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# READY ADCS: a family of ADCS products for a wide range of platforms and missions

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*ABSTRACT*

**The READY ADCS product family consists of an off-the-shelf turnkey ADCS solution for 6U/16U to micro and mini sats platforms. It guarantees high precision, stability and agility in a mass/power/volume efficient package. Its core architecture, based on Skylabs NanoOBC-hpm, provides high reconfigurability and flexibility for a wide range of LEO Earth Observation missions, extendable to Communication or In-orbit Servicing missions and to GEO. Through an extensive catalogue of PUS services, the READY ADCS product is fully commandable and parameterizable from ground and/or platform OBC, and its telemetry is fully accessible and configurable. The READY-200 product (designed for miniSats from 150 kg to 400 kg) is being qualified up to TRL6 in the frame of SAT4EOCE ESA co-funded activity, with a first flight already booked in 2026 in the DRACO mission (Destructive Re-entry Assessment Container Object). Exploiting the heritage from READY-200, reconfigurations are on-going to make the product fully European, and missionize/qualify it to microSat, 16U and 6U use cases. An IOD mission is planned along the second half of 2025 to enhance the TRL of the product to 8/9.**

**Keywords:** ADCS product; European technologies; High performance ADCS; Reconfigurable ADCS;

# Acronyms

| | |
|---|---|
| ADCS | Attitude Determination and Control System |
| AKE | Attitude Knowledge Error |
| AMM | Angular Momentum Management |
| APE | Attitude Pointing Error |
| APR | Automatic Performance Reserve |
| ASW | Application SW |
| BCR | Battery Charge Regulator |
| CAN | Controller Area Network |
| CDHS | Control and Data Handling System |
| CL | Confidence Level |
| DKE | Dynamics and Kinematic Environment |
| DIAS | Data and Information Access Services |
| DRACO | Destructive Re-entry Assessment Container Object |
| DRB | Delivery Review Board |
| DVF | Development and Validation Facility |
| E-ADCS | European ADCS |
| ECU | Electrical Control Unit |
| EO | Earth Observation |
| EPS | Electrical and Power System |
| FDIR | Fault Detection Isolation and Recovery |
| FES | Functional Engineering Simulator |
| FIFO | First In First Out |
| GBDX | Geospatial Big Data |
| GEO | Geostationary Orbit |
| GNSS | Global Navigation Satellite System |
| GS FB | Gyro-Stellar with Feedback |
| HIL | Hardware In the Loop |
| HP | High Performance |
| HPM | High Performance Microcontroller |
| HW | Hardware |
| IOD | In-Orbit Demonstration |
| IOS | In-Orbit Servicing |
| IOT | Internet Of Things |
| ITAR | International Traffic in Arms Regulations |
| LCL | Latching Current Limiter |
| LEO | Low Earth Orbit |
| LLA | Latitude Longitude Altitude |
| MIL | Model In the Loop |
| MoI | Matrix of Inertia |
| MTQ | Magnetorquer |
| OBC | On-Board Computer |
| PCDU | Power Conditioning and Distribution Unit |
| PIL | Processor In the Loop |
| P/L | Payload |
| PPD | Primary Power Distribution |
| PPS | Pulse Per Second |
| PUS | Packet Utilization Standard |
| RPE | Relative Pointing Error |
| RTI | Run-Time Infrastructure |
| RTU | Remote Transfer Unit |
| SCM | Scenario Mode |
| SIL | Software In the Loop |
| SM | Supervisor Module |
| SPD | Secondary Power Distribution |
| SSO | Sun Synchronous Orbit |
| SSW | Service SW |
| SW | Software |
| TC | Telecommand |
| TLE | Two-lines Elements |
| TM | Telemetry |
| TRL | Technology Readiness Level |

# 1 READY-200 Product

## 1.1 Introduction

In the frame of the ESA InCubed co-funded activity SAT4EO Critical Elements (SAT4EOCE), DEIMOS is developing and qualifying up to TRL6 READY-200 (Figure 1), a standalone ADCS product for miniSats Earth Observation LEO missions. The use case for this development and qualification is Sat4EO, the DEIMOS end-to-end solution for Very-High-Pointing/Stability EO missions. READY-200 is developed and qualified in two different versions, a core variant (meeting the needs of most of EO missions) and a high performance (fulfilling more performing pointing and stability requirements).

Exploiting the heritage from this first development, and thanks to the high flexibility of its architecture, new ADCS products based exclusively on European technologies are being developed and qualified in the frame of an extension of the abovementioned InCubed activity, to missionize the READY ADCS to different platforms (from 6U/16U cubeSats to microSats) and missions (e.g. Communications, Internet of Things, In-Orbit Servicing, etc.) in LEO or GEO orbits.

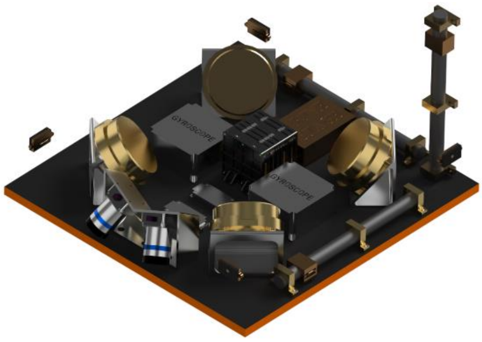


**Figure 1: READY-200 product**

The resulting READY ADCS products family will therefore be able to serve a very high range of customers interested in a plug-and-play ADCS for their missions, providing mass/power/volume/cost-efficient alternatives to non-European (e.g. 7, [2]) or European (e.g. [3], [4]) solutions.

### *1.1.1 SAT4EO use case*

Sat4EO is a complete End-to-End Earth Observation System including all its segments (i.e. Flight segment, Ground segment and User segment) to be commercialized as a single satellite, or as a constellation mission. Sat4EO could also be used as a completely autonomous and independent EO system, or as part of a larger EO ecosystem, as it is intended to be interoperable with other EO systems and platforms (e.g. DIAS, GBDX, etc). Figure 2 below illustrates the Sat4EO spacecraft and the complete end-to-end System, being the ADCS one of the critical elements developed under the Sat4EOCE-InCubed activity together with the EO Imager Payload, the On-board Image Processing, the On-ground Image Processing and the Exploitation Platform, a powerful solution to produce a vast catalogue of different services and applications easily tailored by the platform user.

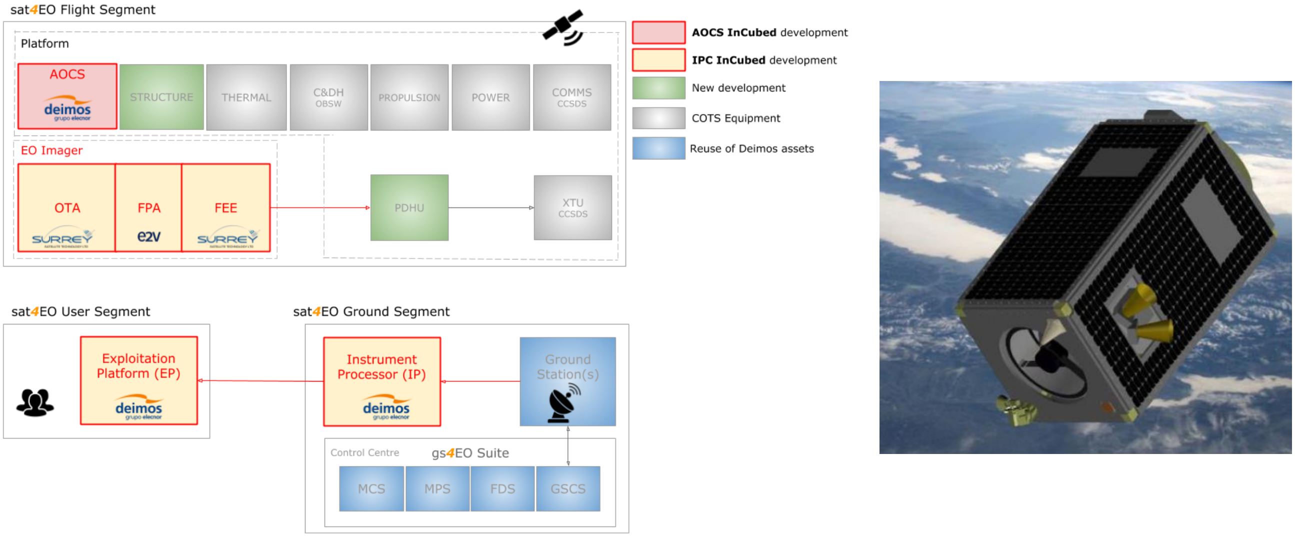



**Figure 2: Sat4EO System Architecture (left) and spacecraft (right)**

### *1.1.2 Envelope and reconfiguration levels*

The READY-200 product envelope is reported in the Table 1 below.

