composed of a sequence of 4 dither exposures with a small re-pointing manoeuvre in between them (Dither Slew). After completion of one observation, a field step (or a larger slew) will be executed, and the next "field" observation will be initiated. In the first instrument observation, which is the longest (currently 565 sec) and is the driver for the RPE requirement, both the VIS and NISP instrument are active. At the start and end of this observation period, the VIS shutter is opened and closed. In periods between observations, and during dither slews, the NISP wheels are operated. One VIS observation has also been introduced in the first dithers observation of the nominal sequence. The above sequence is outlined in Figure 2.

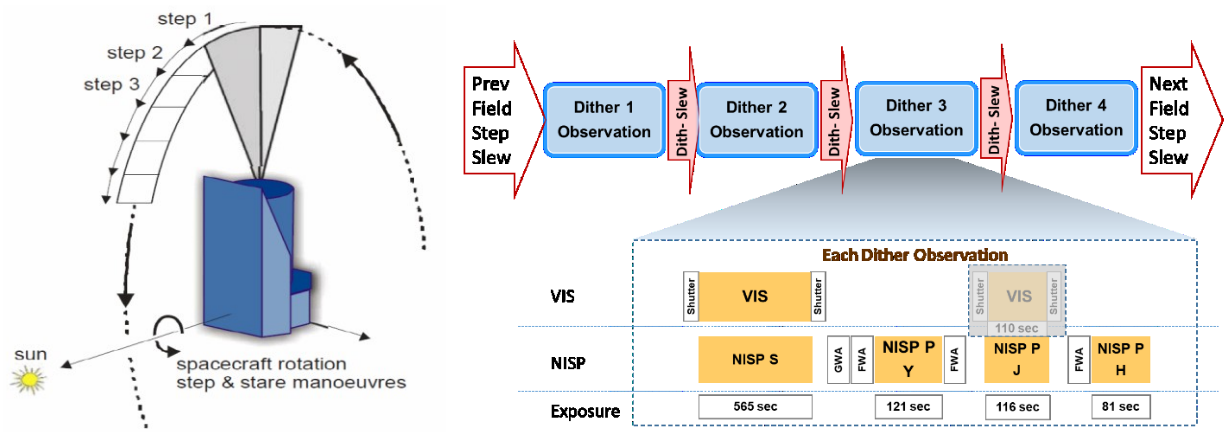

Figure 2: Example of Euclid Science Sequences

2.2 Euclid Spacecraft

Two individually integrated and tested "Modules" (SVM and PLM) will be later integrated into the Euclid Spacecraft with a total mass of about 2200 kg while the size of it is about 4.5 m x 3 m (see Figure 3):

1) The PLM integrates the Euclid Instruments provided by the Euclid consortium (see section 2.1) and include also a 1.2m 3-mirror anastigmatic Korsch telescope, the Optical Bench where the detectors and front ends are mounted, and the structures, thermal control hardware and the harness which connect the instrument units internally and with the Service Module (SVM). The Fine Guidance Sensor detectors and proximity electronics, necessary for the control of the spacecraft (part of the AOCS) are also mounted on the PLM.

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2) The SVM includes all the spacecraft subsystems necessary for the mission (including the Sunshield and the attached Photovoltaic Assembly), and includes also the warm electronics of the payload, providing as well the necessary structural elements for the attachment and support of the PLM and to the Launcher interface.

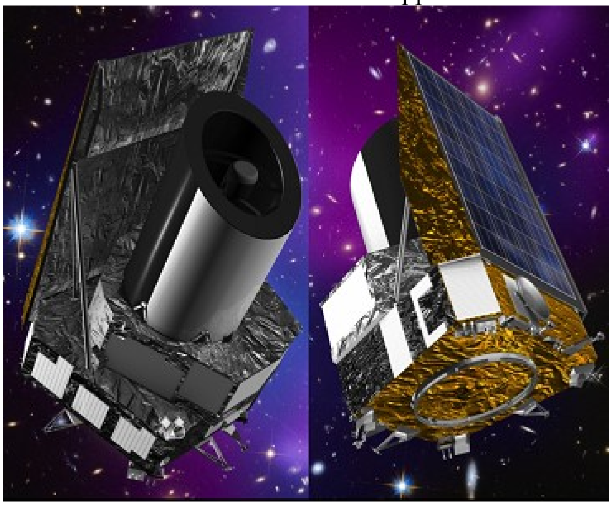

Figure 3: Euclid Spacecraft (source ESA)

The AOCS is one of the most relevant systems in the PLM. The AOCS hardware includes a star trackers(STR), high performance gyroscopes (GYR), coarse rate sensors (CRS), coarse and fine sun sensors(SAS/mFSS) and the reaction wheels(RWL), while it also operates the Reaction Control System (RCS) with hydrazine thrusters and the cold gas MPS including six pairs of amplitude modulated (1-1000 micro-N) thrusters. Apart from those units in the SVM, the AOCS operates and uses a high accuracy attitude sensor, being developed dedicated for this mission, named Fine Guidance Sensor (FGS), which is the main attitude sensor necessary to cope with the very demanding pointing requirements

The SVM incorporates the different units of the systems, accommodated according to the different needs and constrains as reflected in Figure 4 below. The AOCS units are identified with solid red, while the units and elements which are used by the AOCS are marked with dashed red. A more detailed description of the units relevant to the AOCS are shown in the following section.

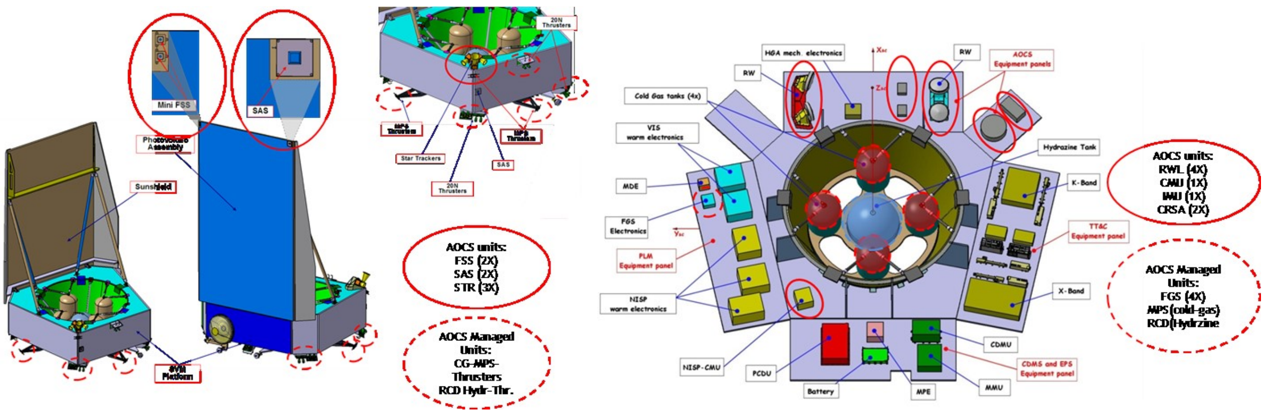

Figure 4: Euclid SVM and systems (elaborated from TAS-I accommodation images)

