A ROBUST AND FLEXIBLE AOCS ARCHITECTURE FOR OHB'S STANDARD EARTH OBSERVATION PLATFORM (EOS)

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ABSTRACT

OHB System has developed a new flexible Standard Earth Observation Platform called Eos with the objective of serving the Sentinel Expansion as well as Extension missions of the Copernicus program. Eos is targeting also Earth Explorer satellites as well as national missions not requiring very high agility. All of them have different orbits, payloads, and therefore pointing requirements. The goal of Eos is to provide a generic platform design with suitable performances and high reliability at low recurring prices to customers. As the satellite platform in most cases is composed of common and well-established technologies, it provides the opportunity for fast track and low risk platform adaptation to different mission needs. The challenge of the AOCS (Attitude & Orbit Control System) architecture for Eos was to determine the kind of sensor/actuators and algorithms necessary to build a reliable and, at the same time, flexible architecture capable of coping with all kinds of Earth Observation missions. The AOCS architecture of the Eos platform is currently serving the Anthropogenic CO2 Monitoring Mission (CO2M) of the Copernicus program, showing its flexibility and capacity to be adapted for a specific purpose while providing the required performances to complete a desired mission.

1 INTRODUCTION

The Copernicus Programme is an Earth monitoring initiative led by the European Union (EU) and carried out in partnership with the EU Member States and the European Space Agency (ESA) to access accurate and timely information services to better manage the environment, understand and mitigate the effects of climate change, and ensure civil security.

Intense use and heightened knowledge of the possibilities of Copernicus have prompted high hopes for a future upgraded Copernicus system ("CSC Expansion"), even as the deployment of the first generation of Sentinels nears completion. Six new Copernicus Sentinel missions, so-called High Priority Candidate Missions (HPCM), were developed to meet the emerging and urgent demands for new types of observations.

Eos served as an OHB's baseline for the HPCM and is currently used in the studies and proposals for multiple Earth Explorer and Sentinel Next-Generation missions. The key feature of the product line is to offer a common platform design that provides high performance for Earth observation applications. The Eos platform is founded on common and well-established technologies, thereby providing the opportunity for fast-track and low-risk platform adaptation to different mission needs.

The design of such a flexible platform represents a big challenge where different satellite subsystems must interact with the objective of achieving the necessary complete functional system (a satellite) that fulfils specific mission requirements. Each mission has design drivers related mainly to the payload instruments and operational activities necessary to achieve the mission goals. Thus, a satellite's platform design is developed by selecting the necessary units/equipment that enable the realization of the mission. However, available units and the satellite layout itself introduce more constraints to the system, and ultimately, costs influence the final product, which nevertheless must be compliant with client requirements. In the interest of identifying all subsystem constraints (related to the selected units, accommodation, mission environment, tasks, and related attitude profiles) and any interaction between them, a design team spent time together in concurrent engineering facilities where design activities were exercised during the very early stages of the project/proposal. The design and, more specifically, the influence of the selection of a particular unit or accommodation are promptly identified with the aid of dedicated software. The latter streamlines the whole design process, giving a baseline that has to be refined as the mission evolves. In the first phase, commonalities between different Earth Observation (EO) missions, even for a very wide set of environments (orbits), were identified, and a generic platform architecture was established. The architecture concept was meant to be flexible, that is, easily adaptable to different missions while using the newest and off-the-shelf technologies and applying standardization, such as defined in Space AVionics Open Interface aRchitecture (SAVOIR) [1] and European Cooperation for Space Standardization (ECSS) [2]. In a few words, the early design phase focused on the satellite architecture definition, in particularly the avionics and structure, including accommodation, as well as extensive market research to identify units that meet the mission needs without jeopardizing the selected architecture. Three main platform sizes were envisaged, depending on the platform dimensions/mass and three levels of performance, all selectable in mixed configurations.

This allowed to serve any EO mission. The realization of the platform had to be however constrained (in size, target orbits and capabilities) in order to mature the design concepts. This is how Eos was born; a concise but at the same time robust and flexible platform, financed by OHB, which supported the HPCM proposals. A real HW/SW engineering model was built as demonstrator of the capabilities and is now in its final stages.

This paper describes the AOCS architecture of Eos and how it has been applied successfully to the Anthropogenic CO2 Monitoring Mission (CO2M).

2 THE EOS PLATFORM

Eos offers a flexible and modular design with subsystems integrated on individual panels to simplify Assembly, Integration and Test (AIT) processes and therefore enhance schedule robustness and mitigate risks. The modular design concept considers high flexibility in design and platform AIT:

- OHB standard avionics provide three Remote Terminal Units (RTU) with high flexibility for equipment accommodation and I/O interfaces. Next Generation On-board computer (OBC) [3] and SW are fully compliant to new architectures.
- Two power distribution units (one for the platform and one for the payload) allow shorter power harness lengths, fast harness AIT and flexibility for platform accommodation.
- Accommodation is spread over six radiator panels, which can be integrated independently.
- Propulsion module design allows integration and testing in parallel to the core structure and panel Manufacturing AIT.
- The mission compartment provides an additional payload radiator area.

The platform design is therefore highly modular, with reduced and well-defined envelope. As the interfaces to a possible payload are also defined, they can be developed in parallel to the payload securing AIT schedule. The payload and platform are thermally decoupled, providing maximum thermal isolation for both radiative and conductive coupling. Principal AOCS sensor elements (such as the star-tracker and gyro) can be mounted on the payload (if it allows it), maximizing the precision of pointing performances. The platform provides all necessary functions to the payload and to the ground to ensure the mission's success.

