ESOC PRECISE FLIGHT DYNAMICS EMULATION FOR THE SWARM MISSION

Riccardo Di Corato[1], Susanne Kasten-Coors[2], and Stefano Pessina[1], [3]
[1] *SCISYS Deutschland GmbH c/o ESA/ESOC, HSO –GFF,*
Robert-Bosch-Str.5, D-64293 Darmstadt, Germany, +49 615190 4207,
email: riccardo.di.corato at scisys.de
[2] *ESA/ESOC, HSO –GFF,*
Robert-Bosch-Str.5, D-64293 Darmstadt, Germany, +49 615190 3914,
email: Susanne.Kasten.Coors at esa.int
[3] *email: stefano.pessina at scisys.de*

Abstract: ESA's Swarm mission, scheduled for launch in early 2013, is dedicated to study the Earth geomagnetic field. It will consist of a constellation of 3 spacecraft.
A Swarm emulator has been developed by the Flight Dynamics (FD) Division of the European Space Operation Centre (ESOC), with the main purpose of testing the FD Command Generation and Attitude Monitoring subsystems and training the whole FD team during operations preparation.
The emulator reproduces in a very representative way the functionality of the AOCS on-board software relevant for FD needs, modelling with high fidelity closed-loop S/C dynamics, space environment, sensors and actuators.
This paper describes the emulator design, development and operational applications. The latter include FD system tests and specific analyses. Two cases are described, where AOCS on-board software investigations have been performed following unexpected results: yaw controller behaviour in Coarse Pointing Mode and response to a stuck open Orbit Control Thruster.

Keywords: Swarm, emulator, AOCS, attitude dynamics and control

1. Introduction

The Swarm mission of the European Space Agency (ESA) is to provide the best ever survey of the Earth geomagnetic field, where variations on time scales from an hour to several years will be represented. The constellation will be constituted by a lower pair of satellites (initial altitude of 460 km) flying side-by-side and a single satellite flying higher (530 km). The spacecraft (S/C) AOCS design is largely based on the ESA mission Cryosat-2; the same sensors/actuators suite as for Cryosat-2 has been used, with the addition of 2 more cold-gas Orbit Control Thrusters (OCT) for inclination control and a GPS receiver unit. A long deployable boom carries the magnetometer package, which is placed at a sufficient distance from the S/C body to keep the magnetic disturbance at a minimum level. The S/C are launched together and separated in stowed configuration; the boom is deployed at an early stage of the Launch and Early Orbit Phase (LEOP). The S/C are currently scheduled for launch in early 2013.

The Orbit Insertion Phase (OIP) will start immediately after the LEOP. Due to the low thrust of the OCTs compared to the required change in semi-major axis and inclination, several batches of manoeuvres are planned, each of which will comprise 40 to 90 manoeuvres. These manoeuvres are performed with different thruster pairs (aligned perpendicular to each other) and an attitude slew is performed after each orbit manoeuvre.

1

Within the Flight Dynamics (FD) Division of the European Space Operations Centre (ESOC), a Swarm emulator has been developed. The main purpose of the emulator is to test the FD Command Generation and Attitude Monitoring subsystems and to train the whole FD team during operations preparation. In addition, the emulator is useful to analyse the AOCS on-board software behaviour in nominal and contingent situations, well in advance with respect to the ESOC-wide Simulation Campaign beginning.

2. Spacecraft layout

The Swarm S/C in boom deployed configuration has an elongated shape, symmetric with respect to its X axis. The S/C reference frame is represented in Fig. 1. The boom extends from the S/C body towards the –X direction; the Orbit Control Thrusters are aligned with the +X, +Y and –Y directions. In Fine Pointing Mode, the target S/C reference frame coincides with the Orbital Frame: the +Z axis points towards the centre of the Earth, the +Y axis is anti-parallel to the orbital angular momentum vector and the +X axis completes the right-handed orthogonal reference frame. As a result, the +X axis has a positive component onto the S/C velocity vector. Therefore, the S/C is flying with the +X panel in front and the boom behind. Because of the OCTs alignment, a slew is always necessary when switching from Fine Pointing Mode to Orbit Control Mode in order to perform manoeuvres in the flight direction.
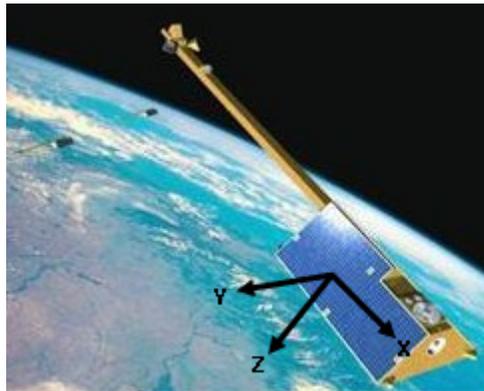
Figure 1. Swarm S/C reference frame

3. Emulator requirements

The following set of generic requirements, applicable to a FD emulator for any mission, shall also be met by the Swarm emulator:

- High precision modelling of S/C dynamics, environment (e.g. ephemerides, attitude, orbit, forces and torques), attitude and orbit control software, sensors and actuators dynamics.
- Generation of emulated test telemetry data for testing the FD system and for training the FD team.
- Validation of operational telecommands created by the FD Command Generation subsystem.
- Capability to inject failures for emulating contingency scenarios.
- Capability to run in real-time and accelerated mode.

- Full integration in the FD system, to interface correctly with existing FD legacy code and data formats.

The emulator shall reproduce in a very representative way the functionality of the AOCS on-board software relevant for FD needs. Further aspects of the on-board software, that are not of FD interest, do not need to be represented. Hardware and environment components of minor relevance for FD can be modelled in the simplest way.

Further requirements for the Swarm emulator originate from the multi-S/C nature of the mission:
- Capability to run three instances of the emulator (one per S/C) at the same time.
- Use of different database per S/C.
- Telemetry generation in the following modes:
  - Continuous.
  - Only during station passes for all S/C.
  - Only during station passes for the S/C to which the current pass is assigned. This represents real LEOP operations where, at each station pass, only one S/C is tracked and provides real-time telemetry.
  - No telemetry.

4. Development and integration

The following paragraphs describe the emulator top level design and provide some details about its models, with particular focus on newly developed components; a complete description of the emulator design is out of the scope of this paper.

