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DESCRIPTION OF A SATELLITE

ATTITUDE AND ORBIT CONTROL SUBSYSTEM

Abstract

This document was written as part of the study "Design and Prototyping of a Software Framework for the AOCS" done under contract Estec/13776/99/NL/MV for ESA-Estec. The purpose of the study is the development of a software framework for the Attitude and Orbit Control Subsystem (AOCS) of a satellite. Its purpose is to describe the application domain of the AOCS framework by providing a model of the generic AOCS to be instantiated from the framework.

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TABLE OF CONTENTS

1 REFERENCES

RD1 W. Larson, J. Wertz (1998). *Space Mission Analysis and Design,* Kluwer Academic Publisher

RD2 J. Wertz (ed.) (1995), *Spacecraft Attitude Determination and Control,* Kluwer Academic Publisher

2 ACRONYMS

AAD	Attitude Anomaly Detection
AOCS	Attitude and Orbit Control Subsystem
AST	Autonomous Star Tracker
CSS	Coarse Sun Sensor
ES	Earth Sensor
FDIR	Failure Detection, Isolation and Recovery
FPM	Fine Pointing Mode
FSS	Fine Sun Sensor
GYR	Gyroscope
IAM	Initial Acquisition Mode
OBDH	On-Board Data Handling system (aka as OBDS)
NM	Normal Mode
OCM	Orbit Control Mode
RRM	Rate Reaction Mode
RW	Reaction Wheel
SAS	Sun Attitude Sensor
SBM	Stand-By Mode
SPS	Sun Presence Sensor
STR	Star Tracker
SLM	Slewing Mode
SM	Safe Mode
TC	Telecommand
THU	Thruster
TM	Telemetry

3 PURPOSE

This document describes the structure and general requirements of the Attitude and Orbit Control Subsystem, or AOCS, of a satellite. It is intended as an input for the design of an AOCS software framework in that it gives an informal description of the application domain of the AOCS framework. Its purpose is to acquaint the framework designers, assumed to have no preliminary knowledge of satellite systems, with an AOCS system.

The description in this document assumes a so-called decentralized satellite architecture where the AOCS has its own dedicated processor.

This document is prepared in the framework of a cooperation with ESA-Estec. Hence, although the objective is to define an AOCS in general, there is a bias towards the architecture normally adopted on typical ESA missions. This in particular implies that the focus is on large satellites. Small and mini-satellites have distinct architectures and the AOCS in some cases may even be non-existent (as when the satellite attitude is stabilized passively).

Owing to the complexity and variety of satellites and AOCS systems, this document can only give an overview of their architecture and requirements. Accuracy of description will often be sacrificed to generality and ease of understanding.

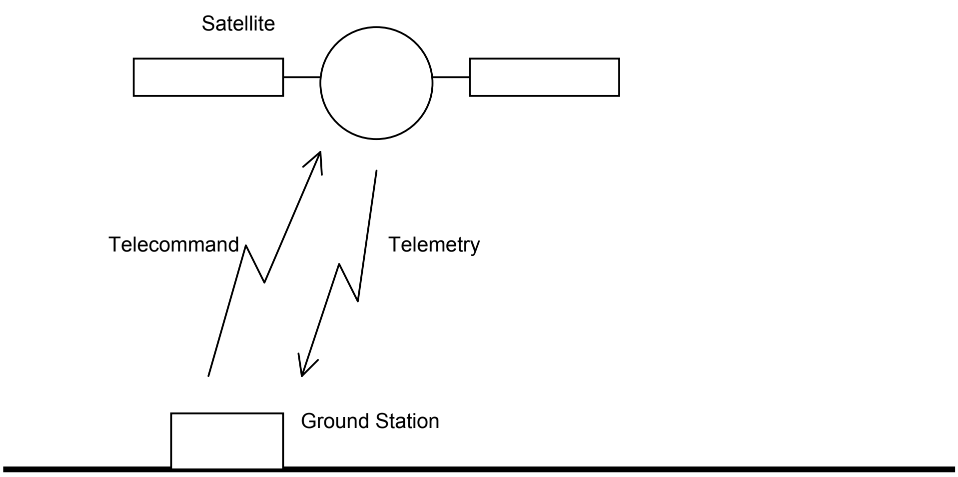
More detailed information about satellite systems in general and the AOCS in particular can be found in RD1 and RD2.

4 SYSTEM LEVEL DESCRIPTION

The figure in this page presents a "black box" view of a satellite. The satellite has two external interfaces:

- *Telecommands*: commands sent from the ground to the satellite;
- *Telemetry*: data sent by the satellite to the ground.

Both telecommands and telemetry are transmitted over a radiofrequency link. In some cases, satellites are continuously in view of a ground station (eg. a geostationary telecommunication satellite) and telecommands and telemetry can therefore be sent and received continuously. In other cases, where the satellite is not in a fixed position relative to the earth (eg. low earth missions), the radio link is only possible when the satellite is passing over the ground station. Visibility intervals can be as short as 10-15 minutes over an orbital period of 100 minutes (low-earth orbit satellite) or they can be several hours long over an orbital period of one or a few days.



4.1 Telecommands

Telecommands are commands sent by the ground station to the satellite. They determine the behaviour of the satellite and can sometimes override internal decisions taken by the on-board software.

Telecommands are sent as asynchronous data packets. ESA has defined standards for the structure of telecommand.

Telecommands are always received by the satellite central computer (the OBDH computer, see below, section 4.3). Sometimes they are also interpreted and executed by this computer. In other cases, the telecommand is intended for a specific subsystem (such as for instance the AOCS). In this case, the telecommand is routed by the OBDH to the target subsystem where the telecommand is interpreted and executed.

4.2 Telemetry

Telemetry data are sent by the satellite to the ground. Telemetry data can be divided into two broad categories:

- Payload telemetry;
- Housekeeping telemetry.

