Performance achievement and verification of unprecedented stability AOCS for EUCLID

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ABSTRACT

The Attitude and Orbit Control Subsystem (AOCS) for the Euclid mission requires outstanding stability performance and jointly with the mission operation needs, mandates the application of a very specific and advanced design. A delicate organisation of the AOCS physical and functional architecture has been implemented in order to meet the Spacecraft needs, involving highest performance sensors and actuators and advanced processing and subsystem management.

The AOCS verification and testing up to qualification and acceptance has followed a staggered verification starting at the Design Environment, including High Fidelity Simulator for Guidance Navigation and Control (GNC), a complete OBSW Verification Facility, and a Hardware In the Loop Facility (HILF). Qualification and Acceptance are completed with specific testing at System Facilities.

With a first introduction on the design specificities of the Euclid AOCS, this paper describes the logic and organisation of the verification process with special attention to the verification of the demanding performance, the complexity and specificities of the subsystem operation and the application of autocoding techniques, addressing the main implications in the verification derived from those considerations. Some representative results are also presented.

1 INTRODUCTION

Within the ESA scientific programme Euclid is a medium class cosmology mission dedicated to the investigation of the properties of Dark Energy and Dark Matter. Euclid will be operated in a large-amplitude libration halo orbit around the Lagrange point L2 of the Sun-Earth system and will scan the sky with a visual instrument (VIS) and a Near-Infrared SPectrometry instrument (NISP).

The scientific objectives of this mission impose challenging requirements on the system performances, with very demanding pointing accuracy, and arriving to outstanding pointing stability levels. The AOCS necessary for achieving those challenging mission requirements includes a very specific and advanced design, with incorporation of dedicated state-of-the-art attitude sensors and actuators. A quite special combination of units and dedicated sequence of operation are also necessary, resulting in a delicate architectural organisation, and specific determination and control process, including several configurations of Attitude Determination functions, organised in an AOCS architecture which includes three organisation levels: modes, submodes and submode states. This design allows minimisation of disturbances and maximisation of performance and stability, however, it requires a very careful and systematic verification plan for the verification of any possible AOCS configuration and operational sequence, with all possible effects affecting the system.

Apart from those design considerations, the resulting AOCS Application SW (AASW) has been split into one part that is manually coded and one part that is auto-coded in C-code from the AOCS design models. The AASW interfaces only with the service framework and the math library of the Central ASW (CASW). Model Based Design (MBD) and Autocoding has been used, allowing an agile development and adjustment when needed. This split introduces many relevant advantages in the AOCS development, however, the integration and verification of the AOCS Software has to be performed with careful consideration of the two different processes.

The verification of such as system cannot be performed in one single stage and environment due to associated complexities and the different type of limitations that it would imply. On the contrary, a dedicated process has been followed for the AOCS verification, involving a staggered verification in time and in complexity, from the design environment, up to the qualification in the AVionics Model (AVM) and acceptance in the Proto-Flight Model (PFM), with application of different intermediate test environments suitable for the different types of verification. This paper provides the logic, organisation and description of the verification process in relation with the AOCS design. SENER Aeroespacial is the overall responsible and prime contractor of the Euclid AOCS, in close cooperation with Airbus Netherlands (Airbus NL) as main partner, while more than seven additional direct subcontractors are contributing to different components of the subsystem. Thales Alenia Space Italy (TASI) is Euclid prime contractor and AOCS customer.

In those functions, SENER assumes responsibility for the AOCS design, AOCS modes software implementation by autocoding, sensors and actuators procurement, and overall subsystem verification, from engineering simulators up to AVM, and including an HIL test benches, while Airbus NL participates with system engineering, Failure Detection Isolation and Recovery (FDIR), operations, the AOCS SCOE with Real-Time-Simulator (RTS) and the AOCS software, and TASI in its prime contractor role, assumed also some relevant areas like the Fine Guidance Sensor (FGS), and the (Micro) Propulsion cold-gas actuation System (MPS).

2 AOCS DESCRIPTION

The verification of the Euclid AOCS is driven by the nature of the mission, the demanding requirements, the complexity of the science sequence of operations and the resulting AOCS and the limitations of the achievable conditions in a ground-based test environment. For those reasons it is quite relevant to recapitulate on those aspects prior to the review of the mechanisms for achieving those performance and for their verification.

2.1 Science Pointing and Operation Requirements

The Euclid AOCS is especially driven by the pointing accuracy and stability mandated by the science observation and the science observation sequence, but is also conditioned by stringent requirements on Orbit control, safety, operation, etc.

The most demanding requirement for the AOCS is to maintain the S/C inertial pointing with a stability (Relative Pointing Error: RPE) requirement of 75 milli-arcsec during 700s, and an Absolute Pointing Error (APE) requirement of 6 arcsec normal to the instrument's boresight during science observations (both with temporal confidence Level 99.7%).

Also very relevant for the AOCS subsystem design and its verification is the specific autonomous operation during the science observation necessary for achieving the mission objectives:

- During the mission, the sky is requested to be mapped by performing small slew repointing manoeuvres between observations. For the observations the S/C is required to be inertial pointing, but slews of different types and sizes are performed regularly between observations to map various regions of the sky, and achieve the observation quality and coverage. Three slew types are necessary during science:
  - Dither slew (DS): small slews of 50+ to 100+ arcsec per axis, to be performed within a time slot of 60 seconds until recovering the RPE requirement for next observation.
  - Field Step (FS): around 1.2 degrees size with time slot of 290 seconds until new observation.
  - Large Slew (LS): other sizes of slew within the operational domain. Large slew functionality needs to be available during the science observation in order to avoid AOCS mode transition and the associated operational complication.