4.1. Top level design

Following the recent ESOC FD approach for Earth Observation missions [1], the Swarm emulator, internally called High Precision Test Data Generator (HPTDG), has been developed in Matlab®/Simulink® environment. Thanks to the similarity between the Cryosat-2 and Swarm S/C, a maximum reuse of Cryosat-2 emulator elements has been made. This allowed the development of a highly representative system with limited time and resources.

The following development approach has been selected: the Cryosat-2 emulator has been used as starting point, and a progressive update or replacement of modules has followed. Figure 2 represents the emulator top level architecture: the blocks marked as grey either required a major update or have been newly developed.
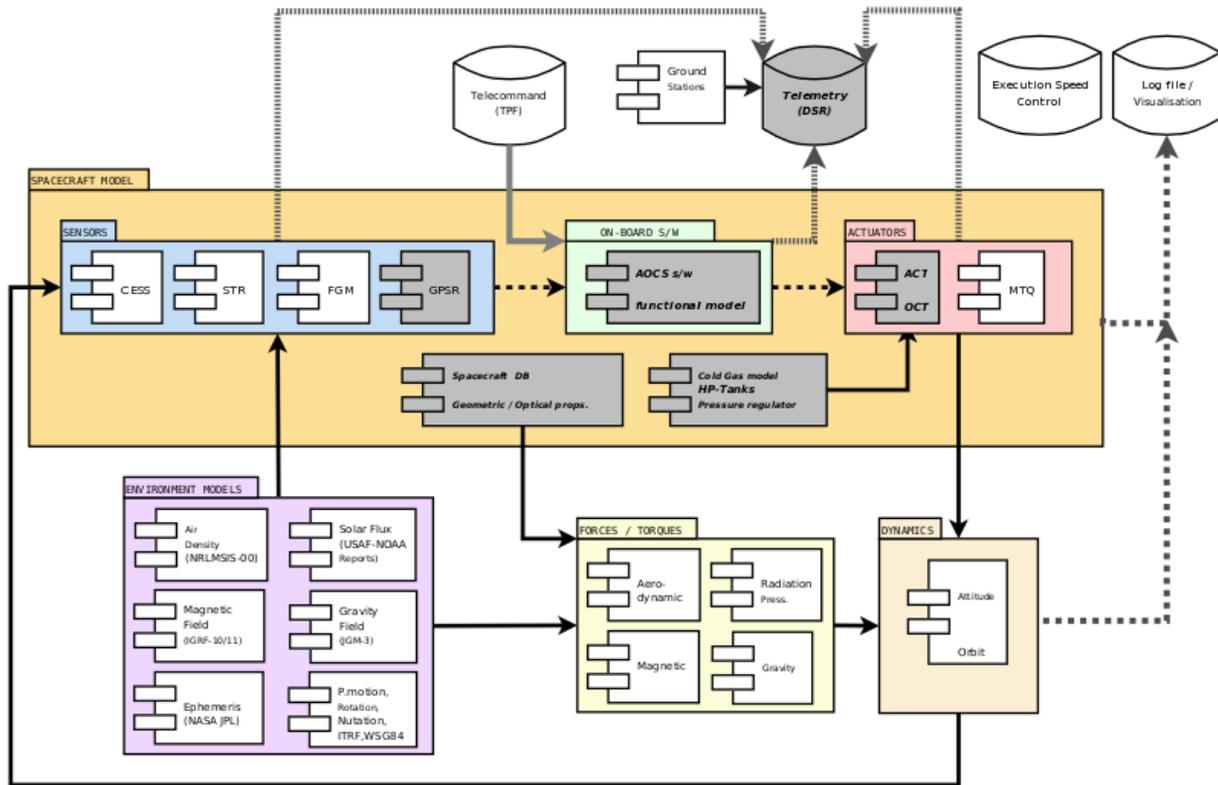
Figure 2. Emulator top level architecture

4.2. Environment models

Environment models for Low Earth Orbit S/C available in-house are also applicable to Swarm, and have been integrated in the emulator (see violet and light yellow blocks in Fig. 2). FD legacy shared object libraries, developed in Fortran and C++, are interfaced to Simulink® by means of gateway S-functions.

The S/C orbital state vector is extracted at each simulation step from a FD orbit file: it is therefore decoupled from the attitude dynamics. This choice has been made for most of the previous FD emulators for Earth Observation missions. The simulation of tracking data for orbit determination purposes is done by another FD tool. In a typical test scenario, the orbit file used to generate tracking data, perturbed with respect to a reference orbit file, is also used by the emulator in order to have a consistent emulated data set across the individual FD subsystems.

The Earth atmospheric density model has been improved with respect to the Cryosat-2 emulator, by using the NRLMSISE-00 model [8]; this allows taking into account the effect of the observed or predicted solar activity for the simulated period.

The aerodynamic and pressure radiation models are based on look-up tables containing the normalised (with respect to aerodynamic and solar flux) force and torque vectors as a function of the originator beam direction (either local wind velocity or Sun vector). These tables have been provided by the S/C manufacturer based on the S/C three-dimensional model, for both stowed

and deployed configurations. Figure 3 represents the aerodynamic force and torque in deployed configuration per unitary aerodynamic flux, as a function of the wind velocity azimuth (λ) and elevation (Φ) in S/C reference frame.
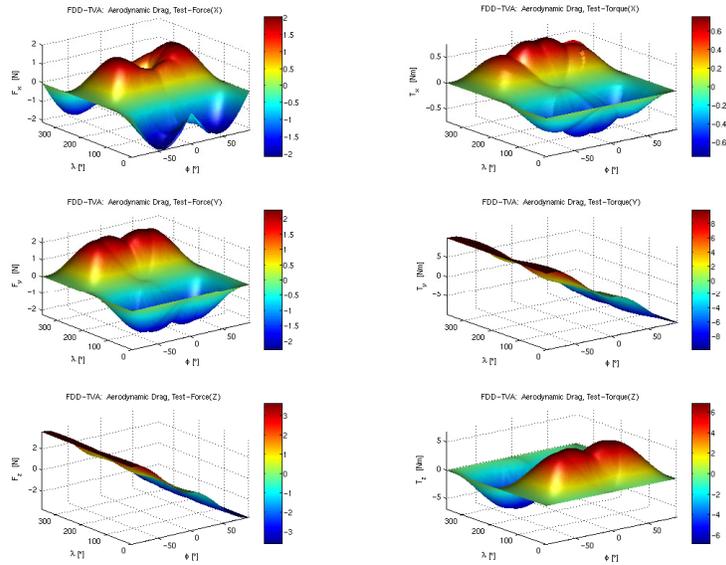
Figure 3. Normalised aerodynamic force and torque in deployed configuration

4.3. S/C hardware models

Swarm is equipped with the following AOCS units (see also Fig. 2):
- Sensors: Coarse Earth and Sun Sensor (CESS), Star Trackers (STR), FluxGate Magnetometers (FGM), GPS Receiver (GPSR).
- Actuators: Attitude and Orbit Control Thrusters (ACT, OCT), Magnetorquers (MTQ).