**Table 1: READY-200 product envelope**

| Category | Characteristic | Value |
|---|---|---|
| Orbit | Type | SSO<br>Polar |
| | Altitude | 400 – 600 km<br>300 – 800 km (level of ADCS reconfiguration to be evaluated on a case by case basis) |
| MCI | Principal Moments of Inertia | up to 75 kg*m^2 |
| | Product of Inertia | Up to 5% MoI |

Starting from READY-200 development and qualification, valid for the abovementioned envelope, the following reconfiguration levels have been defined.

**Table 2: READY-200 product reconfiguration levels**

| | **Description** | **Delta Development/Qualification** |
|---|---|---|
| **Level-0** | The ADCS Product meets the client requirements with an existing parameter set.<br>There is no change on the HW platform baseline (ADCS Units, OBC, communication interfaces) nor on the SW baseline (SW and parameters). | No delta qualification is required. |
| **Level-1a** | The ADCS Product meet the client performance requirements just adapting the tuneable performance parameters.<br>There is no change on the<br>• HW platform baseline (ADCS Units, OBC, communication interfaces).<br>• ADCS SW Functionalities, middle layer or HW interface layer<br>• ADCS Safe Mode and FDIR<br>Retuning to improve performance is considered a level 1-a configuration to be done on demand. | Delta qualification is limited to the Model In the Loop and dedicated analyses (eg stability analysis, freq. domain analysis, …) |
| **Level-1a** | An ADCS HW unit needs its qualification extended to meet the client requirements.<br>No change to the ADCS SW (parameters, code or interface) is required. | Delta qualification is limited to the delta qualification of the ADCS HW unit. |
| **Level-2** | The ADCS algorithms must be changed to meet the client requirements.<br>There is no change on the<br>• HW platform baseline (ADCS Units, OBC, communication interfaces).<br>• HW interface layer<br>• ADCS Safe Mode and FDIR | Delta qualification will range from MIL to HIL depending on the customized items in the ADCS SW |
| **Level-3** | The ADCS product must be updated with a change on any of the<br>• HW platform baseline (ADCS Units, OBC, communication interfaces).<br>• HW interface layer<br>• ADCS Safe Mode and FDIR<br>This change does not require a modification of the ADCS architecture | Delta qualification will range from MIL to HIL. |

### 1.1.3 *Performance*

The pointing performances which can be achieved by the READY-200 product are summarized in Table 3, based on a reference mission scenario for a maximum MoI configuration of 75 kg.m^2.

**Table 3: ADCS product pointing performance (reference mission scenario)**

| Error | High Performance Variant (3σ) | Core Variant (3σ) |
|---|---|---|
| AKE | 0.005 deg | 0.007 deg |
| APE | 0.006 deg | 0.017 deg |
| Attitude rate error (RPE) | 1.8 arcsec/s | 4 arcsec/s |

## 1.2 Architecture

### 1.2.1 *Avionics*

The following Figure 3 and Figure 4 show the main elements of the READY-200 avionics, and the external data and power interfaces with the platform OBC and the EPS subsystem respectively, which makes the READY-200 an easy to be integrated, plug-and-play product. The only external data interface is a CAN bus connection (one nominal and one redundant) and a PPS line for time synchronization over an RS422. Concerning power, standard 5/12/28V interfaces are used.

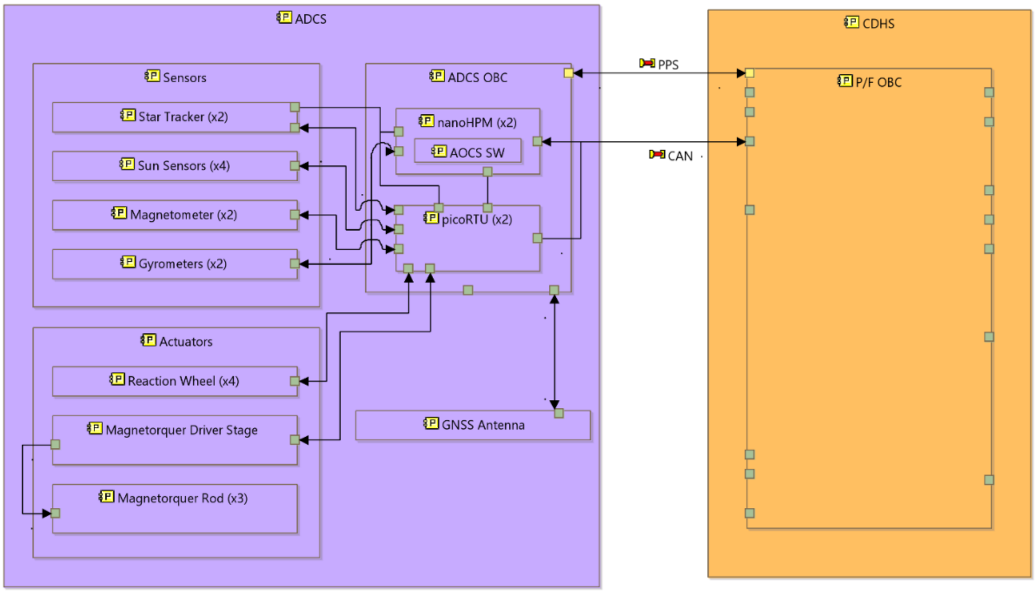



**Figure 3: Main elements of READY-200 architecture and external data interfaces**

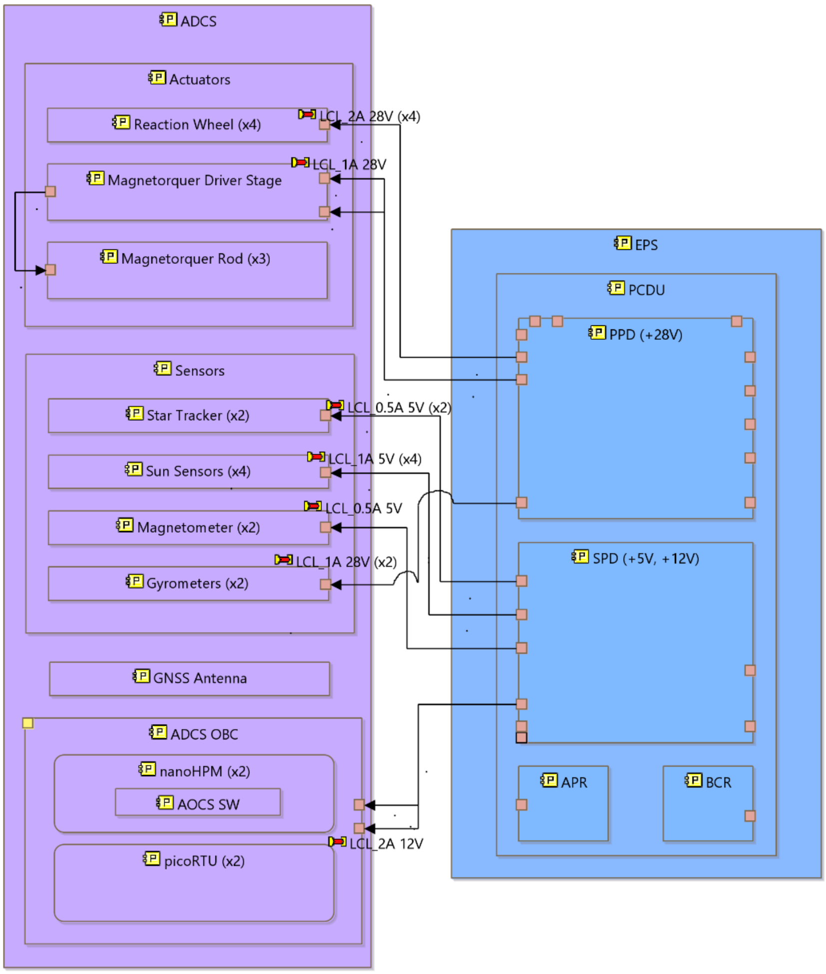



**Figure 4: READY-200 Power Interfaces**

### *1.2.2 OBC and Remote Transfer Unit (RTU)*

The core element of the READY-200 architecture is the Skylabs NANOhpm-obc (Figure 5), a high-performance microcontroller in a single-board computer providing a versatile design in terms of variety of resources, extension possibilities and available interfaces. The equipment itself can be used as a single board computer, or in dual or even multiple redundant configurations. The NANOhpm-obc integrates SM, which is supervising operation, gathers critical housekeeping data and performs a reconfiguration, in case of a serious anomaly. The NANOhpm-obc is highly reconfigurable module, with possibility to store different functions, with respect to SW images. NANOhpm-obc enables also reconfiguration of the function during flight or even uploading new SW or patches of the nominal on-board software.