3. Euclid AOCS

3.1 AOCS Design Drivers

The mission and the science observation include several needs, which strongly drive the design and the capabilities of the AOCS. The AOCS is in fact a major actor for the achievement of the following mission objectives:

- Quality of the Image acquisition, as necessary for the science observations, which is characterised by the Point Spread Function(PSF)quality indices, mainly *ellipticity* and *Full Width at Half Maximum*(FWHM). From

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those needs, the requirement on the ***Pointing Stability*** is established for an extremely demanding value of 75 milli-arcsec (3σ) over 700s. This value is "the" key requirement for the AOCS configuration and operation in particular for the science observation, which in term is the main driver for the rest of the AOCS.
- Accurate acquisition of the desired scientific targets, and maximisation of the sky coverage with the selected observation sequences. In this case the reduction of the observation overlap to a maximum value of 1% marks a telescope pointing accuracy requirement of 7.5 arcsec (3σ), defined as Absolute Pointing Error (***APE***).
- Fast acquisition of individual targets, with revisit of the DS areas along the mission, and the coverage of the desired 15000 deg^2 of WES along the 6 years mandate a significant ***agility***.
- Execution of the small attitude manoeuvres during with a minimum time in between observations, mandates also a very high accuracy in those small manoeuvres for *immediate reacquisition of the science* observation.
- On top of that, observations have to be continued without interruptions during the operation of the large wheels to be rotated during the NISP operation (FWA and GWA). Also the Visual shutter will be activated during the science observation, and the science needs to be continued without interruption.

Apart from those major needs, the AOCS must ensure the safety of the satellite in terms of attitude, with avoidance of any degradation of the sensitive instruments by sun illumination, imposing for the Sun a semi-cone angle of 65 degrees around the X-SC axis. The rest of functions in the AOCS include the acquisition of stable and safe pointing attitude after separation, the maintenance of the fine inertial attitude for long periods without large fuel expenditure, the capability of large attitude changes, and also quite relevant the execution of the precise and autonomous orbit manoeuvres (ΔV accuracy better than 3% are mandated).

The previous requirements imply for the AOCS:
- Usage of top level attitude sensor physically linked with the payload, which is achieved via dedicated Fine Guidance Sensor, with the detector mounted in the same focal plane as the payload detectors, and sharing its optics.
- High accuracy and minimum disturbance actuators to be applied for the attitude pointing maintenance during the science observation. The clod gas based micro-propulsion subsystem (MPS) enables such control.
- Application of high torque authority actuators which can be used as well for small manoeuvres, complemented with capabilities for manoeuvring based on the hydrazine RCS.
- The large amount and size of the intended manoeuvres imply also the usage of RWL for operations outside the observation periods, such as to minimise the fuel consumption.
- Compensation of FWA and GWA dynamic disturbance with application of a dedicate Compensation Mechanism Unit.
- The usage of MPS for observation and the RWL for slewing in particular during science observation has been called the "hybrid solution" ([3],[6]). RWL are used outside the observation time, while they are stopped during observation, when the MPS is used instead.

The combination of the above drivers, with the science and AOCS functions has determined the architecture and design presented in the following sections.

3.2 Hardware and SW Architecture

Based on the considerations from the previous section the following AOCS mandates the introduction of the following state of the art units:
- **Fine Guidance Sensor (FGS).** The unit is a dedicated development for the Euclid mission ensuring integration and precise alignment with the telescope axis, and the corresponding reference stars [3],[6]. The sensor includes 4 CCDs in the payload focal panel operated in pairs, two Proximity Electronics (PEM) located in the PLM, and one internally redundant Electronics Unit (EU) located in the SVM.
  The FGS is able to provide 0.01arcsec (1σ) relative measurement accuracy in transversal axis during periods up to 700s, and that accuracy is driven by the high frequency effects related with mainly with the detector limits. With respect to the absolute errors, they are driven by the star catalogue, the CCD position/alignment, and the focal length knowledge. The first error is minimised with the application of dedicated catalogue derived from Gaia data, while the rest are minimised by calibration [3].
  The sensor has a narrow FOV and must be working with very low transversal angular velocities, implying that it has to be used only during inertial pointing observation periods. Two operational modes are implemented during tracking, depending on the capability to establish an inertial reference: Relative and Absolute Tracking Modes (RTM/ATM) ([3])

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- **1x Inertial Measurement Unit (IMU)** Includes one set of high accuracy, state of the art low noise fibre optic **gyroscope (GYR)** with 4-measurement channels. Allows the SC to perform slew repointing manoeuvres with high accuracy and with very with limited time. The Gyros are combined with a set of 4 **Accelerometers (ACC)** in pyramid configuration dedicated to on-board estimation of the executed ΔV, and sharing electronics with the Gyro sensors in the internally redundant **electronic unit(GEU).**
- **Micro-Propulsion System (MPS).** 6 x 2 cold-gas microthrusters, with controllable thrust magnitude(amplitude modulation) between 1 and 1000 micro-N. These thrusters form part of the MPS mentioned before and provide the high resolution and accuracy of actuation necessary for the high performance observation control.
- **4 x Reaction Wheels (RWL)** in pyramid configuration provide redundant capability to perform attitude manoeuvres in between observations as well as larger repointing manoeuvres, while they will remain stand-still during the observation periods.
  For the compensation of the internal perturbations induced by the rotation of the filters (FWA/GWA) in the NISP instrument, a dedicated wheel (similar to the one of the AOCS) is also mounted, and is known as Compensation Mechanism Unit (CMU).
  A delicate selection of the size and authority of the wheels, has arrived to the selection of 75 mNm RWL, with up to 4 Nms angular momentum capability compatible with its usage as CMU.
  CMU was initially intended to be part of the payload, as a dedicated mechanism outside the AOCS, however, the suitability of the RWL in use for control has allowed the application of the same type of wheel, simplifying a lot their management. CMU is consequently incorporated to the AOCS and is also anaged within it.
- **10 x 2 Reaction Control System (RCS)** hydrazine thrusters providing a nominal thrust at Beginning Of Life(BOL) of 20 N. Two thrusters are aligned to perform ΔV manoeuvres and used only for that purpose, while the rest (8) are used for attitude control.
- **Star Tracker STR** (3 x Optical Heads with 2 x Electronics Units). The absolute attitude provided by the star trackers is used in the Euclid AOCS for all the modes, except for the Sun Acquisition and the safety mode. During the high performance scientific observation periods, the STR is not useful and disregarded in favour of the FGS.
- **2 x Coarse Sun Sensors (CSS).** Internally redundant sensors, with large FOV, one of them mounted along the X-axis (perpendicular to the solar panel), and dedicated to acquire and maintain Sun Pointing, and another one along the telescope line of sight for a proper control of the spacecraft in case the Sun approaches the forbidden zone of the telescope during non-nominal operation.
- **2 x Fine Sun Sensors (FSS)**, both mounted parallel to the X-axis and used for anomaly detection. They provide much better accuracy in sun direction but significantly lower FOV.
- **2 x Coarse Rate Sensor (CRS)** for early detection of attitude and rate anomalies and for the Safe Mode. The sensor is a reliable sensor evolution of the one in applied in Herschel and Planck AOCS

