Challenges of Modelling Drag Free Attitude Control System, DFACS, in Operational Simulators

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ABSTRACT

In operational spacecraft simulators, the modelling of scientific payload instruments is very often limited to their resource usage and their physical/electrical behaviour. The Generation of realistic scientific data of these instruments is in contrary usually not in the scope of these simulators. A new family of scientific missions of the European Space Agency, ESA, such as the Lisa Pathfinder and the GOCE missions, incorporate however sophisticated gravitational measurement instruments. These instruments are integrated in the Drag Free Attitude Control System, DFACS, of the satellite and participate with their scientific data in the closed loop attitude control of the spacecraft. Modelling these instruments introduces therefore new challenges and breaks the traditional borders between the platform and payload modelling in operational simulator development.

NOMENCLATURE

CDMU = Command and Data Management Unit
ESA = European Space Agency
DFACS = Drag Free Attitude Control System
DMU = Data Management Unit
FEEP = Field Emission Electric Propulsion
LISA = Laser Interferometer Space Antenna
L1 = Lagrange Point 1
MCS = Mission Control System
MPS = Micro Propulsion System
OBSW = Onboard Software
SMART = Small Missions for Advanced Research in Technology
TM = Test Mass

INTRODUCTION

Through out the life cycle of a space mission a number of simulators are developed almost independently. Each of these simulators addresses specific aspects of the mission and implements a dedicated set of requirements. Despite an obvious overlap of some functionality among these simulators, the differences in the requirements and objectives of each simulator cause today their almost independent development. The ongoing attempts towards optimising the reuse of functionality and in particular the exchange of simulation models across different simulator platforms address this issue. The operational spacecraft simulator is the most comprehensive software-based simulator built during a space mission, involving elements of both the space and the ground segments and provides the required interfaces to the rest of ground data systems such as the mission control system and the ground station equipments. Being designed to provide realistic telemetry to the operations teams, it runs the actual flight software emulated processors.

It usually includes detailed software models for all spacecraft subsystems such as

- The Electrical Power System
- The Thermal Control System
- The Communication System
- The Propulsion System
- The Command and Data Management Unit, including the onboard computer and the onboard software.
- The payload, such as scientific instruments (cameras, spectrometers, gravitational instruments, etc)
- The Attitude and Orbit Control Subsystem

The main objectives of an operational simulator are the following:

- Training of the Flight Control Team
- Preparation and validation of the Flight Operation Procedures

- Usage in the validation of the complete ground data systems chain, including the Mission Control System (MCS) and the ground station equipment
- Provision of a realistic reference of the flying spacecraft after launch for validation of new procedures and investigation of problems
- Simulation and training related to the contingency recovery procedures
- Testing of emulated flight software uploads

The details of the requirements, design and development of an operational simulator are exhaustive and not in the scope of the present paper. As a general rule, the modelling of the scientific payload instruments in operational spacecraft simulators is however kept simple and limited to provision of simplified functional models, which fulfil the above objectives. These models simulate very often only the basic housekeeping telemetry generation, the instrument mode transitions and the accurate usage of satellite resources. It is in general not necessary to simulate the generation of realistic scientific output of the payload instruments and in some cases, it is not necessary to simulatate the data at all. If modelling of science data packets is required it is therefore usually limited to generation of dummy packets with the correct packet and data size. The actual content of these science packets are very often filled with arbitrary data. The simulation of the scientific results of the operations of the payload instruments is covered by other dedicated payload simulators.

Some scientific missions of the European Space Agency, ESA, such as the Lisa Pathfinder and the GOCE missions incorporate however a new family of sophisticated payload instruments for gravitational measurements. These scientific instruments comprise test masses, complex caging mechanisms as well as internal sensors and actuators. They have also very often their own data handling units with dedicated OBSW. These instruments are moreover integrated in the so called Drag Free Attitude Control System, DEFACS, of the satellite and participate with their scientific data in the closed loop attitude control of the spacecraft.

