

ESOC FLIGHT DYNAMICS LEOP, COMMISSIONING AND ROUTINE OPERATIONS PREPARATION FOR THE GOCE MISSION

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ABSTRACT

The ESA satellite GOCE, launched in March 2009, is dedicated to measuring Earth's gravity field and modelling the geoid with unprecedented accuracy and spatial resolution. It flies on a Sun-synchronous (dusk-dawn), near-circular low-Earth orbit, at very low altitude (down to 260 km). In measurement phases, the spacecraft (S/C) operates in drag-free mode, with air drag compensated by ion propulsion. GOCE has been designed to keep aerodynamic drag force and torque to a minimum by employing a slender body with winglets, for additional aerodynamic stability. Its dynamics are therefore characterised by a strong cross-coupling of orbital and attitude aspects.

The GOCE launch and early orbit phase (LEOP) foresaw several activities where Flight Dynamics (FD) support was essential: ground-stations antenna prediction and orbit-determination over the first orbit revolutions, magnetometers calibration, attitude sensors cross-coherency verification, star-trackers blinding analysis, on-ground orbit determination (based on satellite-to-satellite GPS telemetry data), GPS solutions and on-board orbit propagator performance assessment. Additionally, FD involvement has been crucial for various activities during commissioning and routine operations: co-alignment calibration of star-trackers and digital Sun sensors, estimation of altitude decay/raise rate (while transitioning to the measurement/hibernation phases), drag-free-mode bias determination (for compensating residual along-track acceleration).

The FD Test and Validation group, at the European Space Operations Centre (ESOC), is in charge of the FD system check-out, from individual software components to system level implementation and team training.

To validate the GOCE FD implementation, T&V has developed dedicated test-tools along with a high precision test-data generator. The latter is based on a high-fidelity representation of sensors and actuators, integration of the actual on-board flight software and accurate modelling of S/C dynamics and perturbations, with run-time performance optimisation to quickly produce test-data over long simulated time intervals (e.g. months of telemetry data). Thanks to its accuracy and flexibility, this approach has proved to be very valuable also for additional S/C performance verification.

This paper will focus on the FD system validation and team training performed for the activities mentioned above, both in nominal and contingency scenarios, reporting on the exercised test cases as well as on some relevant operational experiences from GOCE LEOP and S/C commissioning phases.

1. "TEST AND VALIDATION" GROUP OF FLIGHT DYNAMICS DIVISION AT ESOC

In general, flight dynamics deals with the estimation and control of S/C orbits and attitude. The ESOC Flight Dynamics Division, in particular, provides to internal or external customers an end-to-end service extending from initial studies through analysis of requirements, implementation, up to S/C operations.

The FD “Test and Validation” (T&V) group at ESOC defines and performs the testing and validation of the mission-critical operational software (S/W), developed as part of the flight dynamics service preparation as well as specific FD-team training (see [3]). To this end, T&V develops the necessary test tools and procedures and sets up the operational scenarios for training. While using the S/W infrastructure and support layer of the FD division, T&V implements a completely independent mission-specific instance (which doesn’t invoke operational S/W, but rather uses its output for testing) that provides support in terms of validating, verifying and testing critical Flight Dynamics S/W, operations and data products.

Testing of the operational service prepared within the Flight Dynamics Division is performed on different levels (involving different test tools and staff), from individual responsible programmers testing to ESOC-wide System Validation Tests (using actual telemetry data from the satellite before it is launched) and simulations campaign.

The T&V officers are involved directly or indirectly in all of the above mentioned testing activities, but predominantly during launch preparation, in the FD Single Tests campaign (when FD S/W main modules are identified, isolated and tested individually) and System Tests campaign (when the overall FD Operations Service, consisting of the integrated S/W system, operational procedures and the FD Team, is validated in the operational environment for different mission phases using project-specific data and the team trained).

Activities by T&V continue after launch in the areas of validation of critical operations, on-line quality assurance during routine operations, T&V test-tools maintenance, tuning and optimisation, management of configuration control on the operational S/W.

2. GOCE MISSION PROFILE

The Gravity Field and Steady-State Ocean Circulation Explorer (GOCE, see [1] and [2]) is dedicated to measuring the Earth’s gravity field and to model its geoid with extremely high accuracy and spatial resolution.

GOCE was launched on the 17th of March 2009, on a Rockot vehicle from Plesetsk Cosmodrome, in Russia. It is flying in a Sun-synchronous dawn/dusk orbit at very low altitudes (down to 260 km). GOCE has a slender compact body, without deployable or moving parts (see Figure 6).

The core elements of the GOCE payload comprise an Electrostatic Gravity Gradiometer (EGG), i.e. 3 pairs of 3-axis high-sensitivity accelerometers and a 12-channel GPS receiver, called Satellite-to-Satellite Tracking Instrument (SSTI), which provides real-time orbital navigation solutions.

The GOCE Drag Free Attitude Control (DFAC) subsystem provides knowledge of S/C orbit and attitude, and ensures 3-axes stabilised Earth-pointing attitude and orbital control. In particular, the DFAC subsystem allows achieving and maintaining drag free control of the S/C when the gradiometer is measuring. The DFAC subsystem comprises the following sensors and actuators to achieve this functionality:

- Three 3-axis fluxgate magnetometers (MGM), operated in hot redundancy
- A Coarse Earth and Sun sensor (CESS) with 6 sensor heads, providing reliable and robust (but coarse) measurements of the Earth and Sun vectors, based on thermistor readings
- Two hot redundant digital Sun sensors (DSS) for accurate measurements of the Sun direction.
- Three independent star trackers (STR), in hot redundancy, for high accuracy attitude determination.
- Three orthogonal magnetic torquers (MTR), operated in coarse or fine torque regulation mode.
- An Ion Propulsion Assembly (IPA), using Xenon as propellant, providing adjustable thrust to compensate the atmospheric drag forces and to perform altitude change manoeuvres
- Eight cold-gas calibration thrusters used for shaking the S/C during the EGG calibration.

The scientific instrument EGG is also used for drag-free constant altitude maintenance.

LEOP operations foresaw the achievement of the S/C Fine Pointing Mode (FPM, progressively passing through Coarse Pointing Mode – CPM, and Extended Coarse Pointing Mode - ECPM), with calibrated MGM and STR/SSTI data used for closed loop attitude control.

Then the S/C was left in an orbit decay phase (due to air drag without ion propulsion compensation) for transitioning the first long-eclipse season while performing commissioning of the all the other S/C equipment and payloads, before activation of Drag-Free Mode (DFM) in the first science phase. After completion of this, the mission profile foresees an orbit raise (my mean of continuous IPA firing) to put the S/C in hibernation mode during the successive long eclipse season, before decaying again to the selected altitude, maintained constant in DFM for the second science phase.

3. TEST TOOLS AND FLIGHT DYNAMIC EMULATOR

The T&V-Attitude (TVA) group is responsible for single and subsystem testing of the AOCS command generation and attitude monitoring subsystems and operational testing of all external interfaces from these subsystems.

The current TVA implementation has a wide number of s/w libraries (in FORTRAN/C/C++/Matlab/Simulink) and binaries which support FD activities for Earth Observation Satellites; TVA activities for Telecommands (TC) validation, Telemetry (TM) processing and attitude sensors related analyses can be performed using this infrastructure.