3 AOCS DESIGN PROCESSES FOR EOS

The Eos platform, in particular the AOCS architecture, is driven by the platform's attitude knowledge and pointing performances as well as several operational functionalities. This means that the AOCS shall carry out several different functions, derived from mission requirements, payload constraints, and design properties of the satellite platform. The AOCS goal is then to provide attitude control with the required accuracy for the satellite to execute its observation process. The AOCS design process can be roughly summarized as the selection of AOCS sensors/actuators and estimation/control algorithms that provide the means to measure and control the satellite attitude with the necessary accuracy while the units are compatible with the electrical I/Fs of the satellite and thermal/mechanical environments present before/during launch as well as in orbit and possible disposal phases.

For Eos, a full set of compatible AOCS units was identified from an extensive evaluation of European (and, in some cases, non-European) suppliers with the following relevant characteristics.

3.1 Electrical compatibility of AOCS units

The identified applicable AOCS units were divided into two groups according to their electrical interfaces: intelligent units and simple ones. Mainly, the platform dictates the preferred electrical interface (communication protocol) and power supply levels and types (regulated or unregulated). Once a power supply level and type have been selected at system level, with the inputs of all sub-systems, the AOCS units' selection is constrained. Off-the-shelf units are preferred, but, if necessary, the re-design of the AOCS units can be requested/negotiated with suppliers to achieve full electrical compatibility, encouraging platform standardization. This applies especially for those intelligent units that are plugged directly into a platform bus (MIL-Bus) or have serial type communications (RS422). In this group, we can find mainly star-sensors, rate-sensors (gyros), GNSS receivers, and some actuators (e.g., reaction wheels and other mechanisms). As such, a wide range of selectable units can be selected for the Eos platform.

On the other hand, simple units that are required for safe mode purposes cannot be seen as plug-and-play devices. Here is the platform, either the OBC or the RTU, that shall offer the necessary electrical interfaces to read the measurements of those units and even supply specific voltage levels. Fortunately, both OBCs and RTUs are not unique, and a level of standardized interface modules can be used for the interconnection of these AOCS units.

The Eos platform is then electrically prepared to manage all necessary interfaces (and in number) for the identified AOCS units; the choices are summarized in Fig. 1.

Preliminary analyses from EMC compatibility as well as the AOCS recommendations provided input for the selection of final unit accommodation on the platform.

3.2 Mechanical compatibility of AOCS units

The mechanical compatibility was mainly based on the structural analyses for those sensitive units, which may require special handling and make the satellite structure suitable to carry the selected units. Indeed, first the shock and vibration levels are supervised by the unit responsible (in this case the AOCS lead) and compared against the expected levels to be seen by the satellite during its lifetime provided by the system engineering; but ultimately, the range of the acceptable vibration levels of the units is already known, and changing them can be quite risky and costly. While selecting a more suitable launcher would be the easiest solution, it may have financial and political consequences. Executing additional testing on the units can provide more confidence with better cost/benefits.

The most relevant input from AOCS was then to help MTP engineering find suitable places for the AOCS units. For Eos, the structural design was performed to provide the required stiffness through a combination of mechanical arrangements and optimal accommodation of the units, and if necessary, a location for wheel dampers is already in place.

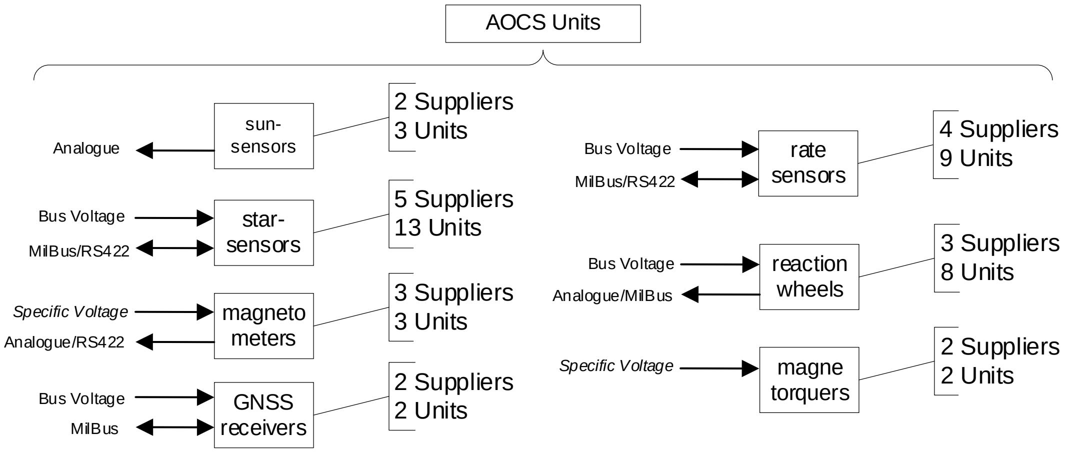

Figure 1. Identified AOCS units with electrical compatibility for Eos

3.3 Thermal compatibility of AOCS units

Here, as in the mechanical assessment, apart from the verification of the unit's operational and non-operational temperature ranges against the expected temperatures during the mission and even requesting specific test extensions to suppliers, the most important AOCS input to the design was to suggest places for accommodation once a unit has been selected. A deeper contribution from the AOCS side was to challenge the selected unit design and maybe select another type; for example, selecting separate electronics for reaction wheels such that the wheels can be placed in a mechanically stable place where the thermal system can regulate the temperature while the electrical unit can stay in a less stable thermal position that does not need any strong temperature regulation. The Eos platform has been configured considering all these variables.