The Swarm Reaction Control System (RCS) is based on cold-gaseous Tetrafluoromethane propulsion, using two High-Pressure storage tanks, mechanical pressure regulators and Low-Pressure thrusters.

The Cryosat-2 FD emulator STR, FGM and MTQ models have been re-used with minor modifications. A GPS receiver simple model has been implemented, substituting the Cryosat-2 "DORIS" ground-based positioning system. The thrusters model has been updated with two additional Orbit Control Thrusters per RCS branch oriented along the S/C Y axis.

The Coarse Earth and Sun Sensor emulator model has been updated based on Cryosat-2 flight data in stable pointing with representative orbit geometry, correcting for the different orbital period; the CESS error level can be set as a multiple of the Cryosat-2 reference case. Figure 4 represents the Cryosat-2 in-flight CESS performances used as reference for the Swarm model; the S/C Position on Orbit, the CESS Sun and Earth vectors and their depointing with respect to the theoretical Sun and Earth vectors are shown.
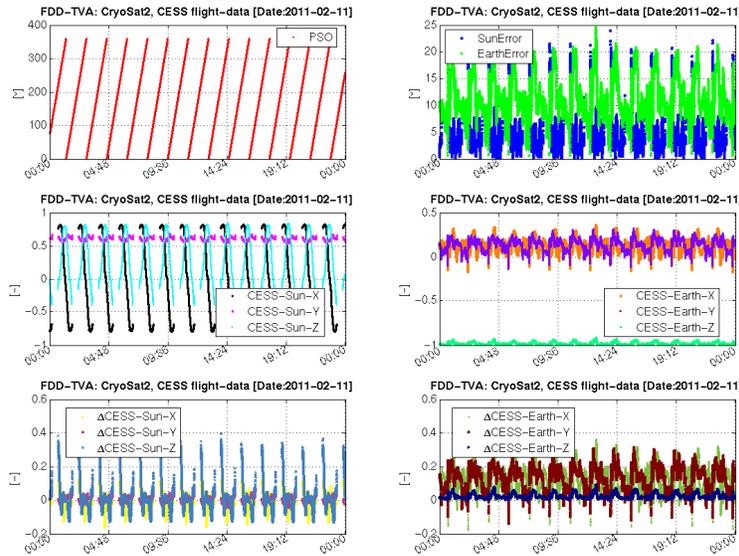
Figure 4. Cryosat-2 in-flight CESS performances

The cold gas model has been updated to use Tetrafluoromethane R14 (CF4) real gas NIST tables [9]. With respect to the model used in the Cryosat-2 emulator (Benedict-Webb-Rubin equation of state, modified by Lee-Kesler), NIST tables provide a higher accuracy at high pressure (about 180 bar), where a discrepancy of 3% on the computation of density between the two models has been observed.

The cold gas pressure is regulated in order to provide the thrusters with a stable pressure in the 1.3-1.5 bar range. The pressure regulator model has been calibrated using pressure regulator and thrusters firing ground tests results [6]. Different cases depending on the number of simultaneously actuated ACTs and OCTs have been considered in order to model the regulated pressure.

4.4. AOCS on-board software

For the AOCS on-board software model implementation, the following options have been considered:
- Adaptation of Cryosat-2 emulator on-board software model.
- Implementation based on software specifications.

Comparing Cryosat-2 and Swarm AOCS on-board software specifications, it was found that they are quite similar from a macroscopic point of view; however, due to lower level differences such as variable naming, it was concluded that an adaptation would be a time-consuming and error prone process. Furthermore, the Swarm AOCS on-board software specification document [4] includes all the core functionalities as pseudo-code in Matlab[®] syntax. Based on this, it was decided to functionally re-implement the AOCS on-board software as a Matlab[®] function, directly importing the pseudo-code from documentation and adding the necessary framework

code. This approach was never followed before, and proved to be efficient and cost-saving; as an additional advantage, it allowed early testing of the emulator performance in lower modes.

4.5. Telemetry and telecommand

For the telemetry generation module, only generic encoding libraries, based on the telemetry format used within FD, could be re-used from previous emulators. The telemetry parameters are generally mission specific and are derived from the AOCS on-board software. In order to support testing of individual FD telemetry monitoring applications, all telemetry parameters processed by them have been included. A telemetry generation logic based on station visibility and pass assignment to the S/C has been implemented.

The emulator is able to process all FD commands and further ones which emulate some of the commands prepared by the Flight Control Team (FCT) during operations, such as Star Tracker switch-on and mode change to Fine Pointing Mode. In order to automatically process FD commands, a generic emulator interface, previously not available, was developed. For the non-FD commands, GPS commands were added to represent the case where GPS is switched on but still not used in the AOCS closed loop. In addition, the emulator can be fed with simulation control commands (such as commands for pausing/stopping the simulation, to switch from real-time to accelerated mode, to force telemetry generation outside of ground-station passes) and time-tagged commands to inject failures in the hardware components (such as thrusters stuck open/closed, sensors unavailability).

5. Operational applications

The Swarm FD emulator has been deployed for operations preparation in November 2011; this date marked the start of the FD system test campaign, about 8 months before the originally planned launch date. The system test campaign covered LEOP and OIP activities, with nominal and contingency scenarios. LEOP system tests were executed for 3 S/C in parallel in real time (with accelerated execution, faster than real-time, during time intervals not including interesting FD activities), generating TM during station visibility according to station-S/C planning. OIP system tests were performed in accelerated mode for one S/C, including one or two manoeuvre batches. These are particularly important for training the FD team, since the ESOC-wide simulation campaign only covers the LEOP phase.
The emulator supported all system tests with generation of TM, processed by FD during the test, and emulated data (environment, dynamics, sensors/actuators, on-board software) for post-test specific analyses.
In the following paragraphs, some operational applications of particular interest are presented.