The present paper will discuss the issues related to the modelling of this category of payloads in more detail and will discuss the new challenges and the difficulties raised from crossing the traditional payload-platform modelling requirements.

LISA PATHFINDER MISSION

The LISA Pathfinder mission, formally known as SMART-2, is the second of the ESA *Small Missions for Advanced Research in Technology.* LISA Pathfinder is a dedicated technology demonstration mission for the future joint ESA/NASA cornerstone mission LISA (Laser Interferometer Space Antenna). The primary scientific objective of the LISA mission will be to detect and observe low frequency gravitational waves from most energetic astronomical sources. The LISA mission will consist of three spacecrafts flying in a triangular formation with an arm length of 5 million kilometres. The three spacecrafts will orbit the Sun as shown in Figure 1-b and act as an interferometer.

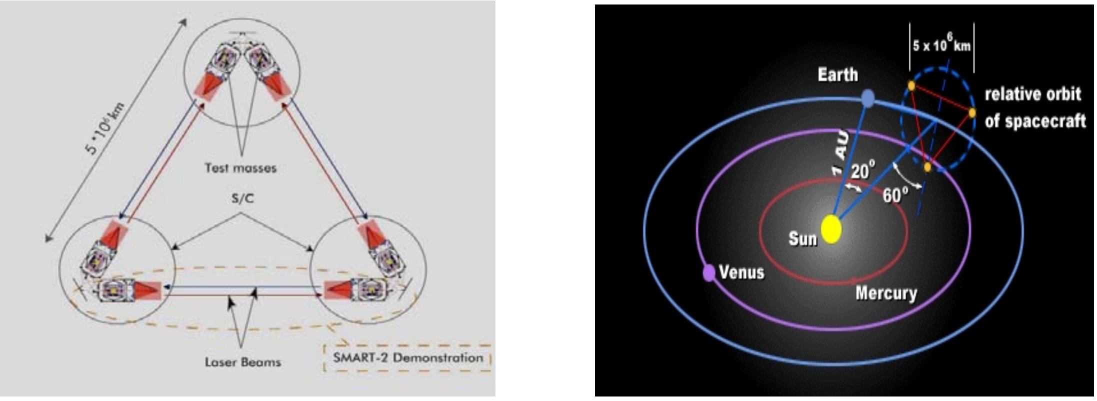

Figure 1 (Left a, Right b) LISA Mission Orbit [1]

The ambitious LISA mission relies however on a number of challenging new technologies, which have not yet been used in any previous space mission. The objective of the LISA Pathfinder mission is therefore to provide in-orbit testing and validation of these critical technologies. The three most challenging new technologies to be demonstrated and validated by the Lisa Pathfinder in this context are the following:

- The Drag-Free Attitude Control System, DFACS, of the spacecraft
- The inertial sensing and high precision Laser interferometry technology

- The micro propulsion technologies

The LISA Pathfinder mission has two scientific payloads: the LISA Test Package, LTP, and the NASA Disturbance Reduction System, DRS. Both payload systems were initially intended to provide similar functionality of optical interferometry and composed of the same group of subsystems, namely Inertial Sensors, Optical Benches for Laser interferometry and Electronic Assemblies. The DRS system now however incorporated only a controller and its own dedicated micro propulsion thrusters, making use of data from the LTP test masses.

The LTP at the other side houses two reference test masses. The basic idea behind the LTP is to squeeze one LISA arm from five million kilometres to a few centimetres as shown in Figure 1-a. The laser interferometer is then used to measure the relative movement of these two nominally free flying test masses. The major performance challenge for the Lisa Pathfinder mission is hereby to establish a disturbance free environment for these free flying test masses. The performance goal of the LISA Pathfinder is therefore to verify that a test mass can be put in pure gravitational free-fall within one order of magnitude from the requirement for LISA, i.e. achieving an acceleration measurement accuracy in the order of 10^{-14} m/s^2 (in the 1mHz and 30mHz bandwidth), as defined by the following function:

$$S_a^{1/2}(f) \leq 3\times10^{-14}\left[1+\left(\frac{f}{3mHz}\right)^2\right]\frac{m}{s^2}\frac{1}{\sqrt{Hz}} \quad \text{for } 1\text{mHz} \leq f \leq 30\text{mHz} \quad (1)$$

This performance requirement is very demanding and implies a strict control of all noise and perturbation sources, in order to keep the differential test mass acceleration in the required range. In order to minimise the effects of planetary gravitational, magnetic and electric fields, the LISA PF target orbit is a Lissajous orbit around the L1 Earth-Sun Lagrange point as shown in Figure 2.