The payload telemetry represents the data collected by the satellite. In the case of an astronomical telescope, for instance, the telemetry contains the pictures taken by the telescope.

Housekeeping telemetry gives information about the general status of the satellite.

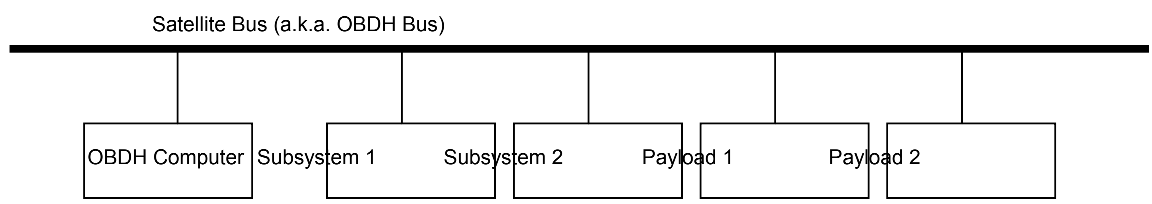
Telemetry data are sent in packets. In the past, the sequence, size and content of packets was fixed. In more recent systems, the ground can select which packets to acquire and how often they should be provided.

Each subsystem normally contributes its own housekeeeping telemetry. Thus, for instance, in the telemetry flow, there is a stream of AOCS data that are generated by the AOCS.

ESA has defined a standard for the structure of telemetry.

4.3 System Level Architecture

A typical internal system architecture of a satellite is shown in the figure:



The satellite system is built around a *system bus* or On Board Data Handling (OBDH) bus. The OBDH computer is the bus master and acts as the central computer for the satellite.

The clients on the system bus are the *satellite subsystems* and the payloads. Satellite subsystems have their own computer and may even have an internal bus. The AOCS is normally one satellite subsystem.

The data travelling over the system bus are telecommands and telemetry. Telecommands are sent by the OBDH computer to the subsystems and payloads, while telemetry is sent by the subsystem and payload to the OBDH computer.

All normal communications between central computer and subsystems and payloads take place over the system bus. However, other links exist for use in special situations such as initialization, power-up, failures or other non-nominal tasks.

4.4 Operational Modes

A satellite can be in various operational modes. The operational mode determines the behaviour of the satellite. Operational modes are adapted to mission phases and to operational circumstances.

Typical operational modes include:

- *Stand-By Mode (SBM)*

  In SBM, the satellite is inactive. It generates basic housekeeping telemetry and listens for incoming telecommands but takes no action to control the spacecraft. The satellite is typically in this mode before it separates from the launcher and in the first seconds after separation.

- *Initial Acquisition Mode (IAM)*

  IAM is typically entered after the satellite has separated from the launcher. In this mode the satellite must perform its initialization and acquire a nominal attitude. IAM may also be entered as part of the recovery sequence after a failure.

- *Normal Mode (NM)*

  In NM the satellite performs the tasks for which it was designed. Thus, for instance, an astronomical telescope in normal mode performs scientific observations. Most of a mission is to be spent in this mode

- *Safe Mode (SM)*

  SM is entered after a very serious anomaly has been detected. The objective of SM is to keep the satellite in a safe state (ie. a state where no permanent damage is done to it or its instruments) and to keep the radio link with the ground open (to allow the ground to identify the cause of the anomaly and if possible to take remedial action).

Transitions from a mode to another may be either autonomous (ie. decided by the on-board software without ground intervention) or it may be commanded by telecommands from the ground.

4.5 Robustness to Failures

Satellites are generally required to be robust to any one failure, regardless of where it arises ("no single point failure" requirement). Robustness in this case is understood as no degradation of performance.

This requirement usually translates into a redundancy requirement: all units and all systems are internally redundant. At the system level, this means that there are two OBDH computers and two system buses.

Redundancy represents a first level of robustness to failure, a second level is normally offered by the presence of a safe mode. The safe mode if one of the operational modes of the satellite (see previous section). In safe mode, the satellite performance is severely degraded but the satellite integrity is ensured.

Thus, when a fault is detected, the following actions are taken:

- First, attempt to reconfigure the satellite to use redundant equipment;
- If the fault conditions disappears, normal operation can continue with full performance;
- If the fault condition persists, fall back to safe mode and wait for further action by the ground.

4.6 Alternative System Architectures

The system architecture presented above is prevalent in large satellites. On smaller missions, the OBDH computer may also host the software for one or more subsystems and perhaps even for the payload (single-computer satellites). In this case, the system bus is also used as a subsystem bus for data exchanges that are internal to a subsystem.

In particular, the AOCS software may sometimes reside on the OBDH computer and the system bus may be used for the data exchanges between the AOCS software and the AOCS sensors and actuators.

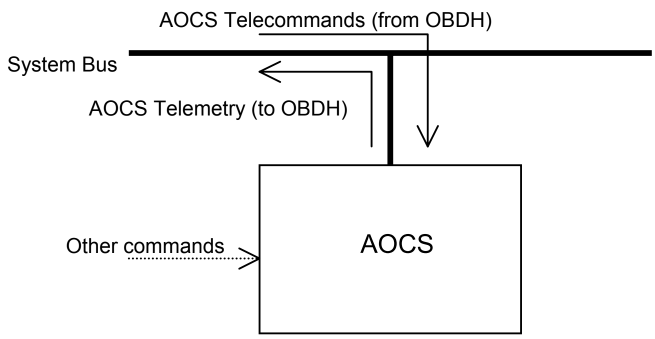
5 THE AOCS SUBSYSTEM

The AOCS subsystem is one of the subsystems of a satellite. Its function is to control the attitude and the orbit of the satellite.

The AOCS subsystem is described in great detail in chapter 11.1 of RD 1 and in RD2.