5.1. Characterization of attitude manoeuvres

As described above, during the Orbit Insertion Phase hundreds of manoeuvres are foreseen for each S/C in order to achieve the required changes in semi-major axis, inclination and phasing to reach the operational orbits. The manoeuvres are performed in batches, each of which includes alternating ascending node and descending node manoeuvres. In the nominal strategy, all manoeuvres of a batch performed at the same node have the same delta-v direction; this means

7

that the S/C is always performing a – mainly yaw – slew between consecutive manoeuvres, switching between two attitudes.

Since Orbit Control Thrusters are available in 3 different directions (+X, +Y and –Y), the FD team can choose which thruster pairs to use for ascending and descending node manoeuvres. In particular, it is always possible to use the same thruster pair for consecutive manoeuvres or to switch to a different pair. If the angle between the two manoeuvre directions is higher than 45 deg, the second option will reduce the size of the slew. However, another criterion to be taken into account is the fuel consumption associated to controlling a biased attitude between slews – this differs considerably depending on the yaw angle, due to the S/C shape.

In order to support this choice, the emulator has been run in a loop, at each step slewing from zero yaw to a different target yaw and maintaining the S/C in this biased attitude for 24 hours. A script has been developed with the purpose of determining the slew duration (based on 0 deg crossing and end of damping phase) and computing the fuel consumption due to the slew and to the attitude control. The results are shown in Tab. 1 and Fig. 5, where the particular case of a 180 deg slew has been represented. It can be observed that the slew fuel consumption is in all cases at least one order of magnitude higher than the consumption needed to maintain a biased attitude for half orbit (approximately 48 minutes). This implies that, if the slew size is sufficiently larger than 45 deg, it is generally advantageous to switch OCT pair. This is actually the case for the nominal OIP manoeuvre strategy, where the required change of about 130 deg in manoeuvre direction is achieved with a 40 deg slew and OCT pair switch.

Table 1. Thruster actuation for slew and attitude control as a function of the target yaw angle

Target yaw [deg]	Slew duration, 0 deg crossing [s]	ACT on-times per axis during slew including damping phase [s]				ACT on-times per axis after slew, 24h interval [s]			
		Roll	Pitch	Yaw	Total	Roll	Pitch	Yaw	Total
0	-	-	-	-	-	46.74	0.00	34.43	**81.17**
-15	161	7.11	0.00	173.86	**180.96**	76.92	2.39	443.37	**522.69**
15	162	7.95	0.00	174.24	**182.19**	76.62	4.30	468.25	**549.16**
-30	227	8.49	45.97	234.06	**288.52**	52.81	50.86	883.73	**987.40**
30	228	9.15	44.62	234.97	**288.74**	54.74	52.90	913.82	**1021.46**
-60	390	4.63	32.90	234.49	**272.02**	3.23	92.88	981.55	**1077.66**
60	393	5.51	63.10	237.52	**306.12**	5.67	86.43	1005.00	**1097.10**
-90	557	4.12	111.41	230.38	**345.91**	0.00	142.16	134.26	**276.42**
90	560	6.17	110.43	230.35	**346.95**	0.00	109.82	135.58	**245.41**
-120	717	2.55	151.64	226.06	**380.26**	23.26	370.71	759.78	**1153.75**
120	720	4.44	152.21	229.15	**385.81**	19.37	434.88	793.14	**1247.39**
-150	864	2.81	171.17	234.21	**408.18**	58.21	80.59	787.77	**926.57**
150	870	5.11	169.18	234.60	**408.89**	62.66	87.54	817.35	**967.55**
180	1009	5.84	160.93	242.47	**409.24**	45.30	2.61	11.73	**59.64**
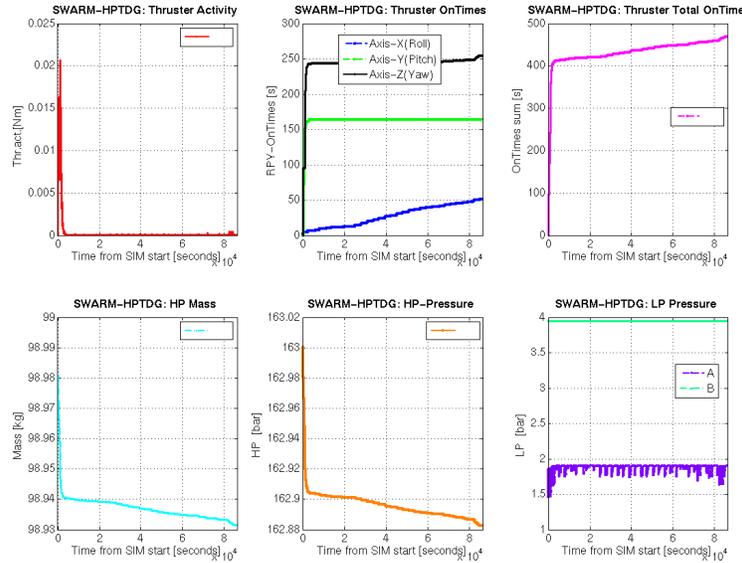
Figure 5. ACT thrusters activity and RCS status for a 180 deg slew and subsequent 24 h attitude control

5.2. Coarse Pointing Mode yaw controller behaviour

After separation and rate damping, the S/C enters automatically the Coarse Pointing Mode (CPM). In the nominal timeline, the S/C spends about 25 hours in CPM, before a transition to Fine Pointing Mode is commanded by the ground segment. Several major events occur in CPM, such as boom deployment, execution of the first Orbit Propagator commands, switch-on of GPS and star trackers. In this phase, star trackers data are processed and checked on-ground, but they are not used in closed loop AOCS control.

