The Cluster Experience - Successful Planning of a Space Mission against the Challenges of an ageing Spacecraft Fleet

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Abstract

Cluster is a four-spacecraft mission launched in 2000 to study the Earth's magnetic field and its interaction with the solar wind. Originally supposed to last two and a half years, the mission is now extended until December 2014. During the last thirteen years, the mission planning strategy continuously evolved following several driving factors such as: new scientific requirements, overall changes in the ground segment structure and its organization and, last but not least, the problems arising from the ageing of the spacecraft components. This paper focuses on the effort spent by the Cluster Flight Control Team to address the operational needs dictated by the spacecraft ageing, in particular the drastic performance loss of the solar array and the batteries. The goal is to underline how a flexible strategy allows us to overcome these difficulties and keep high scientific data return while coping with the restrictions imposed by budget constraints.

Introduction

Cluster is a mission of the European Space Agency (ESA) dedicated to the study of the interaction between cosmic plasma and the Earth's magnetic fields, with emphasis on small scale three-dimensional structures and their variation in time.

Four spacecraft are employed, flying on high eccentric orbits to explore different regions of the magnetosphere, both inside the magnetosheath and outside in the solar wind. When crossing regions of scientific interests, the satellites are arranged in tetrahedron formation to best perform three-dimensional field measurements. The distance between the spacecraft is adjusted from a few km to some thousand km depending on the observation target.

Figure 1 – The four Cluster spacecraft flying in formation

After the loss of the original satellites in the maiden launch of Ariane 5 in June 1996, the spacecraft were re-built and launched in pairs aboard two Soyuz rockets in July and August 2000. The original mission duration was 27 months, however, the scientific achievements prompted for multiple mission extensions. Currently Cluster is confirmed until the end of 2014, and discussions are already ongoing concerning the possibility to keep it running until the end of 2016.

Overview of the Spacecraft Architecture

The Cluster satellites are spin-stabilized cylinders 1.3 m high and 2.9 m in diameter. Six curved solar panels form the outer shape of the spacecraft body and are attached to the Main Equipment Platform. The experiments and the subsystems electronic boxes are accommodated around the rim of this platform on the upper side of the spacecraft. Other instruments units are located at the tip of two 5-m long rigid booms and four 50-m long wire booms.

Cluster is a non-real time mission and the spacecraft are designed to cope with no-visibility periods longer than one day. The On Board Data Handling (OBDH) is able to store up to 2500 time-tagged commands and the Solid State Recorder (SSR) can hold more than 100 hours nominal science and telemetry data.

Telecommunications are ensured via two hemispherical antennas placed on the top and bottom faces. The transponder can operate in High Power Mode (HPM) or Low Power Mode (LPM). These two modes and their different power consumption will be discussed in the remainder of this document as a fundamental aspect to allow the mission to keep operating for the next years.

More details on the spacecraft design, which are outside the scope of this paper, can be found in (Credland 1997).

Cluster Mission Planning Concept

Speaking about Mission Planning goes well beyond the particular hardware and software configuration adopted by a mission. In general terms it is possible to state that

> In a typical mission the complete planning process is a distributed one, where different particular tasks are performed by particular stakeholders who interface among each other with intermediate planning products, and interface with the spacecraft and ground systems with consolidated products. (Sousa 2011)

The three main actors involved in Cluster's mission planning are the Flight Control Team (FCT) and the Flight Dynamics department at the European Space Operations Centre (ESOC), and the Joint Science Operations Centre (JSOC, based at Rutherford Appleton Laboratory, United Kingdom).

Operations are based on a Master Science Plan finalized by the Project Scientists and the Principal Investigators (PI's) months in advance to identify the scientific targets. JSOC supports the planning process providing an up-to-date magnetospheric model, which is used to generate the Master Science Plan.

Flight Dynamics provides both long and short term events and orbit predictions. These are used to identify the time frames when the spacecraft enter regions of scientific interest and to define the calendar of the available ground stations visibility windows.

Science observation requests are submitted from the PI's via JSOC to ESOC, where the FCT translate those request into spacecraft command sequences. The majority of science data acquisitions are performed outside ground station coverage, either in Nominal Mode (22 kbps) or Burst Mode (131 kbps). The data stored in the SSR are downlinked during the passes over the stations that belong to the European Space Tracking Network (ESTRACK). In addition, real time science operations are performed by the Wide Band Data experiment (WBD), which downlinks science data at 262 kbps via the ground stations of NASA's Deep Space Network (DSN).