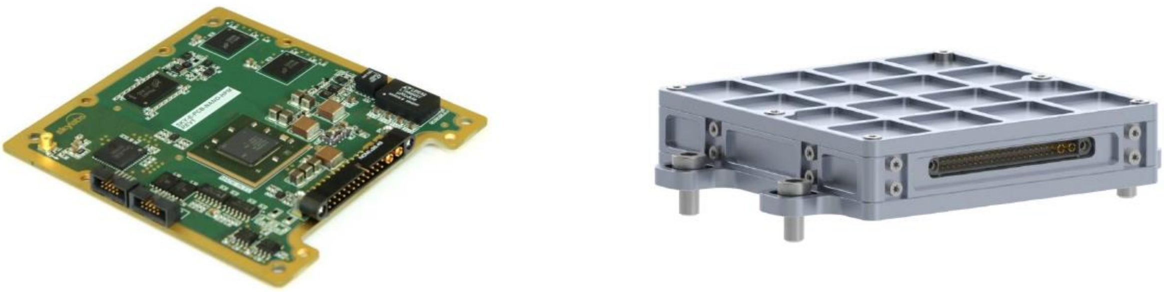


**Figure 5: NANOhpm-obc board (left), standalone NANOstack unit (right)**

NANOhpm-obc interface capabilities are enhanced through two picoRTU systems (one base + one digital, Figure 6). The basic purpose of picoRTU is monitoring digital and analogue signals from different spacecraft equipment and transmitting them to the on-board computer upon request. The picoRTU showcases the use of modern design techniques and components in the context of a Satellite On-Board Data Handling system, facilitating higher modularity and interoperability of satellite components and reducing development and verification time and cost. For this purpose, an innovative distributed architecture of picoRTU units and common RTI has been developed. The RTI uses a common, high-throughput fault tolerant and fail-safe CAN bus to connect all picoRTU units into a common RTU network. The use of a common network facilitates modularity and also enables various types of redundancy (either at the system or at the unit level) that is seamlessly integrated into the network concept.

**Figure 6: picoRTU board**

### *1.2.3 ADCS units*

The selected HW baseline is presented in Table 4, for the high performance and core variants full redundant configurations. The only difference at HW level between the two versions is the gyro, where a lower performance/lower cost unit is selected for the core variant. As shown in the table, almost all the HW is manufactured in Europe and therefore free from ITAR restrictions. A full European version is being implemented in the frame of an extension of the SAT4EOCE activity.

**Table 4: ADCS Product HW baseline**

| Unit | Quantity | Redundancy | Core Variant | HP Variant | European |
|---|---|---|---|---|---|
| OBC/RTU | 2 | 2 cold redundant units | X | X | Yes |
| Solar Sensors | 4 | 2 cold redundant pairs | X | X | Yes |
| Magnetometers | 2 | 2 cold redundant units | X | X | No |
| Star Trackers | 2 | 2 hot redundant units | X | X | Yes |
| Gyros HP | 2 | 2 cold redundant units | | X | Yes |
| Gyros Core Variant | 2 | 2 cold redundant units | X | | Yes |

| Unit | Quantity | Redundancy | Core Variant | HP Variant | European |
|---|---|---|---|---|---|
| GNSS | 2 | 2 cold redundant units | X | X | Yes |
| Reaction Wheels | 4 | 4 hot redundant units | X | X | Yes |
| Magnetorquer | 3 | 3 units each with redundant coils | X | X | Yes |
| MTQ Electrical Control Unit | 1 | 1 internally redundant unit | X | X | Yes |

### *1.2.4 ADCS modes and algorithms*

The ADCS product modes aim to cover a wide range of scenarios:

1) Detumbling
2) Sun acquisition
3) House Keeping
4) Pointing scenarios: imaging, download, orbit control pointing

An overview of the ADCS mode and functional architecture is given in Figure 7, based on the ADCS modes described in Table 5. The following types of transitions are considered:

- Auto: these are automatic transitions handled by the ADCS mode manager
- TC: these are manual transitions, which require a telecommand from the platform
- FDIR: these are FDIR recovery actions which are generated either by the ADCS FDIR or by the platform

Each ADCS mode is defined by:

- The set of active sensors/actuators used in the mode
- The set of states in which the mode can be along the mission (e.g. slew, point, etc.)
- The transition logic between the states of each ADCS mode
- The mapping between each state and the active functions and associated function modes
- The transition logic between different ADCS modes

The configuration of each mode, and associated states, is detailed in Table 6, including the ADCS units and the provided ADCS algorithms (Table 7).

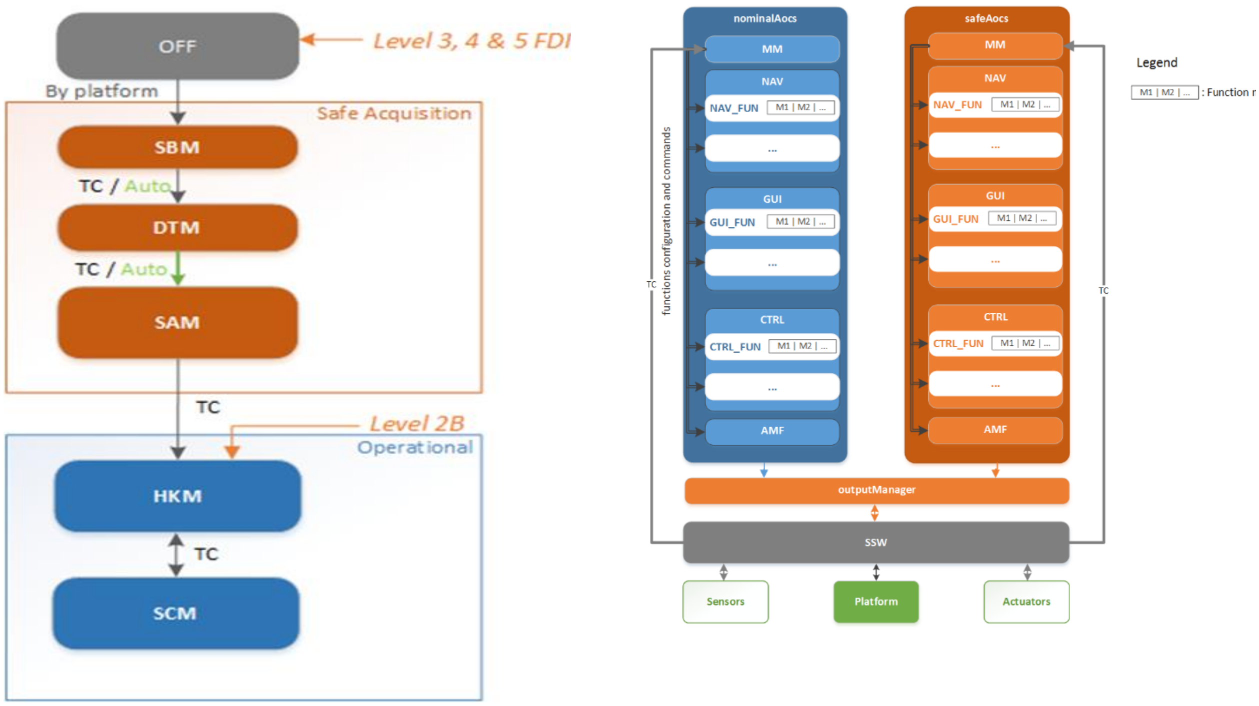



**Figure 7: READY ADCS product modes (left) and functional architecture (right)**

**Table 5: ADCS modes**

| Acronym | Mode | Description |
|---|---|---|
| OFF | **Power Off Mode** | Mode where the ADCS is powered-off |
| SBM | **Stand-By Mode** | Safe mode for the ADCS initialisation performing no actuation |
| DTM | **Detumbling Mode** | Safe mode for the dissipation of angular momentum using magnetorquers |
| SAM | **Sun Acquisition Mode** | Safe mode for the execution of the Sun search, acquisition of the Sun pointing attitude. |
| HKM | **Housekeeping Mode** | Operational housekeeping mode in which the system can remain for extended periods of time waiting for commands. Communication with ground station for TM/TC is performed in this mode. |
| SCM | **Scenario Mode** | Operational mode to perform fine pointing to target attitude. In this mode, thruster pointing for orbit control manoeuvres can be carried out. |