To validate the GOCE FD implementation, T&V has developed additional dedicated test-tools along with a high precision flight dynamic emulator, internally called “High Precision Test-Data Generator” (HPTDG).

The HPTDG is based on a high-fidelity representation of sensors and actuators, integration of the actual on-board flight S/W and accurate modelling of S/C dynamics and perturbations, with run-time performance optimisation to quickly produce test-data over long simulated time intervals (e.g. months of TM data). During operations preparation, this emulator is used to test the FD system and to train the FD team. In operations the HPTDG is a valuable instrument for analysing DFAC performances and investigating contingencies.

The following generic requirements are applicable for a FD emulator of any S/C, and they are satisfied by the FD GOCE emulator:

- High precision modelling of S/C dynamics, environment (including ephemerides, attitude, orbit, forces and torques), attitude and orbit control S/W, sensor and actuator dynamics.
- Generation of emulated TM data, for testing the FD system and for training the FD team.
- Capability to inject failures for emulating contingency scenarios.
- Validation of operational telecommands created by the FD Command Generation subsystem.
- AOCS anomaly troubleshooting and performance analysis (also in-flight).
- Full integration in the FD system and environment, to interface correctly with existing legacy code and data formats.
- High speed execution, to allow generation of test data over long intervals within reduced simulation time.

In addition to these features the HPTDG offers maximum flexibility and versatility of use thanks to great visibility, control and configurability of inputs and S/C database parameters (for tailoring particular dynamic simulation scenarios of interest and for investigating contingencies).

The T&V approach for emulator development consists of model-based design, allowing system decomposition. T&V integrates, when feasible, the real flight S/W (alternatively re-implementing a functional model, see [4]) and makes maximum use of externally developed simulation models, when available and satisfying FD accuracy requirements. In addition, new models, originally not available, are developed to complete the emulation system.

During the emulator development, a rapid-spiral prototyping approach is used, to have a closed-loop emulator running as early as possible in the development process, adding and validating functionality around this core. This greatly facilitates debugging of the interface functions and

developed models. Furthermore, this approach allows testing of the FD operational S/W at an early stage, as well as modularity and clear visibility of the S/W architecture. For the FD GOCE emulator, this strategy has been followed, as detailed in [5].

4. GOCE FD OPERATIONS IN LEOP, COMMISSIONING AND ROUTINE PHASES

The GOCE LEOP, commissioning and routine operations phases foresee several activities where Flight Dynamics (FD) support is essential. They are detailed in the following subsections, highlighting the testing methodology adopted during launch preparation activities, together with operational experiences, detailing specifically those that required extensive TVA staff support.

4.1 Ground-station antenna prediction and orbit-determination

The main driver for the LEOP flight operations approach is the short duration of ground station passes. The LEOP network foresaw the use of four ground-stations: the Kiruna station (Sweden), part of the Agency's core ESTRACK (ESA Tracking) network, and the ESTRACK Augmented (partner) stations of Svalbard (Norway), Troll (Antarctica) and Alaska Satellite Facility (USA). With a mean S/C orbital period at separation around 90 minutes, the longest LEOP pass (combined Kiruna/Svalbard pass) lasted slightly more than 9 minutes, whereas the average ground station pass duration was about 5 minutes. After separation (when the knowledge of the S/C orbit is limited), it is necessary to ensure an updated orbital knowledge that allows ground stations tracking for the subsequent revolutions (thus to keep contact with the GOCE S/C); this was obtained performing initial orbit-determinations based on ground station measurements (radiometric data and antenna angles) for provision of time-offset value (TOV); the TOVs are then reported to the ground-stations to improve the antenna pointing with respect to a pre-launch defined baseline orbit that doesn't contain launcher dispersion errors at separation. Additionally, orbit determination could be made more difficult by the changing drag profile due to the S/C slender shape together with the very variable attitude, during the initial rate-damping phase. After the first orbital revolutions, the determined orbit is used in LEOP as an operational reference for performing check-out of the on-board orbit propagator. This propagator is used for reference attitude construction when the 2 SSTI (GPS Satellite-to-Satellite-Tracking-Instrument) measurements are not available. The propagation is initialised using an orbital state vector generated by the ground segment, and needs to be updated periodically because of intrinsic drift of the simplified on-board orbit propagation algorithm, as well as consolidation with the on-ground determined orbit.

The LEOP timeline also foresees the switch-on and check-out of the SSTI. This is done by comparing the orbit solution based radiometric-data with a trajectory fitted on GPS measurements only. Only if these differences are within thresholds (for LEOP selected to be 100 km in position), the on-board S/W is authorized from ground to use the SSTI navigation data, for attitude control. Processing of ground stations radiometric data is then released during the GOCE commissioning phase and routine operations, relying on GPS data only.

To test the FD system performance in this phase, T&V organised dedicated System Tests, based on internally simulated radiometric measurements with different launcher separation errors and bias/noises on ground station calibration values.

This complemented the dedicated tracking campaigns performed for launch preparation, based on actual radiometric measurements from orbiting satellites, with similar tracking equipment and constraints.

Contingency scenarios have been exercised as well, involving separation orbit/attitude errors beyond the nominal launcher performance multiple ground-stations under-performances and/or unavailability (causing loss of complete passes), to verify the robustness and performances of the FD system in providing antenna predictions and orbit solutions, against strict LEOP timeline constraints.

The simulated orbit was also based on HPTDG dynamic data (see Section 3) to better model the variable effects on the orbital state strictly dependant on the attitude of the S/C, such as air-drag and the solar radiation pressure.

Testing of the SSTI check-out and related orbit determination was extensively exercised during FD Single and System Test campaigns by using the HPTDG that provided full simulation of S/C dynamics, to validate the SSTI TM packets extraction, monitoring and pre-processing by the FD Attitude Monitoring Subsystem, to generate interface data to be passed to the FD Orbit Determination Subsystem.

4.2 Magnetometers in-flight calibration

The magnetometers (MGM) provide measurements of the 3-dimensional earth magnetic field vector, used by GOCE for estimation of the angular-rates and the attitude, in a so-called “Virtual Startracker” algorithm (using also Sun and Earth measurements). This measurement is affected by several disturbances which originate from the GOCE S/C. These disturbances are:

- MTR control actuation (dynamic disturbance, depending on actuation current level because of induced local magnetic-fields);
- MGM electrical scale and bias distortion;
- S/C residual dipole;
- Soft-magnetic disturbances which are functions of the local magnetic field strength (caused by the earth magnetic field, applied MTR dipole, S/C residual dipole, latch valves, etc.).

Pre-launch analysis suggested possible attitude control under-performances in “Extended Coarse Pointing Mode” (ECPM) such as large yaw angle de-pointing, temporary loss of Sun in the DSS field of view after exit from eclipse, and STR blindings for short periods.

The achievable attitude control performances in ECPM are strongly correlated to the level of the magnetometers (MGM) disturbances (in higher control modes, the STR are used as the prime attitude sensor, while in the Coarse Pointing Mode – CPM, higher levels of MGM disturbances can be tolerated). In Particular the controller sensitivity to the MGM bias has been investigated, demonstrating the capability to cope with a specific bias (up to 750nT per S/C axis) on the measured magnetic field with respect to the actual Earth Magnetic Field (EMF).