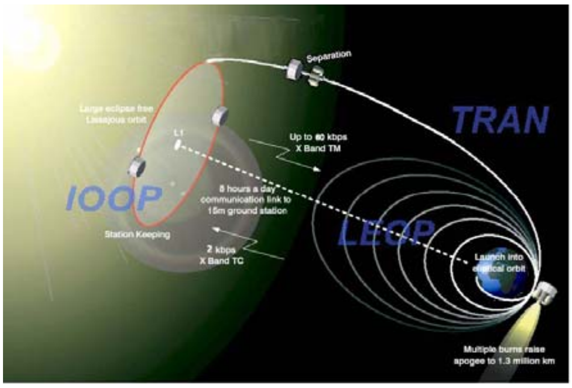

Figure 2 Lisa Pathfinder Mission Orbit [1]

Drag-Free Attitude Control System, DFACS

The drag-free attitude control system of the satellite is responsible for shielding the test masses from the influence of the external disturbances, allowing them to fly in a purely gravitational trajectory. The main sources of disturbance are the solar radiation pressure, internal and external gravity forces, the FEEP force noise as well as magnetic and electrostatic fields. The trajectory of the spacecraft itself is however still affected by all these perturbation forces, so that the relative position of the spacecraft and the test mass would diverge gradually and the test mass would hit its cage eventually, as shown in Figure 3-a.

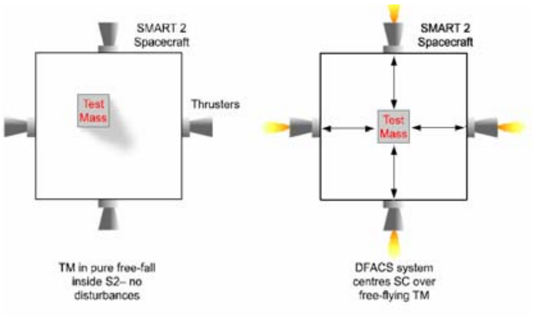

Figure 3 (left a, right b) DFACS Keeps the Test Mass at the Centre of the Spacecraft [1]

In the DFACS mode, the position of the test mass relative to the spacecraft is continuously measured, using the inertial sensors, integrated in the payload. The closed loop drag-free attitude control system, which is implemented in the spacecraft OBSW and runs in the CDMU of the spacecraft calculates the required forces/torques to compensate the disturbance forces and tries to re-centre the free flying test mass, using the micro propulsion thrusters, as shown in Figure 3-b.

Dealing with two test masses, it is however not possible for the spacecraft to follow both free-flying test masses at the same time as shown in Figure 4-a. The payload incorporates for this reason an electro static actuation subsystem which is used to maintain the relative position of the suspended test mass to the drag-free flying test mass and the spacecraft attitude. In order to achieve this suspension, the relative (differential) acceleration of the two test masses is measured continuously inside the payload, using the response from the electrostatic suspension system and, as alternative, a more accurate laser interferometry optical bench. This information is then passed to the drag-free attitude control system of the spacecraft, which will calculate the required forces to compensate the differential acceleration and will send corresponding directive commands to the payload actuators, in order to close the control loop.