The above units are all connected to the central computer (CDMU), which includes an extensive set of interface modules enabling external interfaces with most of the satellite units, as reflected in Figure 5.

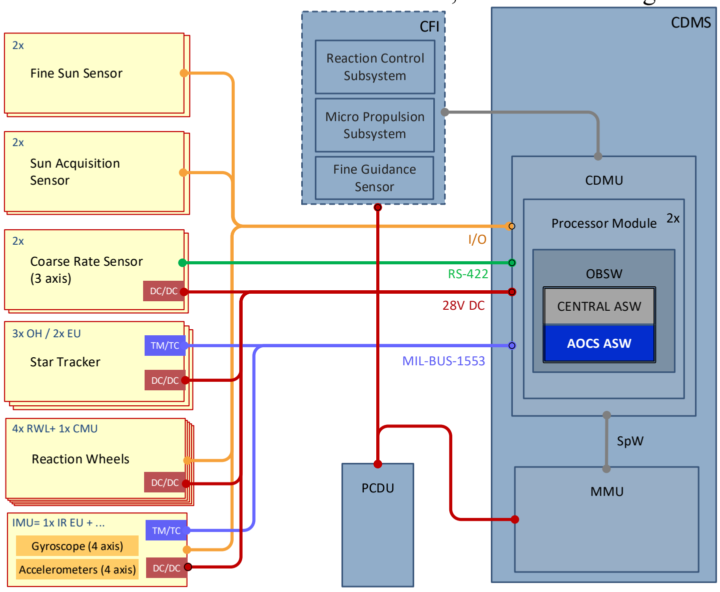

Figure 5. Euclid AOCS Architecture

The AOCS units interface with the CDMU in the following way:
- The FGS, the STR and the IMU communicate via the 1553B MilBus.
- FSS, SAS, RWL and CRS use dedicated analogue and discrete TM/TC lines with the Remote Interface Unit (RIU).

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- RCS and MPS communicate via dedicated CDMU RIU. Although they are not part of the AOCS, they are under control and commanded by the AOCS.

The commanding, data acquisition and processing of the information is also performed in the CDMU and the powering of the AOCS units is executed via the Latch Current Limiters (LCLs) in the Power Control and Distribution Unit (PCDU). The CMDU stores telemetry and science data in the Mass Memory Unit (MMU), and performs the processing for the different functionalities in the On-Board SW (OBSW). The OBSW includes the AOCS Application SW (AAASW), after its integration with the Central Application SW (CASW). The OBSW is integrated and tested at the AOCS level and the AOCS is validated using the complete OBSW in several levels of representative hardware, and for each version of the AASW (see Figure 5 above for an overview of the AOCS communication and IFs).

The AASW is also decomposed in the part of 1) the control modes, produced by autocoding techniques starting with the MATLAB/Simulink® models and called AASW-AUTO, and 2) the AASW-MAN produced with conventional implementation, and including management of the interfaces with CASW, generation of TM, management of TC, and the management of the AOCS units. The majority of the FDIR is also included in the manual code for convenience, while the safe mode is also manually coded in order to obtain a higher independence.

3.3 Functional Architecture

The AOCS functionalities are organised in Modes. Modes are determined by the set of sensors and actuators, and the configuration of the applicable Guidance Navigation and Control functions applied for the achievement of the objectives. The AOCS modes are structured in submodes determining different processes or states applied for the achievement of the objectives identified for the corresponding mode. The Euclid AOCS includes the following modes:

- Sun Acquisition Mode (SAM). Sun acquisition and Sun pointing.
- Fine Pointing Mode (FPM). Fine attitude manoeuvres and pointing, split into FPMRCS and FPMRWL.
- Orbit Control Mode (OCM). Dedicated to execute the commanded Delta-V manoeuvres.
- Science Mode (SCM). For high pointing performance and execution of the science timeline.
- Safe Mode (SFM). For safety in case of critical situation, with similar functionalities to those of SAM.
- The stand-by mode (SBM). Is a transition mode where actuation is inhibited, and entered only at start (Launcher separation) or at computer reset. A dedicated (independent) SBM is available for the reconfiguration after severe FDIR Level 3b or 4.

Modes and transitions schematics are shown in Fig. 4 below.

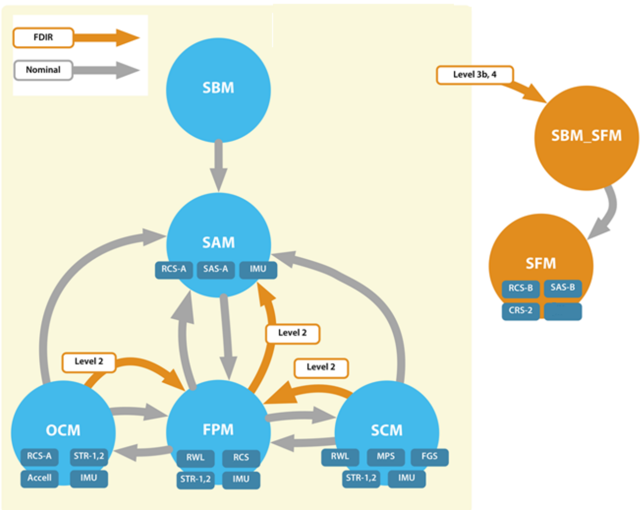

Figure 6. Euclid AOCS Modes Architecture [2]

Some small description of the relevant characteristics of the more conventional modes are included hereafter, while the SCM mode will be described in more detail in dedicated section:

- **SGKF:** all the control modes using STR and Gyro use a multiplicative extended Kalman Filter (SGKF) to obtain an optimal estimation using combination of both types of measurements. This filter makes a limited usage of SC dynamics and has been tuned such that it performs adequately for all the SC dynamic conditions in the AOCS, and is being applied with the same tuning for all the modes involving those sensors, which include OCM, FPMRWL, FPMRCS and SCM (a different filter is used for the submodes with FGS). SGKF is able to work with the 4 Gyro rate measurements, but will also be robust against the loss of at least one channel.