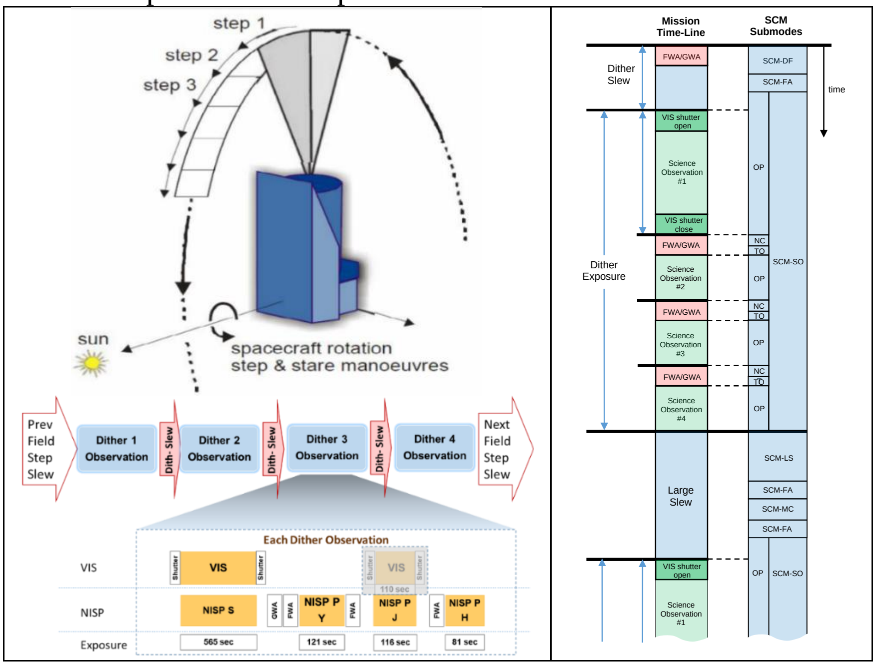

Figure 1. Representation of Euclid’s slew and science mission time-line example

- Each science observation sequence consists of four “dither exposures”, separated by a dither slew. Each dither exposure is further divided into four instrument observations. At the first instrument observation, the VIS shutter is opened and closed, generating a small dynamic perturbation, and temporarily obstruction of the FGS. RPE requirements need to be met during shutter motion.
- Prior to each of these three observations, the NISP Filter/Grism Wheel Assembly (FWA/GWA) are rotated, leading to an internal dynamical disturbance, which is compensated by the AOCS with actuation of the Compensation Mechanism Unit (CMU), via a rotation in opposite direction.

Two consecutive FWA/GWA rotations are commanded to prepare the NISP instrument at start of each dither slew and field step. Extra constrains have to be included due to the specific operation of the AOCS units as later mentioned in section 2.2.

An example of a sequence of operation is shown in Figure 1. On the left the generic telescope observation is shown, showing the general step sequences, which are decomposed in the 4 dither observations at the bottom, later decomposed as well in the exposure sequences. An example of a dither exposure is shown at the right. The subsequent large slew can be also a dither slew or a field step depending on the timeline. The active Science (SCM) submodes (section 2.3 and Figure 3) can be seen on the right, showing how they are activated in accordance with the timeline.

2.2 AOCS Hardware Architecture

Based on previous needs (section 2.1) AOCS mandates high precision sensors and actuators, together with additional robust sensor and actuators necessary to maintain the SC in stable and controlled state, and to bring the AOCS in conditions to acquire the science observation phase. The following equipment have been included in the AOCS design (see Figure 2):

- Fine Guidance Sensor (FGS): dedicated sensor developed for this mission and mounted on the VIS instrument's focal plane (see [1]). Like a narrow field of view (FOV) Star Sensor. Temporal Line of Sight (LOS) noise value of 0.015/0.03 arcsec (3σ) and 2.1 arcsec (3σ) around LOS (ALOS).
- High performing Gyros with equivalent noise of 0.028 arcsec/s (1σ) at a frequency of 10 Hz. Accelerometers (ACC) are also included for ΔV execution.
- Star Tracker (STR) are necessary for acquisition of the FGS and for application during less precise pointing.
- Cold-gas Micro Propulsion System (MPS) with variable force amplitude from 1μN to 1mN.
- Reaction Wheels (RWLs) are also included for agile and fuel-efficient manoeuvres. The same RWL unit has been also selected for the compensation of the science instruments (filter wheel) dynamic disturbance, for which a dedicated RWL is mounted (CMU).
- Sun Acquisition Sensors (SAS), Fine Sun Sensors (FSS) and Coarse Rate Sensors are used for the initial Sun Acquisition and for Safe Mode and for the SC attitude safety functions.
- Additionally, the AOCS uses and handles the RCS thrusters for the Orbit and Attitude Control during SAM, SFM, FPM-RCS and OCM and also for offloading wheels in FPM-RWL.

The on-board control functions of Euclid are implemented in SW within the central computer (CDMU) which is part of the Central Data Management Subsystem (CDMS) together with the Mass Memory Unit (MMU). The CDMU combines all the functions related to Data Handling and allows controlling and monitoring of the platform units.

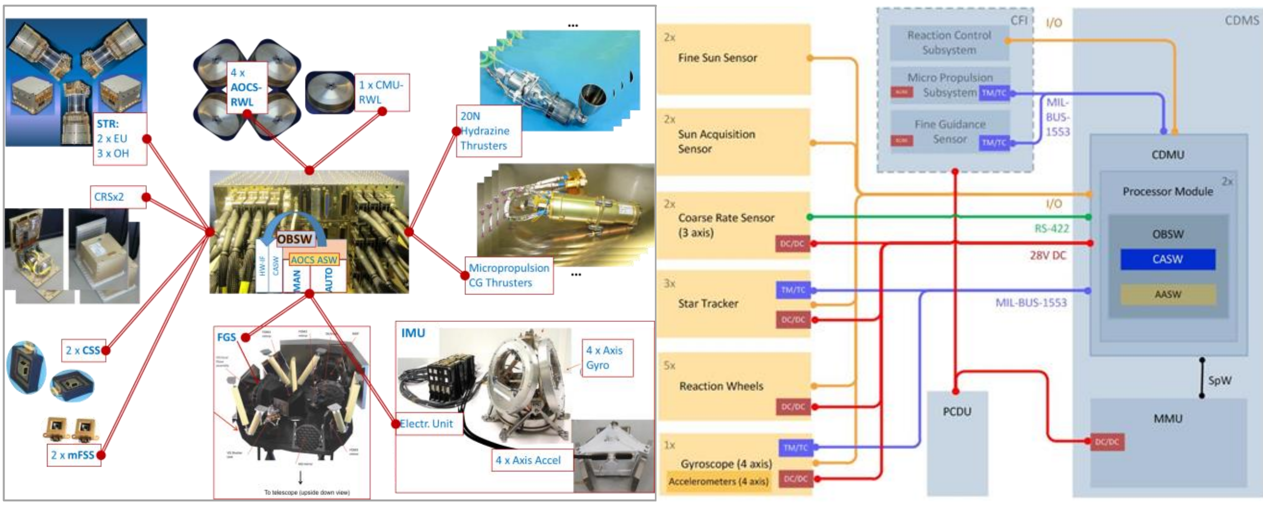

Figure 2. AOCS Hardware configuration

In relation with the hardware configuration and use, it is relevant to mention that during the science operation the AOCS is operated in a very unique way since the RWLs are maintained in stand-still during the science observations periods, and start rotating during manoeuvres to return to zero speed for resuming observation. FGS tracking is usually lost during slews and need to be re-acquired before being able to resume science. This process and in general the FGS operation is management by the AOCS ASW.