ESTRACK stations are used for all routine and contingency mission operations, while DSN cooperate to contingency activities in the frame of the NASA-ESA cross support agreement. The Flight Control Team must interface with the scheduling facilities of ESTRACK and DSN to ensure that the ground stations allocation plan:

- Allows delivering to the users at least 95% of the science data collected by the four spacecraft.
- Accounts for the need to perform operations related to maneuver loading/checking and eclipses preparation/recovery. To this extent, the FCT has also to express to JSOC payload operations constraints when priority hast to be assigned to the eclipses or maneuvers.

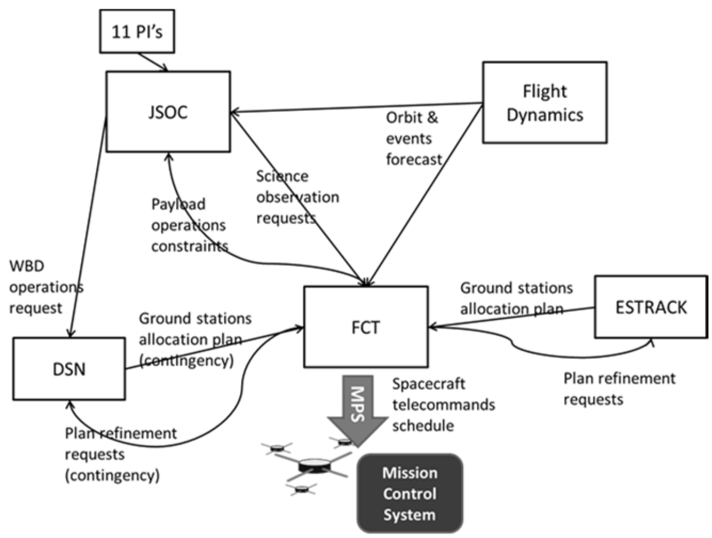

Figure 2 – A schematic representation of the Cluster Mission Planning stakeholders and the relationship among them

Effects of the Spacecraft Ageing

Although they already exceeded their design lifetime by a factor of 4, the Cluster spacecraft are still in good shape. All the redundancies of the OBDH, thermal control, attitude control electronics, and tracking-telemetry-and-control subsystems are still available. Of the total 44 instruments (11 per satellite), 37 are still operational, although some of them are degraded. Most of the propellant embarked at launch is by now depleted, and this has an influence on Flight Dynamics maneuver planning. However, the major mission planning issues related to ageing involve the spacecraft power budget due to the status of the batteries and the solar array.

Batteries Degradation

Each spacecraft was launched with five AgCd batteries, as in the early 1990's this was the only available technology that could guarantee the electromagnetic cleanliness required by the instruments. The battery design lifetime of three years fitted the original mission requirements but turned into a tight limitation when the mission got extended again and again. Despite all the measures taken to prolong their usability (Sangiorgi 2008), most of the batteries had been declared non-operational after one or more cell failures.

	SC1	SC2	SC3	SC4
Battery 1	0.0	**1.1**	0.0	0.0
Battery 2	0.0	0.0	0.0	0.0
Battery 3	0.0	0.0	0.0	**1.7**
Battery 4	0.0	0.0	0.0	0.0
Battery 5	0.0	**1.2**	**1.2**	0.0
Total	0.0	**2.3**	**1.2**	**1.7**

Table 1 – Battery capacity (Ah), March 2013. At launch the total battery capacity was 80 Ah per each spacecraft

At the time of writing, only 4 of the total 20 batteries are still operational, with much less storage capacity than at beginning of life (see table 1). Three out of four spacecraft cannot be powered during eclipses because of insufficient battery capacity; all payload and subsystem must be powered off before umbra entry and reconfigured after the end of the eclipse.

Solar Array Degradation

While the batteries degradation has a heavy impact concentrated in specific time frames (the eclipses seasons), the effects of the solar array ageing spread over the entire remaining mission lifetime.

The consequences of the exposure of the solar cells to the harsh space environment are twofold.