In CPM, the attitude controller is split into two independent controllers, one for roll/pitch and the other for yaw control. Roll and pitch are controlled by a cascaded rate/attitude controller using CESS data, targeting Earth pointing. The yaw angle is controlled by a rate controller augmented by a steering logic based on magnetometer rates to support the acquisition of a yaw equilibrium angle. The latter is set by default to 0 deg in the orbital frame (configuration known as "forward flight", i.e. with the boom oriented opposite to the velocity vector), but it can also be set by ground command to 180 deg ("backwards flight", i.e. with the boom oriented in the same direction as the velocity vector). It is not foreseen to change the yaw equilibrium angle in nominal operations; the purpose of the yaw controller is therefore to bring the S/C yaw angle to 0 deg and to maintain this configuration.

During nominal LEOP system tests, after transition from Rate Damping Mode (RDM) to CPM, the following yaw angle trends have been observed in different simulations:
- Yaw angle stabilizing around 0 deg.
- Yaw angle stabilizing around 180 deg.
- Yaw angle drifting for 1-2 attitude revolutions, followed by stabilization around 180 deg after about 15000 s from CPM start.

9

The most significant difference between the initial conditions of these simulations are the initial S/C rates in RDM, which were set to different levels taking as upper limit the separation requirements. However, no correlation between initial S/C rates and yaw angle behaviour in CPM was found.

As described above, only the first of the 3 observed trends was expected. This triggered a dedicated investigation, which first step was to analyse the consistency of the results and check for possible bugs in the emulator. After this step was completed with negative outcome, it was decided to deepen the investigation to AOCS on-board software level for a particular case: CPM simulation starting from a yaw angle close to 180 deg and staying around 180 deg for 10 hours (see Fig. 6). In particular, the purpose of this investigation was to explain why the yaw controller fails to acquire the yaw equilibrium angle, set to 0 deg.
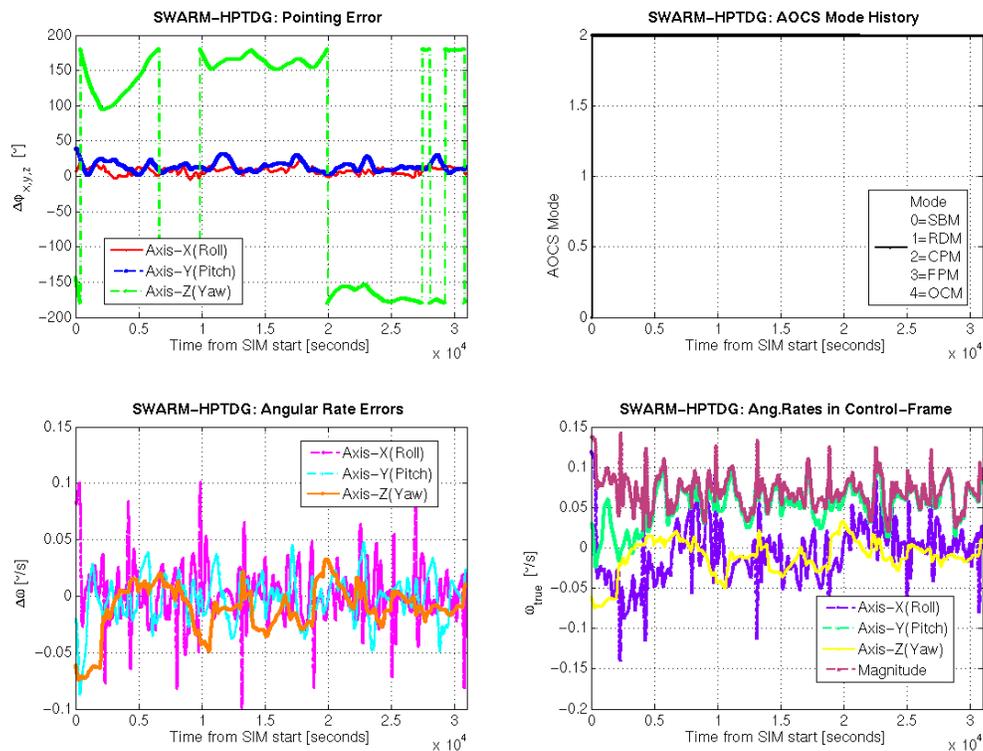
Figure 6. AOCS mode and S/C dynamics for the investigated case

The CPM yaw controller estimates the current yaw angle and the yaw acquisition rate based on filtered FGM magnetic field rates, computed as cross product of magnetic field unitary vectors in S/C frame at two consecutive steps (see Fig. 7, right plot). The yaw controller algorithm is quite simple: if the filtered magnetic field pitch rates are lower than -0.00105 rad/s (which corresponds to the orbital frame pitch rate for an orbital period of 99.68 min), then the S/C yaw angle is estimated near 180 deg, and the acquisition rate magnitude is set. It can be observed from Fig. 9 (left plot) that the acquisition rate magnitude is set to a non-zero value for a large part of the analysed interval.

10
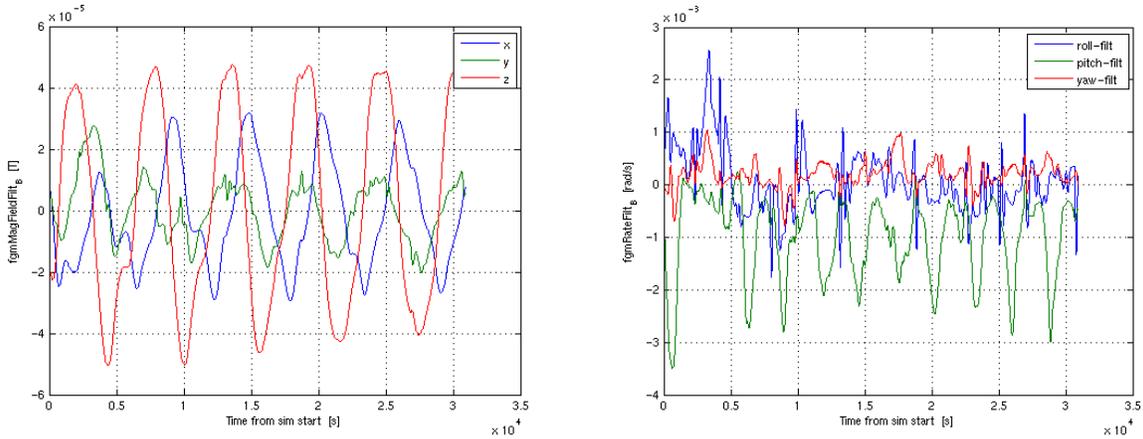
Figure 7. Filtered magnetic field and magnetic field rates in S/C frame

In the next controller step, the so-called "reference" acquisition rate is computed; this is the value actually passed to the actuators commanding module of the on-board software. The algorithm foresees that this parameter is set to zero if the S/C is not Earth pointing, if it is in eclipse, or if the Sun vector forms an angle smaller that 45 deg with the S/C yaw vector. In the analysed case, the S/C is always Earth pointing. The out-of-eclipse condition alone and combined with the Sun-yaw axis angle condition are represented in Fig. 8: the latter is not satisfied for more than half of the time. The consequence is that the reference acquisition rate is set only for isolated and short intervals, shown in Fig. 9, right plot.