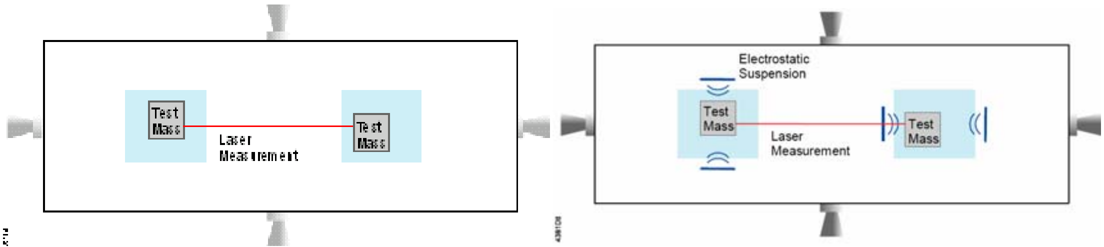

Figure 4 DEFACS with Two Test Masses [1]

Another important factor, which increases the complexity of the system, is the fact that some of the disturbing forces which act on the test masses are not simple constant forces, but highly dependent on the position of the test mass with respect to the centre of mass of the spacecraft. There are in fact 15 degrees of freedom to control, position and attitude of Test Mass 1, Test Mass 2 and the spacecraft attitude. The influence of internal gravitational forces which express the coupling of the test mass and the spacecraft is called ‘stiffness’.

Challenges of modelling DFACS in the Operational Simulator

As it was mentioned in the introduction of this paper, the modelling of the payload instruments in the context of the operational simulator development is traditionally kept simple and mainly limited to the house-keeping telemetry generation and payload-platform interface modelling. The subsystems of the platform must in contrary be modelled in much more detail, in order to achieve the above defined objectives of the operational spacecraft simulator. For missions such as the LISA Pathfinder and GOCE which incorporate a drag-free attitude control system, it is however difficult to draw the separation line between the platform and the payload.

The above described gravitational measurement payload instruments represent complex systems, which comprise themselves sophisticated sensor and actuator subsystems as well as their dedicated data management units. These payload systems participate in the real-time drag-free attitude control loop of the spacecraft, by providing their internal scientific measurements as an input to the DFACS controller and processing the instructions created by the controller to command their internal actuator subsystems.

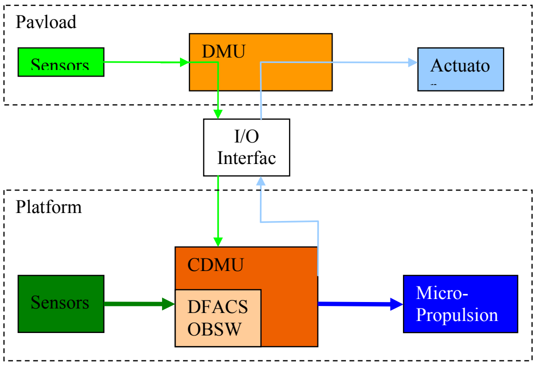

Figure 5 DFACS control loop involving the payload subsystems

As it can easily be observed in Figure 5 it is necessary to model a subset of the internal behaviour of the payload instrument in the scope of the DFACS simulation and to simulate the measurement results, i.e. position, attitude and acceleration of the test masses. The extent of this modelling shall however be restricted to the generation of only the payload data used in the platform software, particularly the part required for the successful execution of the drag-free attitude control application of the on-board software. It should be noted at this place that the operational spacecraft simulator runs the flight image of the on-board software, utilising exactly the same hardware/software interfaces as the real spacecraft. It is also worth mentioning that for purpose of the simulation and verification of the scientific results of the payload operations a dedicated DFACS simulator has been developed by the industrial prime, independently from the subject operational simulator.

It should be noted that the development of the LISA Pathfinder operational simulator was kicked off in October 2007. A gradually step by step development of the simulator is planned, starting with the more nominal operational simulator systems, and developing the subset of payload data required for closed loop control when the rest of the models have been validated and tested.