5.1 AOCS External Interfaces

The typical external interfaces of the AOCS are shown in the figure:



The AOCS receives telecommands from the OBDH computer and it forwards telemetry data to it over the system bus. Other commands, for special contingencies (such as for instance forcing the AOCS into safe mode), may be routed over dedicated command lines.

6 AOCS FUNCTIONS

The objective of the AOCS subsystem is the preservation of the satellite attitude and the control of its orbit.

At any given time, a nominal attitude is defined for the satellite. This is the attitude that the satellite should ideally maintain. For instance, in the case of a geostationary telecommunication satellite, the nominal attitude has the satellite pointed towards the earth. In another example, in the case of an astronomical observatory, the nominal attitude has the boresight of the telescope pointed at the astronomical object that it is desired to study.

The nominal attitude may be either telecommanded by the ground or it may be generated internally by the AOCS software.

In order to achieve its twin objectives of controlling the satellite attitude and orbit, the AOCS implements several main functionalities as described below.

6.1 Attitude Control Function

The attitude is controlled in closed loop and autonomously on-board the satellite. The satellite attitude is controlled by applying torques to the satellite. Torques are applied by *attitude actuators*.

The attitude control function is executed cyclically and its steps are:

- Acquire data from attitude sensors;
- Process sensor data to construct an estimate of the current satellite attitude;
- Compute the deviation of the current attitude from the nominal attitude;
- Compute a control torque to be applied to the satellite to bring the satellite actual attitude closer to its nominal attitude;
- Send commands to the attitude actuators to apply the control torque to the satellite.

The typical frequency for the attitude control cycle is about 2 Hz but higher frequencies up to 20 Hz are possible.

6.2 Orbit Control Function

A nominal orbit is defined for the satellite. This is the orbit that the satellite should maintain. The nominal orbit is defined by the ground.

The orbit of a satellite is controlled by applying forces to the satellite. Forces are applied by *delta-V actuators* (so called because they impart a velocity change, or delta-V, to the satellite).

Orbit control has traditionally been done in open loop mode under ground control. This means that the ground:

- determines the actual satellite orbit (by tracking the satellite as it passes over the ground station);
- computes the corrective forces that need to be applied to the satellite to bring its actual orbit closer to the nominal orbit;
- uplinks telecommands to the satellite commanding the application of the corrective forces to the orbit actuators.

Recently, there has been a trend towards moving the orbit control function to the satellite. In this case, an orbit control cycle would be defined similar to the attitude control cycle. Its frequency would, however, be much lower with typical periods ranging from several minutes to several hours.

6.3 Telecommand Processing Function

Telecommand packets are forwarded by the OBDH computer to the AOCS subsystem. telecommands arrive asynchronously. The typical processing sequence is:

- Perform consistency, validity, and other checks on the telecommand;
- If the telecommand is accepted, execute it.

Typical commands that are sent to the AOCS through telecommands include:

- Set nominal attitude;
- Command orbit control manoeuvre;
- Power up/down an AOCS unit (sensor or actuator);
- Command reconfiguration of AOCS units (fallback from prime to redundant unit, see section 6.6);
- Mark an AOCS unit as ‘unhealthy’ (not to be used in future reconfigurations);
- Command change of AOCS operational mode.

Some of the above commands override functions that can also be performed autonomously by the AOCS.

6.4 Telemetry Processing Function

AOCS cyclically generates telemetry to be sent to the OBDH. Depending on the system architecture, the forwarding of telemetry packets to the OBDH may be initiated by the AOCS itself or the packets may be autonomously acquired by the OBDH.

Telemetry cycles have low frequencies of a fraction of an Hertz.

The format of the telemetry packets (ie, the type of information that they contain) is determined by telecommands.

Typical data that are contained in a telemetry packet include:

- power status of AOCS units;
- health status of AOCS units;
- current AOCS operational mode;
- telecommand log (ID of received telecommands, execution status, etc.);
- latest estimate of satellite attitude;
- latest value of control torques computed by the AOCS;
- latest readings from AOCS sensors;
- latest set of commands sent to the AOCS actuators;
- event log (log of 'special' occurrences such as reconfigurations)

6.5 Failure Detection and Isolation Function

This is a cyclical function where the AOCS attempts to detect anomalies and isolate their cause. This function is very mission specific and can be very complex.

Typical checks that are performed in order to detect anomalies include:

- *Attitude Anomaly Detection (AAD)*

  This check verifies that the attitude is within a pre-specified permissible window. The window may be defined with respect to the sun (eg. "spacecraft X-axis shall not deviate by more that 20 degrees from the sun line") or with respect to the nominal attitude (eg. "actual attitude shall not deviate from the nominal attitude by more than 25 degrees"). In both cases, a violation of the attitude anomaly check indicates that the attitude control function has failed.

  The size of the attitude window may be either fixed or settable by telecommand.

  The attitude anomaly check is a failure *detection* only method as it does not allow *isolation* of the cause of the anomaly.

- *Single Sensor Consistency Check*

  This check verifies that the output of a sensor respects some physical constraints. Sensor outputs should for instance lie within certain ranges, and variations across two consecutive readings must be constrained to be below a certain threshold.

The check thresholds are generally settable by telecommand.

This check allows both detection and isolation of the failure.

- *Multi Sensor Consistency Check*

  Sensors usually provide redundant information (ie. several sensors may be measuring the same physical quantity, for instance the sun direction). This check exploits the redundancy of the measurements to detect and, if the degree of redundancy is sufficient, isolate failures.

  The check thresholds are generally settable by telecommand.

- *Watchdog Alarm*

  The AOCS software cyclically generates a 'watchdog event' that is detected by a dedicated hardware (the 'watchdog'). If the watchdog does not receive the event within a certain time-out, an anomaly is assumed to have occurred.

  This mechanism only allows fault detection, not fault isolation.