In order to reduce the risk and to achieve a significant improvement of the residual EMF measurement errors, it has been decided to introduce an in-orbit calibration for the MGM measurement before entering ECPM, as part of the activities immediately after launch that therefore became critical decision point for the continuation of LEOP operations.

Assuming a linear-cubic model for the magnetorquer actuation effect (disregarding the magnetic effects of latch valves), the estimated magnetic field, at a given time and at the position of each of the MGM (B_{MGM}), can be modelled as in equation (1):

$$B_{MGM} = (I_{[3 \times 3]} + M) * B_E + B_{SC} + a * i + b * i^3 \quad (1)$$

where “ B_E ” is the Earth magnetic field at measurement time at the position of the specific MGM, “ B_{SC} ” is the S/C’s residual magnetic field, “a” and “b” are the linear and cubic coupling coefficients of the MTR actuation, and “M” is the soft-magnetic coupling factor at the position of each MGM (compensating also for errors in the alignment matrix and scale factors). “i” is the commanded currents to magnetorquer coils, while “ $I_{[3 \times 3]}$ ” is the identity square matrix of dimension 3. “M”, “ B_{SC} ”, “a”, “b” are the modelling parameters of the algorithm, and can be calibrated on-ground (before launch) or in-flight.

The adopted calibration procedure, as implemented according to S/C platform prime contractor recommendations (see [6]) is a complex activity that includes:

- Usage of all STRs, for provision of precise attitude data (needed as for generation of the EMF reference in S/C body frame);
- Repeated commanded switch from MTR closed-loop attitude control to open-loop actuation (and back), with feed-forward MTR current on all axes at predefined levels (see Figure 1):
 - MTR currents set to 0 mA, for determination of the S/C residual magnetic bias
 - Actuation of a single MTR at a time, switching between +/- 500 mA current, to determine the MTR disturbances on each MGM axis
 - repetition of the above steps with MTR currents of +/-250mA (for calibrating higher order MGM/MTR disturbance factors);
- Measurements at different orbital positions within one orbit for improvement of statistical representativeness;
- TM data collection and dump, by means of ground mass memory playback, of specifically activated diagnostic packets;
- Solution of the measurement equation, based on a standard batch least-square method;
- Upload and validation of new calibration data by repetition of the calibration manoeuvres, at a single magnetorquer current level.

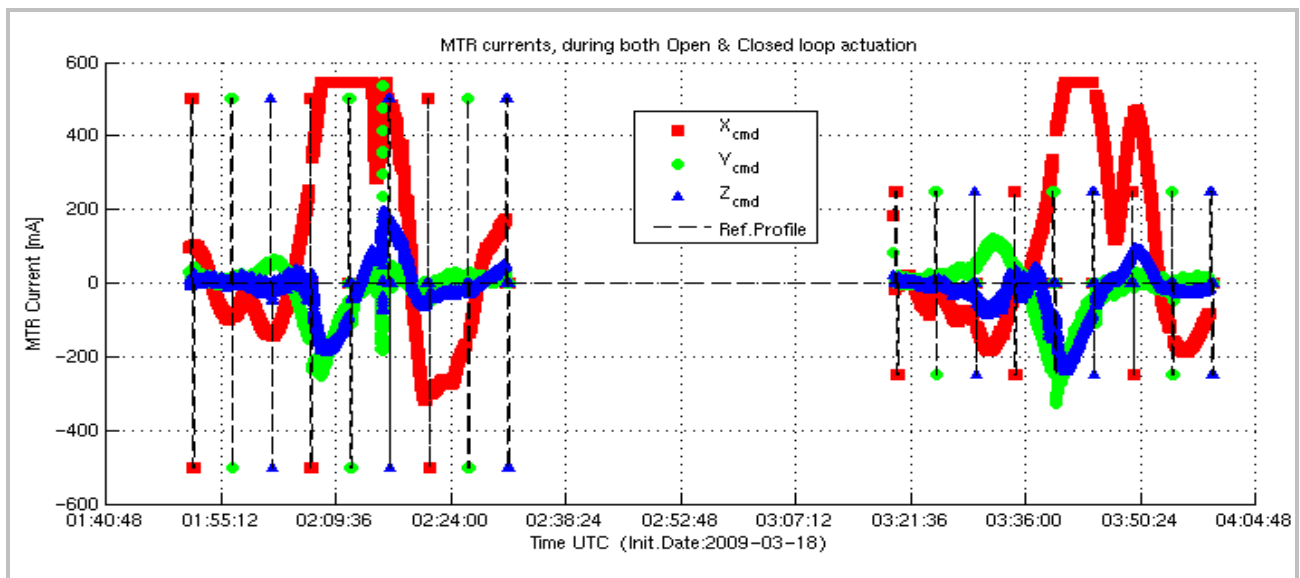


Figure 1: MTR currents for MGM calibration, during closed and open loop actuation in LEOP

The on-board S/W pre-processes the measurements for each MGM sensor, based on the model mentioned above, see (1). Using a set of calibration parameters, together with the commanded current level of the previous control cycle, the S/W applies a compensation algorithm to obtain the actual Earth magnetic field, free of magnetic disturbances, for further processing. As from (1), “ B_E ” is computed on-ground by means of the IGRF-10 model [9], which is based on spherical harmonics as a function of the epoch and S/C position. “ B_{MGM} ” can be obtained from specific TM of the sensor unit. In order to correlate these, the S/C orientation is processed as well, using attitude packets from on-board STR units.

Collected sensor data need to be correlated, applying specific time offsets to the TM packet time stamp, and/or propagated (as for the attitude quaternions) in order to reconstruct the true sensor data at a specific on-board time. Additionally, the MTR physical response to a current command is not immediate, but shows a delay (when operating the MTR in closed-loop control, the step-size is limited by the controller, but when activating them in open-loop, at constant pre-defined current levels, there is a delay to reach the commanded current). These transients need to be excluded from the calibration process. The filtering can be obtained with appropriate synchronisation/shifting of command execution times, cutting additional data to cope with the transient period.

A preliminary step is performed to validate the process of on-ground reconstruction of the on-board measurements estimation. The on-board pre-processed MGM data are compared with their ground computed equivalent, based on raw MGM data and original (currently flying) calibration parameter settings. After the above mentioned validation step and after collection/correlation/filtering of the calibration TM data set, the solution of the measurement equation is based on a standard least-squares method, solving for the modelling parameters (M , B_{SC} , a , b) for each of the magnetometers.