GOCE Mission

The ESA Gravity field and steady-state Ocean Circulation Explorer mission, GOCE, has been developed to achieve a new level of understanding of the Earth's gravity field. The scientific payload instrument of the GOCE mission is a three-axis electrostatic gravity gradiometer that measures gravity gradients in all spatial directions for the first time. The measured signal is the difference in gravitational acceleration at the test-mass location inside the spacecraft caused by gravity anomalies from attracting masses of the Earth. By performing these differential measurements for all three spatial axes, all disturbing forces acting uniformly on the spacecraft such as the drag and the thruster torques resulting in linear or angular accelerations can be compensated. The payload of the GOCE mission is built on the same principles as the LISA Pathfinder. The only major difference is that GOCE has a total of 6 test masses deployed in a star configuration as illustrated in Figure 6, hence able to measure the gravity gradient along all access.

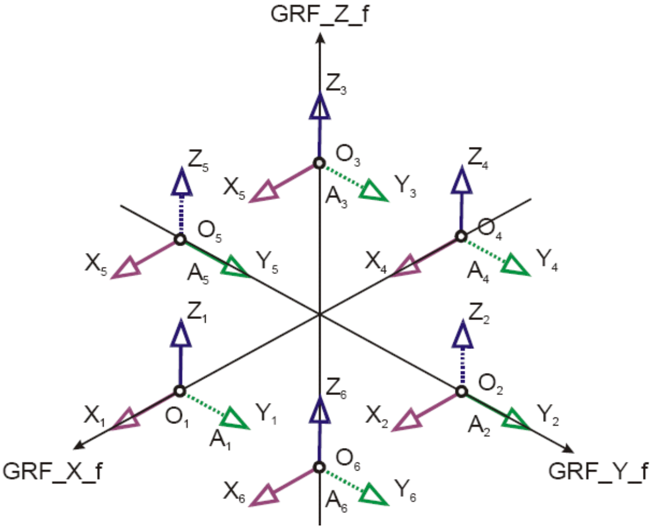

Figure 6 Configuration of the Test Masses in GOCE

This is required for GOCE since the mission aims at reconstructing a very accurate gravity field model of the Earth gravity field. Taking this into account, it is clear that the models of the GOCE payload and the LISA Pathfinder have quite different scientific aims, however the mathematical models required in operational simulators to model these payload are surprisingly similar.

Modelling the Gravitational Payload Instruments

It has been explained in the previous sections that the main difficulty in modelling the gravitational measurement payload instruments is related to the modelling of the position response of the free-flying test masses with respect to the actuation forces (electrostatic actuators and spacecraft micropropulsion thrusters), which is required as an input to the DFACS loop. For the LISA Pathfinder operational simulator the accuracy requirement is to provide an accuracy of 20nm for the mass position and 2000 nrad for the attitude angle.

Assuming the case that one of the test masses (TM2) is suspended to other free flying test mass (TM1), the science measurement equation (gravitation gradient) can be derived from the following linearised equation of motion of the two test masses

$$\begin{aligned} & r_{o1}\dot{\omega} + \ddot{r}_1 = f_1 - f_B \\ & r_{o2}\dot{\omega} + \ddot{r}_2 = f_2 - f_B \;\Rightarrow\; \left(r_{o1} - r_{o1}\right)\dot{\omega} + (\ddot{r}_2 - \ddot{r}_1) = f_2 - f_1 \end{aligned} \quad (2)$$

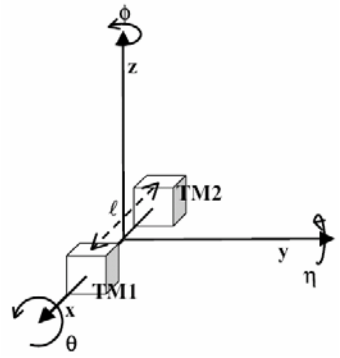

Figure 7 Coordinate Definition [2]