6.6 Failure Recovery Function

A failure recovery action is an action taken in response to the detection of a failure. Typical failure recovery actions include:

- *Failure Reporting*

  The AOCS takes no autonomous action and simply reports the failure to the ground via telemetry.

- *Reconfiguration*

  A reconfiguration is commanded (see next subsection). If the source of the failure has been isolated, the reconfiguration may be local to the equipment or function that has failed. If no failure isolation was possible, the entire subsystem may be reconfigured.

- *Mode Fall-Back*

  A mode change is commanded to a lower-level operational mode in the expectation that the failure will not persist.

The failure recovery function may either be performed cyclically or be triggered in response to a failure detection.

6.7 Reconfiguration Function

At any given instant in time, the AOCS is using only a subset of all its available units. Note in particular that the redundancy requirement (section 4.5) dictates the presence of two sets of each sensor. Hence, not more than half all available equipment are ever used[1].

When the AOCS has detected a failure, it must attempt to recover by performing a *reconfiguration*. A reconfiguration changes the set of units that are being used by the AOCS at a certain instant in time. The intention of a reconfiguration is to exclude the faulty unit.

The configuration logic is highly mission dependent. The following types of reconfigurations can be identified:

- *Unit Reconfiguration*

  If the failure detection and isolation function (see previous section) was able to isolate the faulty unit, then the typical reconfiguration is a switch-over to the redundant copy of the faulty unit.

  If, for instance, a consistency check on the output of a sun sensor shows that the sensor is defective, then this function will switch over to the redundant sun sensor. Overall system performance should remain unaffected.

- *Subsystem Reconfiguration*

  If no fault isolation was possible, the entire subsystem is reconfigured. This means that all units (including the AOCS computer) are switched over to their redundant copies and the subsystem is re-initialized.

  If, for instance, the attitude anomaly safeguard (see previous section, first bullet) has been violated, then it is known that a serious fault has occurred but it is not possible to say which equipment is responsible for it. In this case, all currently used hardware is switched off and there is a switch over to the redundant sets.

6.8 Manoeuvre Management Function

A manoeuvre is a sequence of actions that must be performed by the AOCS at specified times to achieve a specified goal. Examples of manoeuvres include:

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[1] This is strictly speaking not true because there are units, like the reaction wheels or the gyros, where redundancy is achieved without full duplication of hardware.

- A sequence of small torque impulses imparted to the spacecraft to cause the speed of the reaction wheels to change in a desired manner (*wheel momentum unloading*).
- A slew to change the direction of pointing of the spacecraft payload.
- A sequence of thruster firings to change the spacecraft orbit in open-loop mode.

Manoeuvres can either be triggered autonomously by the AOCS or they can be commanded by the ground via telecommands. Mnoeuvre execution may overlap with more than one manoeuvre being active at the same time.

7 AOCS OPERATIONAL MODES

The great variety of external conditions under which a satellite must operate in a given mission, dictates the breakdown of the overall AOCS functionality into several operational modes with each operational mode optimized for certain mission conditions.

The functionalities of the AOCS are always the same as explained in the previous section but their *implementation* changes from operational mode to operational mode. Consider for instance the attitude control function. The accuracy with which the satellite attitude must be aligned to the nominal attitude varies form mission phase to mission phase (and hence from operational mode to operational mode). Consequently, different control laws are used to implement this function depending on the required accuracy.

An important difference between operational modes lies in the set of AOCS units – the sensors an actuators – that are used by the AOCS. In principle, each operational mode has a different set of units that are the optimal ones required to achieve the mode targets. Hence, a mode transition is usually accompanied by a power-up and power-down sequence for some units.

Mode transitions can either be commanded by the ground (or the OBDH) by telecommand or they can be decided autonomously by the AOCS software. In the latter case, however, the ground retains the right to over-ride or inhibit AOCS-initiated transitions.

7.1 Mode Architecture

The mode architectures is very mission specific. However, on most missions, some or all of the following modes are used:

- *Stand-By Mode (SBM)*

  In this mode, only the telecommand and telemetry functions are active. The AOCS does not perform any attitude or orbit control functions and all the AOCS units, except the AOCS computer, are switched off.

  This mode is typically used when the satellite is still attached to the launcher or in the first seconds after separation from the launcher.

- *Rate Reduction Mode (RRM)*

  The objective of this mode is to reduce the angular velocity (or angular rate) of the satellite to a very small value (of the order of 0.01 deg/sec). Thus, the attitude controller in this mode is not concerned with the satellite attitude, but only with the satellite angular rates.

This mode is typically used after separation from the launcher (launcher separation induces comparatively high angular rates on the satellite).

- *Initial Attitude Acquisition (IAM)*

  Pre-condition for entry into this mode is that the satellite angular rates are very low. This mode could thus be entered after RRM.

  In this mode, the satellite is slewed until it is oriented according to a pre-defined attitude. This target attitude is often selected in such a way as to have the solar array sun-pointing (to ensure a steady power supply to the satellite) and the radiofrequency antennas earth-pointed (to ensure a good telecommand and telemetry link).

- *Fine Pointing Mode (FPM)*

  This is a high accuracy mode where the satellite attitude is finely controlled to reduce the attitude error (difference between actual and nominal attitude) to the maximum possible extent.

  This mode is typically used during scientific observations (scientific missions) or earth observations (earth observation mission).

- *Slewing Mode (SLM)*

  This mode is used to change the orientation of the satellite. This is for instance required when a telescope must be pointed to a new target.

- *Orbit Control Mode (OCM)*

  This mode is used when forces are imparted to the satellite to change its orbit.