To test the robustness of the FD operational implementation of the MGM calibration, the T&V group selected specific scenarios, involving discontinuities and noises in the ad-hoc HPTDG generated TM test data (see section 3). Specifically, these scenarios included the following:

- Simulation of attitude dynamics (environmental torques) requiring a high level of MTR actuation current while in closed-loop control. This caused big transient periods while switching from closed- to open-loop MTR actuation, to stress the data filtering process.
- Selection of test scenarios and attitude simulations involving frequent and changing blinding conditions on STR sensors. The MGM calibration is LEOP is foreseen to be performed before the STR co-alignment calibration (see section 4.5). Therefore, switching the reference STR can cause discontinuities in the numerical estimation process. Different test scenarios were selected, involving as well multiple consecutive STR blinding (in the same calibration data set) due to Earth, Moon or Sun invasion in the instrument field of view.
- Generation of different data sets, with changing magnetometer model parameters, such as bias, noise, S/C residual dipole, and MTR/MGM coupling effects. This was done in order to test the stability of the numerical method in a wide range of possible applications.
- Generation of corrupted TM data set or containing gaps, while experiencing pre-arranged concurrent S/C contingencies

The intensive and reiterated testing of various scenarios allowed the achievement of the following improvements of the original MGM calibration operations concept:

- Fine-tuning of the masking profile for selection of the calibration data set, to disregard measurements related to unstable MTR currents while in transient periods between open and closed loop attitude control.
- Identification of the best default STR preference sequence for calibration data analyses, in order to cope with most probable STR blinding condition during LEOP.
- Improvement of STR data pre-processing to identify, visualise and filter possible discontinuities
- Improvement of the stability of the adopted numerical method for the least-squares data fit, utilising a singular value decomposition based on a QR transform (Moon-Penrose method) instead of the originally implemented and mathematically equivalent, but numerically inherently unstable, pseudo inverse computation, with data scaling (to improve the conditioning of the computations).
- Optimisation for performances of Attitude Monitoring programs related to ASCII file creation from TM during pre-processing, to cope with time constraint of LEOP operations.
- Clear definition of acceptance criteria for the MGM calibration parameters and of the assessment data analysis. This was integrated in the nominal LEOP timeline activities as a Go/No-Go criteria for transition to ECPM.
- Introduction of additional LEOP orbit determination activities, to ensure the best possible orbit knowledge, right before the MGM calibration data collection
- Flexibility to cope with partial data set, and/or with MTR open-loop actuations pattern not following the original plan

As a by-product of this development, thanks to the flexible T&V approach in implementing MGM calibration related checks, it was possible to integrate the visualisation of magnetic field residuals within post-LEOP routine operations activities related to S/C attitude monitoring.

The integration of this additional monitoring capability was based on the analysis of raw housekeeping TM only, thus avoiding dependencies to specific diagnostic packets. This functionality proved to be very useful during LEOP and commissioning operations. As an example, an unforeseen disturbance in the measured magnetic field was shown to be linked to SSTI-A/B instrument switch-on and -off (see Figure 2), thanks to T&V monitoring tool.

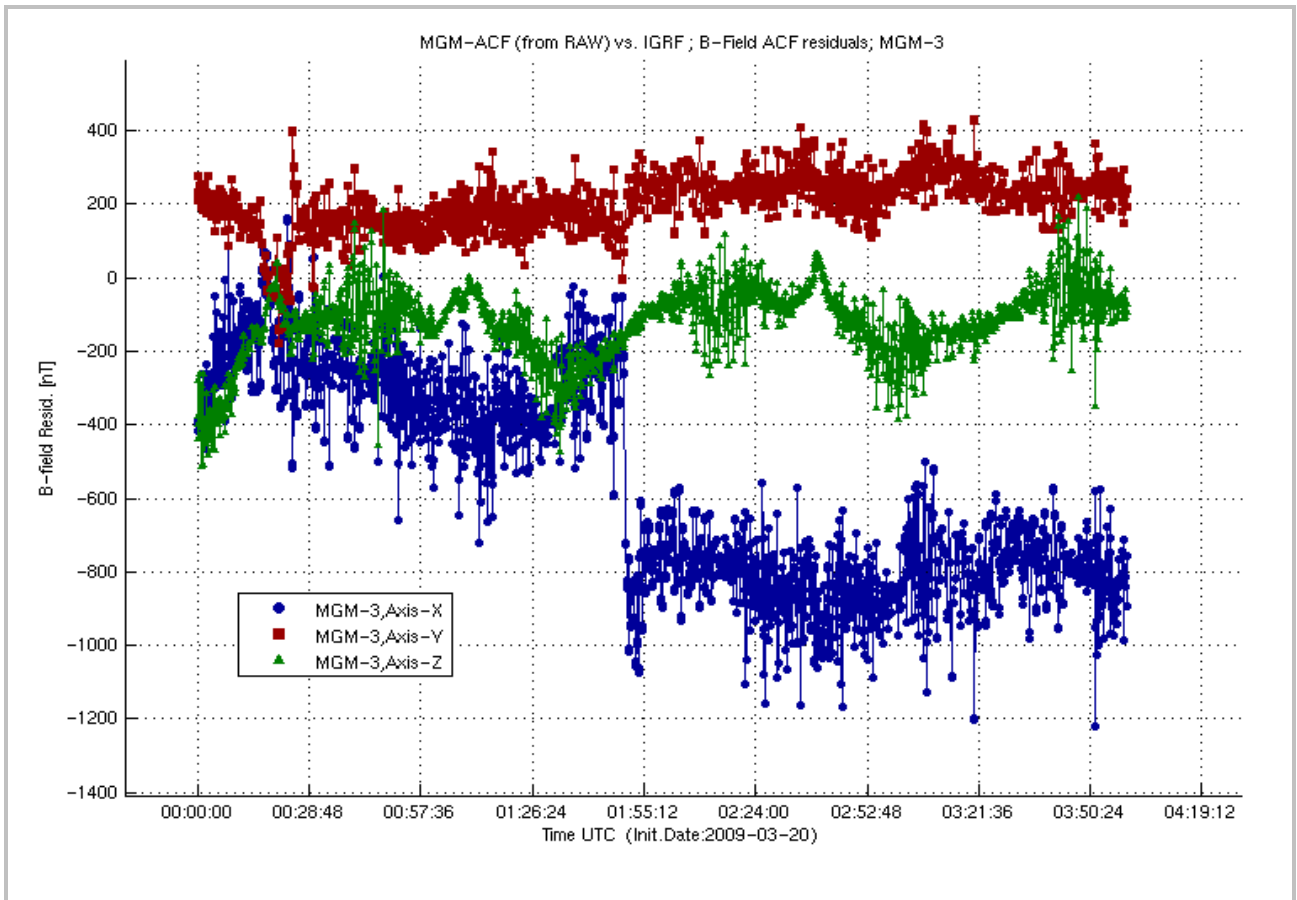


Figure 2: Earth Magnetic field residuals (on-board compensated measurements vs. on-ground model); MGM-3, induced magnetic bias, due to SSTI-B switch-on in LEOP

4.3 Sensor cross coherency check

One of the on-board functional surveillances validates the S/C attitude quaternion by measuring the angular separation of the Sun vector derived from the DSS, and comparing it with the Sun vector calculated from the STR quaternion (using the sensor that is active for closed control loop) and on-board propagated Sun ephemerides. This angle is monitored by the DFAC on-board and has to be lower than a specific threshold, set to 2 deg for GOCE LEOP operations.

When operated in hot redundancy, the DSS-measured Sun direction used by this on-board surveillance is calculated as the mean vector of the two measurements coming from the two DSS. If only one unit is available (the other is failed, switched off, or taken out of the active control loop), its measurements are directly used.

DSS raw TM data was always down-linked either during ground station passes or by means of periodical mass memory dumps.

This TM contains the instrument raw measurements in pixel units, rather than the on-board calibrated DSS Sun vector, which is only available in specific diagnostic TM packets. This packet was only activated for certain analysis periods in order to cope with restrictions on the TM budget, e.g. right before commanding the transition to Fine-Pointing Mode.