3.4 Selection and sizing of AOCS Units

- Design definition

The selection of the set of sensors is based on the pointing requirements for each mission; that is, pointing and stability requirements, mission orbit, and goals. The control stabilization method also defines the kind of sensors/actuators the platform needs.

A set of units to be supported by the Eos platform was selected to ensure that all Copernicus missions are covered, and the final design of each Eos application will only be based on the decision to carry or not a specific unit and on how many of them and at what performance.

Since performance is a key point of the design, 3-axis satellite stabilization was selected for the nominal observation phases. This is the more stable/accurate control method for a satellite, and it also offers easy manoeuvring. A 3-axis satellite stabilization method is based on momentum exchange devices, where momentum and reaction wheel units are normally used as a control source. Since the reaction wheels are well suited for any satellite size and configuration due to their proven performance, relative simplicity, versatility, and capability of providing high accuracy pointing control, they were selected as a primary control actuator. Control momentum gyros were discarded as the agility for Eos was constrained to be only of medium class, and high agility is covered by OHB's SmartAgile platform.

Apart from the momentum exchange system used to stabilize and control the attitude of the satellite in nominal phases, an auxiliary torqueing system is needed to desaturate the wheels. Thrusters or magnetic torquers are normally used. Since the use of thrusters implies a bigger amount of propellant consumption and therefore more weight on the satellite, the magnetic torquers were preferred. This can be achieved for LEO satellites because the Earth's magnetic field strength is still strong enough to be used for such purposes

For the Eos baseline, it was decided that the orientation of a satellite should be based on external common references such as Sun, Earth, stars, and even local magnetic field direction. The attitude provided by star-trackers is the most accurate one and therefore the baseline for the realization of any nominal mode. 3-axis attitude information is delivered directly by the star-tracker and is complemented with accurate earth position by using a GNSS device for nadir pointing applications. Other advantages of using a star-tracker are attitude reference flexibility (because it can be switched from earth-centered to inertial) and hardware reduction (since no earth sensor and fine sun sensors are needed and, in some cases, a high-performance gyro can be avoided). Additionally, inertial sensors are carried to provide short-term attitude reference between external updates, initial stabilization, and bridging phases where the star-tracker head may be blinded or there may be an outage due to a solar storm. It can be, however, that no gyro is at all necessary if the performances are achieved with a star-tracker system containing at least three optical heads for attitude determination.

For the safe mode, a simple sun-pointing attitude with a stabilization spin was selected, where robust and reliable units are of major importance, such that they can provide the necessary information for attitude and control purposes without any dependence on other units or processes. An omnidirectional sun presence system based on orthogonally placed cells was the baseline for safe mode since highly accurate sun pointing is not required. It has better sun visibility than any arrangement/configuration of specific fine sun sensors; this also gives reliable sun presence detection and better tolerance to albedo and any other interferences caused by any reflection. Rate determination in this mode can be done with a low-performance rate sensor or even by a combination of magnetometers. Magnetometers are simple and reliable; they can deliver accurate enough measurements for initial rate dumping and satellite stabilisation together with the sun presence system.

The final configuration of the satellite may impose design constraints, specifically on the accommodation, but the Eos platform is prepared for that.

- Design Selection

As the set and kind of units are already defined for Eos, the selection of specific units for each mission depends on their performances and reliability. For simple units where performances are not crucial, such as sun-sensors, the AOCS architect in charge of a specific Eos application/proposal, analyses how many units shall be carried by the mission. Although there is a baseline of units in Eos, the payload, or any other structure/device not part of the Eos baseline may disturb the initial cell accommodation. Here, the analysis is needed to check whether the units can be simply placed on other parts of the platform or if an additional number of cells are required.

On the other hand, the star-tracker system is more complex. In theory, only one star-tracker is needed to compute the satellite’s attitude for control purposes. However, scalability is necessary due to many aspects: availability, reliability, redundancy, and accuracy. So, the sense of scalability is seen more as the number of star-tracker units or optical heads the complete redundant system has. First, availability forces the system to use more than one star-tracker due to the possible blindings caused by the mission profiles. A star-tracker head can be located in such a way that most of the mission stays without any blinding from Sun/Earth but when a satellite needs to slew (because of an orbit or calibration manoeuvre), there may be a short period of time where it can’t generate any measurements. Reliability and redundancy come together; they are related to the failure of the unit. Therefore, at least one (or two, depending on the availability and reliability number) star-tracker head is added to have a redundant system capable of lasting the entire mission. Accuracy can be improved if more than one star-tracker head is providing attitude information; the quaternions can be fused, and a better estimation can be generated.

The selection of the gyro will be based on the necessity to filter the star-tracker measurements and on the possibility to bridge star-tracker outages, as well as the possibility to have a direct rate measurement in safe mode. Here, the AOCS architect and system engineering have to decide based on the actual mission needs.