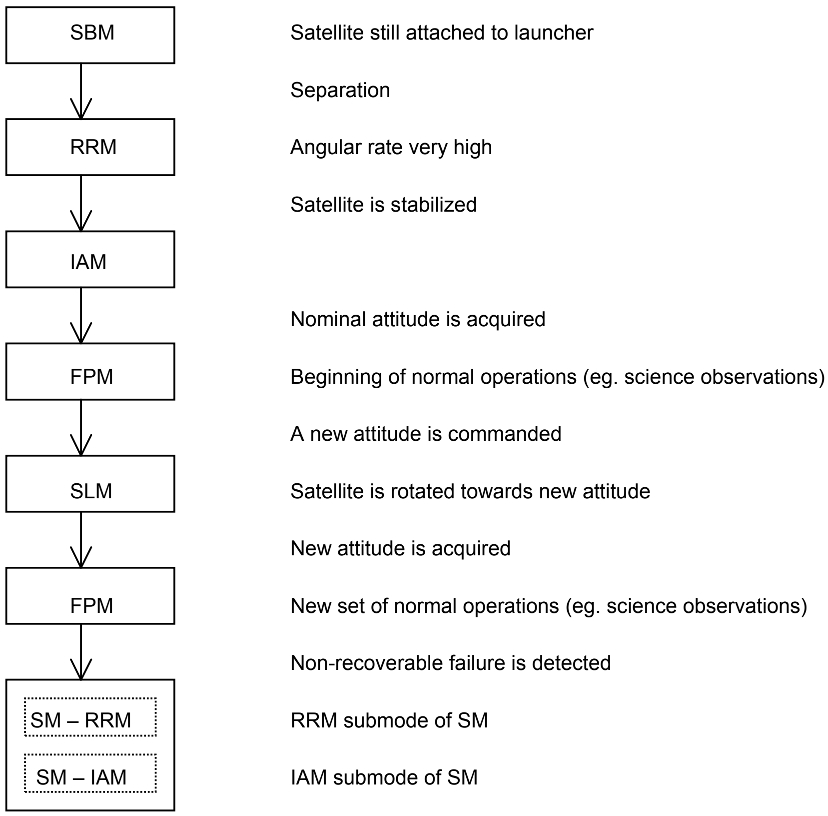
- *Safe Mode (SM)*

  This mode is entered when a failure has been detected and when no reconfiguration is possible to counter the failure. This situation may arise for several reasons. For instance, a reconfiguration may have been attempted and may have failed to restore nominal behaviour. Alternatively, previous reconfigurations may have already caused a fall-back to redundant units thus leaving the AOCS without further options for reconfigurations.

  The objective of safe mode is to keep the satellite in a safe attitude (ie. an attitude in which no permanent damage to the satellite or its instruments can occur). This often means that the satellite must be kept with the solar arrays sun-pointed to ensure that enough power reaches the satellite. Additionally, it is normally required that the radiofrequency link with the ground is kept active to allow the ground station to investigate the failure and take remedial action.

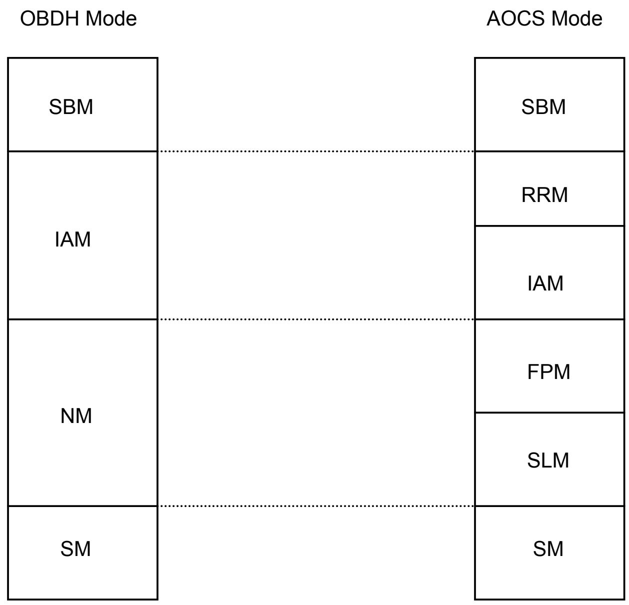
Each of the above modes may in turn be divided into sub-modes. The safe mode in particular will usually contain its own version of the RRM and IAM.

The figure below shows a possible operational sequence:



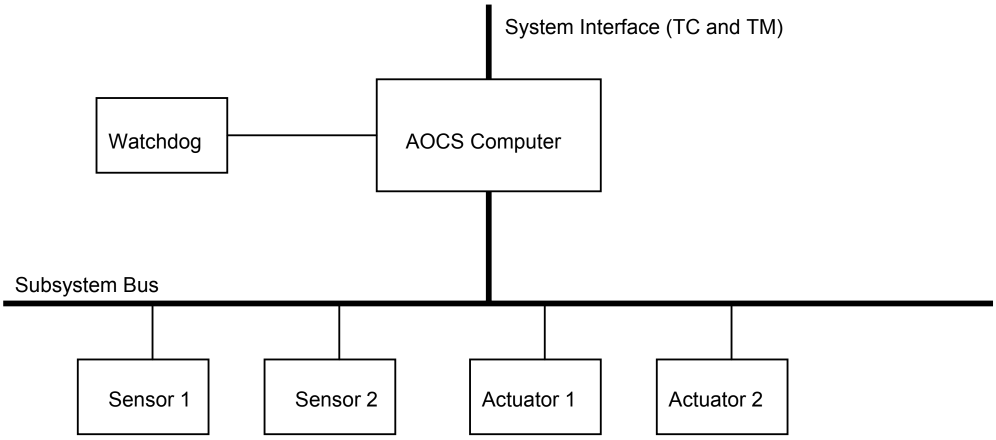
7.2 Relationship with OBDH Modes

Section 4.4 introduced the OBDH (or system-level) operational modes. The AOCS modes need not be identical to the OBDH modes although they are obviously related. In particular, it is common for a single OBDH mode to map to several AOCS mode. The figure below shows a possible mapping between AOCS and OBDH modes:


OBDH Mode
AOCS Mode
SBM
SBM
RRM
IAM
IAM
FPM
NM
SLM
SM
SM

8 AOCS INTERNAL ARCHITECTURE

The usual internal architecture of an AOCS subsystem is shown in the figure:



The AOCS subsystem is built around a dedicated bus. It is controlled by a dedicated computer, the *AOCS computer*. The subsystem bus allows the AOCS computer to exchange data with the *AOCS units*, namely the *AOCS sensors* and *AOCS actuators*. A *watchdog* monitors the AOCS computer and, if triggered, may command a reconfiguration of the subsystem.