**Table 6: ADCS modes configuration**

| ADCS Mode | States | Navigation | Guidance | Control | Sensors | Actuators |
|---|---|---|---|---|---|---|
| **OFF** | - | N/A | N/A | N/A | N/A | N/A |
| **SBM** | - | N/A | N/A | N/A | (MAG/SS1/SS2)[1] | N/A |
| **DTM** | - | N1 | - | C1 | MAG<br>(GYR/SS1/SS2)[2] | MTQ |
| **SAM** | Halt<br>Sweep<br>Repoint<br>Safe slew | N2 | G1 | C2 | SS1/SS2<br>GYR<br>MAG | RW+MTQ |
| | Safe point | | G2 | C3 | | |
| **HKM** | Daylight | N3 | G3 | C4 | SS1/SS2<br>STR + GYR<br>MAG<br>GNSS | RW+MTQ |
| | Eclipse | | G4 | | | |
| **SCM** | Slew<br>Tranquilization | N3/N4 | G5 | C5 | SS1/SS2<br>STR + GYR<br>MAG<br>GNSS | RW+MTQ |
| | Point | | | C4/C5/C6 | | |

**Table 7: ADCS algorithms**

| Function | Description |
|---|---|
| N1 | Magnetic field derivative |
| N2 | Rate only measurement and Sun direction in RBF |
| N3 | Gyrostellar attitude and rate estimation in ECI |
| N4 | Gyroless attitude and rate estimation in ECI |
| G1 | Rate guidance with P/L protection constraints |
| G2 | Constant Sun vector in RBF |
| G3 | Acquire and hold sun pointing attitude |
| G4 | Acquire and hold nadir pointing attitude |
| G5 | Acquire and hold commanded attitude |
| C1 | Bdot control with MTQ |
| C2 | Rate control with RW (+ MTQ mom. management) |
| C3 | Sun vector control (and rate) in RBF with RW (+ MTQ mom. management) |

[1] MAG/SS1/SS2 are available in SBM to support commissioning and ground analyses if needed. These units are not used in closed-loop in the functions.

[2] GYR/SS1/SS2 are available in DTM to evaluate conditions to transition to SAM. These units are not used in closed-loop in the functions.

| Function | Description |
|---|---|
| C4 | Coarse attitude pointing (+ MTQ mom. management) |
| C5 | Slew attitude control (+ MTQ mom. management optional) |
| C6 | Fine pointing attitude control (+ MTQ mom. management optional) |

### *1.2.5 FDIR approach*

The ADCS FDIR concept is based on a hierarchical approach (Table 8), whereby failures are detected and resolved at the lowest possible level.

At the lowest level some units might manage failures autonomously by performing their own built-in health checks and, in some cases, internal reconfigurations, and report this through TM to the ADCS SW.

The next level (2A or 2B), involves the monitoring of the ADCS units by the ADCS SW. Reconfiguration at equipment level or subsystem level is performed by the software.

At higher levels, the reconfiguration action is to reboot the processor and, if finally needed, to switch to the redundant ADCS OBC. This can be triggered by the ADCS SW (by request to the system OBC) or by monitoring done by the System OBC itself.

**Table 8: READY ADCS FDIR levels definition**

| ADCS FDIR Level | ADCS FDIR Reacting Instance | ADCS FDIR Monitors and Events | ADCS FDIR Recovery Action |
|---|---|---|---|
| **Level 5** | External (Ground or System OBC) | External (Ground or System OBC) monitors | Power cycles ADCS HW (inc. ADCS OBC) or any action from Levels 2 to 4 |
| **Level 4** | ADCS SW or HW | ADCS SW generated alarms or HW alarms (ADCS OBC / supervisor) | ADCS OBC requests to System OBC a switch to redundant ADCS OBC triggering ADCS Safe Mode |
| **Level 3** | ADCS SW or HW | ADCS SW generated alarms or HW alarms (ADCS OBC / supervisor) | Reboots ADCS OBC (SW reset) |
| **Level 2B** | ADCS SW | ADCS SW Monitors on ADCS Subsystem/units: subsystem fail-operational monitors | Subsystem reconfiguration (e.g. change of mode)<br>Switching performed by ADCS SW |
| **Level 2A** | ADCS SW | ADCS SW Monitors on ADCS units: unit fail-operational monitors | ADCS unit redundancy<br>Switching performed by ADCS SW |
| **Level 1** | ADCS Unit | ADCS Unit FDIR Monitors:<br>HW with/without functional impact<br>- Built-in Tests<br>Intelligent unit SW with/without functional impact | Recovery performed internally by ADCS unit (no need of action by ADCS SW) |

The on-board FDIR monitoring will be based on a set of monitors which check if a given parameter is out of limits. These monitors are activated only under certain circumstances, e.g. some are active only if the related equipment is in-use or only in a certain ADCS mode.

The monitors trigger the generation of failure events which, if confirmed during a parametrizable time window, will trigger the applicable recovery action. An event is also sent to ground to notify the occurrence of the monitor triggering and any recovery action taken. Ground operator has the capability to enable or disable the monitoring in flight as well as changing the limits of the monitor, given the operator some flexibility based on actual in-flight behaviour or anomaly. It will be also possible to define new monitoring or define new recovery actions through software patches.

### *1.2.6 Telemetry and Telecommands*

The ADCS application software is compliant with the PUS-C standard 7, with the following generic services available:

- PUS 01: Request verification service, in charge of generating TM messages to inform the sender of TC to the OBCSW of the result of such TCs. The request or not of such confirmation messages can be configured separately for each TC by setting the corresponding flags.
- PUS 03: Housekeeping service, in charge of generating periodic (or on-demand) TM reports.
- PUS 05: Event reporting service, in charge of informing other systems (the System OBC and, by extension, Ground) of specific events that occur in the ADCS subsystems.
- PUS 11: Timeline execution service allows uploading series of TC to be executed at specific points in time by the ADCS OBC.
- PUS 12: On-board monitoring service used for FDIR implementation.
- PUS 17: Test service to check a PUS application is responding.
- PUS 19: Event-Action service used for FDIR implementation.
- PUS 20: For reconfiguration of the ADCS subsystem parameters in flight. A list of "Configurable parameters" table will be defined in the Satellite Database, which can be updated in flight by the operator using this service.

Additionally, a generic PUS service 160 has been implemented in order to send specific commands to the ADCS (e.g. mode change, guidance/navigation/control parameters update, switching specific functions on/off, updating Two-Lines-Elements (TLE), etc.).

This list of PUS services guarantees the maximum commandability and observability of the ADCS subsystem from ground and/or platform software.

## 2 Development and Qualification approach

The READY-200 development and qualification is incremental, following the V&V logic shown in Figure 8.

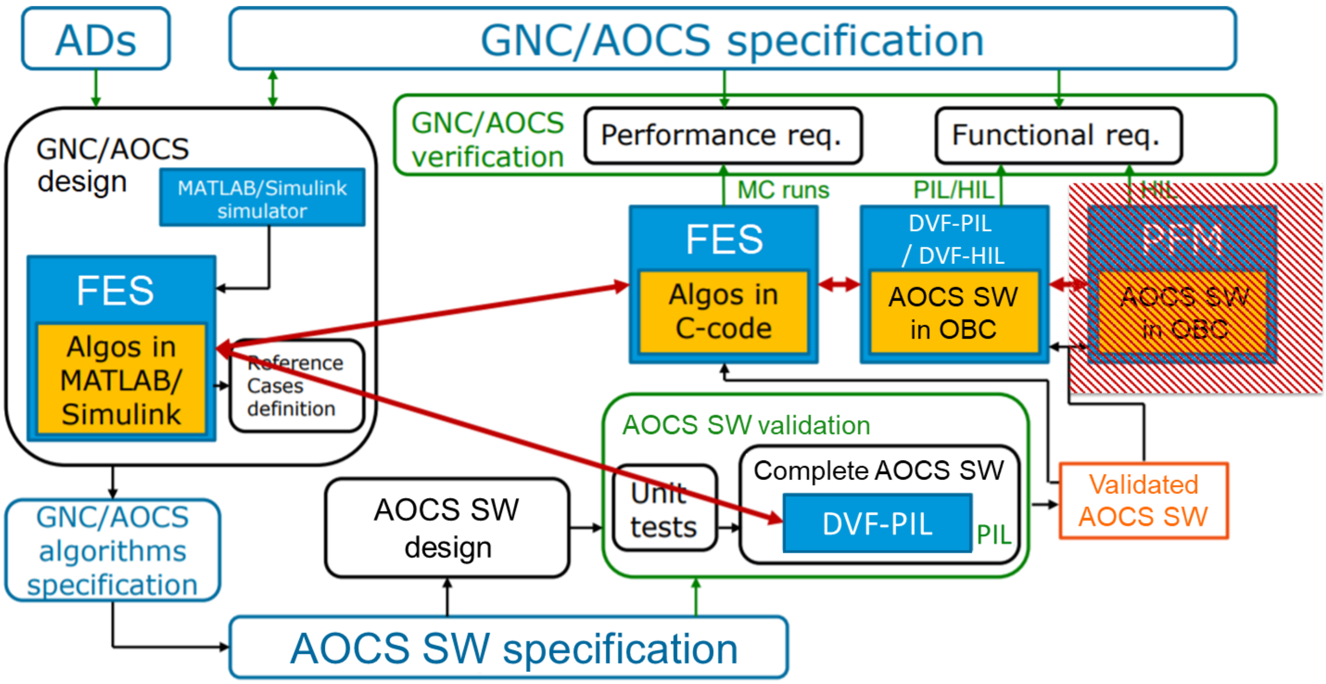



**Figure 8: READY ADCS V&V approach ([6])**

The first step of the qualification is performed through the Functional Engineering Simulator (FES) which is used for analysis, functional and performance simulations/testing in Model-In-the-Loop (MIL) the ADCS application SW (ASW). FDIR tuning and initial validation also makes use of the FES complementing analysis and higher fidelity tests.