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- **SAM:** is the mode dedicated to acquire and maintain sun pointing and uses the measurements from the SAS, IMU and the actuation with the RCS. SAM includes also two special functionalities dedicated to the recovery from unexpected situations, and include the acquisition when starting in the small dark zone (Sun out of the FOV of both SAS), and the second to avoid that the Sun could approach the forbidden telescope region during the attitude control. SAM includes the following submodes:
    - Rate damping. To be used when high angular rates are present prior to the Sun Acquisition.
    - Avoid Telescope. Is entered when the Sun direction arrive close to the +ZSC axis.
    - Dark Zone. Dedicated to search the Sun when the Sun has not been detected in any of the SAS before (i.e. when the mode is started with the Sun in the region not covered by the 2 SAS FOV).
    - Sun Acquisition. When a reliable Sun direction estimation is available, +ZSC axis is protected, and rate is not too high, this submode is in charge of rotating the SC to point the +XSC axis towards the Sun.
    - Sun Pointing. This submode is declared when Sun and the angular rate are within the desired bounds.
- **OCM:** executes autonomously the commanded delta-V manoeuvres for orbit correction and orbit station keeping. The RCS thrusters are used both for the linear actuation (Delta-V), and for the attitude control.
  The mode includes a high degree of autonomy, for which it estimates on-board the executed ΔV, and controls accordingly the delta-V actuation. That estimation is performed with two complementary methods:
    - The accelerometers in the IMU, providing feedback based on the effect in the SC acceleration, later integrated in the on-board SW. The four accelerometers are mounted with its sensing direction along a pyramidal configuration, in which only 3 axes are necessary. When the 4 sensors are available they are used for improvement of the estimation.
    - The on-board delta-V book-keeping evaluates the firing duration and the estimated thrust levels, as performed in Herschel and in Planck, and in certain conditions can provide better estimations than the accelerometers.

  During this mode, the angular momentum of the wheels can be controlled to any desired value, however, the RWLs are not actively involved in the closed loop attitude control. A dedicated bias and hold operation is available, which can be used for wheels acceleration and oil re-distribution after the extended periods of use of the wheels at low regimes during science. Any desired speed in the wheels can be maintained for certain time using the bias and hold for the RWLs and in particular for the CMU.
  Although the OCM can be used for the Bias and Hold operation, and that would save mission time when applied during the DeltaV operation, the time in any RCS based modes implies fuel consumption for attitude control and it shall be limited to the minimum necessary, in order to save propellant. For long re-lubrications, the usage of the RWLs based mode is preferred. FPMRWL is entered before entry to OCM and can be used for that purpose.
  OCM implements the following submodes:
    - **Delta-V:** dedicated to perform ΔV manoeuvres with 1 orbit-control thruster (open continuously during the manoeuvre), while maintaining that thruster in the required fine inertial pointing. The attitude is controlled with the 8 attitude thrusters actuated in pulsed mode. The Delta-V can be executed either with fixed pointing or with a variable attitude profile provided by Ground by means of polynomial coefficients.
    - **Pointing:** This submode is entered in three possible ways, 1) after OCM entry until a ΔV command is received, 2) autonomously once the ΔV manoeuvre has been completed, and 3) as result of a telecommand to abort the on-going ΔV manoeuvre. It also allows for calibration of the accelerometers bias before the execution of the ΔV manoeuvre. In this submode a stable fixed inertial pointing attitude is maintained (as for the FPMRCS pointing), and use the fine RCS actuation to be explained in FPMRCS.
- The system level **FPM** is dedicated to fine attitude maintenance and repointing. Such mode uses STR and IMU as sensors, but requirements impose control based on RWL for long duration and also control based on RCS. The two actuations were initially treated as two submodes, but finally the mode has been split in two AOCS modes:
    - **FPMRCS** uses only the RCS as actuators. This is necessary for operation before RWL commissioning (e.g. for the first orbit correction) and under certain FDIR alarms with medium severity, which would avoid the activation of SFM, and consequently the possibility of a faster continuation of operations. This mode can also implement faster attitude manoeuvres when guidance activates large coasting speed.
      The RCS is a blow-down monopropellant system, without thrust level control, but impulse is only controlled by the commanded on-time. The minimum Impulse Bit (MIB) is 25 msec and the corresponding torque is 50 Nm (BOL). This implies that the resolution using this system is approximately 1.25 Nms (given in terms of change in the angular momentum). The size of thrusters was a compromise between orbit control and attitude control, but they are relatively large for attitude control.
      That situation has been solved with the implementation of a **fine control actuation** in which the firing starts with a combination of thrusters in which a 0 net torque is obtained during the minimum time (e.g. 25 msec) and the firing on-time is increased for the thrusters which provide the desired torque. Since the resolution is much higher than the minimum firing, this allows one order of magnitude better resolution, suitable for the fine attitude control required in some conditions.

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Even with that simultaneous actuation, the consumption of propellant has been demonstrated with analysis and simulation to be improved. This is due to the better control of the angular rate, and the increase of time between pulses which compensates the longer actuation. This functionality is also applied to other operations which require a high level of resolution, including OCM pointing and transition to science in the FPMRWL.

