APPLICATIONS OF A HIGH-PRECISION EMULATION TOOL IN SUPPORT OF THE HERSCHEL MISSION AT ESOC FLIGHT DYNAMICS

Livio Tucci [(1)], Cosimo Greco [(2)], Susanne Kasten-Coors [(3)]

[(1)] *Terma GmbH at ESA/ESOC OPS-GFT, Robert-Bosch Strasse 5, D-64293 Darmstadt, Germany, +496151902053, Livio.Tucci@esa.int*
[(2)] *Terma GmbH at ESA/ESOC OPS-GFT, address as above,+496151902287, Cosimo.Greco@esa.int*
[(3)] *ESA/ESOC OPS-GFT, address as above, +496151903914, Susanne.Kasten-Coors@esa.int*

1. ABSTRACT

In May 2009 ESA has launched from Kourou with Ariane 5, the observatory spacecraft (S/C) Herschel and Planck, targeting libration orbits around the second Lagrange point of the Sun-Earth system.
ESOC Flight Dynamics (FD) is responsible for the end-to-end operations of the S/C related to orbit determination and control and to the commanding and monitoring of the Attitude Control and Monitoring Subsystem (ACMS).
A high-precision emulation tool has been developed in FD to support Herschel operations preparation, LEOP and post-LEOP operations. This tool is called High-Precision Test Data Generator (HPTDG) and its architectural design foresees the integration of the flight version of the Herschel on-board software, limited to the ACMS part (ASW).
The HPTDG is an in-house developed tool, capable of emulating with high representativeness the S/C closed-loop dynamics, accepting ACMS telecommands and providing simulated telemetry data, thus supporting the end-to-end validation of the FD system.
In addition to these internal validation activities the HPTDG has been also used to perform several analyses supporting the project with independent results with respect to those provided by the spacecraft manufacturer.
In particular, the HPTDG has been used for an independent validation of a fuel saving strategy, whereby industry has performed a tuning of a set of on-board parameters to improve the spacecraft performances in thruster-controlled modes in terms of propellant usage and parasitic ΔV reduction.
Several simulations have been run with the HPTDG in order to provide figures that could be compared with industry ones, strengthening the overall confidence in the proposed solution.
Another important analysis has been performed in order to validate the required on-board ACMS software modification for the Herschel Reaction Wheel (RW) controller, to give the final go-ahead from ESOC side for implementation.
Herschel HPTDG has been also used during flight operations (LEOP, commissioning and routine phases), for commands validation, in-flight analyses and/or troubleshooting.
In this paper, after having given a short description of the HPTDG role and its integration with the FD operational software infrastructure, different examples of its applications during the Herschel operations conducted so far are detailed.

2. MISSION

Herschel is a 3-axis stabilized spacecraft, dedicated to perform astronomical observations in the far-infrared and sub-millimetre wavelength range, covering the 60-670 [μm] band.
It has been successfully launched on May 14, 2009 using an Ariane 5 ECA launcher, jointly with Planck, a survey type mission meant to map the temperatures anisotropies of the cosmic microwave background radiation over the whole sky.

After separation, the Herschel and Planck S/C have been travelling targeting respectively a quasi-Halo and Lissajous orbits around the Sun-Earth second Lagrange point L2, located 1.5 million kilometres away from Earth in the opposite direction to the Sun.
Libration point orbits around L2 are mildly unstable; if the orbit of the S/C is not controlled, after few months it will leave the neighbourhood of the L2 point. However, it is possible to perform small manoeuvres at intervals of 20-70 days to correct for residual errors and maintain the orbit.

3. HIGH-PRECISION EMULATION TOOL ROLE AT ESOC FLIGHT DYNAMICS

In ESOC FD a high-precision S/C dynamics emulation tool has been developed during launch preparation for the Herschel mission. High-precision emulators have been implemented for several missions in the past at ESOC (see [1], [2]). FD Test and Validation Attitude (TVA) team is responsible for the development, testing and operations of those complex software systems. They have to emulate the S/C behaviour in closed loop, also in response to ground TCs, in a correct and precise manner. This implies that the on-board ACMS should be modelled representatively. In the case of Herschel, specifically, the architectural design has foreseen the integration of the flight version of the on-board software, limited to the ACMS part.
In addition, the emulators have to generate high precision test telemetry (TM), which led to the FD internal name High-Precision Test Data Generator (HPTDG).
During launch preparation, the emulators are used to test the FD Command Generation and Attitude Monitoring systems and to train the whole FD team.
In operations the emulators validate FD commands and they are valuable in analysing ACMS S/C performances and investigating contingencies.
The detailed design and implementation characteristics of the Herschel HPTDG can be found in [3].

4. OPERATIONAL APPLICATIONS

4.1 <u>ESOC Flight Dynamics system tests support</u>

Another very important application of the Herschel HPTDG, which is actually one of the main requirements for its development, is the support of the FD system tests. Those activities involve the all FD LEOP team.
The purpose of the FD system tests is to perform an end to end test of the FD system, to confirm its readiness for operational support.

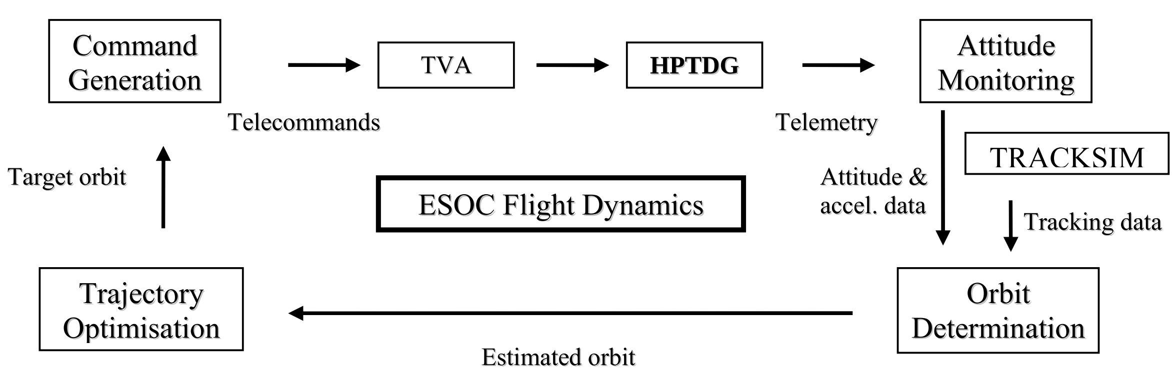

Fig. 1. ESOC FD subsystems and their main data interfaces during system tests

All FD subsystems are participating in these tests, using all the operational software, generating all the foreseen internal and external FD products, and validating the corresponding interfaces.