Apart from those HW components, the disturbance of various internal mechanisms belonging to the payload instrument have to be managed, in tight synchronisation of the different actions. The AOCS through its ASW is in charge of managing them, jointly with the autonomous observation sequence and associated operation as described in section 2.1.

The above operation of the RWLs and the dynamic disturbance compensation with the CMU (RWL), imply a number of start and stop operation which was never applied before. A dedicated lifetime qualification was performed for the selected RWL model, also including the characterisation of the RWL behaviour along the lifetime, in order to command accurately the RWL with enough guarantees of the evolution, even in open-loop, or during the run-down of the wheels for its stop. The process for the RWL qualification was managed by SENER with the selected unit supplier (Rockwell Collins) with the support of the customers, and in particular of TASI, as described in [3].

2.3 AOCS Functional Architecture and Logic

The following AOCS modes and submodes are implemented in the AOCS, which overall schematic is reflected in Figure 3. Table 1 show the actuators and sensors that are used per AOCS mode.

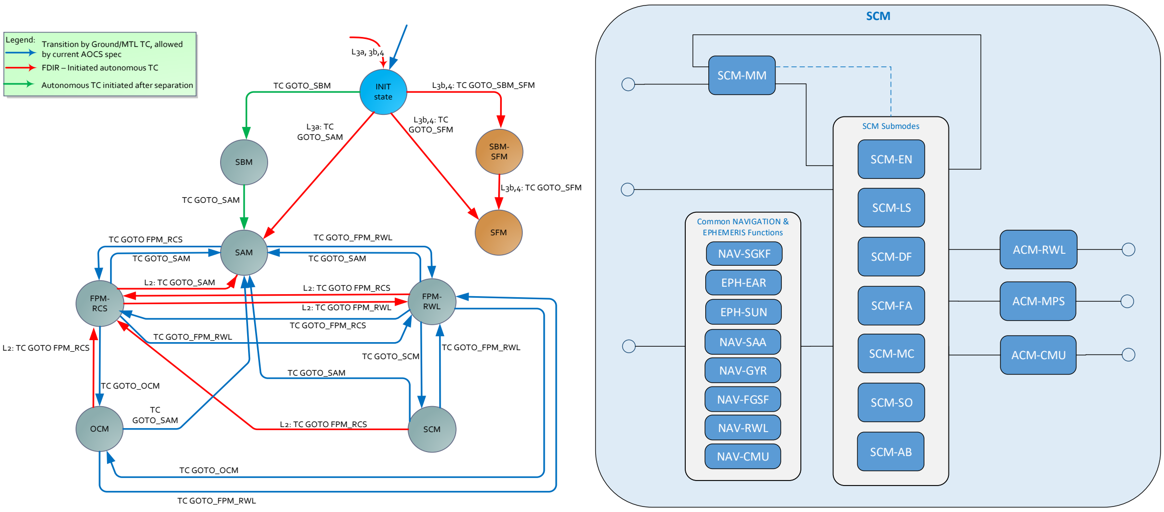

Figure 3. Overall AOCS Modes schematic and transitions(left) and SCM mode (right)

- **<u>SAM:</u>** Sun Acquisition Mode dedicated to reduce the angular rate at mode entry, and to perform the necessary slews to acquire and maintain the Sun vector such that the telescope is never exposed to the Sun. Sun search and Telescope Sun avoidance features are implemented.
- **<u>SFM:</u>** SaFe Mode is functionally the same as the SAM but fully independent, manually coded and replaces the high performing Gyro by a Coarse Rate Sensor (CRS).
- **<u>SBM:</u>** Stand-By Mode is entered for initialisation at AOCS switch-On. SBM is applied before SAM or before SFM.
- **<u>OCM:</u>** Orbit Control Mode dedicated to perform the required ΔV manoeuvres, including transfer orbits and orbital corrections. ΔV control is achieved either by evaluation of thrusters firing effect or by accelerometers (ACC) application. OCM also support a function to control the angular momentum in the RWLs supporting run-in and re-lubrication maintenance operations.
- **<u>FPM-RWL:</u>** Fine Pointing Mode based on RWLs, and dedicated to perform slews and to acquire and maintain the necessary S/C attitude, in particular to enter other modes (e.g. OCM, or SCM). This mode contains the RWL angular momentum (H)-management functions whereby the H-momentum biasing and RWL null-space may be commanded separately or simultaneously. A dedicated function for managing the CMU angular momentum is included for periodic maintenance of the CMU.

  The delicate transition to SCM is performed in this mode, which brings the RWL speeds to stand-still as well as the S/C to a minimum angular rate. A dedicated fine RCS actuation method is applied in this transition in order to minimise residuals.

- **FPM-RCS:** Fine Pointing Mode based on RCS. The pointing and slew functionalities are achieved with thrusters, still meeting the same pointing performance requirements as in FPM-RWL. Primarily used as contingency for certain FDIR situations which do not need to enter Safe Mode (SFM), the mode can be also used and will be applied to perform the slew to enter OCM before the execution of the first transfer orbit when the RWLs are not yet commissioned. High commonality with FPM-RWL is implemented.
- **SCM**: This is the Science Mode and it is by far the most complex mode (See Figure 3) and includes in itself a logic with seven submodes: 1) for SCM Entry, dedicated to reduce the residual S/C angular rate to zero (***SCM-EN***), 2) for Large Slews with RWL (***SCM-LS***), 3) for both the Dither Slew and the Field Step manoeuvres still based on RWL, and oriented to minimisation of APE at the end of the slew (***SCM-DF)***, 4) for MPS based Correction applied for small manoeuvres non-suitable for the RWLs (***SCM-MC***), 5) for FGS Acquisition after a slew or any transition (***SCM-FA***), 6) for Science Observation (***SCM-SO***), including itself substates for Transition to Observation, Observation, and NISP Compensation, and finally 7) one submode for maintaining the AOCS in stable SCM state in case of anomaly in SCM (***SCM-AB***)

Table 1: Sensors & Actuators used per AOCS mode

	RCS	RWL	MPS	CMU	STR	GYR	SAS	ACC	FGS	CRS
SBM						X	X			
SAM	X					X	X			
OCM	X	X*			X	X		X		
FPM-RWL	X	X		X*	X	X				
FPM-RCS	X				X	X				
SCM		X	X	X	X	X			X	
SFM	X						X			X

** For angular momentum biasing purposes*

2.4 AOCS FDIR

The AOCS FDIR is described in detail in Ref. [2]. The AOCS FDIR includes several levels of failure management fully managed internally, however, there is a deep interrelation with the system level safety functions via the System Safeguarding Logic (SSL) application. Apart from the local Level 0 FDIR handling, the AOCS includes Level 1 in the AOCS ASW, while the FDIR Level 2 and Level 4 functions involve the SSL SW at System Level. A Level 2 anomaly detection leads to the so-called Attitude Hold Mode (AHM) in FPMRCS, whereas a Level 4 anomaly results in SFM mode activation.

