Aoc Design and Test for GSTB-V2B

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ABSTRACT

In the frame of the European Galileo program Galileo Industries (GaIn) has been selected as main contractor for delivery of one of two test satellites (GSTB-V2B). This paper concentrates in detail on the GSTB-V2B Attitude and Orbit Control (AOC) function, which has been subcontracted as part of the Avionic subsystem to EADS Astrium. Main topics described are related to the overall requirements, the AOC Hardware and Operational Architecture and to selected topics of AOC analyses and AOC HW open-loop and closed-loop Tests.

1. OVERALL REQUIREMENTS

The spacecraft is operated at a Galileo like circular MEO orbit of 23.230 km altitude (29.601 km semi-major axis) at an orbit inclination of 56°. The operational S/C life-time is expected to be 2 years. The main overall AOC requirements are summarized subsequently

- Rate damping capability after separation from the launch vehicle up to 10°/s
- Autonomous Sun- and Earth- acquisition capability
- Earth pointing in roll and pitch with 0.2° accuracy in normal operation
- Calculation of a S/C yaw steering profile for optimum power generation, where the S/C X-axis is not illuminated from the Sun light due to payload thermal constrains. Following of this profile is required with 2.0° yaw accuracy
- Wheel angular momentum storage and unloading capability in the uncertain MEO environment (incl. Solar storms) with minimum orbit disturbance during normal operation
- High MEO altitude radiation environment

2. AOC HARDWARE ARCHITECTURE

The AOC design is based on a standard bias momentum system using Fine Sun Sensors (FSS) and Earth Sensors (ES) as optical reference, augmented by three-axis rate integrating gyros (GYR) for rate and attitude determination - required only for certain modes. The primary actuation system is based on an assembly of four reaction wheels (RW) for direct attitude control together with a secondary actuation system based on magnetic torque rods (MTQ) for wheel unloading. The propulsion subsystem is mainly used for orbit correction, for safe mode operation and as back-up for wheel unloading. For proper Solar Array orientation and due to payload thermal reasons the AOC provides the necessary guidance laws for control for the S/C yaw steering motion as well as for control of the Solar Array Drive Mechanism (SADM).

Figure 1 basically summarizes the AOC hardware architecture.

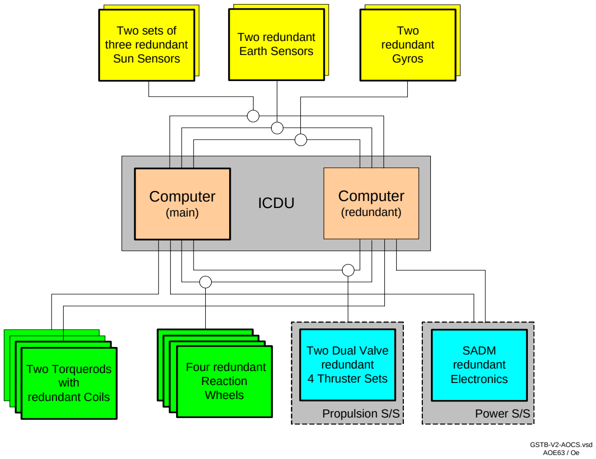

Figure 1: GSTB-V2 AOC Hardware architecture

3. AOC OPERATIONAL ARCHITECTURE

The AOCS provides the following operational modes and functions:

- **Idle Mode (IDM):**
  This mode is mainly used in the satellite Launch state for check-out purposes where the AOCS is in

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an idle state. Sensor equipment can be switched on and monitored by ground.

- **Safe Mode (SFM):**
  SFM performs Sun acquisition with thrusters. It can be entered from any initial conditions (any attitude and any reasonable rate). SFM will be used only in extreme failure cases (like double wheel failure) as ultimate survival mode.
- **Sun Acquisition Mode (SAM):**
  SAM performs Sun acquisition with wheels, where thrusters are used for unloading. It can be entered from any initial conditions (any attitude and any reasonable rate). The duration until mode success will be in general longer (in the range of minutes) than using SFM. SAM is the nominal Sun acquisition mode.
- **Earth acquisition Mode (EAM):**
  This mode is entered to search and acquire the Earth and finally to perform Earth pointing.
- **Normal Mode (NOM):**
  NOM is entered from EAM to meet the two-axis pointing requirements together with the specified yaw steering motion in fully gyro-less operation. NOM is used in the satellite mission state where the payload is operable with full performance.
- **Orbit Correction Mode (OCM):**
  This mode is used for large angle slew manoeuvres for proper thrust vector orientation, for orbit raising, in-plane and out-of-plane correction and de-orbiting.
- **Gyro Calibration Capability**
- **Ground Control Operation**