The AOCS computer is always the master of the AOCS bus. This may change in the future when "intelligent" AOCS units are introduced and the subsystem bus will become multi-master.

The load on the AOCS bus is generally very low.

8.1 Redundancy

The AOCS subsystem is entirely redundant. This implies that there are two AOCS computers (prime and redundant computer), two AOCS buses (prime and redundant), two sets of AOCS units (prime and redundant). The watchdog is not redundant because it is part of the failure detection equipment.

In some implementations, the prime and redundant buses are cross-strapped to the prime and redundant computers. This implies that the prime computer can use the redundant bus as well as the prime one, and vice-versa. In other implementations, the redundant and prime branches of the subsystems are completely independent.

8.2 Alternative Architectures

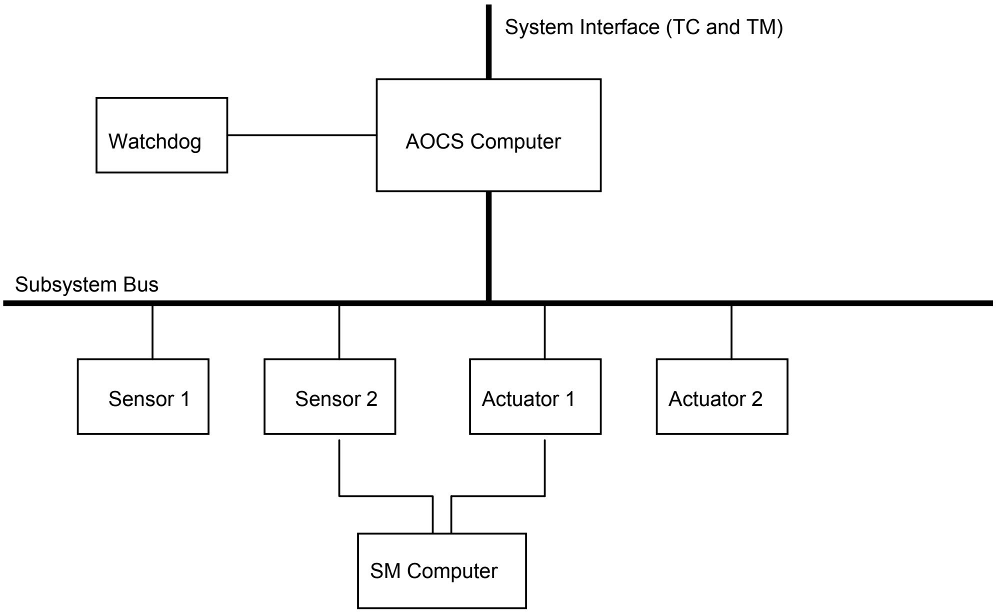
In one alternative architecture, the subsystem bus is the same as the system bus and the AOCS software resides in the same computer hosting the OBDH software.

In another alternative architecture, there is no subsystem bus and the AOCS units are directly connected to the AOCS computer (star configuration).

8.3 Safe Mode Architecture

The safe mode logic and implementation should be as independent from the rest of the subsystem as is possible. This is required to prevent propagation of failures from the nominal software/hardware to the safe mode software/hardware.

A common solution to this problem is to have a second computer, the safe mode computer, that runs the safe mode software and that has its own dedicated connections to the AOCS units. The subsystem architecture then becomes:



In some cases, the safe mode logic (which must be very simple for reasons of reliability), is implemented in hardware.

9 AOCS UNITS

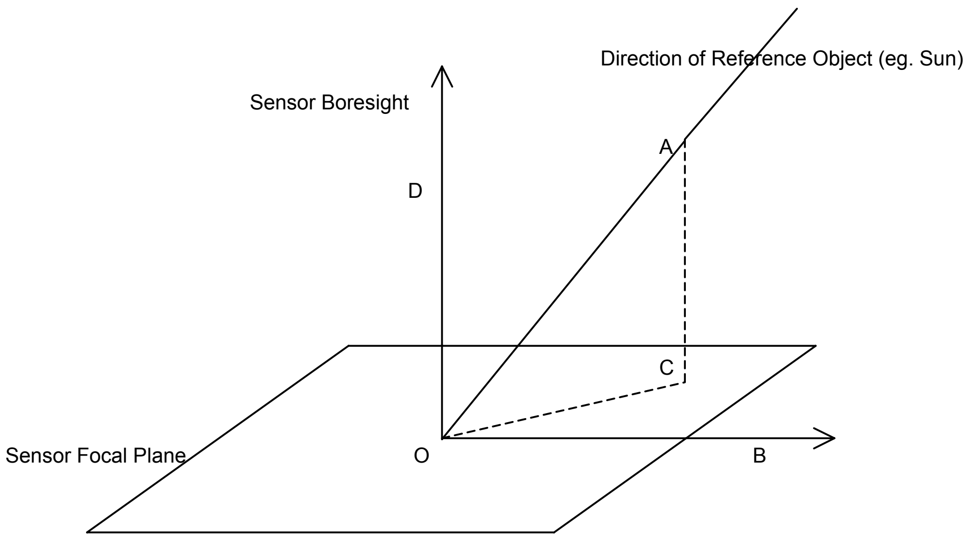
The AOCS units are the AOCS sensors and the AOCS actuators.