The conclusion of this analysis is that the S/C is not reaching the yaw equilibrium angle because of the yaw controller, and in particular because of too restrictive conditions to activate the yaw rate control. The results have been discussed with the S/C manufacturer, who confirmed that this behaviour in CPM is possible. Based on these results, the operations team can treat this behaviour as expected in case it is encountered during LEOP operations.
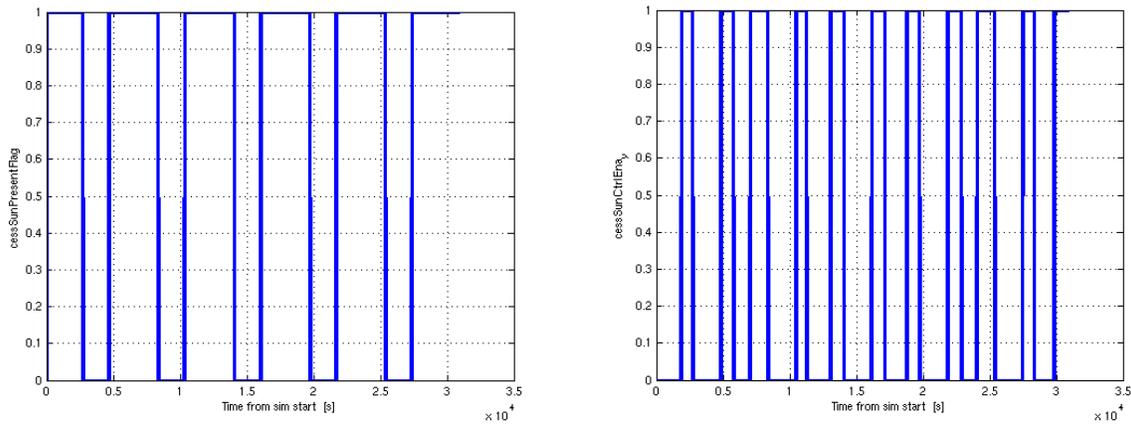
Figure 8. Sun presence flag (left, 0 = eclipse)
and Sun control enabled flag (right, 0 = eclipse or Sun-yaw axis angle < 45 deg)

11
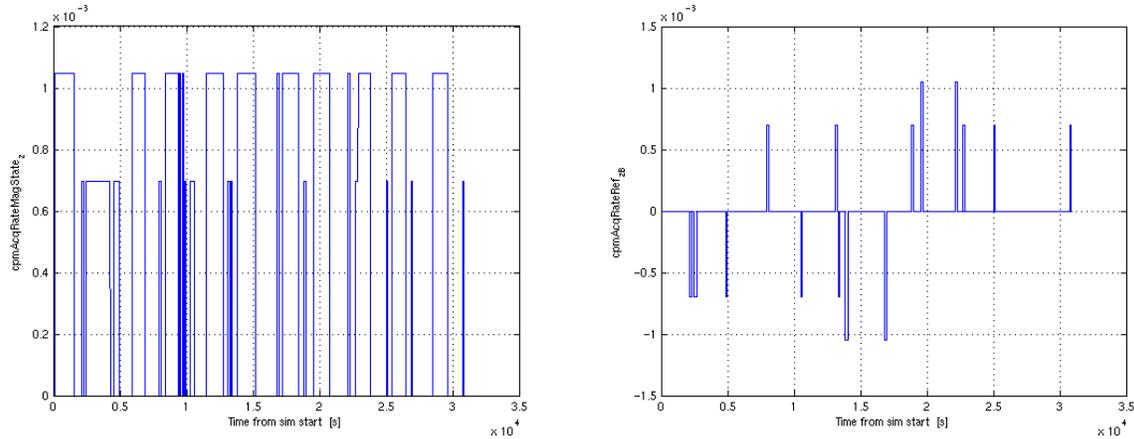
Figure 9. Acquisition rate magnitude (left) and reference acquisition rate (right), rad/s

5.3. Contingency LEOP scenarios

After the FD team had been trained successfully on the FD LEOP activities by nominal system tests, contingency LEOP scenarios were exercised. In the latter ones the FD team members had to perform the nominal tasks according to the timeline and, in addition, they had to detect the injected contingencies and to report and react accordingly.

When exercising these scenarios, orbit related contingencies such as launcher injection errors have been incorporated in the FD orbit file used to generate tracking data; as mentioned earlier in this paper, this orbit file is an input for the emulator. Attitude and command related contingencies have been set-up directly in the emulator. The choice of contingencies to be introduced was made based on the following considerations:

- Three S/C are operated at the same time.
- Star tracker (STR) telemetry data is the primary source of information about the S/C attitude. Before STRs are switched-on, the S/C attitude has to be determined using Earth, Sun and magnetic field sensors.
- Nominal STR performance is a necessary condition to command transition to Fine Pointing Mode.
- GPS telemetry has to be validated against FD determined orbit based on tracking data before it can be used in the AOCS closed loop.
- Before the GPS unit is enabled, the on-board orbit propagator is used in the AOCS closed loop. This is regularly updated by FD command.

Based on the above considerations, the following contingencies were introduced at a certain point of the timeline, affecting one or more S/C:

- Telemetry and tracking data generated for a different S/C than expected.
- Solar flare, affecting STR performances in such a way that the attitude could not be determined.
- Noisy and biased magnetometer data before STRs are switched on.
- Noisy and biased GPS data.
- Failed uplink of an Orbit Propagator Update command.