During launch preparation activities, the necessity for an on-ground STR/DSS consistency check became evident, in order to provide a preliminary assessment of the surveillance described above, before it became active in Fine-Pointing Mode. This check was added to the nominal GOCE LEOP

timeline to ensure smooth transition to higher DFAC modes, when the STRs are used as reference for attitude control.

The FD Attitude Monitoring Subsystem, on the basis of the operational concept described above, implemented a tool performing this comparison in the form of alphanumeric displays. T&V was in charge of testing this tool during LEOP simulation scenarios, providing a validation tool, using a Matlab-based implementation. The testing of this functionality was done using TM generated with the GOCE HPTDG. Different test cases have been set up, changing sensor model parameters (like sensor alignment, measurement bias and noise), in order to verify the robustness of the selected approach in different situations.

Thanks to the availability of accurate sensor simulation models from the GOCE emulator, it was a simple feat to extract the raw-to-Sun vector conversion and use it on routinely available raw TM, not relying on activation of specific diagnostic TM packets. This provides additional monitoring capabilities, like the real-time analysis of data coming from the 2 DSS. Furthermore, thanks to the Matlab built-in functionalities, the T&V monitoring tool allowed to provide on-the-fly additional analyses and user friendly visualisation of the results.

The T&V tool was successfully used for to the operational FD implementation, to validate the attitude monitoring S/W during pre-launch team training and actual LEOP S/C operations.

Additionally, it provided support beyond its operational counterparts, thanks to its flexibility. In fact, after running the T&V test tool during LEOP over long intervals, it was possible to quickly and effectively identify a S/C anomaly.

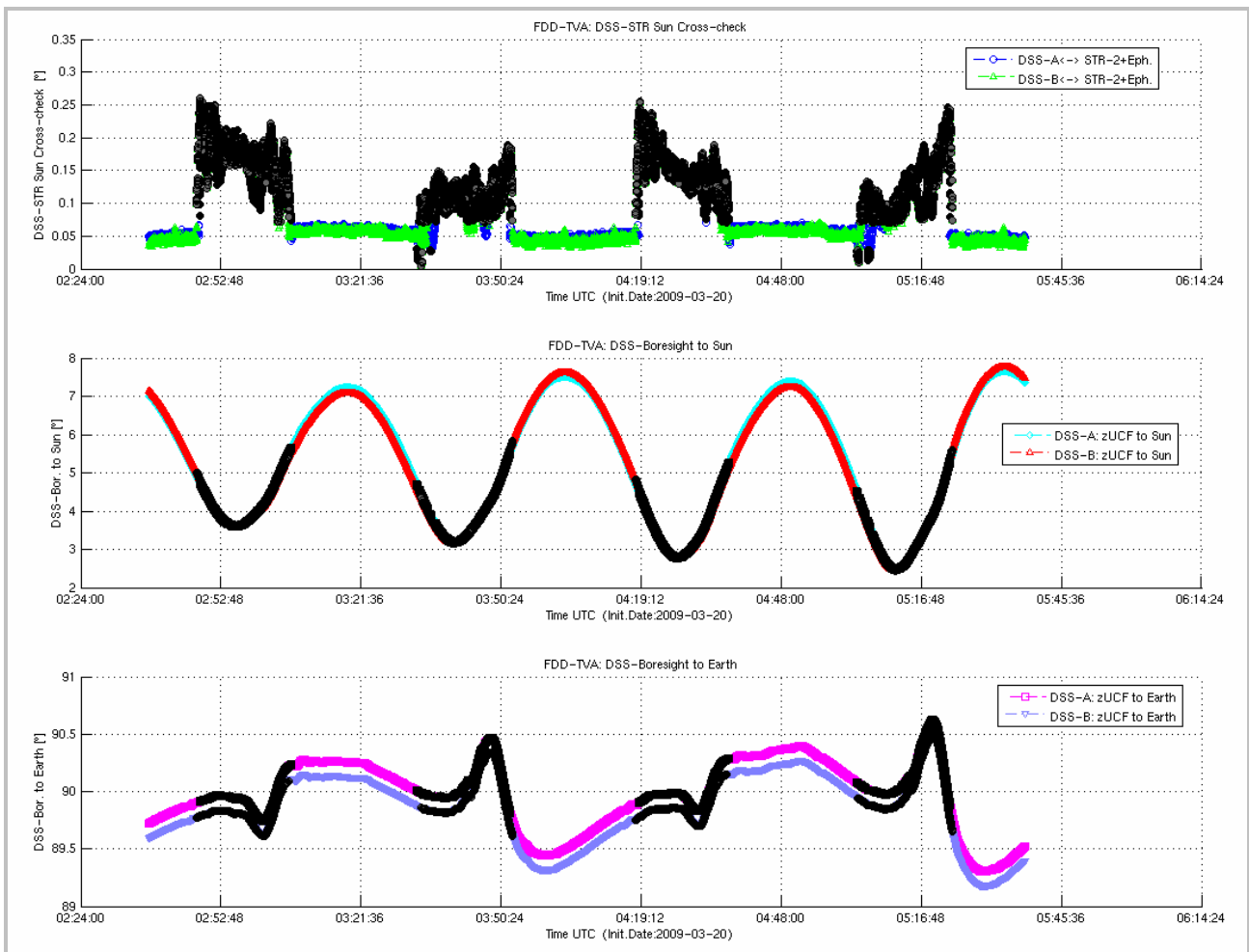


Figure 3: Cross check of DSS/STR Sun vectors, performed with T&V test-tools during S/C commissioning (first plot), with related DSS boresight separation angles, with respect to Sun/Earth directions (latter plots).

During LEOP the DSS/STR cross-coherency surveillance criterion was fully within the requirement (10 times lower). However, at certain orbit positions the consistency check error increased up to 25% of the allowed threshold. In the same orbit position, the angular difference between the two DSS units also increased, behaving differently than expected for unit boresight alignment and S/C attitude (see Figure 3). Initial assessment performed with the help of the T&V test tool revealed that the most probable cause for the anomalous behaviour was a second Sun image entering within the central part of the DSS tracking window. This was suspected to be caused by the reflection of the Sun on the ice of the poles (according to relative Sun reflection angle), as it was later confirmed by the instrument manufacturer, that performed detailed analysis on sensors dynamics.

4.4 STR blinding analysis

As part of the operational implementation of the FD system, it was required to provide reports of STR boresight separation angle with respect to Sun and Moon.

These reports are based on the propagated orbit, assuming the S/C attitude to be constantly equal to a reference, computed with a triad having the S/C X-axis aligned to the orbital velocity, the Y-axis aligned to the orbital angular momentum and Z-axis completing the Cartesian system (and close to the relative Earth direction).