A major effort has been dedicated to the verification and validation of the FDIR functions, however, in the current paper the verification discussion is concentrated on the high performance verification of the EUCLID AOCS, and the FDIR verification is touched in its relation with that.

3 AOCS SW

3.1 OBSW architecture

One only OBSW image runs in the central CDMU computer of the SC. The generation of that OBSW requires the integration of the AOCS Application SW (AASW) with and the rest of the SC SW, called Central SW (CASW), executed in that CDMU.

The AOCS includes in itself three kinds of SW components:

- Nominal AOCS Application SW, containing the AOCS control laws for nominal modes, mode logic and the FDIR aiming at mission continuation.

- System Safeguarding Logic (SSL), containing the detection part of the FDIR ensuring the safety. This is based on measurements taken by FFS, GYROs and CRS. In practice this SSL logic is implemented separately outside the AASW.
- Safe Mode (SFM), containing the AOCS control laws ensuring Sun pointing after a severe failure triggered by FDIR.

In relation with the SW implementation process the AASW is produced with two different methods, allowing the maximisation of the advantages from both methods:

- AUTO SW: Guidance, Navigation and Control functions, including the implementation of most of the algorithms for the attitude and orbit control. Also the majority of the support functions. The SW has been implemented using the widely extended MATLAB/Simulink modelisation SW, with the systematic application of standards and rules, and allowing the usage of the autocoding functions for its implementation, its validation and qualification ([4], [5]).
- MAN SW: this is produced with conventionally coded SW and includes the interfaces with CASW (and with the AOCS units through it), performs the data acquisition, data management, commands processing, TM generation, FDIR functions, etc. Also the SFM control SW is manually coded in order to ensure independence from the nominal SW.
- The AUTO SW is first integrated with the MAN SW, prior to its overall integration with the CASW to produce the OBSW.

3.2 On-Board SW Verification

The SW versions have been organised such as to enable two separate SW generation branches (MAN and AUTO), with different approaches, and incorporating also the need of progressive and staggered development and verifications. Such process avoids risks of major problems and mistakes at the end of the process, while it allows functional and performance verification at GNC level in a Matlab environment at an early stage in the project, pre-empting this at AASW or OBSW level when the impact would be larger.

Apart from that, two major stages in the software development were foreseen:

- AASW v1: Include Nominal functionalities and performance for the AOCS and GNC SW.
- AASW v2: Incorporates FDIR and rest of functions for achieving the complete AASW.

Two additional versions were also planned:

- AASW v0: early version dedicated to the establishment and confirmation of the architecture and interfaces compatibility.
- AASW v3 (or v2f): which is exactly the same scope as v2, but incorporating the measured SC Flight Model(FM) data and properties (e.g. alignments), and the final tuning to them.

While maintaining the above stage logic, in practice, a significant number of delta versions were necessary in order to cope with the different subsystem and system needs, as well as with the incorporation of changes due to different reasons.

A major difference in this process of joint development of the AUTO-SW and the MAN-SW is the different logic and timing applicable for both of them. While the AUTO SW starts almost immediately with early and fast implementation of the SW models (prototype) and the SW behaviour and performance can be verified well before the SW itself is generated, the MAN-SW implements an strict SW development process following all steps from specification, to integration in an standard SW flow which makes the SW usable at the final part of the process. This has generated quite some advantages, but implies a clear need to adapt those different timings in a quite specific approach until the two parts of the SW are integrated. Once both SW pieces are integrated, the full OBSW is systematically tested with a complete set of SW System Tests, as performed with any other type of

SW product. Certainly, one major consideration in the joint implementation of the autocoded SW is the adaptation and matching of the timing for the different activities for the AUTOCODED SW in relation with the MANUAL SW.

3.2.1 Autocoded AOCS/GNC SW

Apart from the staggered versions, each AUTO SW version, but in particular the v1 has been developed also in an evolutive process, starting with a fast prototyping available early in the mission, and even at the start of the project. That fast prototyping has allowed a soft evolution and implementation of the majority of the GNC SW models without major surprises.

Shortly after the start of the process, the prototypes were adapted to the standard and rules applicable to it. Such early (although flexible) application of standard and rules has demonstrated to payback in the later stages. But even when the prototypes were already produced with a high standard levels, a re-elaboration and full adaptation for compliance is introduced in a final stage, in order to ensure proper generation according to the project needs, and adequate automatic documentation and SW accommodation to the formal rules. During the whole process the prototypes are completed and complemented with additional functions whenever necessary ensuring the availability and capability to apply the AOCS SW models during the whole AOCS development.

The above situation has allowed the application already at PDR of the same AOCS SW models to be applied later in the project, ensuring a design validation consistent with the (same) models which are later implemented and tested. This generates a great advantage in the avoidance of risks and unexpected surprises during the implementation and verification of the AASW.

Taking advantage of that situation, the AUTO SW has been submitted to a systematic unitary and integration testing process, involving both the SW models and the autocoded SW, which allows to guarantee a complete matching between the results in the SW models and in the SW itself, confirmed also with the execution of the equivalence tests dedicated to that. It becomes relevant to mention that the process was able to highlight the appearance of minor numerical differences during the autocoding, which causes were properly identified and by certain means, differences have been avoided having finally obtained fully identical results with models and with AUTOCODED SW, a task which was really demanding. Withing this process a 100% coverage has been obtained and a systematic verification of all SW standards and metrics has been systematically verified.

3.2.2 General and Manual AOCS/GNC SW

The Manual SW follows a quite standard SW development approach, with staggered and iterative process, including unitary and integration testing, however, the MAN SW process is also conditioned by the AUTO SW development, especially in relation with different interactions between MAN and AUTO, more intensely during the integration of both parts. Considering that many of the implemented functionalities are obtained in those two separate processes, each one with its own logic and sequence, the development has required an intense coordination and cooperation. Once both products are integrated in the AASW they are integrated with the CASW which is developed in parallel, but outside the AOCS.

The AUTOCODED SW is received within the AASW SDE with the application of dedicated numerical tests, in which the same results obtained during the autocoded SW are obtained by numerical comparison, being this process repeated for any later version of the SW. After the integration of all software components the AOCS software is exposed to systematic SW System Tests, allowing the release for the subsystem verification.