In equation (2) r_{Oi} is the position of the test mass *i* with respect to the centre of the coordinate system and the f_i is the force normilised to the mass. The forces on the test masses, i.e. f_1 and f_2 can be split in two main components. One component is related to the above described "stiffness", i.e. cross-coupling between the test masses and the spacecraft. The major contributors to this component are the internal spacecraft gravity and the spacecraft magnetic and thermal disturbance forces, which are influencing the test masses. The second component is related to the gravity field gradient *U*. We recall at this place that measurement of the differential acceleration of the two test masses, which corresponds to the second component, is the actual scientific objective of this type of missions. Equation (2) can be extended accordingly to

$$\left(r_{o2}-r_{o1}\right)\dot{\omega}+(\ddot{r}_2-\ddot{r}_1)=\Delta f_{stiff}+\Delta f_{science}= func(\Omega, r_{s/c}, \dot{r}_{s/c}, \ddot{r}_{s/c}, d_{mag}, d_{sg})+func(U) \quad (3)$$

where the first component Δf_{stiff} is a function of the spacecraft angular and linear velocity. It also comprises the magnetic and self-gravitational disturbance forces d_{mag} and d_{sg}. The second component is a pure function of the gravity field gradient. The modelling of the payload involves accordingly the following aspects:

- The described equation of motion of the spacecraft and its test masses can be modelled in the payload simulation model
- The angular and linear velocities of the spacecraft are known from the generic satellite dynamic modelling
- The stiffness forces can be incorporated as configurable noise functions in the model
- The gravity field gradient U can be calculated as a first order approximation from the spacecraft orbit position. A variable component can also be forced as a stimuli to the model.

In a more simplified approach the U component is neglected and the same gravity force is assumed to apply on both test masses regardless of their relative position. A noise function must however be added in this case to simulate the actual difference of this component.

Taking this modelling approach for one axis as required, for LISA Pathfinder, the same principle is applied to the each of the 6 test masses of GOCE. For each head, the relative acceleration with respect to the Spacecraft Centre of Mass is calculated. This principle is possible since the payload reports the total of 18 (3 axes * 6 masses) linear accelerations back to the OBSW, hence a very simple interface. Internal modelling of the control loops required to position the test masses are not modelled since this aspect is completely encapsulated inside the payload internal behaviour.

Results from the GOCE mission

The GOCE Operational Simulator development has now been completed and the simulator has undergone extensive testing as part of the GOCE prelaunch simulation campaign and other tests. Based on the results from these tests it has been demonstrated that the modelling principles as outlined in this paper have been successfully implemented in the GOCE Operational Simulator. The Operational Simulator is capable of maintaining drag free environment for the EGG payload and the spacecraft dynamics is regulated to a level where all the platform checks for a good science observation period pass. Obviously the science data reported from the Spacecraft have no scientific interest and can neither be used for DFACS validation nor for testing the science TM processing facilities; however this was as well not the aim of the simulator. Furthermore the current implementation of the DFACS system on GOCE does result in a minor bias on the orbit maintenance aspects of the DFACS. Once again it is important to remember that the aim of the GOCE operational simulator where not to validate the DFACS software, hence such a bias is fully acceptable for the purpose of the simulator. The DFACS implementation has in fact proven to be sufficient for all the foreseen use cases of the Operational Simulator and have served as a good tool for validation of all operational procedures including the once dedicated on the DFACS system.

Conclusion

Modelling the drag-free attitude control system and the corresponding gravitational measurement payload instruments introduce new challenges in the domain of operational spacecraft simulation development. The first implementation of these systems in the ESA scientific missions GOCE and the LISA Pathfinder has however shown that although the overall system may look complicated at the first glance, simple models based on rigid body mechanics are sufficient for what are the needs of the operational simulator. The needs of the operational simulator in this regard are that the OBSW is stable and continues to function correctly with the provided stimuli and commanded actuations. Furthermore it shows that as long as good mathematical model descriptions exist in the available spacecraft documentation, such payloads does not imply major issues within operational simulators.

The GOCE operational simulator has successfully implemented, verified and integrated the above described DFACS models. Following the same approach the development of DFACS models for the operational simulator of the LISA Pathfinder is an achievable goal, although still presenting a challenge for the future, which requires a systematic approach, and close cooperation between teams.

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