For the actuators, an analysis is needed to determine the minimum torque/force level of an actuator to complete the mission within the performance. The necessary torque authority is defined either by slew requirements or the need for the control authority to be well above the peak disturbance torque; so that pointing accuracy is not challenged by the cyclic and secular disturbance torques that originate from the selected orbit (together with the satellite dimensions and shape). Therefore, magnetorquer dipole strength is to be determined for each case, considering accommodation and satellite mass constraints, as these units can easily increase in size and mass. For the reaction wheels, the angular momentum capacity and torque level must be selected; additionally, the accommodation can also be modified in order to bias a particular axis. Although the Eos platform considers four wheels to be the standard flight set, more wheels can be added if necessary

3.5 Overall design assessment related to AOCS

From the AOCS side, the selection of the units is done based on sizing. Later, the selection of the algorithms for attitude estimation and control is done. Although this does not affect the platform itself, because SW can always be updated, it determines the selection of the AOCS units, as the analyses may show that a unit (for example, a star-tracker or gyro) could be used or not because it is enough to reach the required accuracy only based on the unit's performance or advanced filtering is needed. This can also help to reduce the cost (of the unit and engineering used for specification, procurement, integration, and testing) in cases where a lower-performance unit is used while still meeting the pointing and stability requirements. For that, algorithms from heritage missions were quickly adapted. This gave confidence, as the main libraries were already proven (with an already long heritage).

For specific applications of the Eos platform, that is, newer missions, it is expected that the baseline algorithms are enhanced with newer strategies and estimation and control algorithms because each mission presents a particular challenge.

4 AOCS ARCHITECTURE FOR EOS

The AOCS architecture for Eos is based on OHB’s flight-proven heritage design from successful missions from LEO up to MEO (such as SAR-Lupe, EnMAP, and Galileo FOC). The architecture is organized in three layers:

- Hardware Layer: the AOCS units are composed of the sensors and actuators,
- Software Layer: AOCS algorithms in charge of the satellite activities according to mission objectives and within the required performance,
- Human Layer: the operation and monitoring of the AOCS activities; it is the interface (made of TM and TC) to the operations at the ground station. It includes AOCS equipment management, state transitions, and attitude profile uploads

4.1 AOCS hardware

AOCS elements aboard the Eos platform can be sorted into a set of sensors and actuators as in Fig. 2.

- Sensors
    - Star-tracker (STS) provides accurate absolute attitude determination.
    - Navigation System (GNSS Receiver) provides accurate orbit position, velocity, and time.
    - Gyro (GYR) provides accurate inertial rate information.
    - Coarse Rate Sensor (CRS) provides rough inertial rate information for safety purposes.
    - Magnetometer (MGM) used to estimate raw rate information around 3 axes and in general Earth's magnetic field measurements.
    - Coarse Sun Sensor (CSS) set provides the coarse but omni-directional sun direction.
- Actuators
    - Reaction Wheel (RW) set provides internal torque and momentum storage.
    - Magnet Torquer (MTQ) set provides external torque capability.
    - Thruster (THR) set provides external torque and thrust capability.

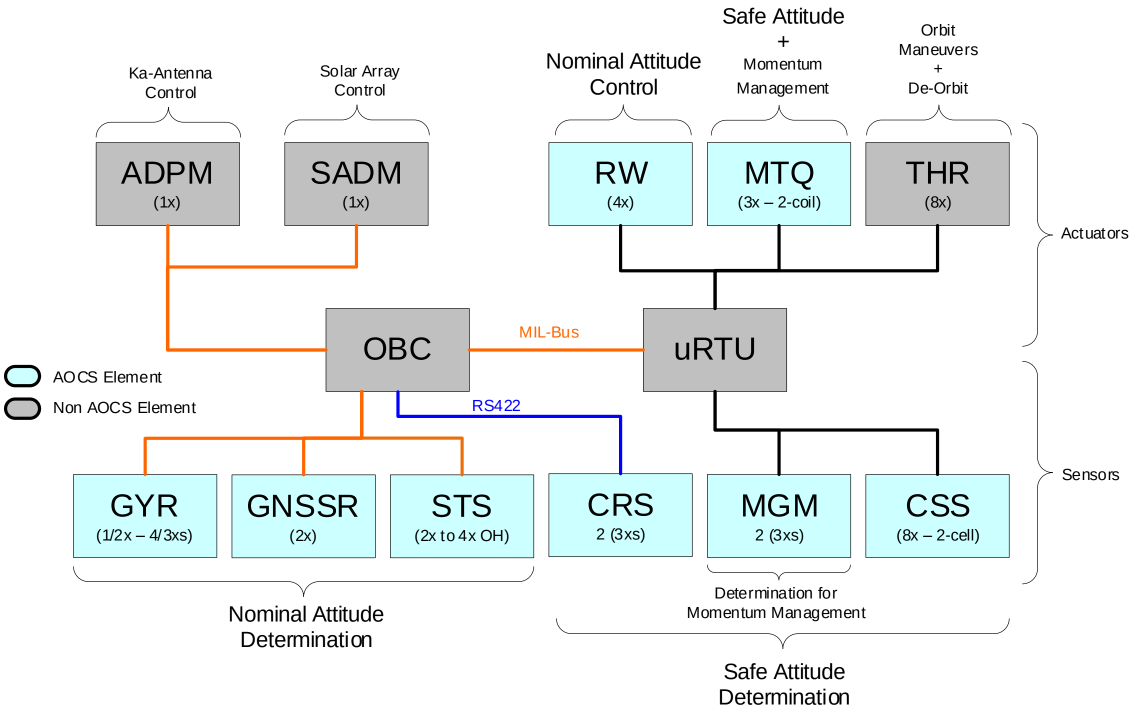

Figure 2. AOCS architecture for Eos

The Solar Array Drive Mechanism (SADM), Antenna Deployment and Pointing Mechanism (ADPM) are not AOCS components, they are shown since they are commanded by or related to the AOCSW. Control, guidance, signal conditioning, and AOCS functions are carried out by the AOCS software (AOCSW) on the OBC.