Last but not least, the FD system tests are considered a very important training session whereby all the subsystems are working together under realistic circumstances, getting ready for the S/C LEOP. The tests can span over several days and different simulation scenarios are prepared and exercised.
In the case of Herschel, separation and autonomous acquisition monitoring, sensor calibration, transition to Orbit Control Mode (OCM) and successive execution and monitoring of launcher dispersion correction manoeuvre were considered as mandatory activities to be performed in the different scenarios of the system test campaign.
In this context, the HPTDG is configured for the selected test scenario and it is run in real time generating TM which is then accessed by the attitude monitoring subsystem. In parallel, the acceleration from the possible thrusters' actuation, solar radiation pressure and helium venting are used by the Test and Validation Orbit (TVO) team to propagate the initial orbit state vector and to generate different sets of tracking data. Those tracking data are then used to perform an orbit determination. The operational orbit file is validated by the TVO team, before being made accessible in the official interface.
Afterwards, as a result of the trajectory optimization, the required orbit manoeuvre parameters in terms of ΔV magnitude and direction and manoeuvre mid-time calculation, are computed and the Mission Planning Subsystem (MPS) can go ahead with the generation of the corresponding telecommand (TC) sequences that are needed to perform the manoeuvre itself.
These products are validated by the TVA team before injecting them in the HPTDG to finally close the loop, allowing the FD team to monitor the correctness of the manoeuvre and later on to evaluate its performances in terms of reconstructed ΔV and consumed propellant.
During system tests, it can be decided to speed up the simulation run during certain time intervals of the exercised scenario, being that timeframe not so relevant for FD monitoring activities.
Additionally, after all the nominal LEOP scenarios have been exercised, some non-nominal scenarios can be also setup and run by the TVA team in order to train the FD team in contingencies situations.
The HPTDG generates TM according to the operational SCOS-2000 format, and can automatically process the TC sequences in the format provided by MPS.
The FD emulation tool is characterized by a high level of flexibility. In fact, in case that new requirements arise which were not originally foreseen, they can be possibly fulfilled by modifying the HPTDG software as needed, normally in relatively short time, so that it is really possible in most of the cases to tailor the HPTDG to the needs of the FD team during operations preparation.
Finally it is worth mentioning that the TVA team, who is responsible for the HPTDG development and operations, naturally achieves at the end of the HPTDG development an in-depth knowledge of the ACMS design of the S/C and of the sensors and actuator interfaces, thanks to the work performed including the on-board software integration.
This knowledge which is a by-pass product of the HPTDG development is beneficial for the whole FD team during the mission.

4.2 Validation of fuel-saving strategy

During operations preparation, in the context of FD system tests, several simulation scenarios have been exercised, focusing on the Herschel thrusters-controlled ACMS modes. Hereafter a brief description of the main features of these modes is given.
Herschel has different modes that make use of thrusters for attitude control: Sun Acquisition Mode (SAM), Sun Acquisition Survival Mode (SASM) and Orbit Control mode (OCM).
Each of the above mentioned S/C modes can be operated with the reaction control system (RCS) either in coarse or fine mode. The RCS fine control with respect to the coarse one provides the highest resolution in the thrusters' firing and therefore better attitude control performances at the expenses of a higher propellant consumption.

SAM is the Herschel nominal safe mode. It is entered autonomously after separation, after specific failures signalled by the Command and Data Management Unit (CDMU) (computer or system in reconfiguration failures), or as response to a ground TC.

SAM makes use of the following units: main Sun Sensors (SAS/Main) and gyros as attitude sensors and main thrusters as actuators (THR/Main).

The sensor data coming from SAS and GYR units are processed in order to provide an estimate of the instantaneous Sun direction in S/C frame and of the S/C rates. Then the attitude error and the angular velocity error are determined and fed to the attitude controller which in turns performs attitude and rate control on each S/C axis individually, calculating the torque commands to be realized by the thrusters.

The target attitude in SAM foresees the +Z spacecraft axis normal to the Sun shield aligned with the Sun direction, performing rate control on all three axes around zero target angular speed. The rotation around the Sun direction is not actively controlled.

SAM has three possible states: Sun acquisition, Sun pointing coarse, Sun pointing fine.

After having completed the Sun acquisition sequence (with RCS in fine mode), when the attitude and velocity errors are both below defined thresholds, the S/C enters autonomously Sun pointing coarse state, waiting for commands to go to higher modes.

Sun pointing fine can only be entered through ground TC and was originally intended as a transition mode to OCM whereby the angular rates are controlled in a narrower band but using much more propellant.

SASM is instead the Herschel survival safe mode. It is entered autonomously either after Attitude and Rate Anomaly Detector (ARAD) triggering (level 4 failure) or after two unsuccessful reset attempts of the main ACC Processor Module (PM) (level 3b failure).

SASM makes use of the following units: redundant Sun Sensors (SAS/Red) and Coarse Rate Sensors (CRS) as attitude sensors and redundant thrusters as actuators (THR/Red).

SASM has the same states as SAM and is very similar to SAM, with the following main differences:

- The attitude error determination function is designed in a different way in order to enter the so-called S/C "safe" zone (+/- 30.6 [deg] in pitch, +/- 5 [deg] in roll) within one minute, following a computed time-optimal slew path.
- Attitude rate estimation is performed using the CRS sensor data as input.
- The mode has different controller parameter tuning.

OCM instead has the primary objective to perform orbit control manoeuvres.

OCM is also the mode in which the RW biasing and hold to ground-commanded speed levels is performed, before transition to Science Mode (SCM), in order to enter it with a known total RW angular momentum.