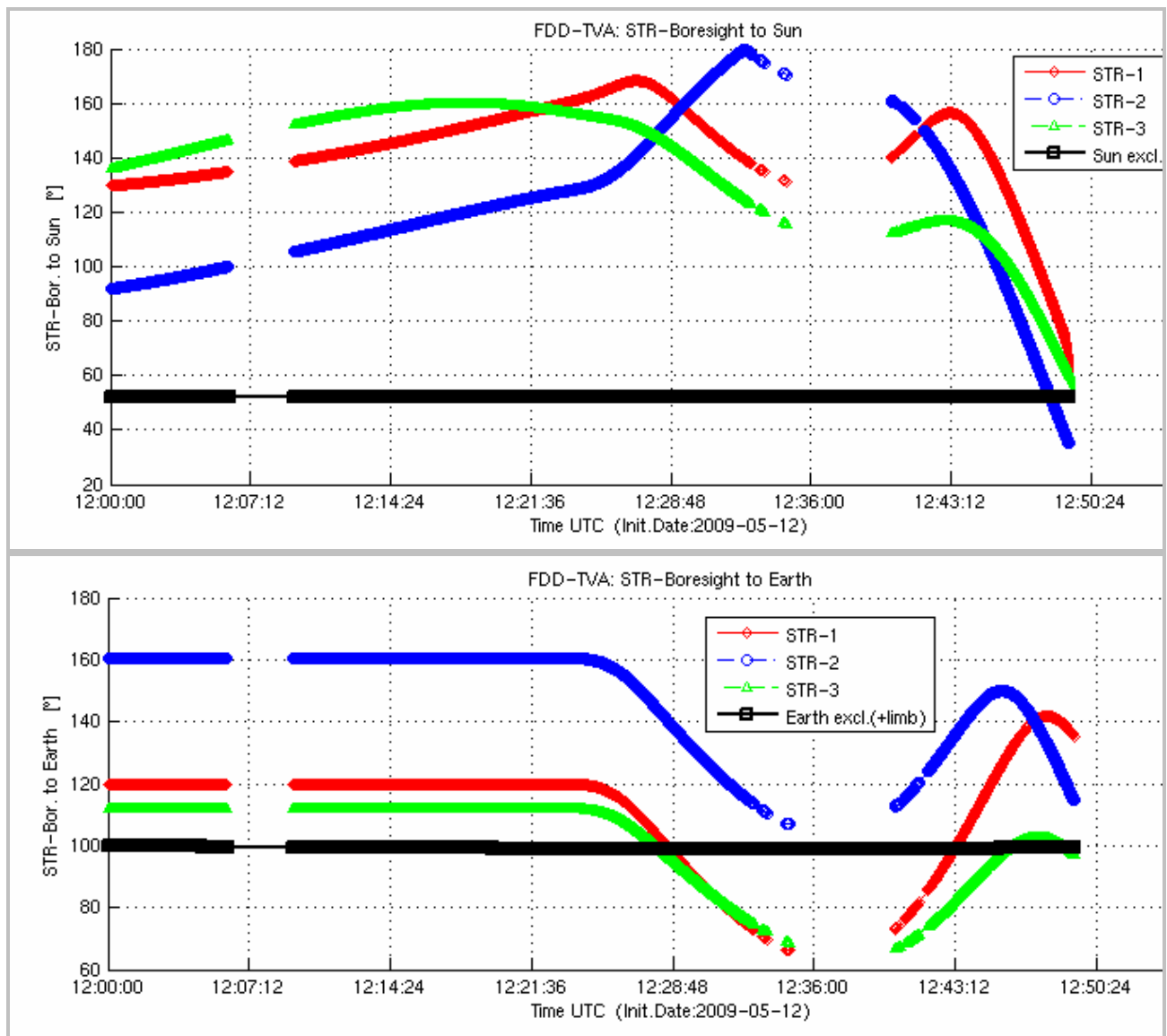


Figure 4: T&V test tool for analysis of STR boresight separation with respect to Sun/Earth directions, based on reconstituted S/C attitude from TM. Commissioning phase, GOCE Survival-Mode entry

Because of aerodynamic disturbances and changing local wind direction, the S/C has a periodical yaw oscillation with respect to the reference attitude. This error is maximal around the equator crossing bands. The magnitude of these oscillations is in the order of a few degrees, thus having a second-order effect on the accuracy of the Sun/Moon blinding predictions.

The S/W for STR report generation has been tested during the Single Test phase with parallel implementation between the Attitude Monitoring and T&V subsystems. During the System Test phase, the T&V tool for post-processing of TM was expanded, to use actual S/C attitude to investigate Sun, Moon, and Earth blinding. This was done to validate the robustness of the FDS implementation against such blinding events (not only Sun and Moon, but also Earth), in various scenarios such as the MGM calibration (see section 4.2). These functionalities are not available (because originally not required) in the operational FDS implementation, and proved to be extremely useful during actual S/C operations in the LEOP and commissioning phases.

In fact, after GOCE launch, the attitude pointing performance proved to be lower than expected, due to unforeseen low atmosphere density levels (because of the low solar activity); this was below the limit assumed for designing the closed loop attitude control, that has been fine-tuned while in flight. During LEOP and Commissioning operations, due to attitude oscillations, different temporary cases of invalid STR had to be investigated; analysis of these periods using the described S/W proved that actual blinding events (e.g. by the Earth and Moon) were causing problems, rather than some artefact of the on-board S/W. As an example, while performing the S/C shaking for calibration of the Gradiometer “Quadratic Factor Matrix” (K2), the activity produced a significant attitude anomaly (related to the bias compensation algorithm for avoidance of jumps in the angular accelerations); GOCE experienced its second in-flight Survival Mode, that T&V tool reconstituted to be triggered by simultaneous STR blinding by the Sun (see Figure 4).

4.5 STR and DSS co-alignment calibration

In addition to being consistent across groups of units (see section 4.3), each of the STR and DSS instruments should give consistent measurements with the redundant unit(s) of the same kind.

The STRs are operated in hot redundancy, with automatic switching of the primary unit in case of invalid data; this includes actual equipment failure, as well as blinding by so-called big-bright objects (Earth, Moon, or Sun). The DSS are operated in averaging mode, i.e. the results of the two units are averaged into a final measurement; if one measurement is not valid (or deactivated from ground), only the measurements of one unit are directly used.

Each of the STR and DSS sensors takes measurements in its own unit-reference frame, then these are converted in a common spacecraft frame by means of on-board stored alignments, that have to be well-calibrated so that the GOCE doesn't face discontinuities when switching units.

In case of nominal sensor performances (otherwise additional investigation would have been necessary to bring the DSS and STR in line), the accuracy of the individual instruments is very high, therefore a master instrument can be defined arbitrarily, and the alignment of the “slave” units are re-computed, to minimize the error in on-board S/W processed measurements.

In order to determine the misalignment of two units, specific diagnostic TM was gathered over one orbit. In particular in the STR case, the measurements of two units are not synchronized, and had therefore to be interpolated. An error quaternion was computed for each sample (interpolated in the case of the STR). The collection of these samples then has to be translated into a single error quaternion.

The method proposed by the S/C manufacturer in [7] and [8] is based on averaging the rotation axes and angles of all error quaternions, with special care taken to avoid discontinuity in the attitude parameterisation; this was selected as baseline for implementation in FD operational S/W, while T&V implemented the same scheme, together with an additional method, to provide an enhanced service in validating the calibration results, improving the robustness of the process.

A non-linear least-squares method was investigated.