The nominal Mode transition logic is outline in ***Figure 2***

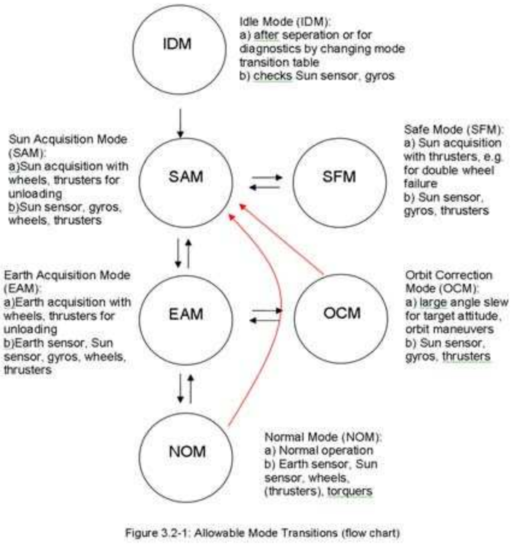

Figure 2: Mode Transition Diagram

and the Equipment / Mode decomposition is presented in the following table:

Table 1: Number of Active Equipment Units Used in each Mode

	ES	FSS	GYR	THR	RW	MTQ	SADM
IDM		**x**	**x**				
SAM		**x**	**x**	**x**	**x**		$\mathbf{x}^{1}$
SFM		**x**	**x**	**x**			$\mathbf{x}^{1}$
EAM	**x**	**x**	**x**	**x**	**x**		**x**
NOM	**x**	**x**		**(x)**	**x**	**x**	**x**
OCM	$\mathbf{x}^{2}$	**x**	**x**	**x**	**x**		**x**

Note:
(x) = optional on: thrusters as backup in NOM on only if torque rods fail
x^1 = SADM will be controlled to a predefined fixed position
$\mathbf{x}^2$ = Earth Sensor not needed in OCM but left on for reliability

It should be mentioned in this context, that due to the selected available PROTEUS platform, which has been adapted for GSTB-V2 needs, OCM has to be performed without Earth reference, because the propulsion subsystem thrusters are not aligned perpendicular to the Earth sensor line-of-sight. Thus, the large angle slew manoeuvres for thrust orientation together with the thrust manoeuvres have to be performed based on rate-integrating gyro angle increments in a strap-down manner with possible two axes updates from the Sun Sensor measurements

4. SELECTED AOC ANALYSES

4.1. GSTB-V2 Yaw Steering Motion

Subsequently the special Yaw Steering Guidance Law as applicable for GSTB-V2 is discussed in detail, where

- Spacecraft continuous Nadir pointing is performed with one selected axis (z-axis)
- Spacecraft rotation is performed around the nadir pointed axis in order to orient the S/C solar array axis perpendicular to the Sun line
- SADM rotation is calculated to align the solar array active plane normal towards the Sun, based on a state-of-the-art one-axis solar array drive mechanism
- One selected spacecraft panel (+x panel) perpendicular to the nadir line and to the solar array axis is oriented such, that Sun incidence is avoided

(with the exception of sliding incidence) due to payload thermal reasons

- The two spacecraft panels (y-panels), the panel normal of which is parallel to the solar array axes, are illuminated from the Sun with an incidence angle less than a predefined critical angle