It must be noted that there are specific RCS thrusters exclusively used for orbit control that is, to perform the actual ΔV, not being used for attitude control.

OCM makes use of the following units: Star Tracker (STR) and gyros as attitude sensors and main thrusters as actuators (THR/Main).

OCM has four possible states: slewing, pointing coarse, pointing fine and thrusting.

The usage of different type of thrusters and different RCS modes in the different states is schematically illustrated in Table 1.

The nominal and usual OCM operations foresee the entering in OCM in the slewing state, whereby the ground-commanded attitude is achieved. After that the S/C nominally enters the pointing coarse state where the attitude is maintained until the actual ΔV command is received by the S/C. This triggers the transition to the thrusting state which is maintained until the commanded duration of firing of the orbit-control thruster has expired, or a timeout specified also by ground is exceeded.

After that the S/C nominally performs a transition to pointing coarse state.

Pointing fine state was originally intended to be entered before transition to SCM in order to reduce even further the residual S/C angular momentum.

In OCM attitude control is performed by using a PID law during both slew and pointing.

To correct for cross-term inertia the torque request vector is multiplied by a decoupling matrix, before being sent to the RCS to compute the corresponding thruster on-times.

Table 1 Different RCS configurations in OCM

OCM State	Thrusters Type	RCS Mode
Slewing	Attitude Control	Fine
	Orbit Control	Off
Pointing coarse	Attitude Control	Coarse
	Orbit Control	Off
Pointing fine	Attitude Control	Fine
	Orbit Control	Off
Thrusting	Attitude Control	Coarse
	Orbit Control	Continuously on

The focus for FD of SAM/SASM simulations was to exercise attitude performance monitoring of the autonomous Sun acquisition sequence and of the successive maintenance of the Sun-pointing attitude until a command to perform transition to higher mode was given.
For what concerns instead OCM simulations the emphasis was, besides the attitude monitoring, the uplink of OCM commands for command validation, ΔV manoeuvre monitoring, post manoeuvre performance assessment in terms of ΔV reconstruction and fuel bookkeeping based on TM data, acquired during the manoeuvre itself.
Finally, OCM simulations were performed to exercise the LEOP timeline whereby the RW where biased to specific values for a relatively long period of time, in order to perform the so-called RW run-in procedure, foreseen as a mandatory step before transition to SCM.
In the HPTDG accurate thrusters' performance models were implemented in cooperation between industry and ESOC FD, which was significantly involved in refining and in many cases improving the thrusters' performance models originally supplied by industry.
The models were based on the Flight Model thrusters' qualification and acceptance data provided by the thrusters' manufacturer.
By analysing simulation results and looking at the attitude control performance in SAM, SASM and OCM, it was initially noticed that the S/C was experiencing a considerably high propellant consumption purely for attitude control.
After having internally double-checked the correctness of the thrusters model implementation in the HPTDG, the fact that the emulator was integrating the flying version of the on-board software led FD to start to believe that we were facing a real issue on the S/C controllers for the thruster-controlled modes.
The problem of extremely high fuel consumption in SAM/SASM was originally addressed in the frame of the Herschel Qualification Review, indicating a non compliance with two system level requirements, namely:

- The S/C shall be able to stay in SASM without any ground contact for at least seven days
- For Herschel, propellant for orbit maintenance attitude control and momentum management shall be dimensioned for 4.5 years

That triggered a change request to industry targeting an average propellant consumption in SAM/SASM steady state of 1 [Kg/day], with the considerable constraint that, being relatively close to Herschel launch, any modification of the on-board software code was excluded, because of the excessive time which would have been needed to perform regression tests on the modified on-board software.
Therefore the only viable identified solution was to perform parameter tuning of the SAM and SASM controllers.

The final results of this first parameter tuning activity are summarized in Table 2 below as reported in [4].

Table 2 SAM/SASM fuel consumption after first OBDB parameter tuning

Mode	BOL (22 bar) [Kg/day]	MOL(12.5 bar)[Kg/day]	EOL (5.5 bar) [Kg/day]
SAM	1.0	5.5	14.5
SASM	11.7	21.1	64.4

It can be seen that the target propellant consumption was achieved only for the SAM beginning of life scenario.
For what concerns SAM, this initial parameter tuning foresaw in fact a reduction of the proportional gains, in order to reduce the number of thruster pulses at the cost of a wider limit cycle and higher rates. The limiting factor in this reduction was the respect of the control stability margins and to also keep the limit cycle within the attitude anomaly detector field of view. With the same rationale the integral gains were reduced significantly, to avoid that the integral term of the PID controller would tighten the limit cycle again, increasing fuel consumption.
While test results showed a good behaviour for the BOL scenario, MOL and EOL scenario showed that the SAS-derived attitude errors were in many cases increasing above the control error boundary of 3 [deg] whereby the controller was triggering a Sun acquisition sequence. The latter is performed with the RCS in fine mode, leading to a considerable increase of propellant consumption.
So, in conclusion the main reason for the high consumption in SAM appeared to be directly linked to the number of times Sun acquisition was triggered.
ESOC FD implemented as well in the HPTDG the above described parameter tuning and was confirming the observed behaviour in SAM.
In Fig. 2 the limit cycle in SAM is shown, together with the S/C rates, clearly showing spikes corresponding to the Sun acquisition triggering.