In parallel to the development of the ADCS application software, it is necessary to develop the lower layers of the ADCS SW: the Service SW (SSW). This includes data handling, SW services, interface protocols (the ADCS OBC includes the operating system), etc. The different layers are then integrated with the application SW and form the complete ADCS SW which needs a bench different from the FES to be tested: the Development and Validation Facility (DVF),

Figure 9 illustrates the SW diagram of the DVF. From a functional point of view, the DVF SW is composed of three major elements that interact and provide a representative testing environment of the ADCS SW: Test Director, ADCS OBC and Real Time Simulator.

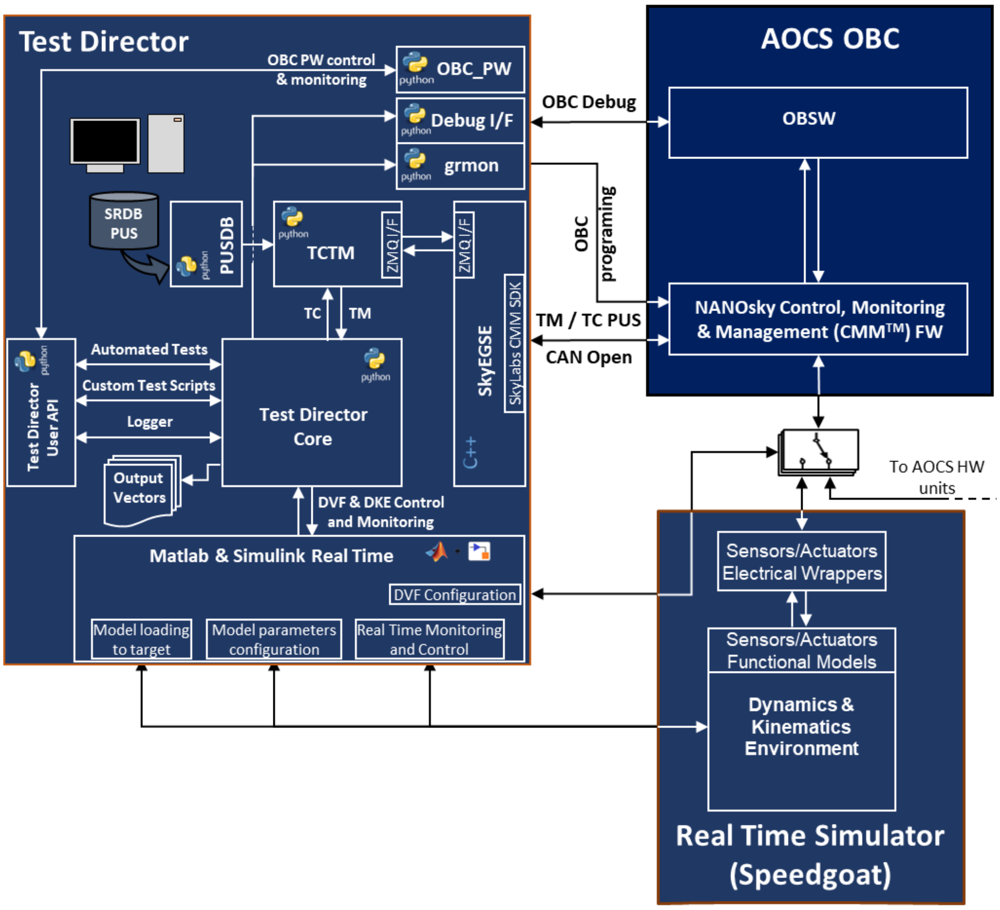



**Figure 9: Software diagram of the SAT4EOCE DVF**

The Test Director allows the user to implement test cases and/or test suites, configure them, run tests, and monitor their execution. The Test Director is the main component that interacts directly with the user while testing the ADCS SW. Test Director implements the following main functionalities:

- Configuration of the complete DVF benches, including simulation models and HW connections.
- Control of loading and execution of the ADCS SW into the ADCS OBC.
- Monitoring during the ADCS OBC SW execution.
- Data collection, storage and classification of test results
- Post-Processing analyses and test comparison

The DVF is an incremental test bench which goes from a Barebone to a HIL environment (Figure 10). The DVF-Barebone includes the ADCS OBC interfaced via its debug interface. It is used for unitary testing of the Service SW layers, and to have a preliminary estimation of the CPU/memory load of the application SW.

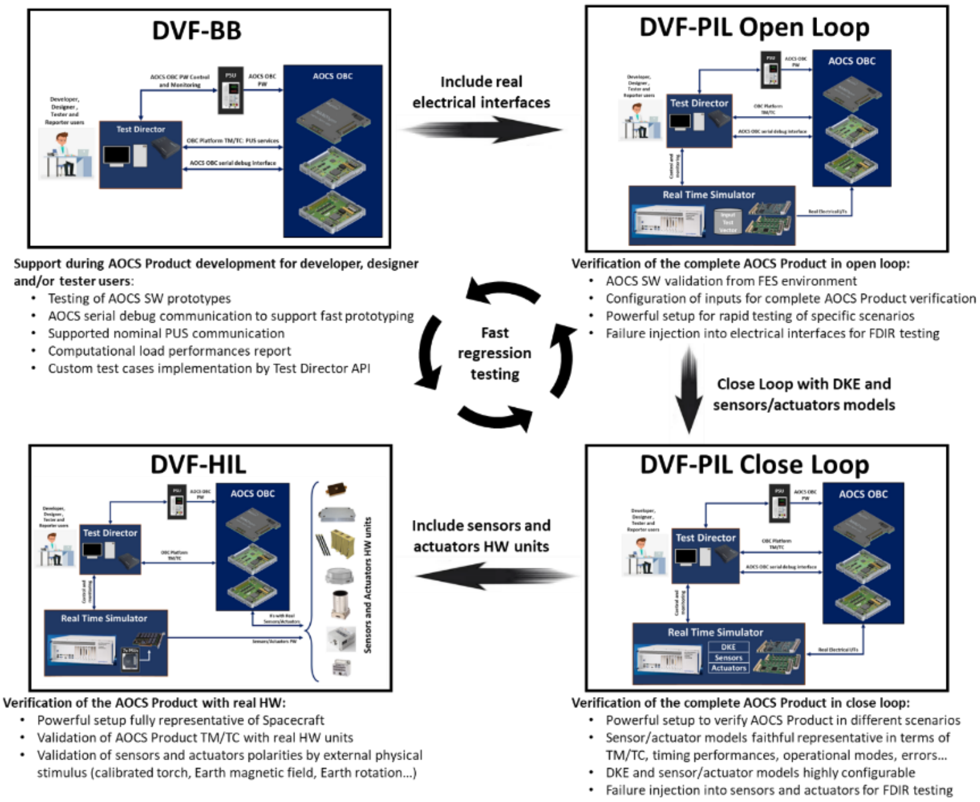



**Figure 10: Incremental Test-Bench approach**

An incremental evolution of the DVF Barebone (DVF-PIL) adds the ADCS units' electrical interfaces to the ADCS OBC model. The DVF-PIL includes the ADCS OBC, the DKE (Dynamics, Kinematic, Environment) and equipment performance models from the FES wrapped around an electrical layer simulating the real equipment interfaces. The FES reference cases are re-run on the DVF-PIL to demonstrate equivalent behavior. Possible deviations are investigated and justified. The DVF-PIL permits to complete the ADCS SW verification (including numerical accuracy and execution time), HW/SW interactions, CPU/memory consolidated performance and all mechanisms involved in the FDIR.

Once the complete ADCS SW has been developed and verified, its interactions with the real HW are tested through the DVF-HIL (Figure 11). The DVF-HIL can be used in open or closed loop. In order to use the DVF-HIL in closed loop, sensors need to allow for stimulation. Stimuli is available in general only for very few units (e.g. gyro, STR). The main objectives of the DVF-HIL are (a) ensuring the SW and the HW interact correctly in mission realistic conditions, (b) ensuring that physical units can be replaced by their numerical models.