All contingencies were detected by the FD team and the overall response was very satisfactory in terms of timing and quality. An interesting case in terms of FD response was the magnetometer contingency. Since STR data were not yet available at the time the contingency was introduced, the S/C attitude and rates could only be determined by FD using two direction vectors, such Sun and magnetometers or Sun and Earth (see Fig. 10), using Triad geometric method for attitude estimation. Because of the magnetometer biased and noisy data, the two methods led to different results; FD could only conclude that the sensors were not producing consistent data, but was unable to determine the S/C attitude. Only later, when STR had been switched-on, it was possible to identify the magnetometers as malfunctioning unit.
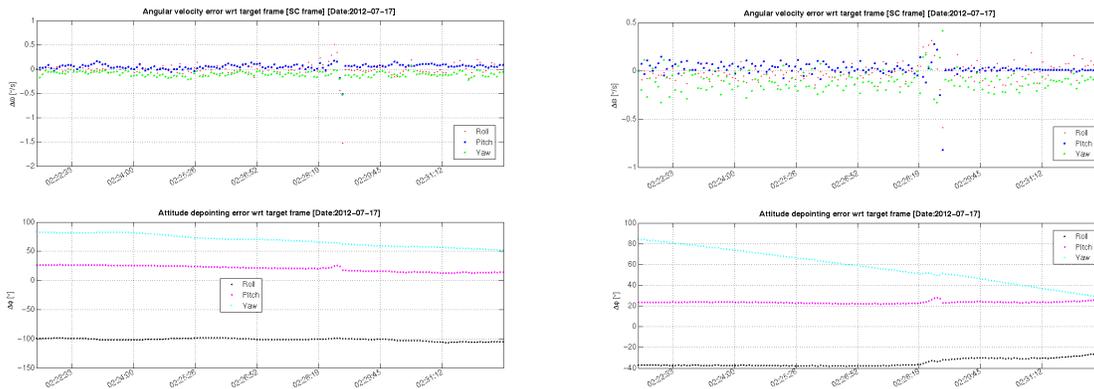
Figure 10: FD determined attitude and rates based on Sun/magnetometers (left) and Sun/Earth (right) telemetry in CPM, with contingent magnetometers performances

5.4. Orbit Control Thrusters stuck open case

In a contingency OIP system test, the Orbit Control Thruster (OCT) A3 of the +Y pair has been simulated stuck open at the end of a manoeuvre in the middle of a manoeuvre batch. Pre-test simulations showed that the on-board software is unable to detect the failure and isolate the thruster branch autonomously. For the system test scenario, it was assumed that the failure is detected on-ground 30 min after the manoeuvre end (e.g. based on the regulated pressure value remaining low after the manoeuvre), a switch to the RCS branch B is commanded and the remaining manoeuvres are consequently aborted. This implies that the slew starting shortly after the manoeuvre is performed with branch A while an OCT thruster is stuck open. A final slew to the normal mode attitude is performed at the end of the simulation, using branch B. In Fig. 11, it is possible to observe the effect of this contingency on the thrusters force at the end of the executed manoeuvre batch.
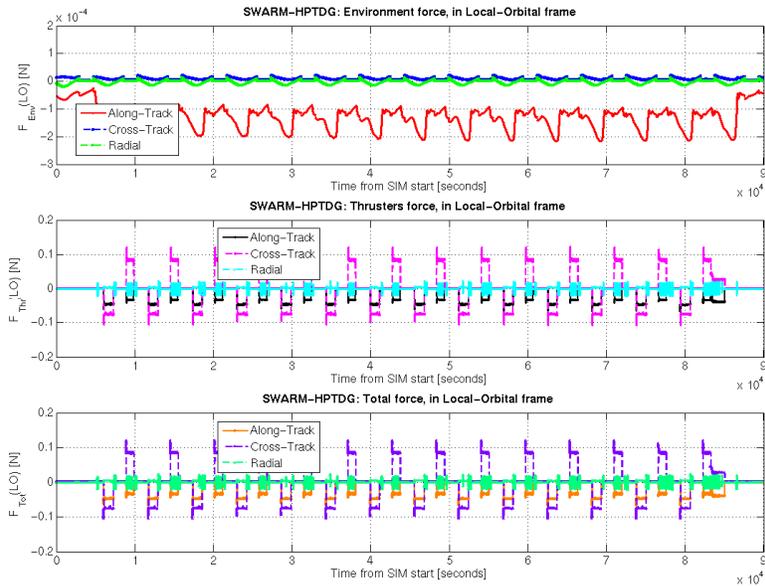
Figure 11. Environment and thrusters force for OCT A3 stuck open case

Figure 12 represents the ACT delivered torque during the last manoeuvre and the subsequent time interval, when OCT A3 is stuck open. The yaw actuation following the manoeuvre end is due to the attitude slew. The roll actuation following the slew has the purpose of counteracting the torque produced by the stuck open OCT; for previous manoeuvres of the commanded batch, such an actuation was not observed. The end time of this roll actuation coincides with the RCS branch switch command.
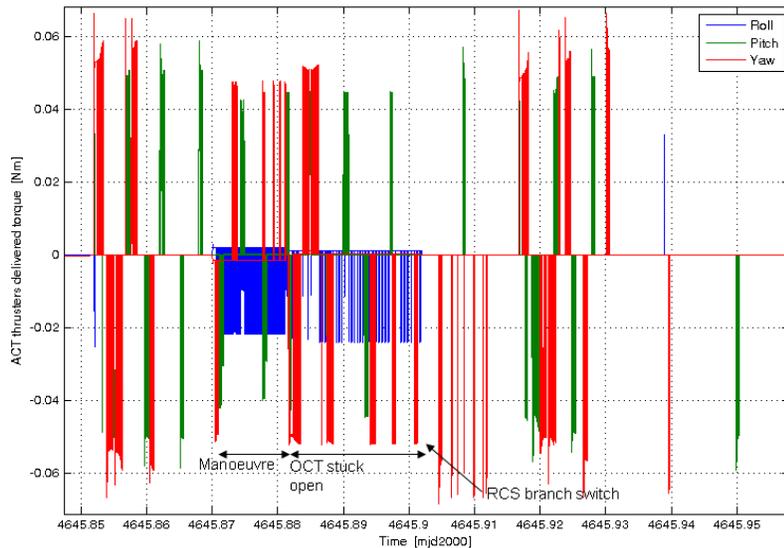
Figure 12. ACT torque during last manoeuvre and OCT A3 stuck open interval

An investigation followed this system test in order to explain why the FDIR is not triggered as a consequence of this OCT A3 failure. The FDIR logic for this type of failure is based on the

14

torque request for the ACT thrusters [7]; the threshold is set to 0.05 Nm. The torque generated by OCT A3 has a roll component of 9.7E-4 Nm and a yaw component of 2.1E-4 Nm. For comparison, a typical value of environment torque is 3E-4 Nm. The FDIR is therefore not triggered simply because the torque generated by the stuck open OCT A3 is lower than the ACT torque request threshold, and it can be compensated by ACT actuation. The S/C attitude can be controlled, but a large waste of propellant occurs. Lowering the threshold is not a safe option, since a high environment torque could exceed it.