- **FPMRWL** is based on RWLs as actuators for attitude control and will allow to maintain stable 3-axis attitude for long duration without significant fuel consumption. The FPMRWL must acquire an Absolute Pointing (APE) of 0.15 and 0.2 degrees during pointing and slew (99.7% confidence level), while high gain antenna is reoriented in parallel.
  This mode implements several functionalities for the Reaction Wheels Management, including on one side the internal management of the individual wheels speed, while maintaining the overall angular momentum (Null Space Management function), and the usage of the RCS attitude thrusters in the overall RWL angular momentum(H) for both unloading and bias management(H-bias). Ground can obtain full control of the RWL speeds by commanding both the null space speed target (scalar) and the total target Angular Momentum. RWL speed distribution can be performed autonomously when activate. H-bias function is automatically activated in any case when the stored H in the RWLs or an individual RWL speed exceeds a user-defined threshold.
  The transition to SCM is performed by the FPMRWL, when an external command is received for that transition, and is executed in a dedicated and quite specific process. In this process the system needs to slow down all the RWL to stand still, and simultaneously achieve minimum angular rate in the spacecraft. Due to the large MIB of the RCS, this process is performed with the fine RCS actuation as described in FPMRCS. Any S/C residual rate remaining after that transition to SCM in FPMRWL will be reduced inside SCM using MPS.

In both FPM modes, two main submodes are included, "**pointing**" and "**slew**". In Pointing, any target direction within the operational domain is maintained, while in Slew, an attitude profile is generated to be followed by the control from the current attitude to the target one. The Guidance ensures that the profile maintains the Sun always within the operational limits (Sun Safe), such that the payload instrument is never at risk of illumination. The slew implements a selectable coasting speed, to be obtained after the acceleration phase, and the manoeuvre finalises with a deceleration phase until target attitude achieved.

3.3 Autocoding in the Euclid AOCS

The SW for the AOCS control modes is generated from the MATLAB/Smulink® models using autocoding techniques (see 3.2 for the SW architecture). The models for the autocoding are produced in the design environment and they are also used for the design and verification in the early phases of the mission. The use of autocoding has demonstrated to be of especial interest for this type of AOCS with advanced concepts and elaborated algorithms, which SW is verified extensively much earlier than in the case of conventional SW. Such extensive usage of the SW benefit from the early detection and correction of problems, resulting in a very limited number of AOCS-SW errors/iterations in the later phases of the process. Additionally it allows a more agile product development and iteration.

However, the generation of SW with enough qualify, and using autocoding, requires the application of rigorous design approach in the implementation of the AOCS modes and the control algorithms in the design environment. Basically that means that design models produced for fast prototyping and evaluation cannot be directly applied for autocoding, on the contrary, a structured design procedure has to be defined and reflected in a set of applicable rules that will ensure a controlled code generation, the maintainability of the models and the verification of the SW requirements. They concern:

- The way in which the algorithms and models are implemented.
- Types of structures to be used for the adequate code production.
- Definition and description of interfaces.
- The "instrumentalisation" of the design models for extraction of numerical information for testing.
- Tracing of design requirements to the code.
- The scheme for the SW validation test (to be afforded early in the design, and prior and after the autocoding).

With an early definition of those rules, both the design and implementation starts and evolves together. The models are organised in several layers, divided in increasing complexity bottom-up. Simpler functions are generated and then gathered in a higher and more complex hierarchical model, following a modular approach. Each of these modules are related to specified modes functionalities, which are traced to the applicable requirements to the model. With adequate

DOI: 10.13009/EUCASS2019-902

autogeneration process definition, these traces are automatically introduced in the C-code, avoiding the tedious process of manual code tracing.
The applied modular design allows to implement a unitary and integration testing (UIT) strategy of the SW based on modular functionalities. When the algorithms are generated, they are individually tested in a dedicated test harness, created per individual module, and where the model functionality is validated both in Model-in-the- Loop (MIL) and in SW-in-the-Loop (SIL), and where the code coverage can be analysed. Both MIL and SIL are run within the MATLAB/Simulink environment. Once a module is validated at one level, it is introduced in a larger module which is validated following the same steps, up to the integrated top level module or AOCS Mode function. This way of functional validation has been automatized in the development of the AASW-AUTO for the Euclid AOCS, which enables a quick function and system validation whenever a change is introduced in the AOCS algorithms.

In order to reduce the UIT required execution time and during the product evolution, the use of the autocoding allows for directly testing C-code within the different integrated simulation facilities (including platform, actuators and sensor models) by means of Software-in-the-loop simulations (SIL). The use of this feature enables a preliminary validation of the autocoding generation process at AOCS mode level when comparing the results with those generated by the model based simulation (i.e., MIL). It shall be noted that the overall performance can be compared and validated by means of SIL, increasing the confidence on the representativity of the validation, before moving to tests in the processor or in the integrated on-board SW. It becomes interesting in this point to carefully consider the numerical differences from low level models and c-code mathematical functions depending on the processor environment. In the Euclid AOCS SW process, numerical equivalence was obtained after careful evaluation and analysis between the modelling environment and the obtained c-code running in the target processor.

In parallel to the AOCS algorithms development, a set of auxiliary tools have been developed by SENER to increase the project effectiveness. These functions are dedicated to cover supplementary tasks such as product documentation, design traceability, design validation, and SW coverage assessment, and are based on the described organisation of the development for autocoding. For the Euclid AASW-AUTO, these tools are in charge of automatic generation of the AOCS algorithms design documents (including traceability to requirements) and execute the UIT campaign of all the AOCS modes in detail, including the autocode validation and coverage analysis.

4. Science Mode (SCM)

The core and the most demanding mode of the EUCLID AOCS is the SCM. The mode serves for preparation and management of the SC pointing for the science observation, and the necessary slewing (large, field and dither) for exercising the mission timeline, while supporting the science operations needs. During the science observation the S/C must be maintained in inertial pointing with an RPE requirement better than 75 milli-arcsec (99.7%) normal to the instrument's Line of Sight (LOS), while for SCM the APE is required to be 6 arcsec (99.7%) normal to the instrument's LOS and 21 arcsec (99.7%) around it (ALOS).

4.1 Science Mode and mission timeline

The SCM has to combine a very delicate process for the achievement and maintenance of the above performance, while supporting the complex timeline necessary for the science (example included in Figure 2), and additionally, the mode has to enable flexibility for any change in such timeline sequence, and restrictions in such flexibility have to be treated as exceptions.
The timeline is driven by observation periods, re-pointing manoeuvres and payload operation. A mission time-line (MTL) with the target attitude quaternions is introduced to the AASW via individual commands to the AOCS. The target quaternions are received by the SCM and the corresponding functions are selected depending on the state and the slew size. Different types of the slew manoeuvres are implemented between the different inertial pointing of the observations, which are categorized according to its purpose into dither slews, field steps and large slews.