**Figure 11: DVF-HIL Test-Bench**

# 3 Results of verification campaign

The test campaign in the FES for READY-200 verification in MIL has been already successfully completed, with thousands of tests run to verify tenths of functional and performance requirements for both the high performance and the core variant versions, in nominal and contingency (failure injection) conditions. The main results are shown hereafter.

The first figures show the results of the detumbling and Sun acquisition Montecarlo campaign, where 850 cases (90% CL) have been run. The detumbling is correctly performed for all the cases, and completed in about 2-3 orbits (Figure 13). The payload (which cannot be blinded by the Sun at angular velocities lower than 0.3 deg/s) is kept safe for all the cases

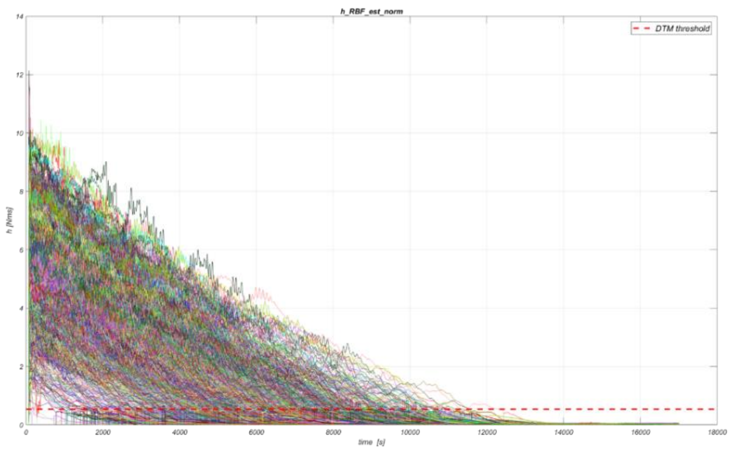



**Figure 13: Detumbling Montecarlo results**

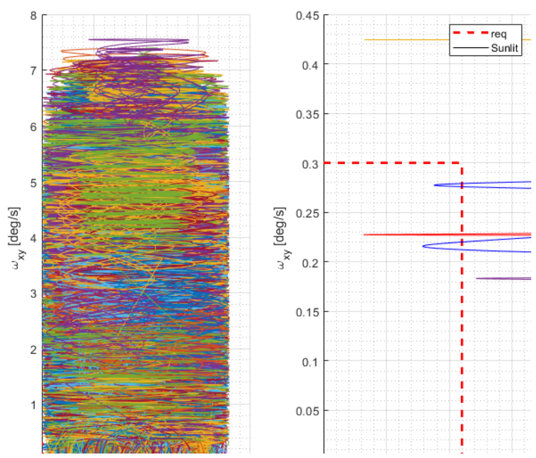



**Figure 12: P/L boresight protection**

during the whole duration of the detumbling (see Figure 12), using the measurements of the solar sensor mounted along the payload boresight. Only for two cases the payload constraint was not fulfilled during sunlight conditions (see Figure 12 right). Analyzing these cases, it has been seen that the SC starts with an undesired initial attitude, with the payload boresight axis pointing towards the sun direction, and an angular rate almost completely around the P/L boresight. The avoidance of such conditions at launcher separation shall be explicitly imposed to the launcher provider.

The Sun acquisition after detumbling is completed for all the cases, as shown in the following Figure 14.

Concerning the fine pointing phase for images acquisition, the READY-200 demonstrated to fulfil with margin the strict pointing, stability and agility requirements for stereo, multi-strap and Latitude-Longitude-Altitude (LLA) imaging. The following plots show the 99.7% percentile with 75% CL (500 cases) for APE (Figure 15 left) and RPE (Figure 15 right) requirements. During each transition to SCM, the attitude Control changes from coarse to fine and the Angular Momentum Management (AMM) stops the continuous desaturation of momentum and starts to just monitor it. Before each imaging event, during the slew pointing, the Navigation algorithm changes to Gyro-Stellar with FeedBack (GS FB). Then the target is pointed accurately, changing the Control algorithm from Fast to Slow, to acquire the images in a smooth way. The imaging acquisition intervals are identified by vertical dotted green lines.

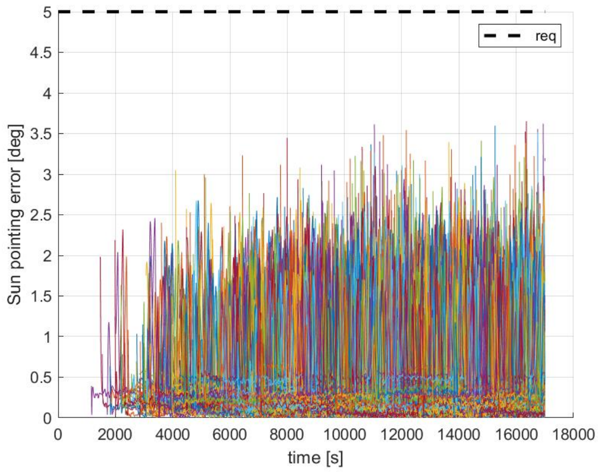
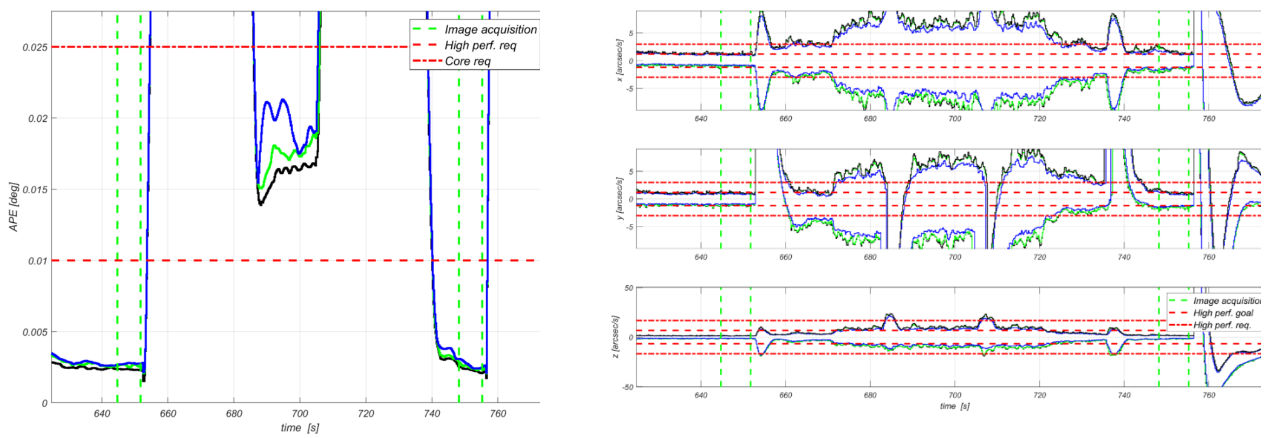



**Figure 14: Sun pointing error**




(a) (b)

**Figure 15: APE cross-boresight (a) and stability (b) during stereo imaging**

Several scenarios with FDIR in the loop and random failure injections (e.g. frozen measurements, null measurements, outages, etc.) for the different ADCS units have been run with the objective of verifying the correct triggering of FDIR events for each failure injection. An example is provided in

Figure 16, where a failure simulated in the star tracker unit raises as recovery action a reset (i.e. power cycle) for this unit. All the tests have provided successful results, showing the reliability of the FDIR function. Also, nominal tests have been run with the FDIR in the loop but without any failure injection, in order to guarantee that the FDIR does not have any impact on the nominal operations. Finally, specific test cases have been run to verify the capability of the ADCS to manage (without FDIR intervention) sensors' temporary outages of few seconds. Successful results have been obtained for all the tests run.

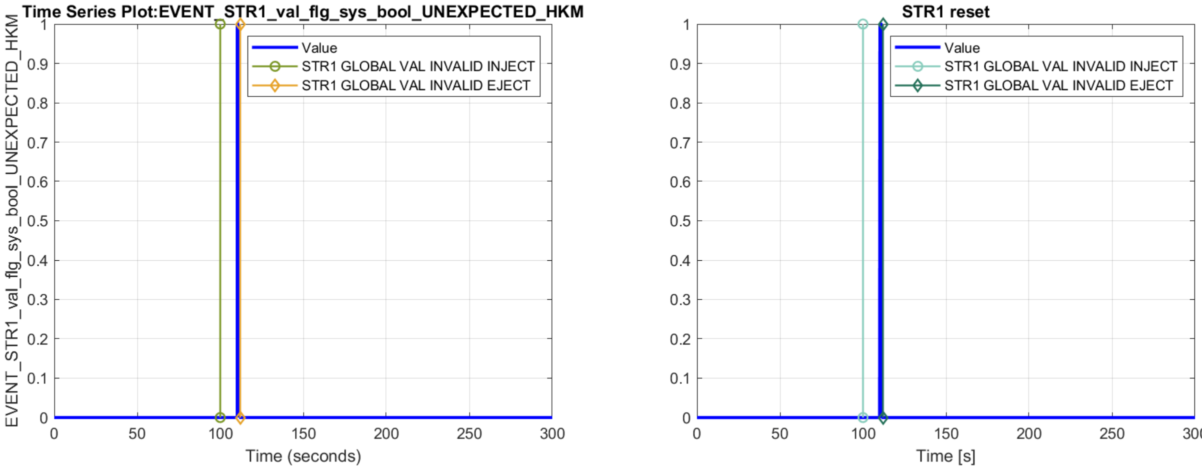



**Figure 16: Example of FDIR action triggering (STR reset) upon a STR failure**

The MIL results have been compared with SIL results, in order to verify that both environments provide the same results and so the autocoding process (used to generate the SIL) has not introduced any inconsistency. The comparison is presented in Figure 17, showing that in most of the cases the differences are of the order of 1e-16/1e-17.