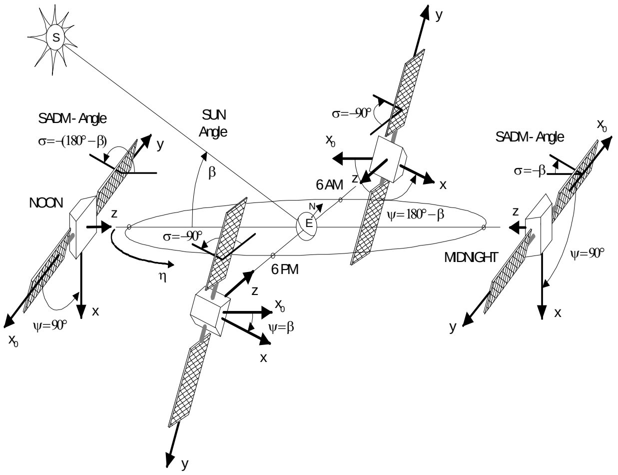

Figure 3: Principle of the Yaw Steering Motion

From Figure 3 it can be concluded, that for fulfilment of the non-Sun-incidence requirement on the S/C x-panel, yaw steering has to be performed every time without interruption. Thus, the well known principle, to stay at a constant yaw angle in the critical band $-\beta_0 < \beta < +\beta_0$, where the yaw motion becomes singular ("Yaw Flip") if the Sun elevation angle β approaches zero, cannot be applied.

Because a bang-bang type Yaw Steering control law in the critical band is not preferable due to high-frequency stimulus, a smooth dynamically limited yaw steering profile is applied in the critical band introducing a smoothing factor f = f(η). In addition to the pure yaw angle profile the knowledge of the yaw steering angular rate and angular acceleration is convenient for

- Engineering purposes (dimensioning of the S/C actuation system)
- Usage as feed-forward commands in the on-board control loops for dynamic control improvement

To avoid numerical differentiation - in particular for calculation of in-orbit feed-forward commands - the analytic equations can be derived simply by calculating the analytical expressions of the derivatives. Subsequently the yaw steering guidance together with the SADM steering control laws are summarized:

- **Kinematic Yaw Steering** for large Sun elevation angles

$$\begin{aligned} &|\beta| \geq \beta_0 : \textit{Kinematic Yaw Steering} \\ &f \ = 0 \end{aligned} \tag{1}$$

- **"Dynamic" Yaw Steering** (Oesterlin and Ebert, 2003) in the critical band $-\beta_0 < \beta < +\beta_0$ by introducing the smoothing factor f = f(η) and a "design" parameter *d* (to be optimized for the individual orbit and the actuation system capabilities). For GSTB-V2 the parameters have been selected according to $\beta_0 = 2°$, $d = 258$.

$$\begin{aligned} &|\beta| < \beta_0 : \textit{DynamicYaw Steering} \\ &f = \frac{\cos^2 \eta}{1 + d \cdot \sin^2 \eta} \end{aligned} \tag{2}$$

  - Definition of the "Smoothed" Sun incidence angle β_d, where $\delta = \pm 1$ has to be properly selected in order to achieve a smooth Sun elevation zero transient within one orbit.

$$\beta_d = \beta + f \cdot \left(\beta_0 \cdot \delta - \beta\right) \quad ; \quad \delta = \pm 1 \tag{3}$$

  - Yaw angle profile

$$\psi \ = \arctan\left(\frac{\tan \beta_d}{\sin \eta}\right) \tag{4}$$

- SADM angle profile (independent from Sun incidence)

$$\sigma \ = \arctan\left(\frac{-\sqrt{1 - \cos^2 \beta \cdot \cos^2 \eta}}{-\cos \beta \cdot \cos \eta}\right) \tag{5}$$

The following figures indicate the relevant profiles as it has been designed for GSTB-V2 for different Sun incidence angles (0°, 2°, 79.44°). The maximum yaw rate is limited to about 0.2 deg/s, the maximum angular acceleration is limited to about 8.1 µrad/s².