4.2 AOCS sofware

The selected AOCSW architecture is based on proven heritage and is completely modular. It is organized into five main components, as shown in Fig. 3, with a sixth element lying within all other modules, dedicated to the following main tasks:

- Pre-processing (PPR): unit data handling, engineering data processing, and units' health checks. This SW part covers each of the AOCS units and delivers data to the other AOCSW components through fixed interfaces.
- States (STA): on-board model propagation as well as filtering algorithms are selected according to performance needs.

- Attitude determination (ADS): satellite attitude determination from measurements and state filters; depending on the available sensors, a solution is selected in order to provide an accurate and reliable attitude determination according to the needs of each AOCS control mode.
- Guidance (GUI): generation of attitude guidance (on-board) or interpretation of attitude information (on-ground). Either pre-programmed or directly commanded attitude profiles can be generated for the different needs of the satellite mission (mainly based on payload/instrument needs).
- Controller (CTR): execution of the attitude control related activities. SW based on proven control algorithms and parameters configurable from ground on mission demand.
- Failure Detection, Identification and Recovery (FDIR): Management of failures on units/processes and related recovery actions. This SW part covers each of the AOCS units and processes; it delivers data to the other AOCSW components through fixed interfaces and is embedded within the five other modules; e.g., it has no exclusive module or file.

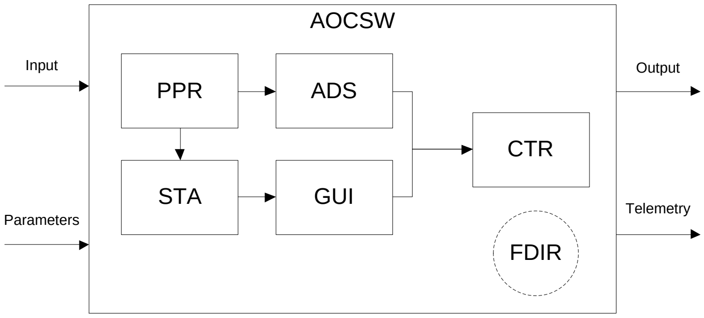

Figure 3. AOCS software components for Eos

The AOCSW is coded in C and tested by simulation; it is later delivered to the SW-Team for integration into Satellite Software (SCSW). Once integrated, it can be tested under the simulation of the Software Verification Facility (SVF), and finally, hardware-in-the-loop tests are executed at satellite level.

4.3 AOCS operations

Referring to the human layer of the AOCS architecture, it is based on on-ground procedures used to operate the satellite and so the AOCSW. The ground procedures are based on mission requirements and accurate step-by-step actions used to command the satellite for a specific goal.

For the execution of the on-ground procedures, a ground operations SW is selected by the mission, along with a complete HW system ready to support and operate it. It must be capable of sending the information to the satellite through a selected communication technology and protocol.

The on-ground procedures are based on TC that are described in the satellite operations manual. These TCs provide the interface for the operators to initiate an action or mode change on the AOCSW. The AOCSW is prepared (programmed) to receive these TCs, and the interface is provided by the SCSW.

The AOCS operation for Eos is autonomous, such that all required processes are executed on-board automatically once ground has decided what is going to be done according to a mission timeline. In the nominal phase, when the instrument is operating, attitude estimation and control are done completely automatically on-board. Orbit corrections are executed autonomously once ground has uploaded the required profiles via time-tagged (or orbit-tagged) telecommands; all processes of slewing to thrust attitude and slewing back to nominal are executed autonomously based on the uploaded profiles. Any calibration attitude manoeuvre is based on ground profiles uploaded for specific needs. Disposal is managed on-ground using the available AOCSW modes.

5 AOCS MODES FOR EOS

The AOCS modes are provided to manage the satellite attitude and were selected from the OHB heritage in response to the main activities realized (and expected) by the EO satellites of Copernicus. Different satellite modes are required to fulfil all necessary functionalities for each satellite, but the main modes proposed for Eos (Fig. 4) can cover all of them; it might be that for a specific mission a sub-mode is required, but in general the design envelope already satisfies all possibilities.