- On one side there is a continuous decay of the power output, as shown in figure 3. The slope of the power output curves is never constant. Between 2000 and 2004 the spacecraft were exposed to solar storms (which provoked the "jumps" visible on the graph). From 2008 the spacecraft orbits cross the Van Allen Belts and the increase in the radiation dose collected by the solar array is reflected by the steeper drop of the power output.
- On the other side, the thermal behavior of the solar cells changed in time and determined the phenomenon of the "perigee power drop" documented in (Letor 2011). Consequently, new operational constraints were introduced to limit the overall power consumption in the power drop region.

Impacts on Operations and Planning

Routine spacecraft operations must ensure the downlink of scientific data and the uplink of commands for the

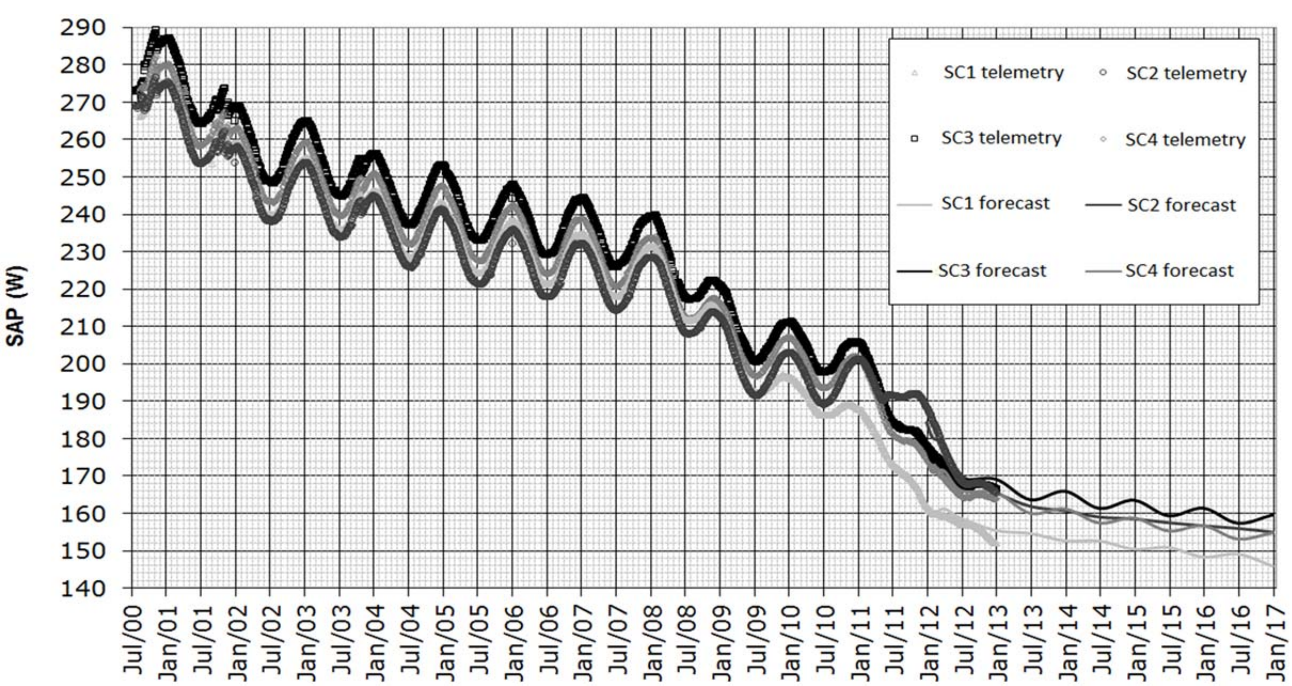

Figure 3 – Solar Array Power output (SAP): telemetry and forecast until January 2017. The seasonal oscillation due to the Sun-Earth distance change over the year is clearly visible but its effect are by now softened by the ageing processes.

spacecraft to execute the planned activities. Normally the uplink is not a concern thanks to the on board commands storage capability. The limiting factor when scheduling the spacecraft passes is the science data volume to dump.

The satellites can downlink data in High Bit Rate (262 kbps) or Low Bit Rate (131 kbps). One hour of High Bit Rate dump allows to bring on ground the equivalent of ten hours nominal science data, thus it allows a very cost effective utilization of the available ground station time.