The *sensors* are used by the AOCS to collect measurements about the current attitude and position of the satellite.

The *actuators* are used to impart torques and forces to the satellite to control, respectively, the satellite's attitude and its position.

9.1 Attitude Sensor Characteristics

Most attitude sensors work by measuring the direction of an inertial object (eg. the sun, a star, the earth, etc.) in the sensor reference frame.



The direction of the inertial object is define by two angles: angle AOD and angle COB where CO is the projection of the inertial direction on the focal plane of the sensor.

The picture depicts a *2-axis* sensor. This is the most common case. Some sensors are *1-axis* sensors in that they only measure one angle expressing the angular separation between the inertial direction and the sensor boresight.

Attitude sensors are characterized by:

- *Field of View*

The size of the window around their boresight where they can observe external objects.

- *Accuracy*

  The error affecting the angular measurements of the angles AOD and COB. Accuracy is made up of two contribution: random error and bias. Accuracy can be either constant throughout the field of view or can be a function of the inertial direction in the field of view (typically, accuracy degrades as one gets away from the sensor's boresight).

- *Sensor Attitude in Satellite Frame*

  Attitude sensors measure the inertial direction in the sensor's own reference frame. The AOCS computer needs the measurements to be expressed in satellite reference frame. Translation from one frame to the other requires knowledge of the sensor reference frame with respect to the satellite reference frame.

- *Misalignment*

  During satellite assembly, misalignments are introduced between the sensor's nominal orientation and its actual orientation. These misalignments are stored in a *misalignment matrix* and they are used to correct the measurements.

- *Calibration*

  Launch vibrations and thermal distortions in orbit introduce new misalignments between a sensor's actual orientation and its nominal orientation. Insofar as these misalignments can be measured (during *calibration campaigns*) they are stored in a *calibration matrix* that is used to correct the sensor's measurements.

Attitude sensors can be of two types. *Passive sensors* have no internal processors. *Active sensors* have an internal processor and the complexity of their software can match that of the AOCS computer itself. In some architectures (proposed but so far not implemented), some of this software is located on the AOCS computer.

9.2 Passive Attitude Sensors

The most common types of passive sensors are:

- *Fine Sun Sensor(FSS)*

  A fine sun sensor measures the direction of the sun line in the sensor's reference frame Typically, FSS's have a nearly-hemispherical field of view and very high accuracy (order of arcsecond).

- *Coarse Sun Sensor(CSS)*

  The CSS is conceptually similar to the FSS but it is constructed in a different way. The different technology results in a lower accuracy (order of 0.1 deg). The field of view is nearly hemispherical with accuracy being highest close to the boresight.

- *Sun Presence Sensor (SPS)*

  This sensor has a binary output. Possible outputs are: "sun present" and "sun not present". The "sun present" output is generated when the sun direction is within the sensor's field of view. Typically the field of view is square with a side of 25 or 30 degrees. The "sun not present" output is generated when the sun is outside the field of view.

  SPS's are often used as attitude anomaly detectors (see section 6.5).

- *Earth Sensor (ES)*

  Earth sensors measures the earth direction in the sensor's field of view. Their accuracy is rather low (order of 0.01 to 0.1 deg).

- *Magnetometers*

  Magnetometers measure the direction of the earth's magnetic field in the sensor's field of view. Their accuracy is low and varies widely from system to system.

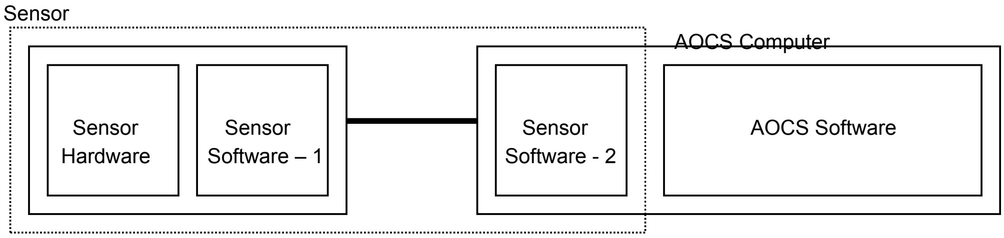
- *Gyroscope (GYR)*

  Gyroscopes measure the inertial angular rate of the satellite. Gyroscopes can have one or two sensitive axes. They give the projection of the satellite angular rate on the sensitive axes.

  Gyroscopes are often combined in packages to give measurements along up to six axes.

9.3 Active Attitude Sensors

Active attitude sensors generate measurements that are obtained by performing sophisticated processing on the raw measurements generated by the sensor's hardware. In the conventional architecture, the sensor's software runs entirely on the sensor's processor. Some proposed architectures instead envisage overcoming processing limitations on the sensor by placing part of its software on the AOCS computer:



Obviously, the distinction between sensor software and AOCS software can become blurred. It exists mainly from a project management point of view as the sensor software is supplied by the sensor supplier who is in general different from the supplier of the AOCS software.

There are at present two types of active AOCS sensors:

- *Star Sensor (STR)*

  A star sensor measures the positions of several stars in its field of view. It also performs pattern recognition on the stars it sees to identify the portion of sky at which it is looking.

- *GPS Receiver*

  GPS receivers are primarily used for position determination but they can also provide an inertial measurement of the host satellite attitude.

9.4 Position Sensor

Position sensors measure the position of the satellite. Position measurements are required as input to the orbit control function (see section 6.2).

There is at present only one position sensor. GPS receiver can on low earth orbits provide an estimate of the host satellite position to an accuracy of 50 m or better.

Indirect position measurements are also possible by combining measurements from star, earth and sun sensors.

9.5 Attitude Actuator Characteristics

Attitude actuators apply torques to the satellite. The application of torques causes the satellite to rotate. Torques can therefore be used to control the satellite attitude.