4 AOCS VERIFICATION APPROACH

Further to the identified staggered approach applied to the Subsystem SW implementation, the AOCS verification at AOCS level is also performed with several methods and levels of complexity.

As for most of the space systems verification, one important aspect of it is the difficulty for reproducing on-ground the environment that the subsystem has to experience in flight allowing sufficient representativity for ensuring the achievement of the objectives. That difficulty is sometimes overcome with approximate reproduction on-ground of those space conditions, however, in our case the verification has to arrive to pointing and stability levels in which the dynamic environment, microgravity, and dynamic isolation makes mandatory to find alternative ways of verification.

In the case of Euclid the highest levels of fidelity in relation with the space environment can only be achieved by means of precise SW simulation, and this has been decided to be achieved by application of High-Fidelity simulators.

Assuming that the simulation is the only suitable way to achieve those levels of performance, the remaining consideration is how to ensure that those performance verified at simulation will be maintained in flight (and with the real HW is in the loop). The following considerations apply:

1) A HiFi Simulator with a detailed and well validated simulation environment, and with precise and well validated SW models for the HW units, can achieve the highest levels of representativity of the AOCS behaviour in terms of performance. In such an environment, the application of GNC models (models of the GNC SW) is fully suitable and representative, since the same models will later be used for the SW generation (autocoding) with exactly the same numerical performance. Those High-Fidelity Simulator models are later applied into the Real Time Simulator (RTS) to be used for the verification of the complete OBSW when installed either in a SW model of the CDMU or in the different CDMU HW models applied for the AOCS validation environments.
2) RTS is applied to the remaining AOCS verification facilities when using the complete OBSW (section 5). However, when the HiFi models are applied in the RTS with the real OBSW mounted in the corresponding CDMU models, certain constrains appear, for instance in the simulation frequency or in the interactions between OBSW and Simulator (e.g. commands feedback to dynamics, synchronisation of operations with OBSW actions and commands with SC dynamics response). Also the RTS implies a major increase of resources which makes difficult to apply it in massive statistical verification by simulation, as necessary to validate the required pointing performance. In those cases, and even more when the cases of HW Units in the Loop, with the incorporation of dedicated EGSE for the generation of the units stimulus introduce, new disturbance/delays in the measurements and actuation make the simulation less accurate than the one obtained within the High Fidelity Simulator.

Highest fidelity in the reproduction of the space environment is achieved within the simulator in 1) running in a SW model based environment, while the rest of the facilities using the RTS in 2) provide a more representative behaviour in terms of HW/SW-SW interactions, tasks timing and operations.

The right combination of those characteristics is necessary for an adequate and reliable verification and validation of the AOCS. The approach followed in Euclid SC is:

- Functional and performance verification for each individual modes and functionalities, to be systematically and statistically achieved within the High-Fidelity Simulator (bullet 1 before). This verification is especially concentrated on the individual modes, and the achievement of the transitions performance and functional conditions. The transition between modes are also simulated although they are not fully representative, due to the absence of accurate CDMU, MAN SW and CASW SW models in this environment. Especial effort is dedicated in guaranteeing the achievement of the transition conditions, and the modes behaviour with realistic initial conditions.

- Functional verification, including all modes and submodes transitions and for the different operational scenarios are verified with the RTS in environments including MAN and CASW and with CDMU models at several levels (HIL) of SW-SW, SW-HW and HW-HW interface representativity.
- The performance requirements are then confirmed to be achieved by adherence to those requirements, comparing the results in both type of tests, while incorporating the RTS and the OBSW (e.g. SW-SW, SW-HW and HW-HW IF representative environments).

5 FACILITIES AND ITS APPLICATION

The following environments are applied during the AOCS process:
- Design Environment. This environment is used as a flexible and fast design tool, it is also used in the early stages of the design verification and for unitary testing of models. With this environment we ensure that only minor discrepancies will later appear in most of the cases, however, results obtained in this environment need to be later confirmed in formal verification environment.
- **ESE** (Engineering Simulation Environment): High-Fidelity simulator is ensured to reproduce with the highest necessary accuracies every different aspect, in particular dynamics, environment, interfaces, HW units characteristics, Units performance, delays, operation sequence, and in general the whole process in flight. The representativeness and fidelity of the SC and Units simulation models is ensured by a thorough and systematic evaluation against dedicated model validation inputs provided by each element responsible party (e.g. unit suppliers).
- **SVF** (Software Verification Facility)**:** the AASW is installed fully integrated with the CASW into the complete OBSW, and include all interactions with the rest of the CDMU SW. Here all the SW-SW interfaces are verified, including also the Ground Segment (GS) Operational environment, by incorporation of a representative version of SCOS2K, TC and TM definition, and the corresponding System DataBase. The OBSW is fully representative, however, the HW and the interactions HW-SW are simulated with the limitations associated to the models of the HW-SW interactions, which may drive the real behaviour of the AOCS in certain aspects. Also constrained by the limited interaction capabilities between RTS and OBSW (e.g. RCS and other dynamics perturbations generated by the OBSW are incorporated to the RTS via special mechanisms, introducing deviations with respect to the ESE). This environment allows a very good verification of the OBSW internal SW-SW IFs. In terms of performance, the environment is used to "confirm" that the results obtained with the high-fidelity simulator remain valid when the SW is fully integrated.
- Hardware in the Loop Testing Environments. Three levels of verification are applied:
  - **HILF** (Hardware in the Loop Facility). This environment includes the CDMU (non-redundant), AOCS SCOE with the AOCS RTS models and all the HW-SW interfaces associated with it, and consequently is fully representative of the internal CDMU processes and timings, allowing the detection of any effect derived from such interactions, sequences and timings.
  - **AVM** (AVionics Model). This environment includes a fully redundant CDMU and engineering models for all the avionics, including in particular the AOCS ones, next to the AOCS SCOE RTS models. This allow the AOCS verification with all the HW-SW interfaces associated with it, and consequently introduces all the HW-HW interfaces in the loop, allowing the detection of any unexpected effect or conflicts.
  - **PFM** (Proto-Flight Model). The PFM environment includes the complete SC, involving all HW and SW elements including redundancies and the AOCS SCOE. This was nominally intended for the AOCS acceptance, however, the verification of certain aspects involving reconfiguration of nominal to redundant units and branches is performed also here.

