Evolution of Cluster Mission Planning

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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 the end of 2014 provided a successful midterm review in June 2012. In time, the Cluster ground segment has undergone a thorough modernization process. Lately, the mission planning system has been the object of the biggest changes. The initial strategy was to optimize the utilization of a single ground station by all four of the spacecraft. This was soon modified to account for a second ground station, in order to increase the science data return. Each station had to be allocated to a specific pair of spacecraft. Such a rigid planning approach became, year after year, more inadequate as the evolving orbit changed the visibility, and the spacecraft power subsystem degraded. Many more ground stations are needed today, and the increased complexity of the spacecraft operations requires the capability for short term re-scheduling. Currently, an interactive and fast adapting mission planning system is used. A key-role is played by Cluster Web, a software package entirely developed by the Cluster flight control team to offer a visual overview of the mission plan and an elegant interface to implement conflict-free changes. Its description is the objective of this paper, together with the discussion of the transition from an 18-years old VMS architecture to a Linux system that took advantage from the on-going development of several mission planning facilities within the European Space Operations Centre. The goal is to underline how a flexible approach and the ability to design and develop ad-hoc tools could cope with continuously evolving operational demands and budget constraints.

I. Introduction

CLUSTER is a ESA mission dedicated to the study of interaction between cosmic plasma and Earth's magnetic fields with emphasis on small scale three-dimensional structures and their variation in time. The space segment consists of four identical spin-stabilized spacecraft carrying particle and field instruments, flying on high eccentric orbits at an altitude variable between 2,000 and 130,000 km from the Earth. When crossing regions of scientific interests, the satellites are arranged in tetrahedron formation to best perform three-dimensional measurements. The distance between the spacecraft is adjusted from a few km to some thousand km depending on the observation target.[1]

The mission is operated by the Cluster Flight Control Team (FCT) from the European Space Operations Centre (ESOC) in Darmstadt, Germany. Science operations are planned by the Joint Science Operations Centre (JSOC) at Rutherford Appleton Laboratory, United Kingdom, with inputs coming from the principal investigators.

After the explosion of Ariane 501 in June 1996, which destroyed the original four spacecraft, the Cluster satellites were re-built and launched in pairs onboard two Soyuz rockets in July and August 2000. Originally

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planned to last 27 months, the mission has undergone three successful extensions, and it is now scheduled to last until the end of 2014, pending a mid-term review due in June 2012.

Throughout the years, the ground segment faced several changes in order to: increase the science data return, maintain high performances in term of science data generation despite complications in operations introduced by the ageing of the satellites, and reduce the operation cost. All these changes triggered modifications in the mission planning process of Cluster and in the systems dedicated to it.

II. Original Cluster mission requirements and Mission Planning implementation

The operational concept of the original Cluster Mission was to acquire science data for defined regions of scientific interest, corresponding to 55% of the orbit. Consistent with this aim, a minimum of 95% of data collected simultaneously from the four spacecraft would have been recovered and made available to the principal investigators.

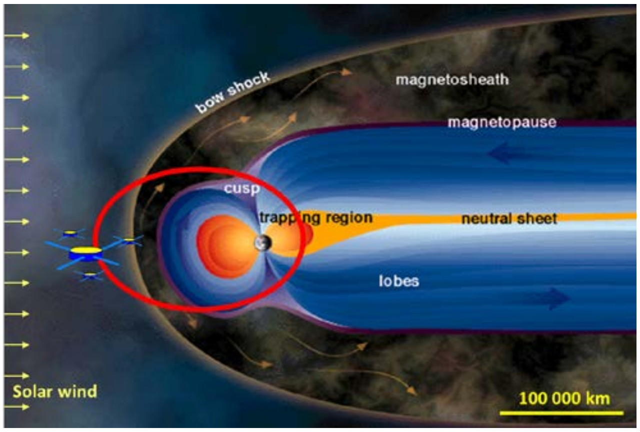


Figure 1. Cluster orbit in 2001

The high elliptical orbit of the satellites resulted in an orbit period of 57.1 hours.

The ESTRACK ground station in Villafranca, Spain was dedicated to Cluster operations. The average visibility over the station was about 23 hours per orbit, shared between all the four spacecraft. Additionally, real time dump of science data collected by the Wide Band Data experiment[2] was performed during spacecraft contact with the DSN ground stations.

Operations were based on a master science plan finalized by the project scientists and the principal investigators months in advance to identify the scientific targets. The Cluster MPS provided control of the spacecraft and of the antenna in Villafranca.