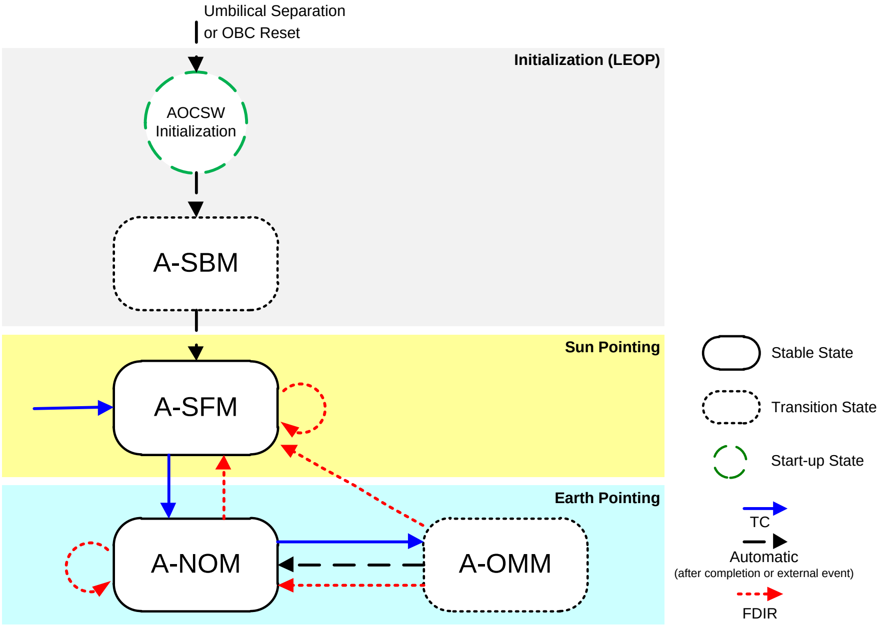

Figure 4. AOCS modes for Eos

Each AOCS mode has different active functions, control algorithms, and configurations of equipment units. The main activities can be sorted as follows:

- Standby Mode (A-SBM), AOCSW initialization with sensor acquisition but no control,
- Safe Mode (A-SFM), safe attitude acquisition and maintenance,
- Nominal Mode (A-NOM), nadir attitude acquisition and maintenance (where any manoeuvring or specific mission task can be added as a sub-mode),
- Orbit Maintenance Mode (A-OMM), for any orbit correction or disposal.

Each of these main AOCS modes may have sub-activities for the entire control process that is defined for each application case. The nominal transitions between AOCS modes as well as the elements used in each mode can also be updated if necessary, depending on the application case.

6 EOS FIRST APPLICATION (CO2M)

On July 31, 2020, OHB System signed a contract with the European Space Agency (ESA) for the realization of the Anthropogenic CO2 Monitoring Mission (CO2M) [4]. The mission is part of the European Copernicus program and, in its first stage of completion, will consist of two satellites equipped with a payload specifically designed to measure carbon dioxide emissions caused by human activities. The payload has the following instruments, according to [5]:

- a CO2 imager (CO2I), consisting of three spatially co-registered push-broom imaging spectrometers, measuring spectral radiance and solar irradiance in the NIR, SWIR-1 and SWIR-2 at moderate spectral resolving power,

- a NO2 imager (NO2I), operating in the visible spectral range and implemented as a fourth spectral band to the CO2I instrument,
- a multi-angle polarimeter (MAP), a compact spectral imager with 40 fields of views spanning a range of ±60°of observation zenith angle (OZA) in along-track direction, and
- a three-band high spatial resolution cloud imager (CLIM).

While the CO2I determines accurate and consistent quantification of anthropogenic CO2 emissions and their trends, the other three instruments provide auxiliary observations of NO2, cloud, and aerosol distribution to support the mission objective.

For CO2M, the Eos platform was adapted, covering all sub-systems within the envelope foreseen in the Eos design. The final product was successful, i.e., it not only covered all mission requirements but also satisfied technically, programmatically, and economically the ESA board.

The following will present a summary of the adaptation of the AOCS for CO2M.

6.1 AOCS architecture for CO2M

Based on the analyses done for CO2M and covering all functional and performance requirements related to AOCS, the generic architecture from Eos shown in Fig. 2 was reduced to Fig. 5.

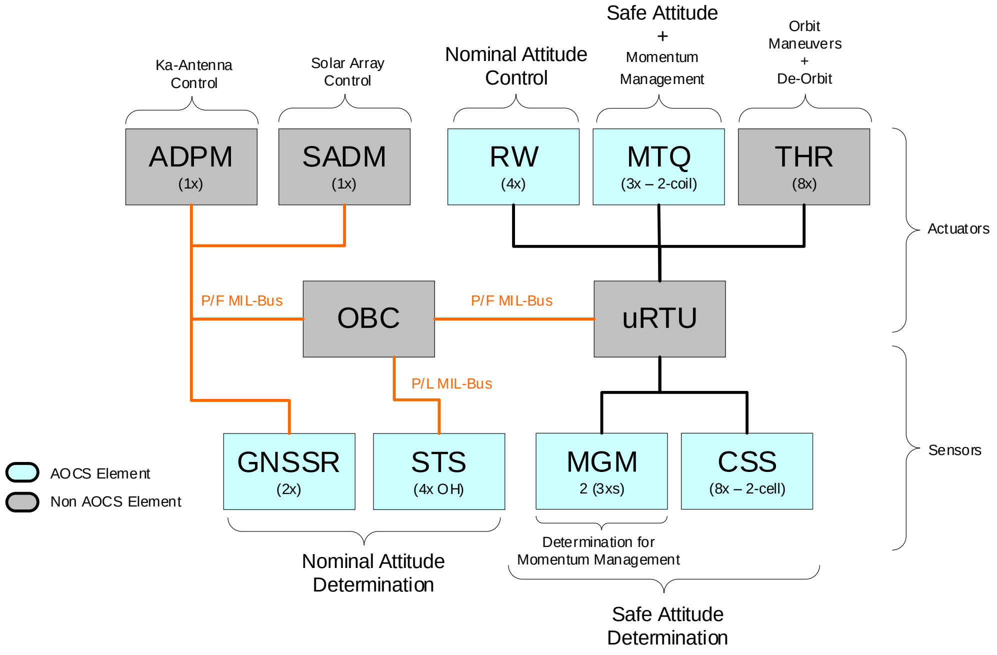

Figure 5. AOCS architecture for CO2M

Attitude determination was achieved with only a fully redundant star-tracker system with four optical heads. The accommodation of the heads ensured no blindings during nominal observation phases, including a Sun-Glint attitude slew manoeuvre requiring up to 58° in pitch as in Fig. 6.