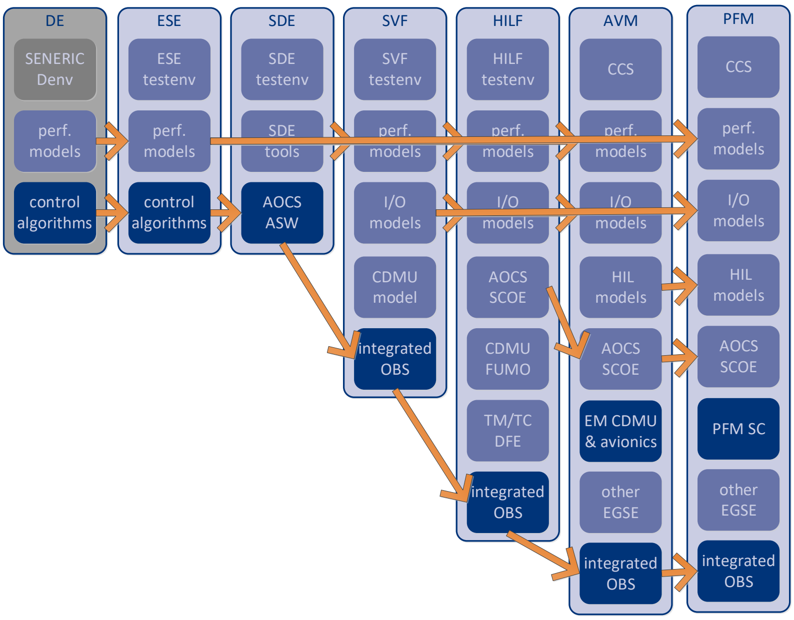

Figure 4. AOCS environments and elements flow

While the highest fidelity in the reproduction of the space environment is achieved within the HiFi ESE, the most representative reproduction of the SW-SW interactions is achieved with the SVF, the HW-SW interaction with the HILF, and the HW-HW interaction with the AVM and with full redundancy representativeness and external HW environment with the PFM model. An adequate combination of the different facilities allows a complete, robust and efficient verification of the AOCS, while the different components evolve and are reused as reflected in Figure 4

Regarding the AOCS verification, it includes the following verification types and tests:

- Functional Verification, mainly verified with dedicated Mode Test, jointly with Signature tests.
- Performance Verification. Although the objective is different, the Performance and functional verification are jointly performed due to the deep link among them in certain operations.
- Nominal Operation (Flight Operations Procedure=FOP) and Contingency Operation (Contingency Recovery Procedure = CRP).
- FDIR: FDIR checks and recovery actions at L1, L2 failures testing and L4 failure testing.
- Confirmation/Non-regression: obtained with signature tests which include a complete set of main functionalities for each mode, also with performance evaluation scenario to ensure consistency over the different facilities and with the different OBSW version used in time.

Table 2: Scope and map of verification and facilities

Testing	Des. Env.	ESE	SVF	HILF	AVM	PFM
Functional	Each function	Modes, functions & transition	Each mode & transition	HW-SW relevant	HW-unit relevant	Nom. & Red. branch/units
Performance	All critical	Each GNC Perf. figure	SW-SW Adherence	HW-SW IF adherence	HW-HW IF adherence	Adherence in Special cases
FDIR	Specific functions	Singular cases	Each FDIR fail-recovery	All L2 & L4 situations.	Most L2, L4 situations	Specific L2, L4 cases
Operation			All FOP & FCPs	Relevant FOP & FCPs	Specific FOP & FCPs	Specific FOP & FCPs
Signature / Regression		Sync/compare with SVF	Every mode / submode and function	Every mode / submode and function	Every mode / submode and function	Every mode / submode and function

6 The extent and application of those verifications is reflected in Table 2. The selection and mapping of the tests and facilities to be applied is a critical aspect involving the System Engineering and the affected disciplines, to evaluate the involved IF, HW features, and the relevant changes included in the corresponding version being tested.SPECIFIC AREAS OF INTEREST IN THE VERIFICATION

6.1 AOCS Functional and Performance Verification in ESE

The core of the highly demanding performance verification is achieved with testing at ESE level. Testing was initially performed with the preliminary SW models at AOCS PDR, and was later complemented and confirmed at AOCS CDR with validated SW models of the HW units and consolidate SW models for the GNC SW. Verification was subsequently updated until AOCS Qualification completion.

In order to achieve the complete verification and validation, a test plan was introduced with a systematic identification of the different types of functions and transitions present in the AOCS, and with the elaboration of dedicated tests, in order to maximise the return in the verification with the limitation in time. A full map of coverage of functions and transitions was used and checked for 100% coverage. The following type of tests were applied in the AOCS-AUTO SW verification in ESE:

- Representative Tests: AOCS modes mainly in nominal scenarios. Cover all the code paths/branches (i.e. functions, modules, methods). Some test cases for specific functionalities verification and/or design robustness are also included.
- Worst-Case Tests: Verify AOCS modes in worst-case scenarios. Selection of worst case configuration is performed by engineering analysis and assessment in the team, for parameters affecting the verified condition. Selection of verification by worst case, is a delicate issue.

Table 3: EUCLID Functional and Performance Verification in ESE

Type / Cases	Test	Runs	Each run(s)	Total (s)
Representative	Each Mode and Function.	22	800 to 7 000	40 900
Worst Case	SFM, SCM-MC, FPMRWL-LS, OCM Large Delta V	14	600 to 6 500	15 000
Montecarlo	SAM & SFM separation, FPMRWL to SCM, OCM of different sizes	2700	300 to 8 000	3 500 000
Confidence	SCM-SEQ, SCM-LS, FMPRWL-Hbias, FPMRCS-LS	401	2 000 to 16 000	2 500 000
Long Tests	SAM, SFM and FRPRWL	4	45 000	180 000

- Confidence Tests: applied when worst case configuration cannot be clearly discriminated (frequent situation). Those tests are intended to introduce a limited parametric variation of certain conditions/parameters, avoiding the massive statistic simulation of MonteCarlo tests.
- MonteCarlo Tests: implement a random variation following probability density functions, for a priori un-known and relevant parameters, such as to obtain statistics of the performance. Depending on how demanding the performance achievement is, the parameters probability distribution and the level of confidence, the number of runs are seleted.

During the tests plan and its specification, the separation between Confidence tests (parametric variation) and Montecarlo became weaker than anticipated. Finally the main difference has been the number of runs which is smaller, but still large. To be noted that the Confidence tests in SCM sequence include several observation periods, which allow to extract and combine them for the elaboration of the statistics, generating a more comprehensive amount of data for such statistics. Some relevant performance results can be seen in Figures 5 [pointing (APE)], 6 [stability (RPE)] and 7 [RPE statistics].