Four different planning levels were defined:

1) Long Term Plan (LTP), which covered six months and provided a general frame on which the next planning levels were developed. Input came from JSOC, which defined the scientific regions of interest (i.e. the parts of the orbit where the instruments would have been used) to comply with the master science plan, and from ESOC Flight Dynamics department, which provided predictions of the orbital geometry in the form of Long Term Event Files (LTEF).
2) Medium Term Plan (MTP), covering a period of two weeks, concerned the scheduling of ground station passes to guarantee the recovery of all the data collected outside visibility and in the on-board Solid State Recorder (SSR). The ground station visibility was known from Flight Dynamics' Short Term Event Files (STEF), resulting from more refined orbit determination with respect to the LTEF. MPS calculated the SSR fill level curves according to the science Observation Requests (OBRQ) submitted by JSOC and optimized the ground station contact time to allow a complete data dump. The resulting ground station utilization schedule was then forwarded to ESTRACK six weeks before the plan start time.

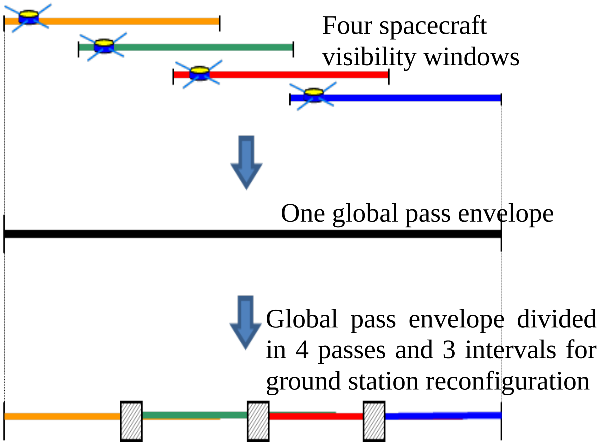


Figure 2. Example of ground station allocation

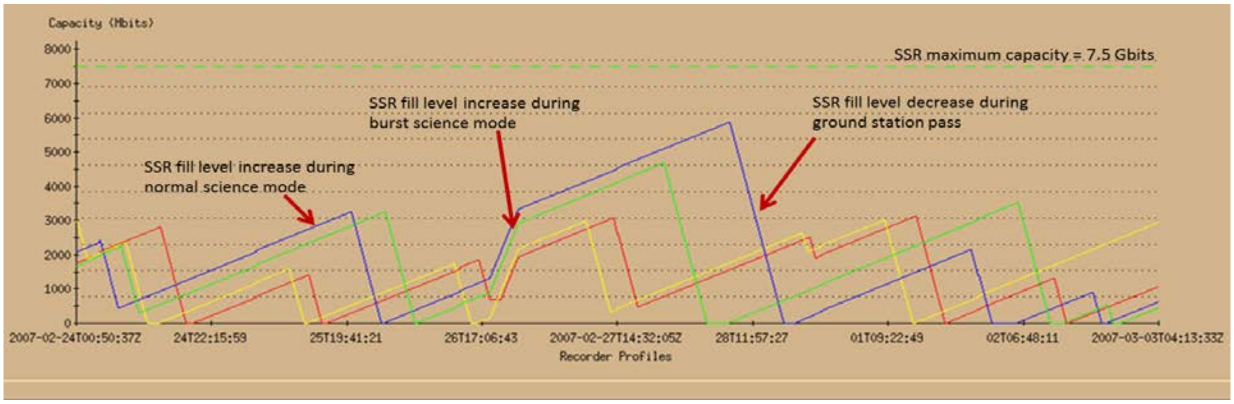


Figure 3. VAX MPS user interface with prediction of SSR fill level curves. *Each color represents a spacecraft. The definition of normal and burst science mode came from the observation request issued by JSOC*

3) Short Term Plan (STP) covered one week time and was dedicated to the generation of the spacecraft command schedule. According to a precise set of planning rules and constraints:
    a. OBRQ coming from JSOC were translated into payload command sequences.
    b. STEF information were used to time-tag platform sequences related to the selection of the appropriate on-board antenna and transmitter power, depending on the spacecraft height and attitude with respect to the ground station.
    c. Other platform command sequences were generated as response to operational requests defined by Cluster FCT concerning platform maintenance (e.g. battery conditioning cycles).
4) Operational Plan (OP) covered the same time span of the STP. The mission planner checked the content of the plan to make sure that all operational and scientific requests had been implemented in the spacecraft command list. Afterwards, the files containing the command sequences (so-called DSF, Detailed Schedule Files) were released to the Mission Control System, ready to be uplinked.