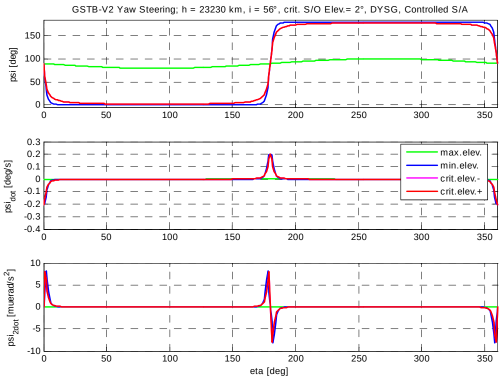

Figure 4: S/C Yaw Steering Motion

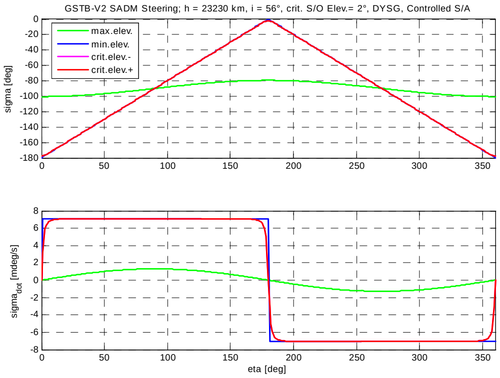

Figure 5: S/C SADM Steering Motion

4.2. Short Description of Normal Mode

In Normal Mode the AOCS shall be able to establish and maintain high accuracy pointing of the spacecraft. The mode entry conditions for NOM are the end conditions of EAM.

The NOM is working as a bias momentum system with yaw steering to ensure thermal safety of the payload and optimal power generation. A 3-axis measurement of the attitude is performed using the Earth sensor for roll and pitch measurement, yaw is derived from Sun sensor.

Challenges:

- When the Sun elevation angle w.r.t. orbit plane is zero, two regions of co-linearity between S/C, Earth and Sun occur: If the S/C is located between Earth and Sun, yaw cannot be derived (due to singularity in the computation). If the Sun is located behind the Earth as seen from the S/C, i.e. in eclipse, Sun sensor measurement is not available. In those co-linearity regions yaw is determined on the basis of an observer.
- If the S/C is in co-linearity (when yaw cannot be measured), see Figure 3, the largest yaw rates (0.2 deg/s) are required to follow the yaw steering law.

The following submodes are designed in Normal Mode:

Table 2: Submodes of Normal Mode

Submode	***Description***
Nominal 2-Axis Reference (N2A)	Earth pointing is achieved with 2-axis measurement and yaw is derived from an observer. Wheel unloading is performed with torquerods.
Nominal 3-Axis Reference (N3A)	Earth pointing is achieved with 3-axis measurement and yaw is derived from FSS. Wheel unloading is performed with torquerods.
Backup 2-Axis Reference (B2A)	Earth pointing is achieved with 2-axis measurement and yaw is derived from an observer. Wheel unloading is performed with thrusters (backup).
Backup 3-Axis Reference (B3A)	Earth pointing is achieved with 3-axis measurement and yaw is derived from FSS. Wheel unloading is performed with thrusters (backup).

Observer during Co-linearity Phases

In co-linearity and eclipse when 3-axis measurement is not possible yaw attitude information is derived from a nonlinear observer. The basic principle is as follows:

- Estimation of the angular momentum w.r.t. the body system, h_b
- Estimation of the angular momentum w.r.t. the orbit (LVLH) system, h_o
- Attitude determination using the Earth vector expressed in body- as well as reference system (e_b, e_r) and the estimated angular momentum vectors $h_{b,}$ $h_{r,}$ replacing in co-linearity phases the standard Sun vector expressed in body- as well as reference system.

The fundamental advantage is, that in bias momentum systems the Earth vector and the total angular momentum are always almost perpendicular to each other, thus avoiding any co-linearity, see (Fischer and Chemnitz, 2004).

Results

Below the result of attitude deviation in NOM with 2-axis- reference before co-linearity; torquerods are used to unload the wheels. 4 wheels are on control:

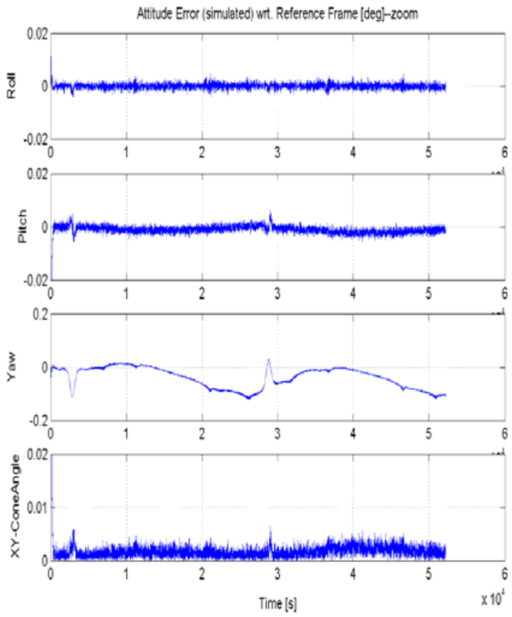

Figure 6: Attitude Error (simulated) wrt. Reference Frame

4.3. Short Description of Sun Acquisition Mode

The purpose of the sun acquisition mode is to orient the -z-spacecraft axis (AOCS system) towards the sun with a low rotation rate of 0.2 deg / s around the satellite -z-axis. This operational mode will be triggered in the following cases:

- Damping of nominal initial Satellite rates (about 2.5 deg/s) at separation
- as safe mode in case of all failures apart from double wheel failure.

The AOCS shall be able to acquire the Sun with the spacecraft -z-axis from any arbitrary orientation and with initial tumbling rates up to approximately 10 deg./sec

During eclipses, a rate control phase based on gyro measurements shall be possible to maintain SC rates in the required range.

Gyroscopes are used to estimate the body rates.

SAM shall use wheels as actuators in the attitude control loop.

The thrusters are used for angular momentum control.

Submodes

The submodes perform the following tasks:

Table 3: Submodes of Sun Acquisition Mode

Submode	***Description***
Rate Damping (RD)	Performs rate damping until predefined commanded (small) rate
Sun Search (SS)	Performs rotation about the satellite z-axis until Sun presence is established.
Sun Capture (SC)	Performs position control and rotates the satellite such that the -z-axis points into the Sun. A rotation of 0.2 deg/s about the sunline is established.

Results

After the first SAM after separation the sun vector finally approaches the –z- axis w.r.t. body frame (Figure 7)

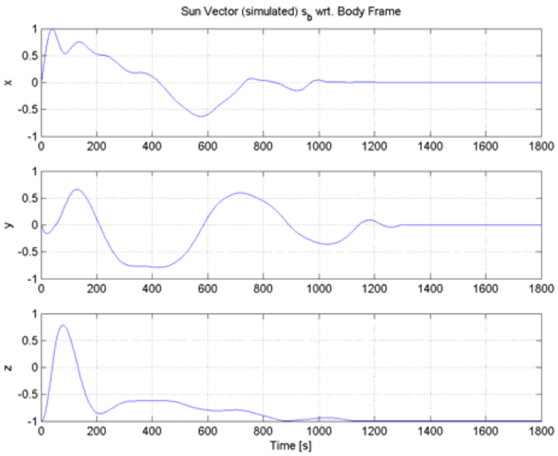

Figure 7: Sun Vector (simulated) wrt. Body Frame

The wheel angular momentum storage capacity (+/- 12 Nms) is maintained during the scenario as shown in Figure 8.

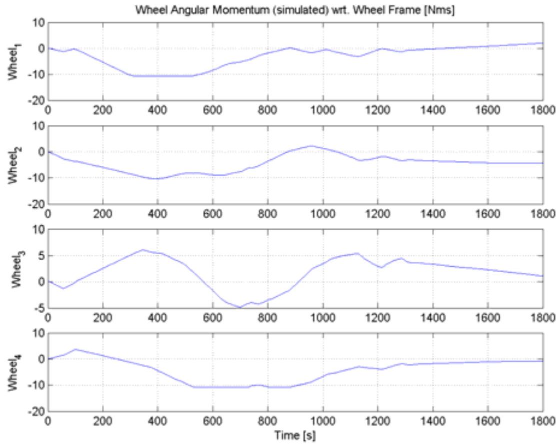

Figure 8:Wheel AngularMomentum (simulated) wrt. Wheel Frame

5. AOC TEST AND VERIFICATION

Due to the extremely dense GSTB-V2 overall schedule the AOC equipment has been agreed to be delivered early for system integration before avionics subsystem acceptance. In order to achieve this goal the AOC test campaign has been started on AOC equipment end-to-end testing. The following test approach was applied in order to test the AOC equipment functional chain with the on-board computer and for validation of the AOC simulation models used inside the AOC Functional Development Environment (FDVE) and the Real-time test bed (RTB):