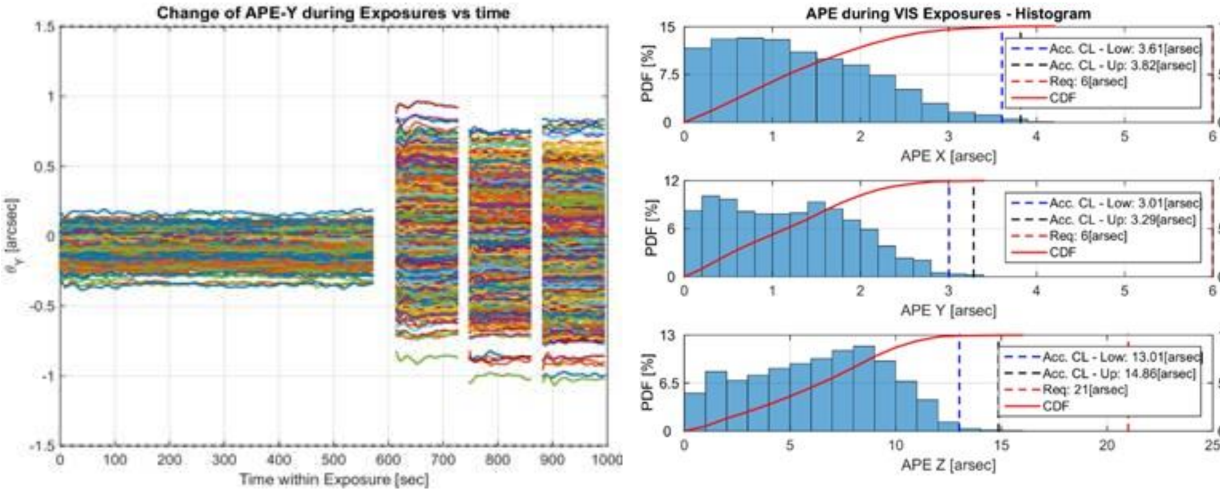

Figure 5. APE (pointing) performance achieved in the Montecarlo simulation for the VIS exposure

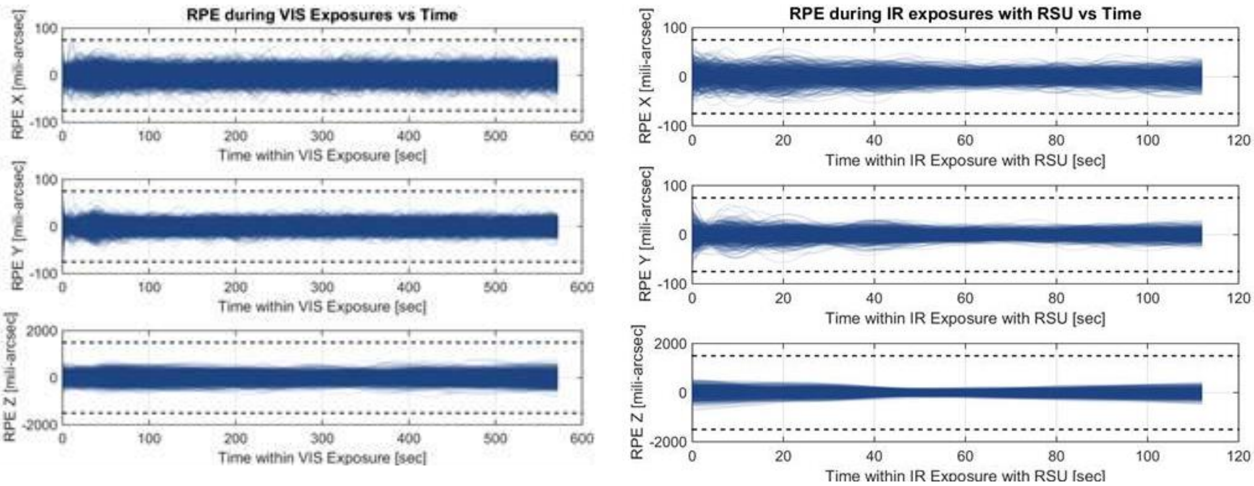

Figure 6. RPE (Stability) performance achieved in the Montecarlo simulation for the VIS exposure

The confidence level (CL or accuracy determining the percentile 99.7%) can be derived as function of the number of cases exceeding the requirement (i.e., the number of failures):

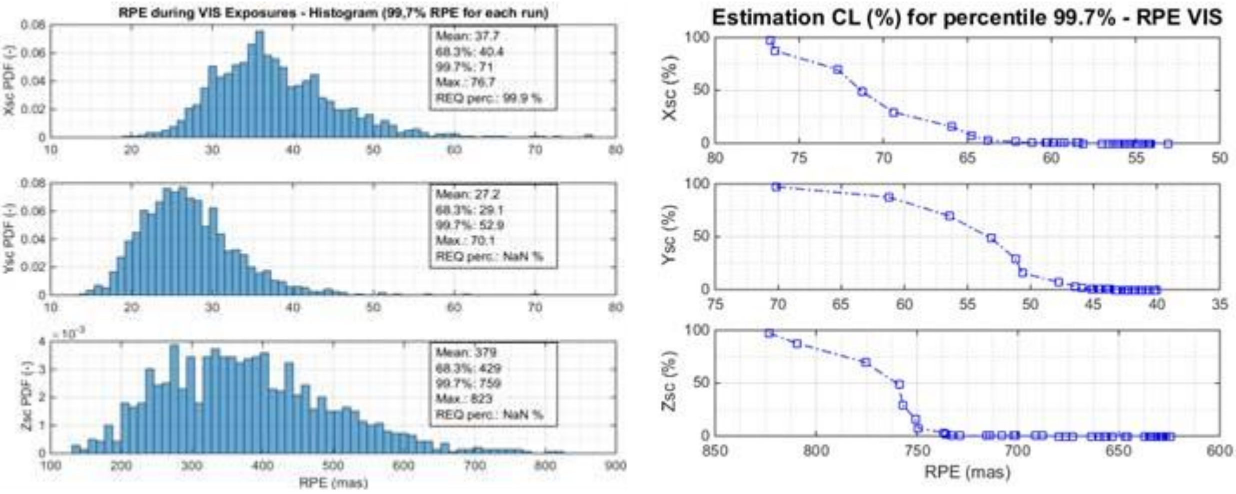

Figure 7. RPE statistics and estimation of the confidence level from failed cases for VIS exposure

6.2 Verification of the complete AOCS

While performance are mainly verified in ESE (as well as most of the modes functionalities, individually considered), the great majority of the AOCS requirements are verified using the complete OBSW integrated in the CDMU, either in a SW model of it or in a HW model.