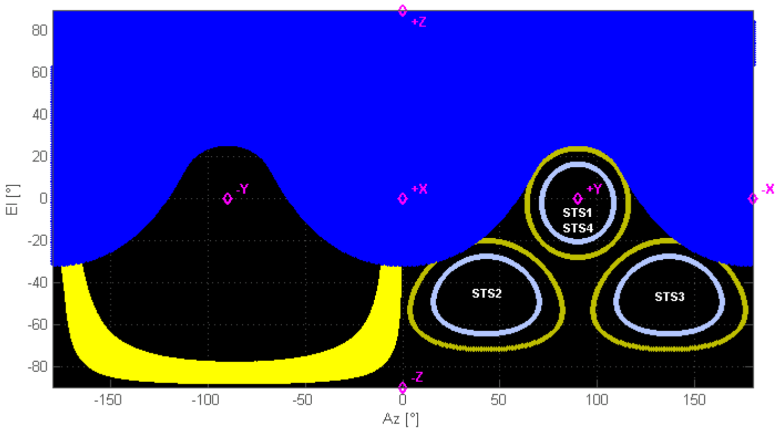

Figure 6. Star-tracker optical heads accommodation for CO2M

Three different sub-modes were added for the nominal case to satisfy the required attitude slew manoeuvres for the payload observation and calibration phases. The detailed mode and sub-mode transitions are in Fig. 7, while in Table 1, the necessary equipment used for each AOCS mode is given.

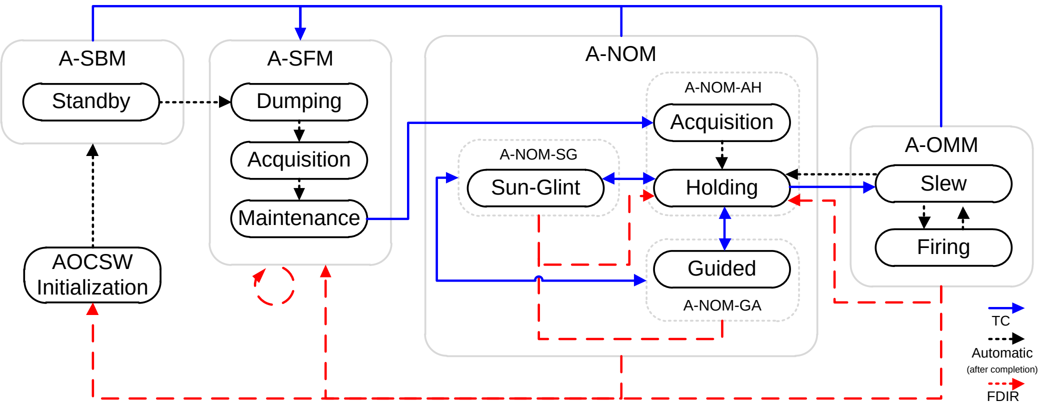

Figure 7. Detailed AOCS modes and transitions for CO2M

Table 1: Units usage in AOCS modes

Unit	A-SBM	A-SFM	A-NOM	A-OMM
STS	-	Z	X	X
GNSS	-	Z	X	X
MGM	-	X	con	con
CSS	X	X	con	con
RW	-	Z	X	X
MTQ	-	X	X	-
THR	-	-	-	X
ADPM	-	-	X	-

X = Activated and used
Y = Activated and used in case it is available
Z = ON depending on SAT Mode but not used by AOCS Mode
con = Active & used only for consistency checks

A redundant element configuration exists for all proposed AOCS elements and functions for CO2M; thus, the conditions for tolerance of single-point failures are given.

6.2 AOCS modes for CO2M

A brief summary of the AOCS modes and added sub-modes for CO2M is given next.

- A-SBM: the Standby Mode is used to initialize the ACOSW and allow on-ground testing. It is started only after launcher separation, and an automatic transition into A-SFM is activated as default after timeout.

- A-SFM: the aim of this mode consists of autonomously reaching a safe attitude (with power and thermal balance). The mode consists of three-phases with a logic triggered by the satellite's angular rates magnitude:
  - Initial rate damping down to a defined rate magnitude value and deployment allowance.
  - Orientation of the satellite to a safe attitude (sun pointing) for full power generation (where the deployed solar array normal is aligned to the target axis).
  - Maintenance (with thermal stabilization) of the safe attitude by moderate rotation around the sun pointing-axis.

- A-NOM: the aim of this mode is to acquire an earth-pointing attitude and keep Nadir pointing in order to allow the payload to execute its functions, that is, provide generic or specific services as required by the payload, including power generation, observability and commandability of status, precise datation, and fine pointing.
  The mode consists of three main sub-modes, of which the first one is the primary and stable sub-mode for Nadir attitude acquisition and keeping:
  - Earth Acquisition and Holding (A-NOM-AH), where earth acquisition is regulated and Nadir pointing attitude secured. The holding sub-mode provides the Nadir pointing with the accuracy required for the nominal payload operation in case two star-tracker optical heads are available.
  - Sun-Glint (A-NOM-SG), in this sub-mode, autonomous on-board computed guidance, based on seasonal profile and orbit position, is applied to generate a profile that observes the sun glint point of the Earth.
  - Guided Attitude (A-NOM-GA), based on ground profiles with respect to time/position that are non-nominal attitude slews used for payload calibration purposes.