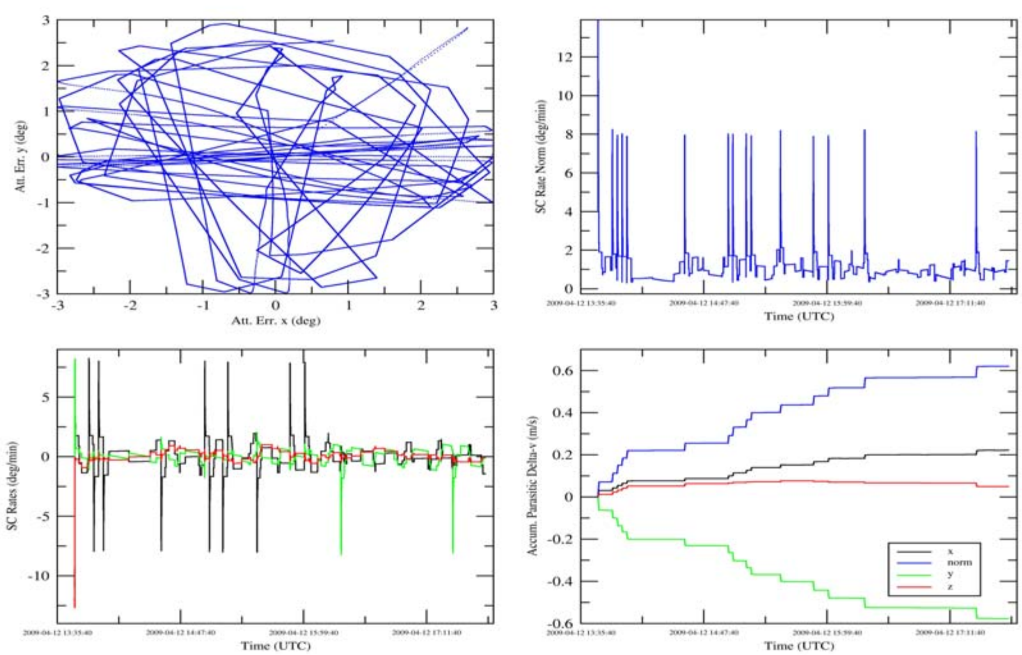

Fig. 2 SAM controller behaviour from a HPTDG simulation after first OBDB parameter tuning

Similar reasoning has been applied for SASM, whereby a similar tuning of the controller gains was performed also together with an update of the On-board Database (OBDB) parameters representing the thrust level assumed on-board as a function of the actual pressure, in order to achieve roughly the same relative error between actual force delivered by the thrusters and the one assumed on-board over all pressure ranges.

Unfortunately the simulation results were not satisfactory mainly because the S/C rates are estimated from the CRS sensors without any low-pass filtering neither at hardware level nor at software level. Therefore the estimated S/C rates exhibit such a large noise that the controller reacts to peaks in the noise to correct for non-existent rate errors, resulting in a SM limit cycle much tighter than SAM with a corresponding increase in fuel consumption.

As a consequence of these first results, upon request of the Herschel/Planck project, a dedicated team, the Herschel Fuel Consumption Tiger Team (HFCTT) was formed, gathering experts from industry and ESA. In parallel another team was also formed, the so called Herschel ACMS Independent Validation Team (HAIVT), which was in charge of assessing the S/C ACMS from a system point of view and also of reviewing the requirements from system level down to ACMS subsystem level.

The HFCTT mandate was to investigate and initiate recovery measures to bring the fuel consumption estimation in line with the allocated amount at system level for SAM/SASM, budgeted to 20 [Kg] (see [4]) with the following target scenario: the mission should be compatible with three major failures during mission lifetime (BOL, MOL and EOL), therefore foreseeing 3 times 7 days of SASM and 3 days of SAM to recover for each individual SAM.

After an intensive work, the identified solution foresaw a re-tuning of the ACMS control gains and some of the OBDB parameters related to the thruster on-time calculation function of the on-board software, towards a more balanced compromise between pointing performances and propellant consumption.

The major advantages of the foreseen approach were that no ACMS ASW modifications were required while the drawbacks were that the extent of the improvements was limited, that excessive relaxation of the ACMS control gains, in combination with the expected large thruster error, could compromise the attitude control stability margins and therefore a successive stability analysis after the parameter retuning was necessary.

In summary there were two kinds of tuning: one valid for the overall mission and another valid only for a certain period of the mission. The latter had operational implications, because new parameters needed to be uploaded during the mission.

The tuning valid for the overall mission consisted in:

- Increase of the SAM controller thresholds to trigger Sun acquisition
- Tuning of SASM PID gains (significant reduction of derivative gain to limit controller sensitivity to high CRS noise, update of proportional gains to consider updated attitude limit cycle)
- Optimisation of RCS commanding parameters for both coarse and fine mode

The tuning to be changed during the mission lifetime consisted instead in:

- On-board torque matrix and RM flag for default thrust level in SM update; this is as a function of the thruster force evolution during the mission in order to compensate for the fact that no thruster model is implemented on-board, therefore maximising the correct knowledge on-board of the thruster force and torque capability
- Update of the RCS commanding rounding threshold in coarse mode in order to maintain the torque dead band (and consequently the attitude limit cycle) quite constant during the mission lifetime

The OBDB parameter re-tuning managed indeed to fix the problem and to effectively mitigate the high propellant consumption in the steady state of SAM and SASM, with a consumption for the target scenario between 22.6 and 27.2 [Kg], compatible with the fuel system budget, in which it was possible, after revision, to increase the SAM/SASM budget from 20 [kg] to indeed 27.2 [kg] (see [4], [6]). Also the fuel necessary to recover from the parasitic ΔV effects caused by prolonged periods in SAM and SASM was assessed and included in the system level fuel budget.

In order to validate the OBDB parameter re-tuning and to provide to the HFCTT propellant consumption figures for SAM and SASM in different phases of the mission (BOL, MOL and EOL), the ACMS manufacturer needed to identify and run a set of simulations scenarios.
In parallel to the activities performed by the S/C manufacturer, ESOC FD ran a selection of the above mentioned simulation scenarios in SAM/SASM.
The idea was to setup the HPTDG environment as close as possible to the industry emulator one in order to be able at a later stage to compare results with them.
The main purpose was to cross-validate the proposed parameter changes and gain therefore confidence on the fact that the problem was effectively solved by OBDB parameter tuning only.
A large number of simulations could be run thanks to the high speed of the HPTDG (about 70 times faster than real time).
FD results were collected and sent to all involved parties showing a general agreement and compatibility with the ones provided later on by the HFCTT.
The exercise turned out to be extremely useful and appreciated also by the S/C manufacturer, because of the fact that they could benefit from a completely independent assessment of the successful implementation of the fuel saving strategy.
A summary of the comparison between ESOC FD and HFCTT results in terms of propellant consumption figures for BOL, MOL and EOL scenarios is given in Table 3 (see [4]). A comparison for the reference target scenario is then given in Table 4 (see [6])
Each scenario has been run with the RCS in coarse mode and with a specified either under (MFL) or over performance (MFH) of the simulated thrust level to see its potential impact in the propellant consumption. Additionally the parasitic ΔV nom rate computed by FD ESOC is shown in Table 3.