1) The dither slews are small rotations of approximately 100 arcsec, with a rotation axis normal to the instrument's boresight and serve to fill the gaps in the VIS/NISP detectors. They are performed within a time slot of 60 seconds in total (including tranquilisation), for continuation with the required stability, after which, science observation is resumed.
2) The field slews (or field steps) are used to acquire and observe adjacent fields, and its size arrives up to 1.2 degrees. They have allocated a time slot of 290 seconds, and science observation is resumed with the same performance after that. Larger time is allocated to them also for instrument calibration purposes.
3) Large slews are manoeuvres with larger size. The manoeuvre duration is depending on the slew size, and serve to acquire new or distant targets or areas in the sky.

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After completion of one observation, the next "field" initiates, once the corresponding field slew has been completed. The "nominal" operational sequence consists of three dither slews in between 4 inertial observations. Field steps separate two consecutive science observations (see Figure 2).
Quite relevant difficulties include:

- The VIS shutter is opened and closed before and after every VIS observation. The shutter generates a small dynamic perturbation, and temporarily obstructs the FGS making some measurements invalid, however, the RPE has to be maintained also during the operation of the Shutter, and this generates another challenge in the SCM.
- In periods between observations, and during dither slews, the NISP wheels are operated. They generate important dynamic disturbance, which need to be compensated immediately for the continuation with the science in the required time. This situation has imposed the usage of the CMU for compensation.

4.2 Some special features of SCM

In this section, some specific aspects of the SCM are shown:

1) Reaction wheels usage during Science.
The achievement of the high stability required in the mission mandates the minimisation of any dynamic disturbance, and in particular the usage of ball-bearing Reaction Wheels would introduce undesirable micro-vibrations, while the rest of technologies were considered still immature. On the other side, very frequent and precise manoeuvres are necessary with short time in between.
The AOCS combines those two needs with alternative application of RWL control during the manoeuvres, and the attitude control during the observations with the high prevision and low noise MPS system, while the wheels are brought to 0 speed during the observations. This is identified as the hybrid solution in [3],[6]. This solution allows also to achieve the necessary agility and propellant optimization while performing small slew manoeuvres (i.e., dither and field step). Figure 7 shows a schematic of the combination of the two actuation systems, and shows the evolution of the angular rate of the wheel with time, followed by the handover to closed loop control managed with the MPS:

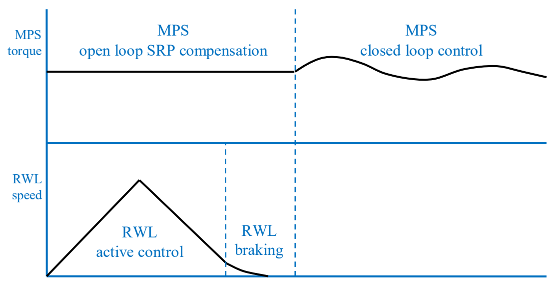

Figure 7. MPS+RWL commanding scenario

For the control with RWL in science, a dedicated wheel speed profile is followed, as generated by the guidance profile, including an acceleration and deceleration phase. However, since the RWL have to return to the stop condition, the external torque (i.e. solar radiation pressure) has to be compensated by the MPS which is commanded in open loop during such period. The external torque is estimated during the observation submode and applied during the slew.
When the RWL profile is close to completion, and the RWLs are approaching the zero speed, the RWL commanded torques are set to zero and the wheels brake towards zero via their own internal friction. In those decision points, accurate speed estimates and timing are essential such as to avoid zero-crossings and to avoid time drift and angular errors. Enhanced speed estimations are used on top of the RWL tacho counts.
The MPS based closed loop control takes over at the point when the RWLs are declared at stand-still, and the FGS is reacquired. The pointing will be maintained for the science observation period with the MPS.
Application of this scheme had some relevant uncertainties, which risk has been eliminated by a dedicated characterisation of the RWL behaviour, resulting in a precise and systematic evaluation of the response and repeatability. Additionally, a very detailed and precise SW model of the wheel provided by the RWL supplier is included in the AOCS simulations. That ensures a realistic validation of the RWL and the AOCS behaviour during such special operation.

2) CMU compensation
For each individual FWA/GWA rotation, a total time of 12 seconds is allocated (10 seconds for the FWA/GWA rotation itself and 2 seconds margin for the speed braking of the CMU) and an additional 8 seconds is allocated

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for controller tranquilisation to resume the science observation. The dynamic compensation by the CMU allows to maintain the FGS in tracking, however, the FWA/GWA motion contains a high frequency signal that translates into an additional perturbation torque with a large amplitude at a high frequency. This perturbation induces an oscillatory S/C rate, which imposes an additional challenge for the control design to maintain FGS tracking.

On-board modelling of the FWA/GWA disturbances was necessary, while the precise RWL SW model existing from the AOCS are applied for the validation. The predicted torque is applied in a feed-forward compensation, while the deviation are corrected with the corresponding feedback control, allowing the avoidance of the FGS track loss in all the performed simulations.

3) RWL start and stop lifetime tests

With the above strategy, the RWLs will be operated such that very frequent start and stop operation of the wheels is applied, even more for the CMU, and operation in low regime is used very frequently during the science operations.

Ball-bearing RWLs are usually operating at high regimes, and typically some restrictions apply for its operation at very low speed, since a stable elasto-hydro-dynamic (EHD) lubricant film cannot be guaranteed to be established. In the Euclid case, start and stop is repeated for hundreds of thousands of cycles during nominal AOCS operation, while they can arrive well above one million cycles for the CMU nominal operation. Although the RWLs were declared to be resistant to such type of operation,

- In order to avoid any risk of degradation, a regular acceleration of the wheels is planned, and proposed to be performed at frequencies similar to the expected orbit maintenance, such that the associated science interruption can be used for this purpose.
- Additionally a re-qualification campaign has been run, including a lifetime dynamic testing for two candidate wheels, such as to guarantee that there is no risk of degradation with such operation.
- The dedicated life-test campaign has been carefully defined using the ECSS standards for the applied margins. The qualification has completed more than 2 million cycles of start and stop covering the types and number of operations during flight and with the expected environmental conditions.
- A massive amount of information has been collected and processed, and demonstrated that the behaviour is fully compatible with the models in use, its behaviour is very deterministic, and the inspection of the internal wheels have shown no degradation in the achievable functions and performance.

Life-test profiles has been organised in 14 seasons depending on the type of speed profiles, all of them representative of the flight operation and including 168000 cycles each, arriving to a global number of more than 2 million cycles. Some test profiles characteristics are shown in Table 1 below.

Table 1: Type of profiles in the reaction wheel life-test.