The SVF is the first and main facility for the requirements validation whenever the HW-SW IF´s or the HW units involvement is not specifically relevant. In SVF the CDMU and all the HW units are replaced by the SW models.

In those cases when the HW-SW interface or the units IFs may be relevant, the tests are first exercised and debugged in SVF, but the requirements are closed in the HILF. In HILF all the relevant functionalities and performance are also verified for adherence, including:

- Signature Tests
- Most relevant Mode tests, including SAM, SCM-Long Duration, FPMRWL, OCM, FPMRCS
- FDIR reconfigurations and anomalies for Level 2 and Level 4 (L2/L4)
- Operations for alternative Transitions, Contingency Procedures, Orchestra.

Tests when HW units and/or its physical IF are relevant, they are also run in AVM. A number of AOCS closed-loop tests were also executed in PFM (full redundancy & reconfiguration):

- Units reconfiguration in AVM
- Direct actuation operation with redundant unit, and Operations of the FGS unit in AVM
- FDIR Level 2 (Subsystem reconfiguration), anomaly handling in AVM and PFM
- FDIR Level 4 (System reconfiguration to SFM) in AVM and PFM

Table 4: EUCLID number of tests in each facility with complete OBSW

	SVF	HILF	AVM	PFM
Mode Tests	7	3	2	2
Operations	13	3	5	3
FDIR	52	27	24	21
Signature	10	10	10	10

7 AOCS PERFORMANCE VALIDATION RESULTS

The performance obtained in the ESE have been systematically evaluated against the performance and some examples of the results are presented in section 6.1

The same performance functions have been exercised in the SVF and in the HILF with Mode and Signature tests with dedicated periods for collection of obtained results, and performance have been compared with those obtained in the ESE for the same test cases. The comparison has allowed to identify the main reasons of the small variations observed, due to the limitations in the OBSW interaction and the models stimulation (as expected), and even when explained, differences are small enough to remain within performance requirements.

The results presented in Figure 8 show a non-identical but fully equivalent behaviour (to be noted the scales of the differences). One effect generating significant differences is the time of command execution, which cannot be precisely determined a-priori when using the SVF Operational SW for commanding the OBSW. That effect generates that the different operation, and in particular the commanded transitions of modes, execution of manoeuvres, etc, happen in different times than those in the ESE, as well as the desynchronisation associated to the other effect discussed in previous sections of this paper. In order to overcome the larger differences generated by those timings, the

ESE tests had to be revisited and re-aligned for better synchronisation in its execution, but still with the deviations shown in the figure 8.

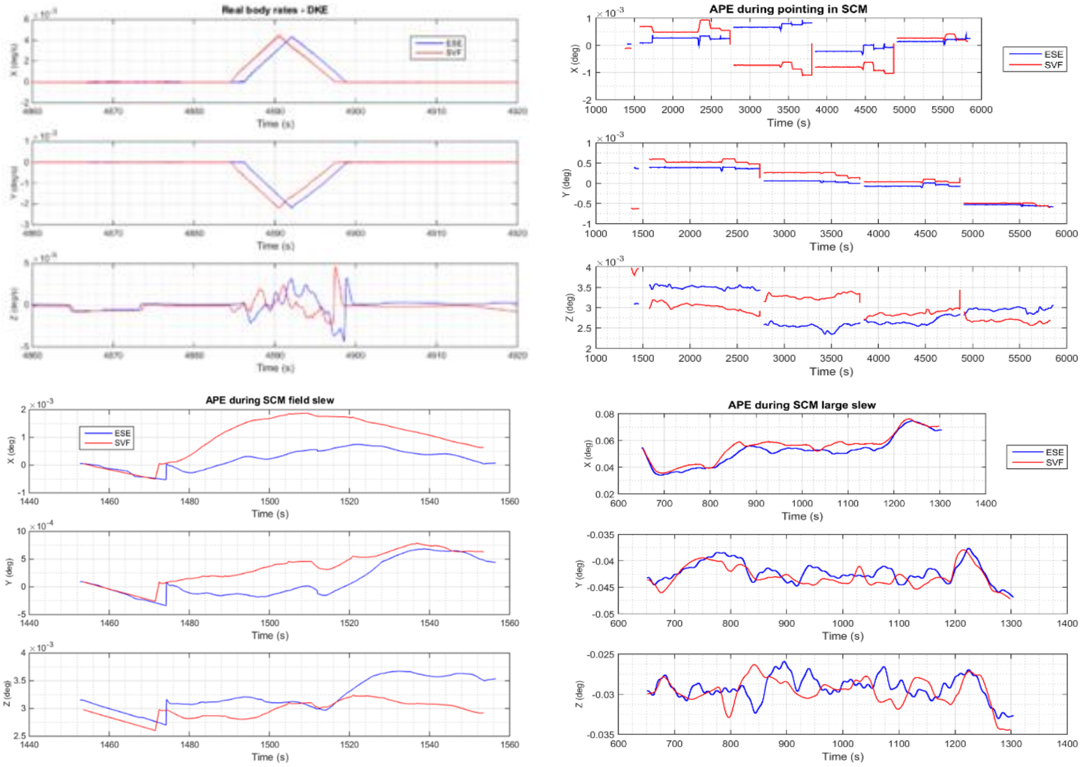

Figure 8. Parallel representation ESE and SVF. SC rate during a dither (upper-left), APE during science(upper-right), APE during field slew(lower-left) and APE during large slew (lower-right).

8 CONCLUSIONS

Euclid mission and its AOCS is extremely demanding in terms of performance, and in particular pointing stability and accuracy, and combined with the science operation needs it has generated an AOCS with a wide variety of configurations, situations, and functionalities to be implemented, most of them linked to the achievement of those very challenging performance.

Under those considerations and taking into account the limitations of the ground verification environments, a combined and staggered approach was necessary in order to guarantee the proper execution of all the functionalities necessary to arrive to the observation conditions, and then to verify the pointing and stability performance.

In order to achieve this, an optimum combination of conventional (Manually coded) Software, and Autocoded SW has been implemented, allowing the staggered and incremental verification starting with a High-Fidelity but simulated environment (ESE) up to the most complete all HW in the Loop environment (PFM), passing through intermediate partially HW-In-the-Loop, and ensuring a continuity of verification results, and proper equivalence of the results being obtained in each of the test facilities. A massive verification has been performed in the ESE, from which some extracts have been shown in section 6, while its applicability when the models are replaced by the HW has been demonstrated along the verification process, and some examples have been shown in section 7, allowing to ensure that the requested performance will be achieved in flight.

In summary Euclid AOCS has been demonstrated to achieve those levels of performance with completely qualified HW units, and AASW integrated in the OBSW.

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