Table 3 SAM/SASM fuel consumption comparison between HFCTT and HPTDG simulation results

Test Case	Number of Sun Acquisition triggerings	Fuel Consumption [Kg/day]	Number of Sun Acquisition triggerings	Fuel Consumption [Kg/day]	Parasitic ΔV Norm Variation [cm/s/hr]
	HFCTT results		HPTDG results		
SAM MFH BOL	0	2.1	0	1.07	0.61
SAM MFL BOL	0	0.9	1	0.93	0.41
SAM MFH MOL	0	0.8	0	0.64	0.33
SAM MFL MOL	0	0.8	0	0.61	0.28
SAM MFH EOL	0	1.2	0	0.43	0.27
SAM MFL EOL	0	0.6	0	0.49	0.23
SASM MFH BOL	0	1.3	0	1.39	0.84
SASM MFL BOL	0	1.1	0	1.42	0.66
SASM MFH MOL	0	1.1	0	1.45	0.99
SASM MFL MOL	0	1.2	0	1.48	0.83
SASM MFH EOL	0	0.7	0	1.04	0.86
SASM MFL EOL	0	0.8	0	0.99	0.57

Table 4 Fuel consumption comparison for reference target scenario between HFCTT and HPTDG simulation results

SASM BOL [Kg]	SAM BOL [Kg]	Orbit Recovery [Kg]	SASM MOL [Kg]	SAM MOL [Kg]	Orbit Recovery [Kg]	SASM EOL [Kg]	SAM EOL [Kg]	Orbit Recovery [Kg]	Total [Kg]	Fuel Budget [Kg]
9.1	2.1	1.426	8.4	0.8	0.869	5.6	1.2	0.841	30.336	30.336
10.11	1.0	1.06	10.48	0.62	0.94	7.29	0.46	0.66	32.62	30.336

The S/C manufacturer later on performed also a detailed analysis of the propellant consumption in OCM pointing coarse and OCM pointing fine, obtaining figures with with 35 [Kg/day] and 71 [Kg/day] respectively and consuming therefore much more than SAM/SASM (see [5]).
Very high consumption figures were computed also for SAM/SASM fine modes.
It should be mentioned that, even if outside of the scope of this paper, associated with the high propellant consumption the problem of a high parasitic ΔV as a result of attitude control in thruster-controlled modes needed also to be considered with high-priority, by proving that the S/C could meet all the requirements of the parasitic ΔV budget.
Re-tuning of OBDB parameters for OCM control was instead only envisaged to temporarily support the RW run-in in LEOP (part of which was foreseen to be performed in OCM coarse indeed), where once again lower fuel consumption and lower parasitic ΔV were traded against a larger attitude error limit cycle.
In fact, from FD perspective, staying for several hours in that mode, would have had a strong repercussion on the accuracy of the first orbit determination, e.g. the sustained level of noisy accelerations would have hampered the orbit determination process.
Additionally, the parasitic ΔV immediately after separation could have led to a risk of collision with the other bodies (Planck, Sylda and ESC-A), flying at a relatively close distance for an extended period of time.
After the finalization of the ACMS control re-tuning an operational strategy was defined at ESOC to cope with the S/C final estimated performances in terms of propellant consumption and parasitic ΔV.
As an example, it was decided to avoid the SAM and OCM fine modes as much as possible. Since those modes were meant to be intermediate modes for the transition SAM coarse to OCM coarse and OCM coarse to SCM respectively, it was decided to analyse the possibility to perform direct transitions to those modes without passing through SAM and OCM fine. This turned out to be possible and therefore was implemented as baseline.

4.3 Validation of reaction wheel controller modification

FD ESOC was also involved in the process of proposing and later on validating a software modification of the on-board RW controller algorithm, in order to improve its performances, allowing a higher degree of flexibility in the RW momentum management strategy.
MPS is responsible for the operational implementation of this strategy. The inputs to this activity are the sequences of scientific pointing requests coming from the Herschel Science Centre (HSC).
Herschel scientific observations are performed in SCM, which is a purely wheel-controlled mode, either on three or four wheels.
Therefore optimal RW levels are computed for the bias to be commanded, such that, starting from the achieved target levels, they evolve during the selected time interval within the allowed speed region, neither exceeding a maximum speed limit nor staying during stable pointings close to zero (stiction zone avoidance), nor violating maximum torque constraints.
In order to verify the correctness of the RW bias command, MPS also performs a RW level propagation to confirm that the predictions are fulfilling all the imposed operational constraints.
The baseline for Herschel RW operations is the simultaneous usage of four wheels, to provide larger control authority and momentum capacity.
Because of the fact that in a four-wheel configuration there is not a unique decomposition of the torque requested by the attitude controller, the MPS propagation software needs to emulate the on-board software logic for the RW torque commanding to determine the four individual RW torques.
This on-board algorithm (see [7]) converts the torque request in S/C frame to requests to individual wheels. The conversion is based on the following relation:

$$\vec{T}^{SC} = A \cdot \vec{T}^{RWL} \tag{1}$$

where $A = [\vec{a}_1 \quad \vec{a}_2 \quad \vec{a}_3 \quad \vec{a}_4]$ is a matrix in which each column is one of the 4 RW axes in S/C frame, $\vec{T}^{SC}$ is the 3x1 requested torque vector in S/C frame and $\vec{T}^{RWL}$ is the 4x1 vector of the individual torques requested by the controller to the RWs.
$\vec{T}^{RWL}$ is computed as:

$$\vec{T}^{RWL} = [A^T \cdot (A \cdot A^T)^{-1}] \cdot \vec{T}^{SC} + \vec{T}^{RWL}_{\mathrm{mod}} \tag{2}$$

$$\vec{T}^{RWL}_{\mathrm{mod}} = K_P \cdot (J \cdot \vec{H}^{RWL}_{des} - \vec{\omega}^{RWL}_{meas}) \tag{3}$$

where $\vec{\omega}^{RWL}_{meas}$ is the measured RW speed, K_p a proportional gain and J a diagonal matrix having as elements the inverse of the RW inertias I_k^{-1} (k = 1,4) and $\vec{H}^{RWL}_{des}$ is computed as follows:

$$\vec{H}^{RWL}_{des} = [A^T \cdot (A \cdot A^T)^{-1}] \cdot A \cdot \vec{H}^{RWL}_{meas} \tag{4}$$

where $\vec{H}^{RWL}_{meas}$ is the RW angular momentum computed from measured RW speeds $\vec{\omega}^{RWL}_{meas}$.