Given a quaternion $[e_1 \sin(\varphi/2), e_2 \sin(\varphi/2), e_3 \sin(\varphi/2), \cos(\varphi/2)]$ defined by a rotation axis (e_1, e_2, e_3) and rotation angle φ , the above can be written as follows:

$$\min_{q_{ACF/STR2}} \sum_{i=1}^n \|q_{ACF/STR2} - q_{meas}^i\|^2 = \min_{e_1, e_2, e_3, \varphi} \sum_{i=1}^n \left\| \begin{pmatrix} e_1 \sin \frac{\varphi}{2} - q_1^i \\ e_2 \sin \frac{\varphi}{2} - q_2^i \\ e_3 \sin \frac{\varphi}{2} - q_3^i \\ \cos \frac{\varphi}{2} - q_4^i \end{pmatrix} \right\|^2 \quad q_{meas}^i = (q_1^i, q_2^i, q_3^i, q_4^i) \quad (2)$$

In (2), $q_{ACF/STR}$ is the alignment matrix of the STR with respect to the Attitude Control Frame (ACF), and q_{STRx}^i is the i^{th} measurement of the STR; the quantity q_{meas}^i is given by the default STR1 alignment and the measurements taken.

Since the problem is not linear in its parameters, a Gauss-Newton method has to be employed to solve it.

During launch preparation, no dedicated real S/C TM was available. Therefore the HPTDG (see section 3) was set up with defined misalignments of all sensors; the simulated TM was the passed to the Attitude Monitoring FD subsystem for processing. The resulting corrected alignments for the sensors were compared to T&V results, as well as to the misalignment fed into the simulation.

Noise (sometimes considerably more than would be expected on the real S/C) was added to the measurements in order to investigate the robustness of the method.

This went through several iterations to smooth out all the kinks in the S/W, and ultimately to decide on the method to be used. Improvements to the FD implementation guaranteed by this approach include:

- Instable sign-ambiguity resolution of the error quaternion;
- Improvement of the interpolation of measurements in the case of the STR attitude quaternions
- Provision of an alternative method for validating the calibration results

During S/C commissioning operations, the DSS/STR co-alignment calibrations were performed as planned, after collection of the necessary data set, assuming DSS-A and STR-1 as master units.

The analysis of the calibration residuals with respect to on-ground estimated alignments showed a correction with respect to the original reference unit boresight direction of less than 15 mdeg for STR-2, 27 mdeg for STR-3 and 50 mdeg for DSS-B.

After uplinking the newly computed unit alignments to the S/C, to assess the calibration, a new data set of TM was collected, and the calibration was re-performed, in order to asses the remaining residuals co-alignment process. The STR-2 and STR-3 alignment results were accurate, with difference between uplinked and new alignments on the order of magnitude of less than 3 mdeg.

For the DSS however a new calibration would have resulted in better data for this set of TM. The uplinked and the new alignments differed by around 30 mdeg (see Figure 5). The discrepancy in calculated alignments is due to the fact that the original co-alignment calibration contained periods of DSS-inaccuracy (also indicated by the sudden jumps in the comparison with STR data and Sun ephemerides, according to F1 surveillance concept, see section 4.3). However, during operations it has been decided not to perform additional tuning of the DSS alignment (in favour of continuing with the dense timeline of commissioning activities), since the improvement would have been small and the residual error had no effect on the lower S/C modes where the DSS are used.

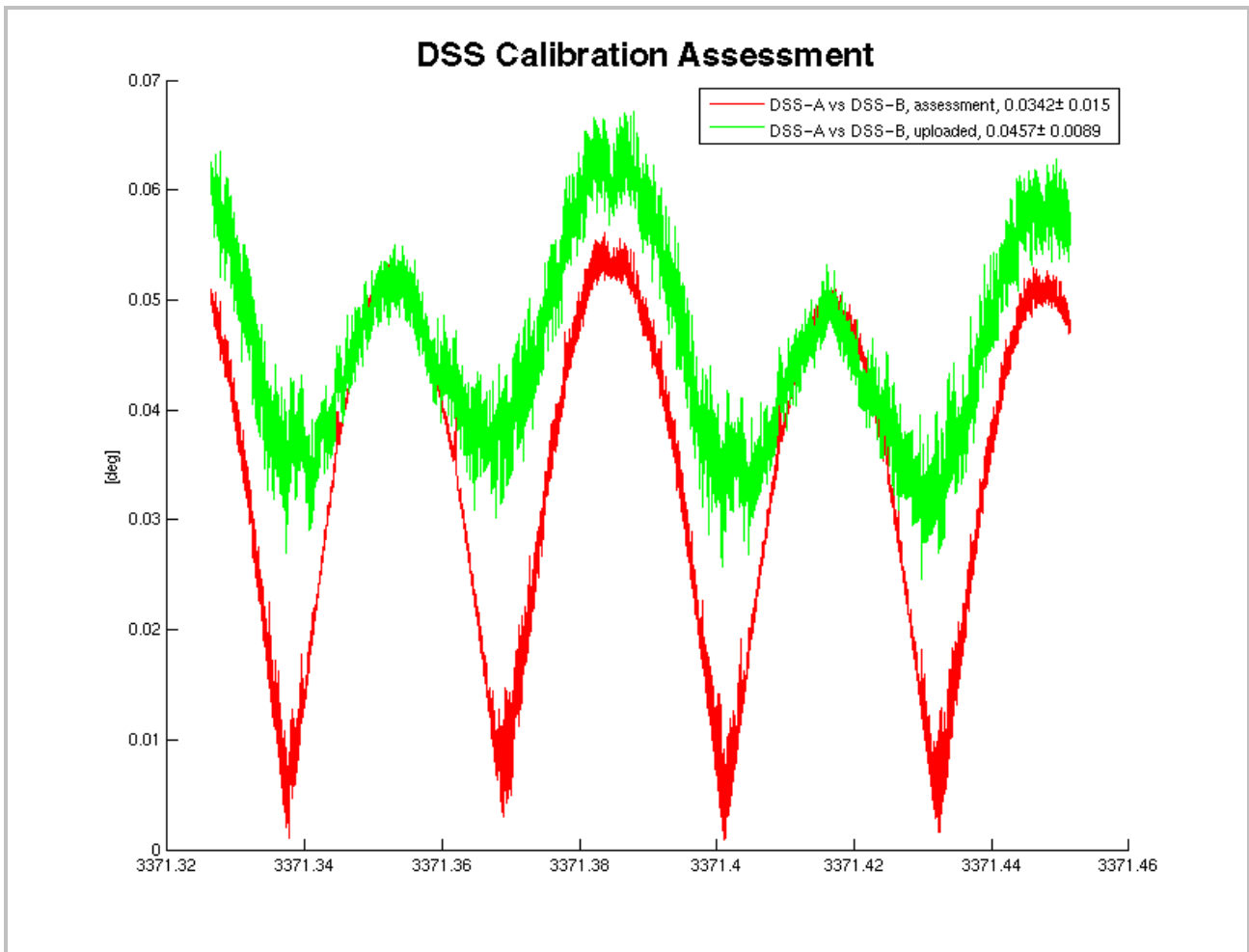


Figure 5: In-flight assessment of the DSS co-alignment results, during GOCE commissioning phase

4.6 Altitude decay/raise rate, Drag-free acceleration bias estimation

Due to the nature of the GOCE orbit, one long eclipse phase will occur per year. The mission reference scenario foresees hibernation phases during these eclipse periods, placing the S/C at higher altitudes. Measurement phases (outside the eclipse seasons) on the other hand are performed at lower altitudes, kept constant by the Drag-free Mode attitude control. Orbit decay is achieved naturally using the air drag (potentially accelerated by means of ground commanded pitch bias to the S/C platform), orbit-raising is achieved by constant firing of the ion-thrusters.