  The logic triggered by each of the sub-modes depends on ground TC. All operations are completed autonomously on board based on 3-axis attitude stabilization control, current sensor data and filters for attitude determination, and guidance. In case a specific slew is needed for calibration purposes, ground guidance is necessary, and it must be updated to the on-board computer through TC.

- A-OMM: the aim of this mode is to correct the satellite's orbit by means of thruster firings; it is used to change the satellite's velocity magnitude and/or direction. Due to the location of the thrusters for CO2M, attitude slews of |90°| are required only for out-of-plane manoeuvres and no yaw slew for In-plane manoeuvres to complete the nominal orbit corrections. Anti-velocity manoeuvres (of |180°|) are required only in the disposal phase or collision avoidance. The Nadir pointing is kept with degraded performance compared to A-NOM. The duration, kind, and periodicity of the manoeuvres depend on specific mission analysis and control.
  A-OMM needs specific guidance computed on-board based on on-ground selected targets uploaded by TC. The AOCSW will take this information and generate the guidance automatically. The thrust direction is kept stable by the thrusters in off-modulation while fired to produce the desired delta-v.
  Three main phases (covered by two activities) define the manoeuvre:

  - Slew to target; basically, the yaw slew made by the satellite to reach and stabilize the desired direction of the thrust.
  - Thrust phase; refers to the boost phase when the thrusters are fired for the orbit correction.
  - Slew back; the final slew manoeuvre used to bring the satellite back to the nominal yaw profile.

  After manoeuvre completion, an automatic transition into A-NOM is performed.

6.3 CO2M Challenges

CO2M presents some challenges that have been solved by the Eos baseline design or by specific developments done for this mission. A list of the most relevant platform design extensions is presented next.

- Transition from safe mode to Nadir pointing (A-SFM → A-NOM).
  As a result of the gyro-less AOCS architecture, the transition from sun pointing (-Z axis of satellite reference frame) to earth pointing (+Z) might pose a problem during an acquisition attitude manoeuvre in case all three active star tracker optical heads become unavailable due to either Earth or Sun blinding. This is solved by a series of attitude slews around specific axes. The earth acquisition consists of two main phases:
  - Sun stabilization with reaction wheels: the goal of this is to provide a predictable starting point for the next phase by damping the angular rate bias of A-SFM and reducing the sun pointing error.
  - Earth acquisition slews: this function provides an autonomous algorithm that rotates the satellite around a global optical head field of view such that full star tracker blinding is avoided while a final stable earth pointing is guaranteed. The automatic on-board generated guidance is asynchronous because the slews are pre-computed at the A-NOM entrance and executed until stable nadir pointing

- On-board orbital propagator.
  In order to maintain the stringent system performances, the AOCS shall provide orbital estimation even in the unlikely event of a GNSS receiver contingency. This leads to the development of a precise on-board orbital propagator. The propagator is also constantly used to bridge the 1 Hz receiver navigation solution to the 10 Hz working frequency of the AOCSW. An initial trade-off led to the selection of a numerical integration-based propagator over the analytical Simplified Perturbation Model (SGP4), which is typically used with a two-line element set.

- Management of specific attitude calibration slews and Sun-Glint profile.
  Due to the high degree of flexibility required by the customer, specific attitude manoeuvre profiles are handled with manual guidance (interpolation by Chebyshev polynomials). The star tracker accommodation shall ensure a smooth, blinding-free operation over the whole range of required manoeuvres. In addition to the manual guidance, autonomous on-board seasonal profile shifting and ESA's Packet Utilisation Standard (PUS) orbit position-based TC scheduling can be used at the same time for Sun-Glint mode to guarantee the desired level of autonomy.

- Ka-band antenna steering.
  Ka-band downlink is practically required at each satellite pass over the mission ground stations (two in total). The satellite antenna is mounted on a 2-axis gimbal ADPM and will be

steered accurately to the ground receiving antenna. The steering function implemented inside AOCSW fulfils the following constraints and faces some challenges:

- maximum actuator speed,
- maximum actuator acceleration,
- avoidance of start-stop behaviour,
- avoidance of no-go speed zones for micro-vibration,
- “antenna keyhole” problem (for example, in the case of an overhead pass),
- potentially switching between two ground stations per orbit,
- ready at the desired target as soon as the link is established.

7 CONCLUSIONS AND OUTLOOK

OHB’s Eos platform is already a mature product able to provide a reliable and affordable satellite solution for any EO mission. It is a reliable, scalable, and robust platform aimed at small to relatively large satellites with low to medium agility needs but high estimation and pointing attitude performances.

The AOCS is fully scalable and adaptable; multiple units from the market can be put on board. The main design is fully modular for both HW and SW. The operation of the AOCS modes was conceived to be as simple as possible while covering all aspects required for all missions. It can also be adapted to fit a low-cost, low-reliability new space approach.

The very first application of EOS is the CO2M mission. The design was adapted successfully, and every milestone has been completed as planned. Currently, the satellite is facing the CDR phase, and from the AOCS side, all control processes are already defined and in verification stages to testify to the entire design's performance and robustness through Monte Carlo type analyses. The first hardware in the loop on the engineering model was achieved at the end of 2021 for the safe mode.

OHB is currently using the Eos platform as a baseline for the Sentinel next-generation mission studies and proposals, as well as the Earth Explorer 10 and 11 missions.

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