FLIGHT DYNAMICS OPERATIONS DURING SMART-1 COMMISSIONING

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ABSTRACT

SMART-1, the first of ESA's Small Missions for Advanced Research in Technology, was launched late in September 2003. A number of anomalies, which affected Flight Dynamics operations, were finally mostly overcome by improvements to the onboard software.

After LEOP, routine tasks performed by Flight Dynamics (FD) in a weekly cycle included the generation of attitude and EP thrust profiles and calibration of the Attitude Rate Sensor biases. Telemetry related to the Attitude and Orbit Control system was monitored regularly.

When SMART-1 finally had escaped the radiation belts, the payload commissioning phase started. This required from FD great flexibility in providing special pointings.

Reaction wheel offloadings using the hydrazine thrusters were commanded during phases without EP thrust, before eclipses and in regular intervals since July 2004. Each offloading was postprocessed to estimate the effect on the orbit and the hydrazine consumption.

The following paper describes the experiences and observations made by FD during the commissioning phase.

1. DESCRIPTION OF THE MISSION AND THE SPACECRAFT

SMART-1 is the first of ESA's Small Missions for Advanced Research in Technology and also the first ESA mission to the moon. Its objectives include testing new technologies, in particular the use of Electric Propulsion (EP), for interplanetary missions and investigating the chemical composition of the lunar surface.

SMART-1 is a three-axis stabilised spacecraft that can follow arbitrary attitude profiles defined by telecommand (TC). Its main attitude sensors are two cold redundant star trackers (ST) that share two hot redundant camera head units (CHU). In addition three Sun Sensors and five Attitude Rate Sensors (ARS) are used for sun acquisition; the latter are also used to bridge short periods in which no attitude information is available from the STs.

Reaction Wheels (RW) (3 nominal + 1 redundant) are used as attitude actuators, four 1 N hydrazine thrusters for detumbling (after separation and in case of contingencies) and for RW offloading. The main propulsion system consists of a Hall effect EP engine, which is gimballed for compensation of the misalignment of the thrusters with respect to the centre of mass and for control of angular momentum.

For communications the spacecraft has two Low Gain Antennas (LGA) mounted on opposite sides to give omnidirectional coverage, and a Medium Gain Antenna (MGA). Electric power is generated by GaAs cells mounted two Solar Array wings. In addition payload instruments for imaging, spectroscopy, plasma measurements and communications experiments are mounted to the platform.

2. MISSION PHASES

The main phases of the SMART-1 mission are

- the Launch and Early Orbit Phase (LEOP) with initial spacecraft acquisition and the checkout of platform subsystems,
- the Earth escape phase, in which the EP is used to raise the orbit,
- the lunar capture phase, in which the orbit around the Moon is reached and subsequently lowered,
- the operational lunar orbit.

3. FLIGHT DYNAMICS OPERATIONS DURING LEOP

SMART-1 was launched on Spetember 27th 2003 by an Ariane 5 launcher into a standard Geostationary Transfer Orbit. The autonomous separation sequence, which performed nominally, left the spacecraft in safe mode with the solar arrays deployed, rotating around the sun direction with 1 revolution per hour. After that, ground took over control of the spacecraft in order to check out the platform subsystems and instruments to prepare the spacecraft for the start of the EP.

The main tasks of Flight Dynamics (FD) during this phase were:

- repeated orbit determinations,

- continuous monitoring of the checkout, in particular of the Attitude and Orbit Control (AOCS) and the EP subsystems,
- prediction of LGA switching times,
- transitions from Safe mode to Science mode,
- calibration of the CHU coalignment by comparing the attitude quaternions delivered by the two CHUs,
- calibration of the ARS biases by comparing the angular rates measured by the rate sensors to the rates derived from star tracker measurements.

Each transition from Safe to Science mode required calculating the right time for stopping the rotation around the z axis and generating a slew to the operational attitude. Since the attitude in which the rotation was stopped was not known in advance, the generation of the slew could only be started after the rotation had stopped.