This controller for the four-wheel configuration has been designed with the purpose of minimizing the power consumption of the RW system, while delivering a certain requested torque $\vec{T}^{SC}$.
This minimization is done by minimizing independently the norm of the RW torque and angular momentum, being each of these vectors expressed in RW frame.
As illustrated in Eq. 2, the 4x1 $\vec{T}^{RWL}$ vector is composed by two terms: the first term is perpendicular by construction to the null-space vector of the matrix A, and therefore is the torque vector which has minimum norm among all the possible torque vectors resulting in a requested torque in S/C frame $\vec{T}^{SC}$; the second term, $\vec{T}^{RWL}_{\mathrm{mod}}$, is proportional to the difference between the measured and desired RW speed, controlling therefore the RW around a desired angular momentum $\vec{H}^{RWL}_{des}$. The latter is computed from the measured angular momentum $\vec{H}^{RWL}_{meas}$ as shown in Eq. 4, being therefore the component of $\vec{H}^{RWL}_{meas}$ perpendicular to the null-space vector of A. $\vec{H}^{RWL}_{des}$ is the vector with minimum norm mapping into $A \cdot \vec{H}^{RWL}_{meas}$.
Therefore the difference $(\vec{H}^{RWL}_{des} - \vec{H}^{RWL}_{meas})$ and consequently $\vec{T}^{RWL}_{\mathrm{mod}}$ is along the null space vector of the matrix A and maps to a corresponding null torque vector in S/C frame.
With this approach, the $\vec{H}^{RWL}_{meas}$ is controlled to move along the hyper plane perpendicular to the null-space vector of A; it changes as a result of disturbance torques acting on the S/C and/or slew manoeuvres, leading to the risk of RW operation in zero crossing regimes during steady state pointing; the RW manufacturer recommends not to dwell for period longer than 1 hour at speeds corresponding to an angular momentum below 2 [Nms].
While it is always possible to find an initial RW bias level for one individual slew such that the RWs are not operating after the slew in zero-crossing regime, with an increasing number of S/C re-orientations to be performed as planned by the HSC, this task become more and more difficult up to the point that it does not have solution at all.
This in fact happened to ESOC FD in the context of a S/C validation test whereby MPS was not able to find optimal RW levels for the scenario, satisfying all the operational constraints. The HPTDG was preliminarily used by FD to confirm the predicted RW level evolution by MPS.

More in-depth analyses led FD to have a closer look at the RW controller and after several iterations with industry and the Herschel project, a decision was taken to modify the on-board software code of the RW controller in order to improve its performance.
The proposed modification consisted in introducing an additional scalar offset h_{offset} (commandable by ground) in the original $\vec{T}_{\text{mod}}^{RWL}$ calculation as follows:

$$\vec{T}_{\text{mod}}^{RWL} = K_P \cdot (J \cdot \vec{H}_{des}^{RWL} - \vec{\omega}_{meas}^{RWL}) + K_P \cdot J \cdot h_{offset} \cdot \hat{V} \tag{5}$$

where $\hat{V}$ is a unit-norm vector belonging to the null-space of A.
Therefore, this additional term does not result in any net control torque in S/C frame, not disturbing the attitude control.
With the addition of this offset along $\hat{V}$ the RW angular momentum $\vec{H}_{meas}^{RWL}$ is controlled to move along the hyper plane perpendicular to $\hat{V}$ but with a constant component h_{offset} along $\hat{V}$.
This in turn allows commanding RW biases which bring $\vec{H}_{meas}^{RWL}$ along $\hat{V}$ direction, corresponding to RW total angular momentum zero. After any slew initiating from this condition, in the ideal case of absence of external torques, the RW total angular momentum norm is preserved and therefore still equal to zero.
This implies that $\vec{H}_{meas}^{RWL}$ is still directed along $\hat{V}$ with the original offset, thanks to the action of the control of the angular momentum null-space component, implying in the ideal case identical RW speed levels before and after the slew.
In reality the effect of external torques will not allow to come back exactly to the original RW speed levels but close to them.
In conclusion, by choosing an appropriate value for h_{offset} together with targeting initial RW levels corresponding to an angular momentum along $\hat{V}$, it has become possible over a given planning period to operate the wheels avoiding zero-crossing regimes during steady state and maximum speed constraint violation.

The modification was formally tested by the ACMS manufacturer, but ESOC FD was asked to provide an additional verification with the HPTDG of the improved behaviour of the RW controller after the introduction of the null space offset.
A scenario was created covering all the pointing requests which created problems with the original software; the on-board software code was modified in accordance with industry instructions, and simulation results were analyzed comparing the behaviour with those obtained before the modifications.
The outcome were very satisfactory and FD got quite a good insight of the controller behaviour strengthening the confidence of the correctness of the modification proposed by ESOC and agreed by industry.
The agreed software modification could not be implemented before launch due to schedule constraints, and therefore it was decided to perform a software patch after LEOP, during the S/C commissioning and performance verification (CPV) phase.
Herschel, almost at the end of its CPV phase, is currently flying with the above described on-board software patch and the expected behaviour from simulation has been confirmed by flight data.
Controlling around RW total angular momentum close to zero and possibly changing the null-space offset depending on operational needs results in a much more efficient momentum management strategy in terms of propellant consumption and parasitic ΔV effects during the RW biases.
The considerable reduction of these parasitic accelerations has made smoother the process of orbit determination within FD.