Estimation of the current orbit (based on SSTI data) and prediction of altitude changes, taking into account the solar flux forecast and attitude performances evolution, are necessary for mission control and planning.

Additionally, while operating in drag-free mode (with ion propulsion continuously compensating air drag, to allow scientific measurements by the gradiometer, the primary payload) it is necessary to estimate the potential low-frequency residual along-track acceleration, and to compute an acceleration bias in order to facilitate a constant altitude flight or to impose gradual changes to the orbit.

These scenarios have been internally tested by T&V during the System Test campaign during pre-launch activities, making use of the FD emulator HPTDG (see section 3).

In particular, the emulator has been tuned and optimised for speed, as an example de-activating all modules not necessary for the simulation of current DFAC mode or mission phase.

This was necessary because the evaluation of long term orbit prediction in decay/raise phase is possibly only comparing prediction and determined orbit at the end of the analysed time span, that are usually long (that is in the order of magnitude of months). FD System Test sessions are usually arranged within one working day, with optional completion the following day. Therefore, the

GOCE HPTDG was specifically optimised to produce in this restricted timespan (maintaining high-accuracy attitude/orbit dynamics simulation) months of SSTI telemetry data. These were generally analysed at the beginning of a specific mission phase (e.g. orbit decay/raise), performing SSTI GPS measurement based orbit determination (as introduced in section 4.1) to produce long term orbit prediction; the analysis of test TM was then repeated at the (predicted) end of the mission phase, to verify (again with analysis of SSTI data) the performances of the prediction with respect to simulated “actual” orbit evolution. Different scenarios were simulated, including variable solar flux characteristics affecting air drag level (to evaluate sensitivity of the predictions to the solar-flux forecast quality) as well as contingency cases (as an example in case of Ion-Propulsion outage during the orbit raise phase, to evaluate FDS readiness in correcting the short-term antenna prediction).

The same approach, based on HPTDG data generation for orbit determination purposes, has been adopted for the drag-free acceleration bias estimation, when performing dedicated System Tests. T&V created specific test scenarios, inserting a random acceleration-bias in the emulator, when simulating closed-loop attitude control in drag-free mode. As before, after orbit determination based on generated SSTI TM, the trend of the altitude evolution could be evaluated in order to produce an acceleration bias telecommands (to keep the altitude in a specific dead band). The test scenario foresaw a (simulated) uplink of the telecommand to evaluate its performance. Thanks to the high accuracy simulation provided by the HPTDG, it was possible to identify and take into account the dependency of the acceleration-bias correction on the actual pointing performances of the S/C.

5. CONCLUSIONS

The process of testing and validating Flight Dynamics software during the launch preparations of GOCE was discussed. The importance of this step in the operational software development was demonstrated using several poignant examples. During the required validation process of the operational software, many analysis and monitoring tools were created as by-products (including also animation of spacecraft attitude, from live TM data; see Figure 6).

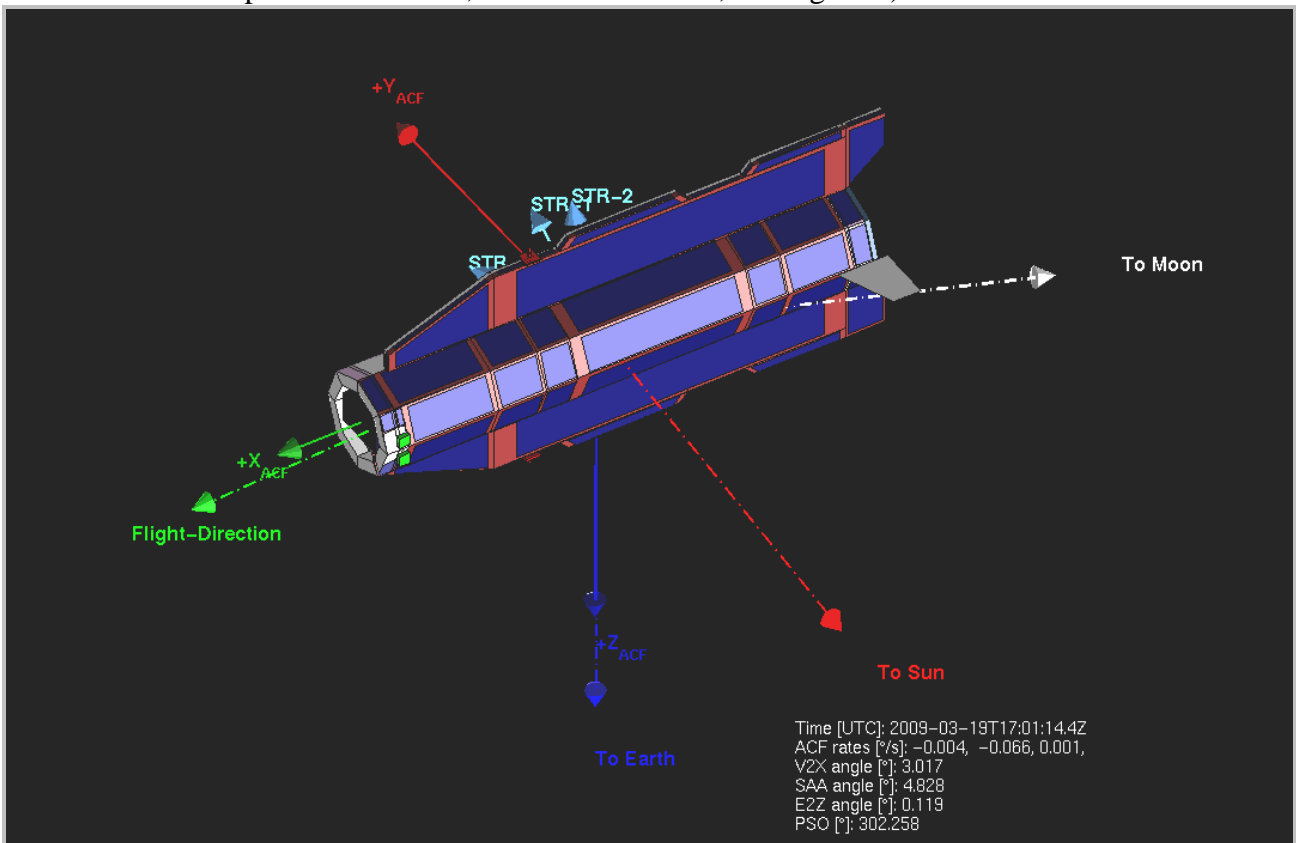


Figure 6: TVA 3-D animation of GOCE attitude from live TM data (LEOP, Fine-Pointing Mode entry)

These proved to be extremely useful during actual operations, when several spacecraft anomalies and unexplained behaviour were investigated in a very short time, yielding information on which further spacecraft operations could be planned.

Using GOCE as an example, the benefits of “Test and Validation” for implementation and conduction of Flight Dynamics support service became evident. Not only is operational software verified to function correctly and robustly, but know-how and experience is built up among several flight dynamics engineers, all of whom can then handle nominal and unexpected behaviour of the spacecraft.

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