Already during LEOP some major anomalies were observed, which could be traced back to software errors in the controller and the ST. They caused several reboots of the controller, which, if happening in Science mode, meant that the above-mentioned procedure had to be repeated each time. These anomaly made it necessary to develop, test and uplink the first updates to the onboard software during the first few days after launch.

4. EP OPERATIONS

After LEOP, the EP system was switched on in order to escape the Earth's radiation belts as soon as possible. For this reason the aim was to maximise the EP uptime. The plan was to thrust along the velocity direction continuously except during eclipses, until a perigee height of 20 000 km was reached. This was compromised due to a number of anomalies, in particular during a large solar eruption in October/November 2003:

- Radiation-induced Optocoupler Single Event Transients (OSET) caused the EP to shut down itself unexpectedly.
- Radiation-induced fluctuations in an EP telemetry parameter were wrongly interpreted as errors by the Failure Detection, Isolation and Recovery (FDIR) software and lead to a shutdown of the EP.
- Reboots of the controller led to transitions to Safe mode.
- The radiation dose received by the CHUs, in combination with higher than expected CHU temperatures, created a large number of hot spots which affected the capability of the star tracker to generate valid attitude data. In several cases when both CHUs did not deliver a valid attitude for an extended period, the FDIR shut down the EP due to the large offpointing accumulated or even caused a transition to Safe mode.

Each of these anomalies interrupted the EP thrust, changed the orbit and invalidated the attitude and EP commands, which then had to be regenerated and uplinked. In case of a Safe mode, the procedure for the transition to Science mode described in section 3 had to be repeated.

Due to limited resources it was not possible to monitor the spacecraft continuously after LEOP. This meant that the detection and recovery from an anomaly was often delayed. In one extreme case, when an anomaly happened on Friday evening, the spacecraft could not be acquired at its predicted position on Monday morning. Only when tracking data from unmanned ground station passes during the weekend had been evaluated was it possible to find the spacecraft.

Most of these problems were finally overcome by changes to the onboard software:

- For the OSETs, a patch to the controller software to restart the EP after a cooling period of 30 minutes was developed.
- A filtering capability was added to the FDIR software to resolve the issue of the TM fluctuations.
- The controller reboots ceased to occur after SMART-1 had left the radiation belts.
- The software of the star tracker was modified to improve its ability to distinguish between real stars and hot spots.

With these improvements the EP system was working quite well. Since the degradation of the solar arrays during the radiation belt escape was smaller than predicted, the thrusters could be operated at a higher specific impulse. This, in combination with the effect of a favourable launch date, made it possible to reduce the duration of the earth escape phase and to reach a lunar orbit more favourable for observations than planned.

5. ROUTINE OPERATIONS AFTER LEOP

Since the end of the LEOP, routine operations have been performed in a weekly cycle. Based on the latest orbit determination, new optimised thrust and attitude profiles were calculated, and the corresponding command sequences were prepared for uplink. Auxiliary data, like ASCII orbit and attitude files and eventfiles containing the times of important events (e.g. ground station visibility, LGA switching times, EP on/off, RW offloadings, eclipses) were generated and provided to users outside the Flight Dynamics Division. Predictions of the times when either of the star tracker CHUs was blinded by the Earth or the Moon and could therefore not be expected to deliver valid attitude data were obtained from the orbit and the attitude profile.

A calibration of the ARSs was also performed weekly to compensate for the drift of the biases. This drift was found to be within the expected range.

The EP gimbal mechanism used to control the angular momentum was working as expected, so that no reaction wheel offloadings with the hydrazine subsystem were necessary during the first 6 months of the mission as long as the EP was used regularly. Nevertheless, during the eclipse period in March an offloading was commanded before each eclipse. This was done to avoid possible autonomous offloadings during the eclipses, which would have consumed electric power for the heating of the thrusters' catalyst beds.