The chief characteristics of attitude actuators are:

- *Torque Level*

  Maximum value of the torque that the actuator can deliver.

- *Actuator Attitude in Satellite Frame*

  Attitude actuators apply torques whose intensity and direction is defined in the actuator's reference frame. The AOCS computer expresses the torque in satellite reference frame. Translation from one frame to the other requires knowledge of the actuator reference frame with respect to the satellite reference frame.

- *Misalignment*

  During satellite assembly, misalignments are introduced between the actuator's nominal orientation and its actual orientation. These alignments are stored in a *misalignement matrix* and they are used to correct the torque demand made by the AOCS computer.

- *Calibration*

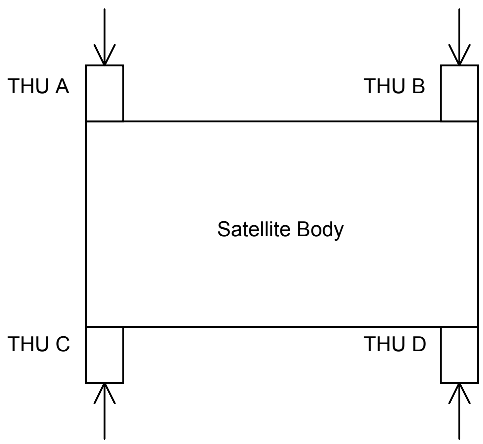
  Launch vibrations and thermal distortions in orbit introduce new misalignments between an actuator's actual orientation and its nominal orientation. Insofar as these misalignments can be measured (during *calibration campaigns*) they are stored in a *calibration matrix* that is used to correct the actuator's torque demands.

9.6 Attitude Actuators

There are three types of attitude actuators:

- *Thrusters (THU)*

  Thrusters can emit gas jets that impart a force to the satellite. If the direction of the gas jet does not go through the satellite centre of gravity, then a torque on the satellite results. By combining jets from suitably located thrusters it is possible to apply either pure forces or pure torques to the satellite:



The arrows in the figure represent the force applied by each thruster to the satellite body. Assuming that all thrusters deliver the same force level, then firing thrusters A and B at the same time will result in a pure force being applied to the satellite. Firing A and D at the same time will result in a pure torque being applied to the satellite.

- *Reaction Wheels (RW)*

  A reaction wheel is a rotating wheel that can be accelerated or braked. The action of accelerating or braking causes a torque to be applied to the satellite by reaction. Conceptually, reaction wheels are devices that can apply a torque along one axis.

- *Magnetorquers*

  Magnetorquers are devices that interact with the earth's magnetic field to generate a control torque.

9.7 Position Actuators

Position actuators apply forces to the satellite to change its position and hence its orbit. The only position actuators are thrusters. Thrusters serve also as attitude actuators. They work in attitude or position control mode depending on the sequence in which they are fired (see previous section).

10 AOCS SOFTWARE

The AOCS software is generally built as one single load module that is burned into PROM on the AOCS computer or uplinked by telecommand.

For power reasons, the software normally runs from RAM and patches to the software are therefore possible after launch.

10.1 Hardware

The size and complexity of the AOCS software has in the past been limited by the available hardware. Processors for use in space must undergo a lengthy and expensive qualification process that certifies their robustness to the space environment (radiation, launch shock, temperature range, etc.). The traditional processor used in space missions implements the mil-std 1750 architecture. Available memory in the "standard" configuration is only 64 Kbytes (data + code) and many AOCS load modules had to fit within this rather constrained space.

Recently, a more advanced processor, the ERC32, has been qualified for use in space that implements the SPARC architecture and can have several Mbytes of memory.

10.2 Language

The language of choice for the AOCS software on ESA projects has been ADA83.

10.3 Scheduling

The AOCS software is organized as a collection of tasks. A cyclic scheduling policy without pre-emption is used. The cycle period is the same as the AOCS control cycle (often 500 ms but also 1 sec or 50 ms). Tasks are allocated a slot in this cycle and must return within the allotted time. Overruns are normally fatal errors causing a reset of the software.

Ada tasking is generally not used because of its overheads.

Interfaces with the hardware are interrupt-based.

10.4 Layering

A layer architecture is adopted for the AOCS software with at least two layers being present. The bottom layer, often called the *operating system*, takes care of scheduling and interfacing with the underlying hardware. The upper layer, often called *application software,* implements the AOCS functionalities in a hardware-independent fashion.

10.5 Hardware Interfaces

The AOCS software has two major hardware interfaces (see also section 8): with the subsystem bus and with the system bus. Through the former interface, data exchanges with the AOCS units are routed. Through the latter interface, telemetry and telecommands are collected and received.

On the subsystem bus, the AOCS computer is the master and initiates all communications. Data exchanges with the subsystem bus can be either through I/O instructions or through DMA. When the AOCS computer initiates a data exchange on the subsystem bus, interrupts may be used to notify the AOCS software of the termination of the data exchange or of the arrival of a response from a unit. In general the time for a full cycle on the subsystem bus (interrogation sent by the AOCS computer to a unit, reception of response, if any, from the unit) is well below 1 ms.

On the system bus, the AOCS computer normally behaves as a slave. The arrival of telecommands can be signalled by an interrupt. Telemetry is instead stored by the AOCS computer in a dedicated buffer from which it can then be autonomously collected by the system bus interface in DMA mode.

10.6 Exception Handling

The occurrence of exceptions (eg. divide-by-zero errors, hardware errors, etc) is usually not handled and simply causes a reset of the software.

10.7 Software Lifecycle

A waterfall-type approach is taken to the software lifecycle. The development phases are: user requirement definition, software requirement definition, architectural design, detailed design.

On ESA projects, the software lifecycle follows a very rigorous standard developed by ESA (PSS 05 standard).

More recently, the ECSS-E40 standard has been introduced for satellite software development. This is a tailorable standard that does not dictate any lifecycle model.