4.4 Validation of Flight Dynamics software for gyro calibration

While the previously described application of the HPTDG were focusing on the independent validation by FD of important on-board software parameter tuning and modification, as a consequence of a problem detected on the space segment, other important applications of the Herschel HPTDG lie completely within the FD domain, being part of an established process of validation of the operational software.

One important example is the validation of the FD software for gyro calibration [8].

On Herschel, gyros are used for rate measurement during nominal control in SAM, OCM and SCM. Coarse rate sensors are used instead as input to the ARAD functionality and during survival mode.

The four gyros are mounted in tetrahedral configuration; a selectable set of three of them is used for control while the fourth one serves to detect inconsistencies in the output of the others.

The FD gyro calibration software processes TM data from the S/C, using at the same time gyro and STR information, to perform the calibration of the gyros by estimating their biases, their scale factor and their misalignments. In order to verify the correctness of the algorithm in the software, it was very important to use the Herschel HPTDG as an end to end test tool.

Thanks to the high-precision modelling of the sensors, including the gyros, it has been possible to individually introduce all the parameters which needed to be estimated, by giving them realistic values in accordance with the gyro manufacturer specification, analytical performance analysis and test. After that, ad-hoc simulations were run and TM was generated as an input to the FD gyro calibration software.

The computed calibrations parameter were then up linked to the emulator verifying, when possible, the correctness of the computation by looking at the S/C ACMS telemetry. In other cases the injected quantities were afterwards compared with the calibration results.

The process, just described, not only allowed operational software validation but also gave realistic figures on how accurate the calibration results could be under realistic sensor output conditions, as expected in flight.

Table 5 Comparison of gyro calibration results against HPTDG simulated data

Gyro unit	Gyro drift [deg/hr]		Gyro scale factor error		Alignment of gyro frame wrt. S/C frame	
	HPTDG	Gyro cal. s/w	HPTDG	Gyro cal s/w	HPTDG	Gyro cal. s/w
GYR-1	0.165012	0.1650092	0.001	0.0009992	-0.576573716 -0.575153381 0.580311415	-0.5766342 -0.57510046 0.580303755
GYR-2	0.165012	0.1648690	0.001	0.0009892	0.578155921 -0.57189656 0.581953654	0.578108495 -0.57194825 0.581949965
GYR-3	0.165012	0.1653410	0.001	0.0010118	0.579811461 -0.578525082 -0.57369626	0.579765613 -0.57856878 -0.57369852
GYR-4	0.165012	0.1650186	0.001	0.0010017	-0.574227364 -0.584135099 -0.573628033	-0.57427597 -0.58408560 -0.57362976

Gyro drift is estimated autonomously on-board but only at S/C axes level. On-ground based estimation for each individual unit provides a better starting point for the on-board algorithm. Collection of gyro data must be performed over a period of stable pointing (typically in SCM) for at least 10 minutes. Any observed rate in the gyro measurements can then be attributed to a rate drift.

The gyro rate drift is computed for each gyro as:

$$D = \frac{G_{lsb} \cdot GYRACC}{t_{end} - t_{start}} \quad (6)$$

where:

- G_{lsb} is the gyro measurement LSB in [rad]
- $GYRACC$ is the accumulation value over the interval from [t_{start}, t_{end}]
- t_{start}, t_{end} are respectively the gyro accumulation start and end time [s]
- D is the rate drift in [rad/s]

Gyro scale factor and misalignment calibration requires instead a sequence of attitude manoeuvres (slews) to be performed around each S/C axes (2 pure pitch (40°), 2 pure roll (5°) and 2 pure yaw (40°)).
For each gyro a least square estimation algorithm is applied to determine the gyro parameters using the gyro accumulated angles and the slew amplitudes computed from the STR start and end attitudes.
First the 6x1 vector of the gyro accumulated angle during 6 individual calibration slews $\Delta\gamma$ is compensated for the drift estimated prior to the slew as follows:

$$\Delta\gamma = G_{lsb} \cdot GYRACC - D \cdot \left(t_{start} - t_{end}\right) \quad (7)$$

where $\Delta\gamma$ is the accumulated gyro output over a calibration slew corrected for the drift [rad].
A 6x1 observation vector f [rad] can be computed from the 6 calibration slews as follows:

$$f = \Delta\gamma \cdot S - \Delta\phi \cos\delta \cos\alpha - \Delta\theta \cos\delta \sin\alpha - \Delta\psi \sin\delta \quad (8)$$

where:

- S is the scale factor
- α and δ are the polar coordinates of the gyro axis in the S/C frame [rad]
- $\Delta\phi$, $\Delta\theta$ and $\Delta\psi$ are each 6x1 vectors of the actual slew amplitudes [rad]

The partial derivatives with respect to the three scalar parameters S, δ and α can be then computed analytically:

$$\frac{\partial f}{\partial S} = \Delta\gamma \quad (9)$$

$$\frac{\partial f}{\partial \delta} = \Delta\phi \sin\delta \cos\alpha + \Delta\theta \sin\delta \sin\alpha - \Delta\psi \cos\delta \quad (10)$$

$$\frac{\partial f}{\partial \alpha} = \Delta\phi \cos\delta \sin\alpha - \Delta\theta \cos\delta \cos\alpha \quad (11)$$

and a 6x3 matrix is built

$$A = \left[\frac{\partial f}{\partial S} \quad \frac{\partial f}{\partial \delta} \quad \frac{\partial f}{\partial \alpha}\right] \quad (12)$$

Vector f and matrix A are then evaluated using the nominal parameter set for $\overline{S}$, $\overline{\delta}$ and $\overline{\alpha}$. By performing a Taylor series expansion truncated to the first order the following equation holds:

$$f\big|_{S=\bar{S},\delta=\bar{\delta},\alpha=\bar{\alpha}} = -A\big|_{S=\bar{S},\delta=\bar{\delta},\alpha=\bar{\alpha}} \cdot \begin{bmatrix} \Delta S \\ \Delta \delta \\ \Delta \alpha \end{bmatrix} \tag{13}$$

The 3x1 vector of the correction terms representing the calibration results $[\Delta S \quad \Delta\delta \quad \Delta\alpha]^T$ is then computed by solving in the least-square sense the over-determined linear equation system of Eq. 13. A summary of the comparison between HPTDG simulated data and gyro calibration results is shown in Table 5.