The bitrate selection is constrained by the link budget. The drivers for the choice of High or Low Bit Rate is the power radiated by the on board transponder and the spacecraft distance. Currently the orbits of Cluster span from a perigee as low as 6000[1] km up to an apogee above 131000 km.

Cluster's flight control operations are performed mostly using ESTRACK's 15m antennas. For these ground terminals it is possible to state that, when the transponder is set to High Power Mode, each spacecraft can downlink in High Bit Rate up to a slant range of at least 100000km, and in Low Bit Rate up to the apogee distance (and actually much beyond it). The exact value is different for each spacecraft / ground station pair considered, but the figure provided above is a good reference for the remainder of the discussion.

At the beginning of life, the Solar Array Power output (SAP) was 290W. The power demand of the platform and the payload at their maximum consumption is about 200W; the excess power was partly radiated into space and partly dissipated internally to keep the units within their thermal limits. The transponder could be operated in High Power Mode all the time, giving the best conditions from the link budget point of view. The planning strategy consisted in splitting the available ground station time evenly among all the spacecraft.

As the solar array power output decreased, this simple approach was not sustainable any longer. Even reducing at the minimum the amount of power dissipated in heat, High Power Mode operations cannot be performed once the solar array power is less than 190W. As soon as this threshold is breached, new, less demanding power consumption schemes have to be adopted.

Figure 3 shows clearly that the solar array performance was never the same for all the spacecraft, nor was it its decrease. The consequence is that one of the main assumptions made at the beginning of the mission, i.e. to fly four identical spacecraft, is not valid any longer, at least not from the platform point of view. What is still true, in any case, is that the scientific data are mostly valuable only if measurements are performed by all four spacecraft – or at least by a subset of two or three of them, for some special investigation which study only bi-dimensional structures of the magnetosphere. Therefore, the mission planning cannot give privileges to a particular spacecraft over the other three. Instead, it is possible to define priorities according to the scientific operations the spacecraft are intended to perform.

In the latest years the FCT defined several scenarios characterized by different power requirements. All the scenarios are valid for the entire fleet, although some fine tuning adjustments can be necessary depending on the spacecraft. Each satellite is assigned to the scenario that best suits its power budget. This way it is possible to optimize the overall mission plan, so that no spacecraft is impaired by the performance limitations of the other three ones.

The discussion involves three topics:

1) nominal operations along the orbit
2) operations at perigee, influenced by the power drop
3) operations in eclipse

Low Power Consumption Schemes for Operations along the Orbit

As long as the available power was not an issue, High Power Mode transmissions were performed by default and Low Power Mode was used only in proximity of the Earth to limit the amount of power radiated towards the planet's surface in accordance with ITU regulations. With the extension of the mission, the possibility to keep a high science volume in Low Power Mode became a vital asset.

Low Power Mode transmissions need 32W less than HPM. The SAP threshold above which LPM operations can be performed is therefore 158W. The drawback is that the possibility to dump in High Bit Rate gets drastically reduced. For the 15m antennas used by Cluster, the maximum slant range to achieve high bit rate in LPM is in the order of 60000 - 80000 km. For bigger distances, only Low Bit Rate dump is possible, and in proximity of the apogee no dump is possible at all.

Operating in LPM, therefore, not only reduces the orbit time that can be used for data downlink, but it also implies that a large part of the downlink has to be performed in Low Bit Rate, i.e. twice the time is needed to dump the same amount of data compared to High Bit Rate. In order not to reduce the science data volume return, the ground station utilization time would then reach a cost that is absolutely outside the Cluster mission budget.

A solution to keep the mission inside a sustainable budget without a drastic reduction of the scientific output consists in power sharing between the payload and the transponder. During selected ground station passes, part of the payload is switched off, so to have enough power to operate the transponder in HPM.

[1] Note that all the distance and power values given in this documents are averaged on the four spacecraft, as the precise values are slightly different for each of them.

This has the inevitable downside of interrupting the science operations of one spacecraft for the duration of the pass. However, such a time frame is normally very limited, and power sharing is adopted in a way that minimizes the impact on the scientific data collection. HPM power sharing is not performed during Burst Mode operations, as they are executed in regions of the magnetosphere utmost important from the scientific point of view, nor it can influence WBD operations, which are anyway not much impaired by using LPM, as they run over the larger DSN antennas.