The next investigation step was to run a new simulation, where the OCT A1 of the X pair was stuck open. In this case, the FDIR was triggered as expected and resulted in a mode change to RDM (see Fig. 13, where the yaw depointing before the mode change to RDM is not due to a commanded slew, but to the OCT A1 torque).
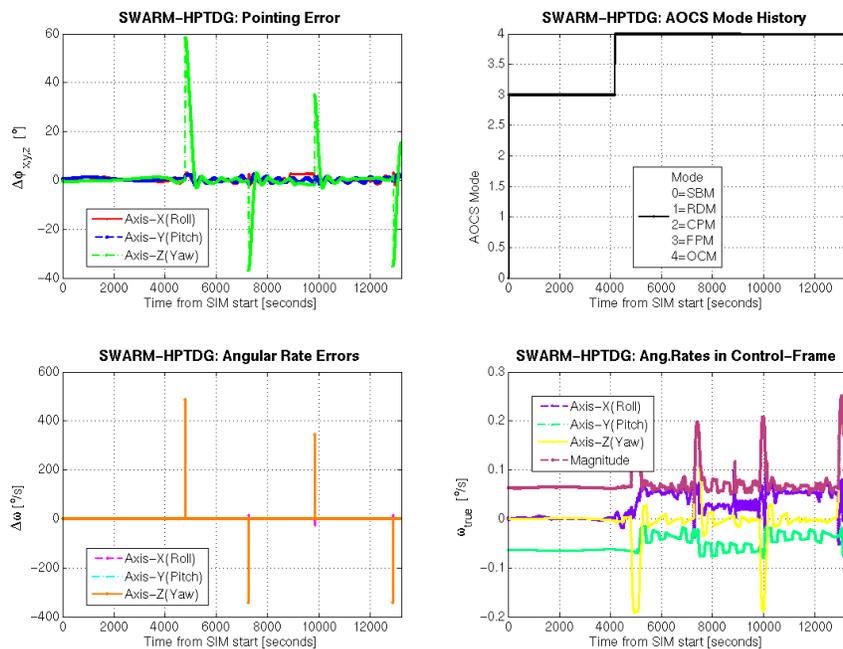
Figure 13. AOCS mode and S/C dynamics for OCT A1 stuck open case

This result was expected, since the torque produced by an OCT of the X pair is about 20 times higher than the one produced by an OCT of the Y pair, due to different thruster position and alignment.

The results were sent to the S/C manufacturer, who confirmed their validity and recommended an improvement in the operational procedures in order to properly react to this kind of failure, which is not safety-critical for the mission. The recommendation is to command a "Mechanical OCT Stuck Open Check" on-board verification after each manoeuvre performed with the Y thruster pair, instead of only once at the end of a manoeuvre batch. This verification consists in a comparison of the regulated pressure with a threshold: a too low value indicates that one of the OCT thrusters is possibly still open.

6. Conclusions

The Swarm emulator has been successfully and timely developed following the envisaged approach, based on the Cryosat-2 emulator as starting point and progressively updating or replacing models in order to represent the Swarm S/C with high fidelity. The selected approach for the AOCS on-board software functional model, based on S/C manufacturer documentation in the form of Matlab® pseudo-code, has proved to be an efficient and cost-saving strategy.

The emulator has been a key tool during the FD test campaign since its early stage. It provided emulated telemetry to test individual Attitude Monitoring applications and it supported a number of nominal and contingent FD launch preparation activities. These included both LEOP and OIP scenarios, while only the first are covered by the ESOC-wide simulation campaign. The FD team benefited from being trained in specific scenarios of FD interest.

Unexpected S/C performance observed during FD launch preparation activities have been thoroughly investigated thanks to the data and analyses provided by the emulator: this included yaw controller behaviour in Coarse Pointing Mode and response to a stuck open Orbit Control Thruster. This gave a valuable insight about the AOCS on-board software behaviour that will be beneficial during operations.

The FD system test campaign has been successfully conducted and, due to launch delay, additional tests are foreseen to re-train the FD team for LEOP and OIP operations. During operations, the emulator will be available to support specific analyses and in-flight trouble-shooting.

7. References

[1] S. Pessina, L. Tucci, S. Kasten-Coors, "ESOC Flight Dynamics Precise Emulators for the Cryosat, Herschel and Planck Missions: Development and Applications", 25th International Symposium on Space Technology and Science, 2006

[2] S. Pessina, L. Tucci, S. Kasten-Coors, M. L. Flegel, "ESOC Precise Flight Dynamics Emulation for the GOCE Mission", 58th International Astronautical Congress, 2007

[3] S. Pessina, S. Kasten-Coors, "In-Flight Characterisation of Cryosat-2 Reaction Control System", 22nd International Symposium on Space Flight Dynamics, 2011

[4] EADS-Astrium tech. report, "OBC S/W AOCS Requirements Specification", SW.RS.EAD.SY.00035, Issue 3.4, 2010

[5] EADS-Astrium tech. report, "Swarm Flight Operations Manual", SW.MA.EAD.SY.00001, Issue 4, 2012

[6] EADS-Astrium tech. report, "TV Functional Test Report – CGPS", SW.TR.ASTR.SY.00002069, Issue 1, 2011

[7] EADS-Astrium tech. report, "Swarm FDIR Analysis, SW.TN.EAD.SY.00082, Issue 3, 2011

[8] NRLMSISE-00 Model 2001, http://modelweb.gsfc.nasa.gov/atmos/nrlmsise00.html

[9] NIST Chemistry WebBook, "NIST Standard Reference Database Number 69", "ThermophysicalProperties of Fluid Systems", http://webbook.nist.gov/chemistry/fluid/