III. Gradual adaptation for changing mission needs

The scientific achievements and the overall good performance of spacecraft and payload granted Cluster two consecutive mission extensions, 2003-2005 and 2006-2009. For most of those years the mission planning workflow depicted in section II remained unaltered, with only two major milestones for change, due the extension of the science observation time to the whole orbit period and the southern shift of the apogee.

A. Science Data Return Extension

Already after the first year of operations the scientific community recognized that the Cluster mission *had led to major breakthroughs in our understanding of the Earth's space plasma environment*. However, it was also clear that *an enormous range of length and time scales could not be fully explored during the nominal mission with its limited range of spacecraft separations and with the restriction of the science operations to just 55% the orbit period.*[3]

In order to exploit the full potential of the mission, the principal investigators requested ESA in 2001 to consider increasing the science data return to the whole orbit time.

The Cluster spacecraft operate in two distinct science modes, called Nominal Mode (NM) and Burst Mode (BM). One hour observation in BM generates an amount of data corresponding to about 6 hours observation in NM. The feasibility study for the Science Data Return Extension confirmed that not only the 100% science data target could have been achieved, but that *a combination of NM and BM science observation would have allowed reaching a data volume equivalent to 115% nominal science data per orbit, without impairing the possibility to return the 95% of that data to the scientists.* [3]

A necessary condition for the fulfillment of this goal was an increase in the available ground station time. For this reason, since June 2002 the ground station of Maspalomas, in the Canary Islands, was dedicated to Cluster operations, and the Mission Planning System was reprogrammed to optimize the utilization of Villafranca station for spacecraft 1 and 2 and of Maspalomas station for spacecraft 3 and 4.

B. Southern drift of the apogee

The natural evolution of the orbit caused the shift of the apogee towards southern latitudes. The Cluster science working group decided not to counteract this drift via maneuvers, as it brought the satellites to visit unexplored regions of the magnetosphere: the sub solar magnetopause, the tail current disruption region and the aurora acceleration zone. In 2006 as the visibility from Villafranca was no longer enough to ensure the desired data return, the ground support was moved to the ESTRACK antenna located in Perth, Australia. This had two major implications on mission planning:

1) The visibility window over Perth has a considerable overlap with the one over Canberra. At the long term level, JSOC had to account for this overlap to avoid conflict between ESTRACK passes and WBD operations. On the positive side, abandoning Villafranca made the DSN antenna in Madrid available for WBD compensating for the reduction of dump time over Canberra.
2) The MPS was reprogrammed to optimize the usage of Maspalomas for spacecraft 1 and 2 and of Perth for spacecraft 3 and 4. The algorithm had to account for the fact that Perth supported also XMM-Newton, the ESA X-ray space telescope. As a real-time mission with no onboard memory capacity, XMM had priority over Cluster in the usage of Perth. The MPS upgrade was therefore implemented so to avoid scheduling Cluster passes over Perth during any time XMM was visible.

The move to Perth allowed Cluster to satisfy the requirement of 95% data return over 115% equivalent NM science time, and the shared use of the station with XMM contributed to an overall reduction of the mission cost.

IV. Space segment evolution: driving factors for mission planning major changes

As the mission lifetime got extended, new operational needs arose from the natural orbit evolution and the decrease of solar array and batteries performances.

A. Orbit evolution

Perturbations, mainly due to the influence of the Sun and the Moon, determined a radical change in the orbit, summarized in table 1.

	2001	**2005**	**2009**	**2012**
Perigee height (km)	26300	21500	2700 to 3800	1800 to 5000
Apogee height (km)	124200	116200	130000	127700 to 130900
Inclination	89.6°	89.5 to 91.5°	113.3 to 121.9°	141.5°
Argument of Perigee	4.2°	22.6 to 30.6°	32.2 to 39.0°	88.3 to 95.4°
Period	57.1 h	56.6 h	54.4 h	54.4 h

Table 1. General evolution of orbital parameters. *Actual values are different for each spacecraft. Spacecraft 2 had the largest change: in 2011 perigee decreased below 300km*

The decreasing perigee height brought the spacecraft to cross the Van Allen belts causing considerable damage to the solar array, and to enter a densely populated region of space (the GEO ring and the low earth orbit) increasing the collision risk. Additionally, to avoid exceeding the power flux density on ground permitted by the International Telecommunication Units (ITU), an operational constraint was introduced to switch off the transponders below 3000km altitude, and to constrain the allowed bitrate below 6000km altitude.