The advantage of this approach is that passes at low altitude can be executed in LPM and still in High Bit Rate (because of the smaller free space loss of the radio wave); while passes at high altitude can be selected to perform power sharing if High Bit Rate dump is required. HPM operations in power sharing are anyway more power demanding than LPM operations. The precise power need is different for each spacecraft, because the instrument consumption is not the same and the set of instruments that can be switched off is not the same. For general purpose discussion it is possible to state that the threshold above which power sharing in HPM is possible is around 170W.

The scheduling process for HPM power sharing operations is depicted in figure 4. It can be summarized in four steps:

1) ESTRACK planning software (EPS) generates a ground station plan that optimizes the utilization of the visibility windows.
2) The ground station plan is used by Cluster FCT to define the calendar for HPM power sharing operations.
3) Software checks are implemented in the Mission Planning System to ensure that the power sharing calendar does not impair Burst Mode science operations or WBD operations.
4) If no conflicts are raised between power sharing and science operations, the relevant spacecraft telecommands sequences are produced. In case the Mission Planning spots an operational conflict, it will flag a warning message to the planner to allow for a prompt rescheduling.

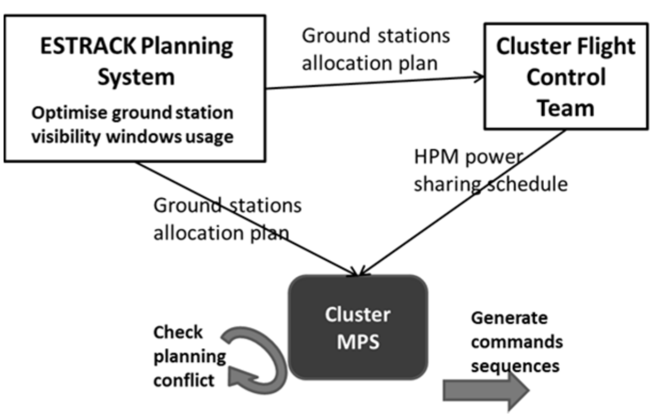

Figure 4 – A schematic representation of the scheduling process for HPM power sharing. Boundary conditions for the conflict check are represented by JSOC science observation requests

At the time of writing, the SAP for spacecraft 1 and 2 is already well below this threshold, i.e. this two spacecraft can operate only in LPM. Is it easy to conclude that the ground station scheduling for Cluster is done attempting to make the most effective use of low altitude visibility on spacecraft 1 and 2, and trying to use high altitude passes only for spacecraft 3 and 4. All efforts are made to schedule the power sharing only for those passes where HPM selection gives great confidence to perform High Bit Rate dump (according to the link budget), since it is not worthy to do power sharing if the interruption in science data production cannot be “compensated” by a high volume of data dump.

The SAP trend is such that soon HPM power sharing operations will not be feasible any longer also for spacecraft 4. By that time, a reduction in the science data volume generation will be inevitable. Even more dramatic is the fact that the SAP of spacecraft 1 and 2 is going to breach the limit for LPM operations with the entire payload on. Soon it will be necessary to perform power sharing to allow switching on the transponder in LPM: science data taking period will not be possible during ground station contact and vice versa.

To a certain extent this is already true for spacecraft 1 and one of its instruments, the Cluster Ion Spectrometer (CIS). This is a very important experiment, but the unit onboard spacecraft 1 unfortunately suffered severe anomalies. Consequence of these anomalies is that CIS on spacecraft 1 can operate only 1.5 hours per orbit. Together with the CIS PI it has been agreed not to perform CIS operations when the transponder is on and vice versa.

Currently the policy of no overlap between CIS-on and transponder-on windows enables spacecraft 1 to perform LPM operations almost as nominal, as the power needed to have LPM with CIS off is 149W, but inevitably the SAP decrease in the next months will force to adopt more strict power sharing strategies, i.e. to switch off also other instruments to allow telecommunications.