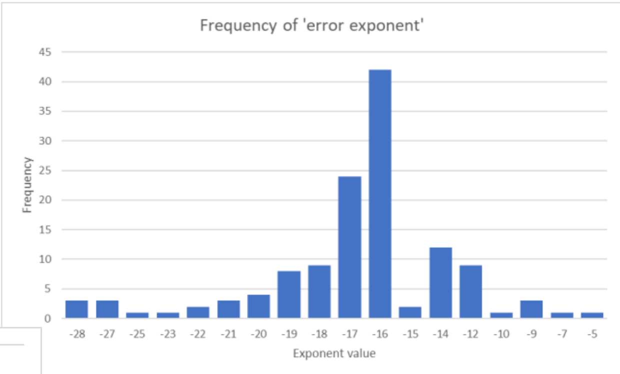



**Figure 17: MIL/SIL comparison**

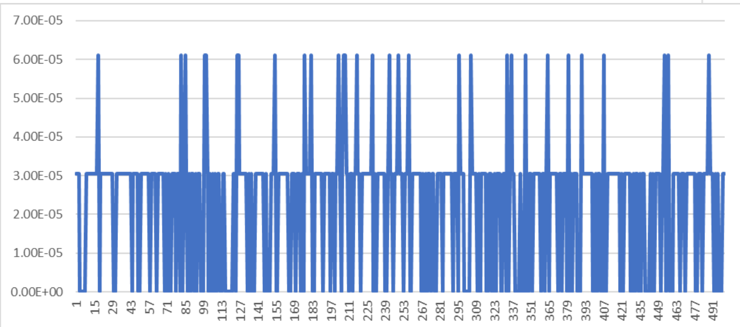


**Figure 18: SIL/PIL comparison for Sun distance**

SIL/PIL comparison provides similar results. In this case, there are few variables (the ones with the biggest absolute values) whose difference jump from zero to 1e-5, depending on the timestep. The source of this 'jumping' behavior is the last precision bit of the number. Since the number is big, a change in the last bit means a big change in value (although a small error relatively to the signal absolute value).

ADCS execution time statistics have also been generated through PIL tests in the DVF-Barebone. The results are reported in the table hereafter for a worst-case scenario, showing how the maximum value for the ADCS execution time is slightly above the 30 ms. The cycle duration is 200 ms (5 Hz), and considering safety margins ADCS shall remain below the 50% of this execution time (i.e. 100 ms). The results obtained show therefore a comfortable margin of about 70 ms.

**Table 9: ADCS execution time**

| Metric | Value |
|---|---|
| **Number of steps** | 1000 |
| **Average execution time** | 21669.824 µs |
| **Min execution time** | 12083 µs |
| **Max execution time** | 30317 µs |
| **Standard deviation** | 3559.238 µs |

After the verification of the ADCS algorithm in PIL scenario using the DVF-Barebone, the verification of the complete ADCS-OBC is enabled by using the DVF-PIL close loop scenario.

DVF-PIL close loop setup provides the additional capabilities required to verify the complete ADCS-OBC

- Integrates the DKE, Sensors and Actuators models (inherited from FES simulator) into a real time simulator providing the measurements and actuations to the real world with hard real time performances.
- The Real Time Simulator machine is equipped with the required interface boards to provide the real electrical interfaces to communicate with the OBC.
- The Sensors and Actuators models are integrated into the Electrical Wrappers. The electrical wrapper implements the required layers to manage the real electrical interfaces, and to implement the corresponding protocols and packets framing. Additionally, the Electrical Wrappers reproduce timing performances of each Sensor and Actuator, delaying the response according to the unit specifications.
- The main bus communication to the ADCS-OBC is implemented into the Test Director, providing all the required PUS services to control and monitor the ADCS-OBC.

At the beginning of any DVF-PIL close loop scenario, Test Director sends the PUS services packets to configure the Housekeeping TMs and commands the ADCS mode to perform the required maneuvers. During the maneuver, the ADCS-OBC will request sensors measurements by sending TCs and retrieving the TMs from sensors to be injected into the ADCS algorithm. After the execution of the ADCS algorithm, the required actuations are sent to the actuators by TCs. All the communications with the units are performed through the real electrical interfaces, verifying the correct communication from the ADCS-OBC. The actuations commanded by TCs are used to propagate the DKE into the Real Time Simulator to close the loop.

The following pictures exposes the correct execution of a detumbling maneuver using the ACS-OBC with the DVF-PIL close loop configuration.

The DVF-PIL close loop infrastructure reports the results from the electrical wrappers of all the units, allowing the analysis in detail of the TM/TCs of the ADCS units, as well as the functional values according to the real-world propagation. Figure 19 shows the transmission of the bytes reported by the Magnetometer Electrical Wrapper. Left figure shows the TC number of bytes received by the input FIFO and forwarded to the Magnetometer Model, the TM bytes generated by the model, and the TM bytes sent to the OBC which are delayed according to the unit timing performances. Right figure shows the Electrical Wrapper Log, which informs about the content of the TM/TCs and the timing performances.

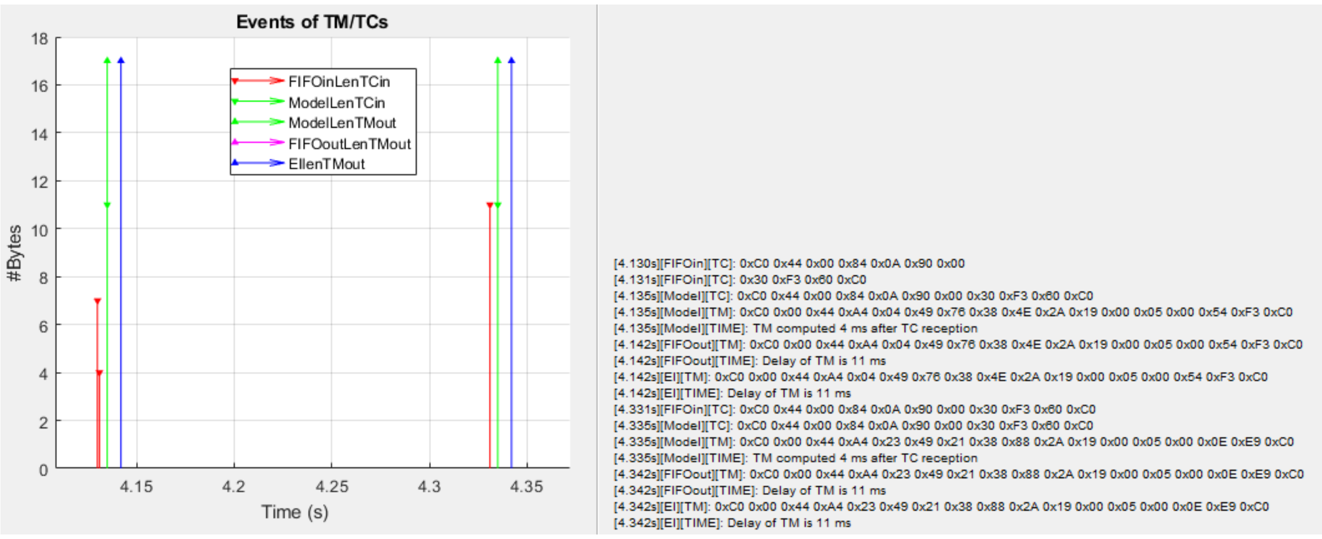



**Figure 19: Magnetometer Electrical Wrapper - TM/TCs events Report**

Figure 20 shows the Functional Report of the Magnetometer Electrical Wrapper, where continuous line reports the values provided by the Real-World propagation (DKE), and the cross symbols reports the values sent by TMs to the ADCS OBC. In the right, the values reported to the OBC through TMs, are compared with the Real-World values. The error threshold is stated in the less significant bit of the codified value into the TM (resolution of the functional value codified into the TM frame).