Profile	Maxspeed [rpm]	Rotated angle [revs]	tacho-evts [48evts/rev]	Accel. durattion[s]	Accel. TOCO [mNm]	Plateau time [s]	Plateau TOCO [mNm]	Decel TOCO [mNm]	Min. Idle time after[s]
FWA 1	-50	4,75	228	0,7	-49	5	-3,0	51	4
GWA 1	-90	9,60	461	1,4	-45		-3,8	44	
FWA 2	-40	4,13	198	1,2	-24		-2,8	25	
GWA 2	-80	9,87	474	2,4	-24		-3,6	22	
FWA 3	-25	2;58	124	1,2	-15		-2,3	20	
GWA 3	-70	9,33	448	3,0	-18		-3,4	16	
Dither 1	25	0,83	40	2,0	10,0	0	-	-6	4
Dither 2	100	3,33	160	2,0	37		-	-35	
Dither 3	420	35,00	1680	5,0	60		-	-53	
Field Slew 1	20	0,50	24	1,5	10,7	0	-	-8	4
Field Slew 2	200	16,67	800	5,0	30		-	-23	4
Field Slew 3	1000	233,33	11200	14,0	53		-	-44	9
Field Slew 4	2500	1458,33	70000	35,0	54		-	-41	9

4.2 Science submodes architecture

The science operation in SCM is organised in various submodes which are operated by a mode manager (SCM-MM) that centralise the decisions. The target quaternions of the MTL are received and processed by the mode manager. This manager selects the appropriate submodes to be entered for the desired operation. A symbolic representation of the SCM architecture is shown in Figure 8. More details can be found in [5]

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- **Entry (SCM-EN):** Whenever SCM is entered, this submode is activated by default. The submode will reduce the remaining S/C angular velocity after the transition from FPMRWL. The exit of the submode will happen once a new target quaternion is provided by the MTL.
- **Large Slew (SCM-LS):** dedicated to slew repointing rotation when it is larger than a predefined threshold. The same functionality exist in FPMRWL. By implementing the SC-LS, the complex transition from FPMRWL to SCM is avoided, allowing a short and deterministic time until next observation. This submode contains a RWL based control and its Guidance function is shared with FPMRWL, and is consequently Sun Safe.
- **Dither Field/Slew (SCM-DF):** dedicated to dither slew and field step, when such slew size is smaller than the large slew threshold. It is a RWL based control with a dedicated Guidance function with the objective to minimise the time in it, maximise APE performance at the end of the slew, and make all of it deterministic, both in terms of RWL angular velocity and time spent. High performance GYR are used to provide the pointing accuracy via integration. At larger rotation angles such as in field steps, STR data is used to maintain the systematic errors of the Gyro integration, bounded at the end of the slew. Due to the above constrains, this mode uses only 3 wheels, even in case that the 4 wheels are healthy.
- **FGS Acquisition (SCM-FA):** any residual SC rate is reduced and maintained at zero while the FGS is in process of acquisition for the continuation of the science.
- **MPS Correction (SCM-MC):** this submode serves to perform small corrections after a slew that are too small for RWLs. A dedicated manoeuvre based on MPS is then performed to achieve the APE requirement.
- **Science Observation (SCM-SO):** dedicated to maintain inertial pointing and to meet the highly demanding RPE requirements. A dedicated FGS + Gyro Kalman Filter (FGKF) is used, enhanced with precise MPS model for state propagation. Actuation is based on MPS and the controller concentrates on relative deviations with respect to a locked reference attitude.
  During SCM-SO, the FWA/GWA will be operated with the associated dynamic perturbations. The CMU controller is implemented to compensate the FWA/GWA motion by following the corresponding rate profile. In that period the RPE is not necessary to be maintained, but the angular velocity of the SC has to be maintained very low, such that the FGS tracking is maintained.

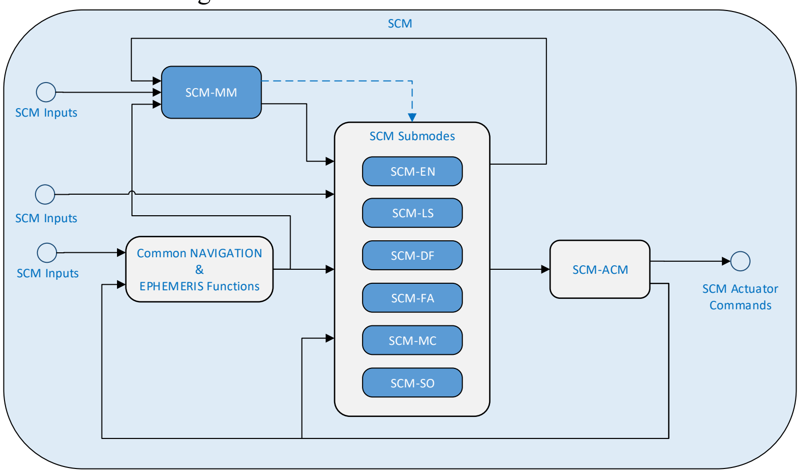

Figure 8. Schematic SCM submodes architecture, [5]

For the SCM a dedicated actuator manger (SCM-ACT) is included which receives the torque commands and generates the appropriate actuator commands for the MPS, RWLs and CMU. On top of the architecture reflected above, a **SCM-AB** submode has been introduced for staying in SCM after certain non-nominal situations, for the case that a recovery is obtained without the need to exit the SCM mode.

4.2 AOCS Results

The EUCLID AOCS has followed a progressive and extensive validation process. As declared in 3.3, the usage of autocoding has allowed to exploit the models in the early phases of the design which become later “the flight SW”. The AOCS development process uses the following environment and steps:

- Design Environment: Based on company tools and environment, implements the AOCS models in a flexible and friendly design environment, suitable for the SW development up to the Unitary and Integration Testing. The results obtained in that environment were used for the Preliminary Design Review, and later maintained and used for evolution of the design.

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The models evolved from prototype to autocoding condition. The produced autocoded SW is numerically checked against the SW Models in this environment, with the so-called Equivalence tests, also tested in the target processor emulator.