- Actuators were tested in open-loop
- Sensors were tested in open-loop and in closed loop for selected critical modes

Due to the fact, that the available AOC off-the-shelf sensor equipment did not provide separate test stimuli inputs, the sensor tests have been performed on the Dynamic Bench Test (DBT) Facility, where the optical sensors have been stimulated through their optical path and the gyros by an appropriate "inertial" motion. The test bench motion (bench Cardan angles) have been controlled accordingly from the RTB spacecraft dynamics simulation. The following figures present the relevant AOC sensor equipment accommodation on the two benches, which could be controlled separately or simultaneously, i.e. when all sensor equipment was in use:

Figure 9: DBT U-Table with 3 redundant Fine Sun Sensor heads & 2 Gyros accommodated

Figure 10: DBT C-table with 2 Earth Sensors

With this DBT configuration the following tests have been performed among others against the test references from the AOC engineering team:

- Large angle rotation (-180° to + 180°) of the U-Table for verification of proper on-board Sun vector reconstruction including the transitions from one sensor Field of View (FoV) to the next one with zero and high Sun elevation
- Fast rotation of the U-table with 10 deg/s in order to test the out-of-range characteristic of the gyros, together with very smooth rotations
- Special rotation sequences for proper Earth vector reconstruction with Earth image in the FoV, at its limits or outside the FoV.
- Closed loop tests for the critical AOC modes, such as Safe Mode, Sun Acquisition Mode and Earth Acquisition Mode under most realistic conditions.

As an example for a typical test evaluation the run-down motion of the wheels from maximum angular momentum has been analysed in rather detail in order to evaluate the uncertain friction torque component for each wheel. The following figures have been obtained (under gravitation conditions):

Table 2: Wheel parameters obtained from run-down test

	RW 1	**RW 2**	**RW 3**	**RW4**
Run-up time [min] 0 → 12 Nms	3.57	3.27	3.18	3.23
Run-down time [min] 12 Nms → 0	17.85	22.90	22.70	18.90
Constant friction torque [Nm]	0.0055	0.0039	0.0051	0.0047
Friction torque gradient [Nm/Nms]	0.0014	0.0012	0.00084	0.0014
Maximum friction torque at 12 Nms [Nm]	0.0221	0.0188	0.0152	0.0220

The following figure presents in one graph each the obtained test results together with the results obtained from the wheel simulation after parameter adaptation to the above values:

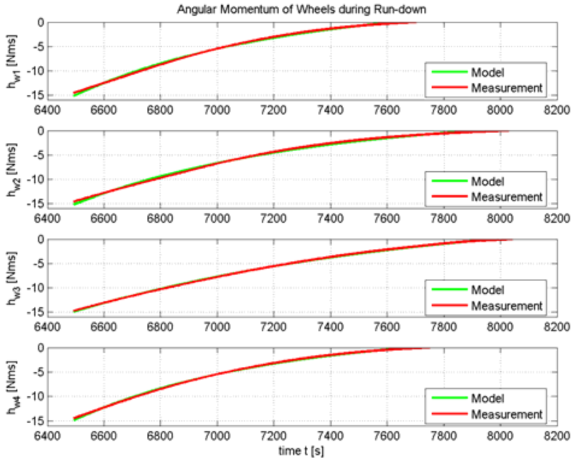

Figure 7: Wheel-run down with real and simulated equipment

Thus, as one of the overall tests results, together with some fine-tuning, the validity of the AOC equipment models could be demonstrated for the subsequent overall Avionics validation campaign on the RTB, to be completed at October 2005.

6. CONCLUSIONS

The GSTB-V2B AOC function has been presented. It should be noted that main purpose of GSTB-V2 is to serve as precursor for the Galileo program. This means the challenges here are more to build an AOC function within an extremely tight schedule under the collaboration of several European space companies. From the technical point of view a lot of topics are addressed which will directly be used to the Galileo IOV AOC design which is currently running up. Dedicated literature apart from state of the art (Wertz, 1978) is purely project specific and is not open to public, however in the internet a lot of general information can be found under keyword “GSTBV2”.

7. REFERENCES

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