4.5 HPTDG use for operational commands validation

Herschel FD supports the ground segment with the following main activities:

- ACMS monitoring and improved attitude reconstruction
- generation of mission planning products (ACMS command parameters)
- orbit determination and prediction
- trajectory and orbit manoeuvre optimization and evaluation
- fuel book-keeping
- ACMS calibrations

FD generates mission planning products covering a time-span of one Operational Day (OD), whose nominal duration is about 24 hrs, but can be longer or shorter depending on the start time of an OD. The latter is defined to be the start time of the Daily Telecommunication Period (DTCP), i.e. the allocated ground station coverage period.

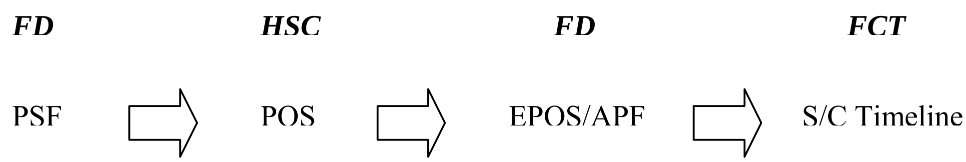

Fig. 3. Mission planning products flow chart

Taking the orbit events files from the concurring missions and taking into account planned ground station/segment outages (e.g. for maintenance), the ESOC scheduling office produces the ground station schedule which defines the times of the DTCPs for Herschel.
As illustrated in Fig. 3, for each OD, FD prepares a Planning Skeleton File (PSF) containing ground stations coverage intervals, spacecraft operations and scientific observation windows.
The PSF is then sent to the Herschel Science Centre (HSC) which generates a Preferred Observation Sequence (POS), an expanded version of the PSF covering the same period; all the original entries present in the PSF are echoed in the POS. The POS additionally contains the pointings to be scheduled for a given OD within the scientific observation windows, including target inertial pointing directions and associated instrument parameters.
FD processes the POS to produce an Enhanced POS (EPOS) and an associated Attitude Parameter File (APF). The EPOS is an expanded version of the previous POS containing additional Event Designators (ED) to support e.g. slew manoeuvres for scientific pointings, perform RW biasing or ΔV manoeuvres. The data associated with each ED are contained in the APF. The pairs of EPOS, APF files are sent to the Flight Control Team which uses them to generate the final sequence of commands up-linked to the S/C, the so-called timeline.

The TVA team checks the MPS products before they are sent out by the FD by running:

- dedicated test tools for format and constraint violation checking
- a HPTDG simulation, in order to verify that the whole sequence of commands is correctly executed and performs as expected by MPS in terms of pointing, constraint violations avoidance and S/C additional operations such as RW biases or ΔV manoeuvres.

An initialization script is used to set-up the FD simulator with the proper starting epoch and mass properties and to load the APF onto the HPTDG command stack. The simulation is then run and the following output products are then examined:

- Attitude profile, which is compared to that predicted by MPS.
- RW profile, to confirm the correct execution of any commanded RW bias and to check that the values of their speeds evolve within the allowed margins. RW speeds should not exceed a maximum limit and should not stay during stable pointings close to zero (stiction zone avoidance).

Special cases are those ODs where ΔV manoeuvres are planned. In this case the HPTDG run allows TVA to verify the correctness of the command implemented by MPS by comparing the simulated ΔV direction and magnitude with that requested by the Manoeuvre Optimization Subsystem. The simulation provides as well an estimate of the fuel consumption and of the manoeuvre duration.

4.6 Conclusions and future applications

The Herschel HPTDG has demonstrated to be a very useful emulation tool for ESOC FD in all the different phases of the mission, during launch preparation, LEOP and routine operations. It has shown a high degree of flexibility thanks to the fact that it has been possible to implement in a relative short time additional capabilities, not foreseen at the beginning of the project.
Its usage as effective analysis tool to perform independent validation of required on-board software modifications has also been shown.
With Herschel having successfully reached its operational orbit around L2, the test and validation group will continue to use the HPTDG for operational command validation and, if needed, for analysis of different operational scenarios and for ACMS S/C anomalies troubleshooting.

5. REFERENCES

[1] Tucci L., Keil J., Companys V., *Precise Command Emulation for ESA Interplanetary Missions*, 18th International Symposium on Space Flight Dynamics, Munich, Germany, 2004

[2] Tucci L., Pessina S.M., Flegel M., Kasten-Coors M., *GOCE Precise Emulator for ESOC Flight Dynamics Operations Preparation*, 2007 AAS/AIAA Astrodynamics Specialist Conference, Mackinac Island, Michigan, USA, 2007

[3] Pessina S.M., Tucci L., Kasten-Coors S., *ESOC Flight Dynamics Precise Emulators for the CryoSat, Herschel and Planck Missions: Development and Applications*, 25th International Symposium on Space Technology and Science, Kanazawa, Japan, 2006

[4] Guichon D., Palomba M., *Herschel Fuel Consumption Tiger Team Final Report*, H-P-2-ASP-RP-1765, Issue 1.0, ThalesAlenia Space, 2009

[5] Herschel ACMS Team, *Test Report Herschel HAIVT Fuel Issues Test*, H-P-4-DS-TR-248, Issue 1.0, Dutch Space B.V., 2009

[6] Herschel/Planck Team, *Herschel/Planck System Budget Report*, H-P-1-ASPI-BT-0264, Issue 11.0, ThalesAlenia Space, 2009

[7] Bos J.F.T., *ACC ASW Requirements Specification*, H-P-4-DS-SP-018, Issue 5.1, Dutch Space B.V., 2009

[8] Tuttlebee M., *ACMS Units Calibration*, PT-CMOC-FD-SSD-2205-OPS-GFT, Issue 1.0, ESA OPS-GFT, 2006