The PI's have already been made aware of this necessity by the Flight Control Team, and they already agreed to define a "science driven" power sharing program which will be organized primarily by JSOC, taking in input the link budget studies conducted by the FCT, the orbit data supplied by Flight Dynamics and the station visibility and availability times. JSOC will define regions of low scientific interest where no science data taking is necessary, i.e. time frames where the instruments can be switched off without impairing the quality of the Cluster science data production. Within these time frames, the FCT will coordinate with ESTRACK to generate a schedule of ground station passes that allows the downlink of the data collected in the rest of the orbit, where science is made. Iterations between JSOC and ESOC will enable finding the best compromise between the hunger for the collection of science data and the possibility to downlink those data. While currently the HPM power sharing schedule is dropped in the mission planning process towards the end of the workflow, in the frame of LPM "science driven" power sharing the scheduling of science observation and power sharing operations will become a single process with a tighter binding between FCT, JSOC and ESTRACK, as depicted in figure 5.

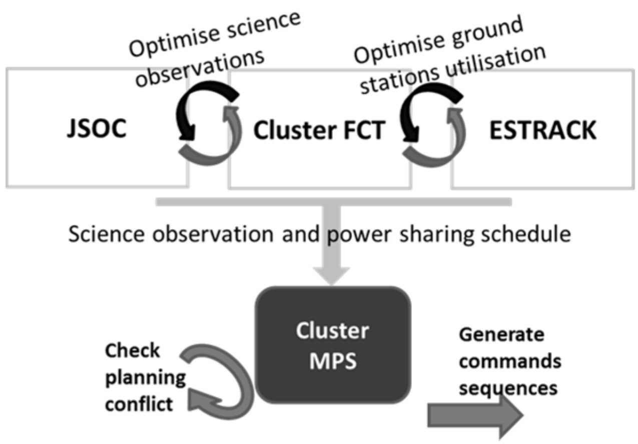

Figure 5 – A schematic representation of the scheduling process for LPM science driven power sharing.

The solar array evolution forecast shows that spacecraft 1 will need to start performing LPM power sharing already in 2013, and spacecraft 2 may follow soon. As WBD is one of the instrument that need to be switched off in order to have enough power for the transponder, real time WBD operations won't be performed any longer and will be replaced by special burst mode configurations.

The workflow of the science driven power sharing has been approved by ESOC and JSOC, and the feasibility studies demonstrate that the mission cost in terms of ground station usage will not increase. The inevitable science data loss will be less than 10% overall when spacecraft 1 and 2 will start operating in LPM power sharing. Thanks to an improving ground station visibility, it won't breach the 25% even if all spacecraft would have to follow the same strategy (which might be possible in 2015 – 2016). The mission planning rules to perform LPM power sharing have already been written and tested, as they are mere adjustments of the rules defined for HPM power sharing. In brief, the strategy and instruments for LPM power sharing are already in place, waiting to be used when the spacecraft status will require it.

Addressing the Problem of the Perigee Power Drop

From 2008 onwards, i.e. from the time the spacecraft orbits started crossing the Van Allen belts, it has been observed a remarkable drop in solar array power close to the perigee. The spacecraft more sensitive are the ones with the lowest available SAP, spacecraft 1 and 2.

Transponder-off windows around perigee have been defined to avoid the risk of a main bus undervoltage triggered by the power drop. The limits of these windows depend on the depth and duration of the drop; also in this case the same strategy has been tailored to fit the different spacecraft needs. A general scheme about the orbit division according to link budget and power budget constraints is given in figure 6. At the time of writing, the transponder-off window for spacecraft 1 is 90 minutes long and starts at the perigee crossing; the transponder-off window for spacecraft 2 is just 60 minutes long. Spacecraft 3 and 4 do not have any perigee transponder-off window.

The following points deserve to be remarked.

- The definition of the transponder-off window is not rigid, as the Cluster Power Engineers constantly monitor the pattern of the power drop and have the task to notify the Mission Planning Engineers in case the window boundaries need to be redefined.
- The window boundary does not represent a hard barrier, rather a safety net. Mission planning rules have been implemented to raise warnings when the system spots passes that breach the transponder-off window. The Mission Planner notifies this conflict to the Power Engineers, who assess whether the pass must be shortened (to avoid breaching the boundary) or it is possible to keep the schedule unchanged. Drivers for the decision are the duration of the conflict and the depth of the drop registered during the latest few