After each offloading (commanded or autonomous) the hydrazine consumption was calculated from telemetry data. For accurate orbit determination, the delta-v caused by the offloading was calculated from the change of angular momentum, taking into account the known geometry of the hydrazine thrusters. This gave rather accurate values.

The Xenon consumption of the EP was calculated at first after each thrust arc, later also once a week.

Telemetry was also monitored by FD regularly, especially parameters related to the AOCS subsystem like attitude, attitude error, RW levels and star tracker performance. Any anomalies detected were immediately reported to the Flight Control Team to enable them to take measures. Such anomalies detected by FD include a case when the synchronisation between star tracker and spacecraft clocks was lost, and a case when one CHU was switched off by a latchup event. In both cases the anomaly could be resolved by power cycling the star tracker or the affected CHU, respectively.

6. OPERATIONS DURING PAYLOAD COMMISSIONING

In order to start the EP as soon as possible, only the plasma diagnostic instruments were commissioned during LEOP. The commissioning of the other payload instruments began early in January, when SMART-1 had escaped the radiation belts and the EP was used only around the perigee passages.

During the first three weeks of February the EP was completely switched off in order to reduce the durations of the eclipses later in March. This mission phase was utilised extensively for commissioning activities requiring special pointings that would have been incompatible with EP thrust attitude.

The attitude profiles and commands for these special pointings were generated weekly by FD based on the pointing requirements provided by the Science and Technology Coordination Centre (STOC). They included pointings of several different instruments to inertial targets, to ground stations or other points on the earth, or to the moon, both as fixed pointings and as scans with specific rates. Using a combination of FORTRAN library routines and binaries for speed and computer algebra systems for flexibility, the SMART-1 FD telecommand subsystem was able to provide an extensive pointing support for the SMART-1 commissioning and cruise phase.

All pointing profiles were prepared in advance, and a special tool was used before uplink to adapt them to the results of the latest orbit determination and manoeuvre optimisation.

7. OPERATIONS AFTER COMMISSIONING

At the end of February, the payload commissioning phase was succeeded by the cruise science phase. For FD this meant essentially that the generation of special pointing profiles continued as before.

Starting on July 5th, autonomous reaction wheel offloadings occurred after more than two months without any offloading. The main reason was that the EP thrust arcs were no longer symmetric with respect to the perigee, but covered mainly the descending part of the orbit. Therefore, the disturbance torque of the thruster along the thrust direction (about 6×10^{-5} Nm), which cannot be compensated by the EP gimbal mechanism led to a buildup of angular momentum along the spacecraft z axis. Since then, manual offloadings were commanded about once per 15 hours during EP thrust periods. This value resulted from the observed disturbance torque and the known momentum capacity of the RWs.

In addition, a new pointing strategy during thrust arcs was implemented in order to reduce the solar incidence angle on the star tracker. This was done by rotating the spacecraft around the thrust direction to compensate for the articulation of the EP mechanism, using average articulation angles obtained from telemetry [1]. Thereby the temperature of one of the CHUs was lowered by about 5 °C, which increased the availability of star tracker measurements considerably.

After capture into lunar orbit, which is planned for mid November 2004, the EP will be used to bring SMART-1 into its operational orbit around the moon, which will be reached in January 2005.

8. CONCLUSIONS

In the beginning of the SMART-1 mission, a large number of anomalies interrupted regular EP operations and increased the workload of FD considerably. A number of software patches to solve or at least work around these issues increased the reliability of the spacecraft to a reasonable level and allowed FD to focus on routine operations and the support of special pointing requests for payload commissioning and cruise science.

The SMART-1 Flight Dynamics team is now preparing for the arrival in the lunar orbit and the FD support of the Science phase.

References

1. Rigger R., Juul Yde J., Müller M., Companys V., *The Optimisation of Attitude Profiles for SMART-1: A Highly Constrained Problem*, 18th International Symposium on Space Flight Dynamics, 2004