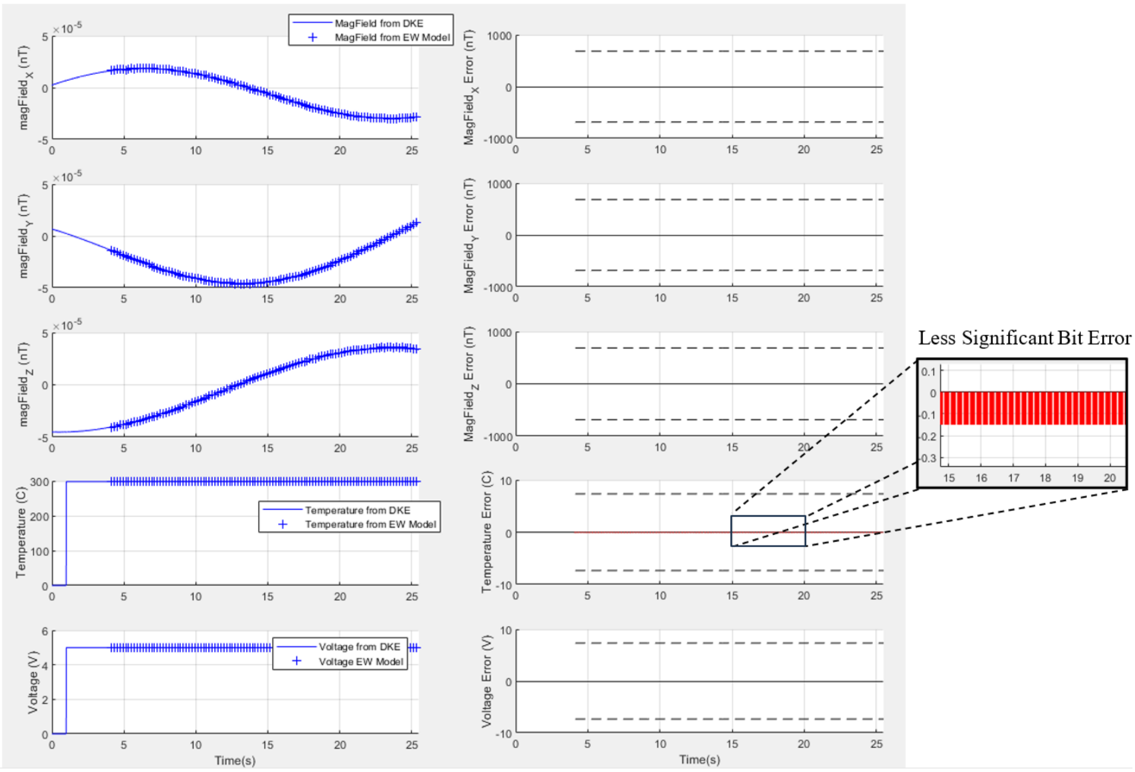



**Figure 20: Magnetometer Electrical Wrapper - Functional Values Report**

The detumbling is performed until the estimated angular velocity is stablished under the configured threshold into the ADCS OBC. Figure 21 shows the evolution of the Spacecraft angular velocity.

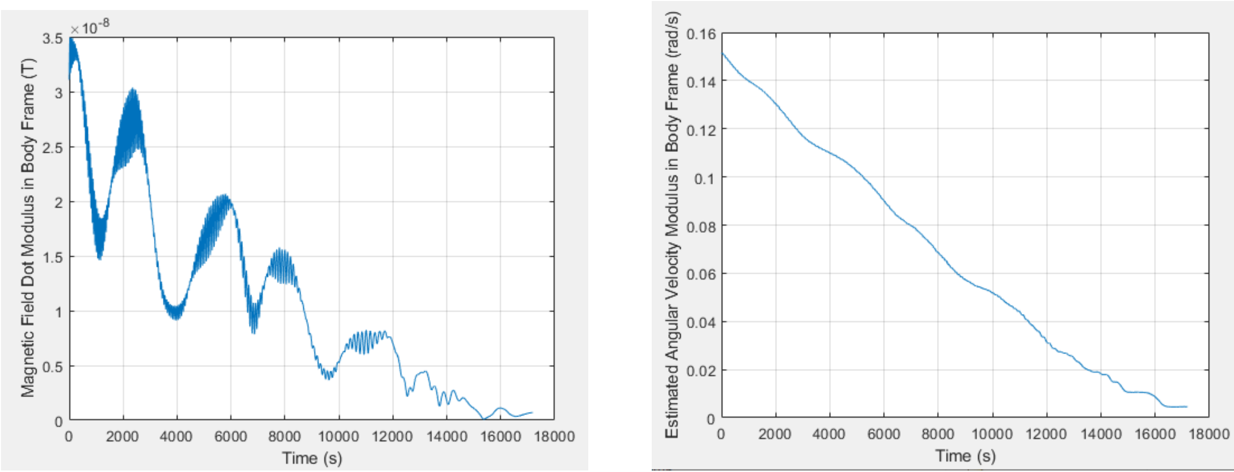



**Figure 21: Magnetic Field Dot (left) and Estimated Angular Velocity (right) during Detumbling**

As reported previously, the detumbling maneuver is performed successfully, taking almost 5 hours. During the maneuver, the ADCS-OBC has successfully performed the transition from standby to detumbling, has sent/received $1.87 \cdot 10^6$ TC/TMs to the units without transmission fails, has reported 17 thousand housekeeping TMs by PUS services to the OBC-Platform, and has satisfied the detumbling exit conditions at the end of the maneuver.

The test campaign PIL/HIL is ongoing and will be finalized by June 2024 leading the READY-200 ADCS qualification to TRL6.

# 4 Reconfiguration of the READY ADCS product to Cubesats and Microsats

Exploiting the experience and heritage from READY-200 development/qualification, DEIMOS is extending the scope of the ADCS product to other platforms, ranging from 6U to microSats and to other types of orbits and missions (GEO, IOS, IOT, etc.). The ADCS product, furthermore, is being enhanced in order to provide full power management of ADCS units, thanks to a new Skylabs interface board called NANOadcs-IF, which will substitute the picoRTU. The ADCS HW will be fully European, easing up any matter related with ITAR, and will be PC-104 compliant, in order to ease up the integration in cubesat platforms. The delta-development/qualification is being implemented in the frame of an extension of the original SAT4EOCE activity, co-funded by DEIMOS and ESA through the InCube programme. The activity foresees also an IOD flight for the product, which is currently planned by the second half of 2025 and will increase the TRL of the product to 8/9. Figure 22 shows the READY product for 6U and 16U.

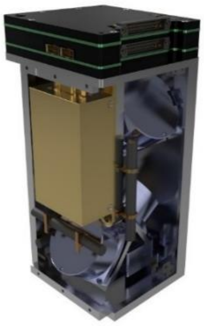
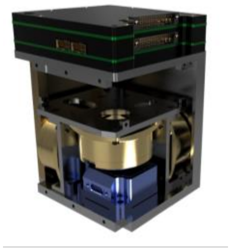
 

**Figure 22: READY-16U (left) and READY-6U (right) products**

# 5 Mass, Power and Volume budget

The following Table 10 shows preliminary mass, power and volume budgets for the different products of the READY ADCS family:

**Table 10: Mass, Power and Volume budgets for READY ADCS product family**

| | READY-6U | READY-16U | READY-100 | READY-200 |
|---|---|---|---|---|
| **Mass [kg]** | 1.3 | 1.8 | 8 | 19 (HP)<br>16 (core-variant) |
| **Power (Housekeeping) [W]** | 10 | 12 | 20 | 55 (HP)<br>50 (core-variant) |
| **Volume [U]** | 1.35 | 1.8 | 4 | 8.5 (HP)<br>8 (core-variant) |

# 6 Acknowledgement

DEIMOS would like to thank ESA for co-funding READY product development through SAT4EOCE contract (4000129462/19/I-LG). A particular thank goes to Nicola Melega and Fabrice Bouquet which, with their always constructive feedbacks, have permitted improving the quality and the performance of the product.

# 7 References

[1] XACT ADCS solution by Blue Canyon https://www.bluecanyontech.com/components

[2] CubeADCS solution by CubeSpace https://www.cubespace.co.za/products/gen-1/integrated-adcs/cubeadcs/

[3] AOCS Suite by D-Orbit https://www.dorbit.space/systems-components

[4] I-ADCS solution by AAC Clyde Space https://www.aac-clyde.space/what-we-do/space-products-components/adcs/iadcs200

[5] ECSS-E-ST-70-41C - Telemetry and telecommand packet utilization.

[6] M. Casasco et. al., "GNC and AOCS functional chains engineering and verification", *8th ESA Workshop on Avionics, Data, Control and Software Systems - ADCSS 2014, 28 October 2014*