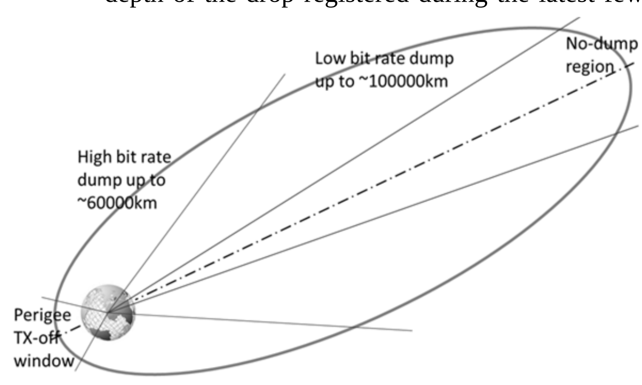

Figure 6 – In general, power budget and link budget constraints allow to divide the orbit of Cluster orbit in four regions: transponder-off window at perigee, high bit rate window, low bit rate window and no dump window.

perigee crossings before the warning is raised. Also, in eclipse season there is a larger window around perigee with the instruments off, and this allows switching on the transponder despite the power drop.

While the check about the occurrence of transponder-off window violations is automated, the reaction to this conflict is not, because it would require adopting a very restrictive approach, i.e. to re-schedule all the passes that raise a conflict. The correspondent re-scheduling effort is not acceptable for the mission.

Remarks about the Strategies for Eclipse Operations

Cluster is world famous for flying in eclipses without relying on battery power. This is another example of how design characteristics of the spacecraft were exploited to address situations that were not foreseen at the time the mission was planned.

By the fact that a spinning body doesn't need active control to keep the orientation of its spin axis, all the electronics on board the spacecraft can be switched off when they enter eclipse. This happens any time the battery capacity is not enough to satisfy the spacecraft power demand in eclipse.

The Power Engineers are in charge of defining the eclipse strategy depending on the eclipse duration and available battery capacity. The various eclipse scenarios have already been described extensively in (Volpp 2008). Nowadays the choice is even more limited, as the residual battery capacity allows only a small amount of low power consumption operations with spacecraft 2. Other than that, "decoder only" or "no battery" strategies have to be implemented, which involves a heavy load of real time operations before and after each eclipse.

Before the eclipse it is necessary to dump the data (as they will be lost as soon as the SSR is switched off) and, more important, to configure the spacecraft for eclipses, powering off all the electronic units to ensure a clean eclipse entry and exit. After the eclipse, the spacecraft need to be reconfigured to run nominal operations for the rest of the orbit. Automation System has been adopted for eclipse operations (Clérigo 2011), and it brought down the duration of an eclipse preparation to less than 10 minutes, and the recovery to 1 h 45 minutes per spacecraft. Still, to fit in the passes schedule the time for preparation and recovery is not always easy. The FCT is heavily involved in ensuring that the operations schedule is such that eclipse operations can be carried out successfully. The close cooperation of ESTRACK and DSN is fundamental to achieve this objective.

Conclusions

Once a mission is extended largely beyond its design lifetime, chances are high to enter operational scenarios that were not expected nor foreseen at the time when the mission had been designed.

In this paper, the planning strategy implemented for Cluster is presented. Such a strategy allows coping with the limitations imposed by the degraded solar array and battery without spoiling the high science data volume generation that was achieved in the earlier mission years, when the conditions of the flight segment were more favorable. The way forward is already paved to address the future challenges, with the forthcoming implementation of the "science driven" power sharing.

As the strategies have been clearly defined, the mission planning process has not been impaired even when the software and hardware dedicated to it had to be replaced due to natural end of life of computers used since the launch. A detailed description of the mission planning instruments and their evolution, outside the scope of this paper, can be found in (Bartesaghi 2012).

The introduction of modern technologies already proofed worthy by other ESOC mission (as Mars and Venus Express) constituted of course a valuable support and allowed for an easier implementation of the necessary solutions to the new operational requirements, but they were not mentioned here as they do not constitute the solution per se. Creativity and flexibility are the irreplaceable assets in addressing the new challenges with a successful outcome.

The Cluster experience proves how the capability of exploiting existing features in an unexpected way to cope with the upcoming necessities can make the difference between successful mission extension and end of operations.

Acknowledgments

The authors wish to acknowledge all the people that over the last years worked in the Cluster Flight Control Team for their substantial contribution to the development of the new mission planning strategies and instruments. Without their effort, little or none of the results depicted in this document would have been achieved.

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