- Engineering Simulation Environment (ESE). AOCS SW models are incorporated and verified in a high fidelity, rigorously and strictly configured and controlled environment. This environment provides highest fidelity in the space environment and is used for the Functional and Performance validation, with usage of Montecarlo simulations. The results from this environment served to complete the Critical Design Review.
- Software Validation Facility (SVF). This environment is fully representative of the SW interfaces and processor interactions/behaviour, and serves to test the complete OBSW in a high-fidelity simulator of the CDMU with processor emulator. The results obtained in ESE are confirmed in this environment.
- Hardware in the Loop Facility (HILF). In this environment all the HW interfaces are incorporated, and a Functional Model of the CDMU is used to verify all the HW-SW interfaces, and including all the electrical signals in the loop.
- Avionics Model (AVM). This is the environment where the subsystem qualification is complete, and includes one Engineering Model of each type of HW unit.
- Finally the AOCS will be tested after full integration with the rest of the spacecraft in the PFM.

The AOCS completed the PDR process, during 2016, and the CDR was already closed in 2018, while now the HILF testing in the functional and performance version is being complete for delivery to the AVM(June 2019). CDR has confirmed with massive evaluation of statistical properties, including Montecarlo simulations, the proper accomplishment of the driving requirements mentioned in this paper. All the AOCS units have been fully qualified, and the Flight Models delivery are close to completion and currently are being integrated to the spacecraft.

The verification in the SVF and HILF have confirmed the results obtained in ESE, and provide a clean way forward for the following steps in the project.

<u>Some results from ESE obtained for CDR:</u>
ESE uses high High-Fidelity simulator, applied for testing and validation purposes, and incorporates models from every HW unit validated in collaboration with the corresponding suppliers. For critical cases, the High Fidelity SW models existing at the suppliers have been adapted for its incorporation to the simulator (e.g. RWL, FGS, etc.). The S/C dynamics include models for sloshing, SRP torques, and rotating elements for the FWA/GWA, High Gain Antennas, and VIS shutter, which follow representative activation sequences and response with the realistic disturbance profiles.
Some SCM simulation results are shown hereafter. The most demanding pointing performance during the science observation is shown in Figure 9, which shows the Montecarlo results in ESE for a complete observation sequence. Data from the slew periods and NISP compensation are removed to enhance visualisation. The compliance to the RPE is clearly observable, both in the time sequence and in the histogram presented on the right side.

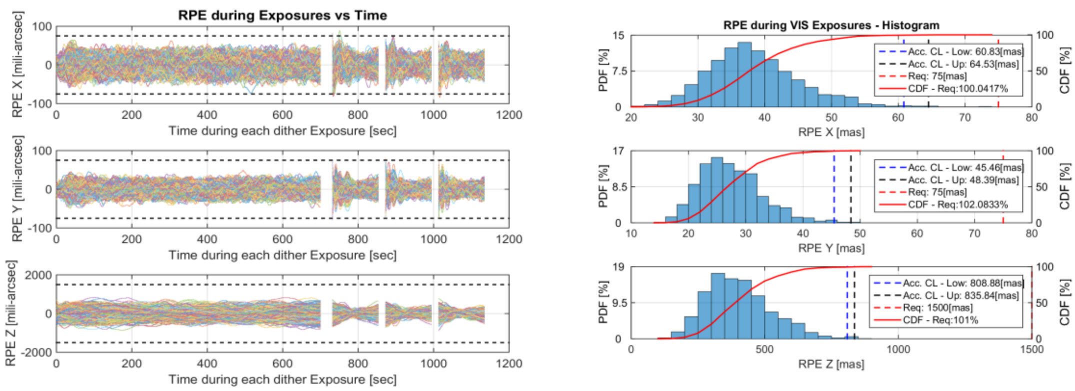

Figure 9. Montecarlo results for RPE during science observation

Figure 10 shows on the left side the angular velocity evolution in one RWL, in a Montecarlo simulation of a dither slew range with changing slew size and direction. On the right side the CMU angular velocity evolution observed in Montecarlo simulation of observation sequences, which include all the NISP (FWA/GWA) rotations in the Montecarlo. The left part reflects 3 different sizes of NISP rotation, and the right side shows the second rotation in cases of two consecutive NISP operation, in that case always with the same size.

DOI: 10.13009/EUCASS2019-902

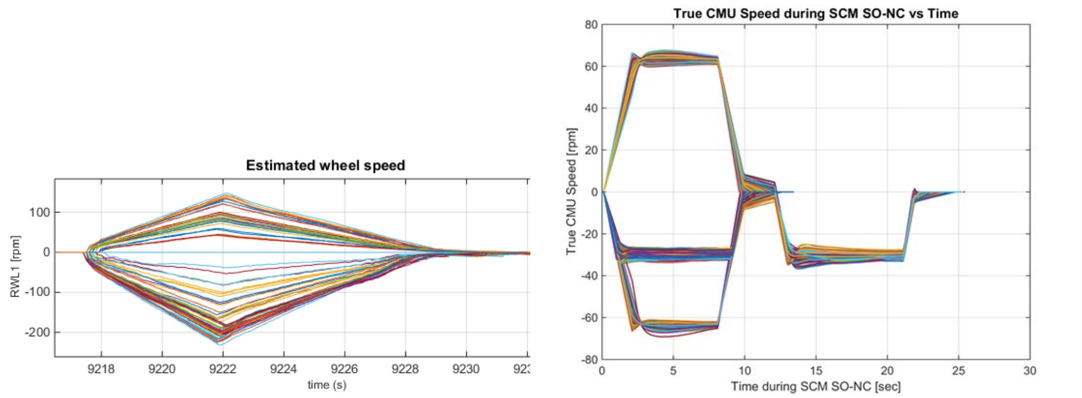

Figure 10. RWL speed during a dither and CMU speed for two consecutive FWA/GWA actuations

1. Conclusions

The paper has introduced the main aspects of the Euclid AOCS design, showing the architecture and configuration obtained. The main design drivers and constrains, have been discussed and the disturbances and the operational needs were explained, with particular dedication to the impact in the SCM mode, which design has been outlined in the SCM section. The process for the application of the autocoding techniques has been introduced, indicating the main advantages and needs with respect to the models development and implications.

Although a special effort has been dedicated in trying to simplify the design, the complexity of the mission and the level of requirements remains present in the complexity of the design, which includes many advances and special characteristics. The subsystem includes sensors and actuators with very high performance, and applied in a delicate combination, including hybrid MPS and RWL operation with start-stop operation, such that RWL microvibration disturbance are eliminated, and with active compensation of internal dynamic disturbances, all of that in a complex and flexible mission timelines.

That design has been implemented and verified for the PDR, CDR and currently for the delivery of the functional and performance version, and some relevant results are presented. Verification confirms very satisfactory results, which meet the identified critical requirements, while the extensive evaluation and verification during the whole project allows to remove the risk with such complexity.

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