The increasing apogee height impaired the possibility of receiving telemetry at the highest possible data rate for a large section of the orbit, complicating the planning of the ground station passes.

The change in inclination and argument of perigee caused a drastic reduction in the visibility from the northern hemisphere. As explained, this led to the decision to move nominal operations support from Villafranca to Perth in 2006.

Last but not least, the orbit drift radically modified the pattern and duration of eclipses. At the beginning of the mission, it was possible to identify a “long eclipse season” (eclipse duration longer than 1.5 hour) lasting a few days and a “short eclipse season” (less than 1 hour duration) lasting a few weeks. In time, the two seasons became longer and longer, and merged into a record-lasting eclipse season spreading over 9

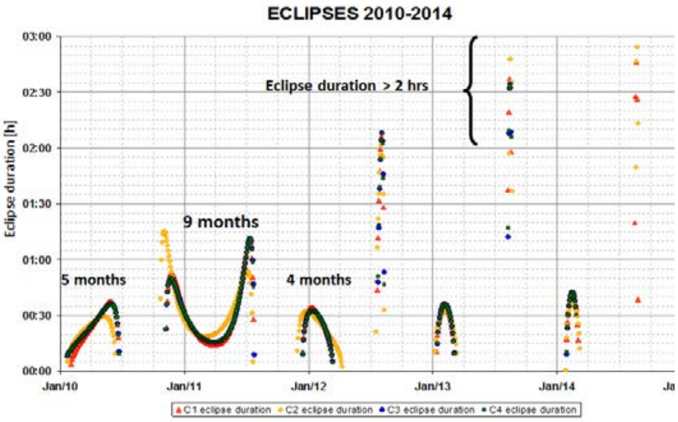


Figure 4. Change of eclipse pattern since 2010

months between 2010 and 2011. As from beginning of 2012 the seasons are separating and shortening again, but the long eclipses are going to reach 2 hours in the summer of 2012 and 2.5 hours in the summer of 2013.

B. Battery degradation

The Silver-Cadmium batteries of the Cluster spacecraft had a design lifetime of 3 years. They have now been flying for almost 12 years, and despite all the measures taken to extend their usability[4], most of them had to be declared non-operational after one or more cell failures. Today, only 5 of the total 20 batteries are still operational, with much less storage capacity than at beginning of life.

Three out of four spacecraft cannot be powered during eclipses because of insufficient battery capacity; in particular spacecraft 1 no longer has an operational battery. All payload and subsystem must be powered off before umbra entry and reconfigured after the end of the eclipse. Real-time contingency eclipse preparation and recovery became one of the most outstanding features of Cluster operations[5].

	C1	C2	C3	C4
Battery 1	0.0	**1.2**	0.0	0.0
Battery 2	0.0	0.0	0.0	0.0
Battery 3	0.0	0.0	0.0	**1.9**
Battery 4	0.0	**2.4**	0.0	0.0
Battery 5	0.0	**1.9**	**1.1**	0.0
total	0.0	**5.6**	**1.1**	**1.9**

Table 2. Battery capacity (Ah), April 2012. *At beginning of life the total battery capacity was equal 80 Ah per spacecraft*

C. Solar array degradation

The solar array power (SAP) decreased during the years as consequence of the exposure of the solar cells to the harsh space environment, in particular due to solar storms in the period 2000-2004, and to the crossing of the Van Allen belts from 2008[6]. Nominal operation scenarios considered the spacecraft High Power Amplified (HPA) to be set in high power mode to be able to always downlink telemetry at the highest bitrate. Nowadays, the solar array power is below the threshold for HPA high power mode operations, and new scenarios have been defined.

1) Low power mode: the HPA is operated in the lowest power consumption mode. This allows all the instruments to be kept on while transmitting, but forces downlink telemetry to a low bit rate for most of the orbit.
2) Payload/HPA power sharing: during the passes some instruments are switched off to allow setting the HPA to high power mode and exploit the high bit rate telemetry dump. Outside passes, all instruments are on and HPA operates in low power mode.
3) Payload/transponder power sharing: outside passes, the payload is on and the transponder is off. During passes most of the instruments have to be switched off to allow switching on the transponder.

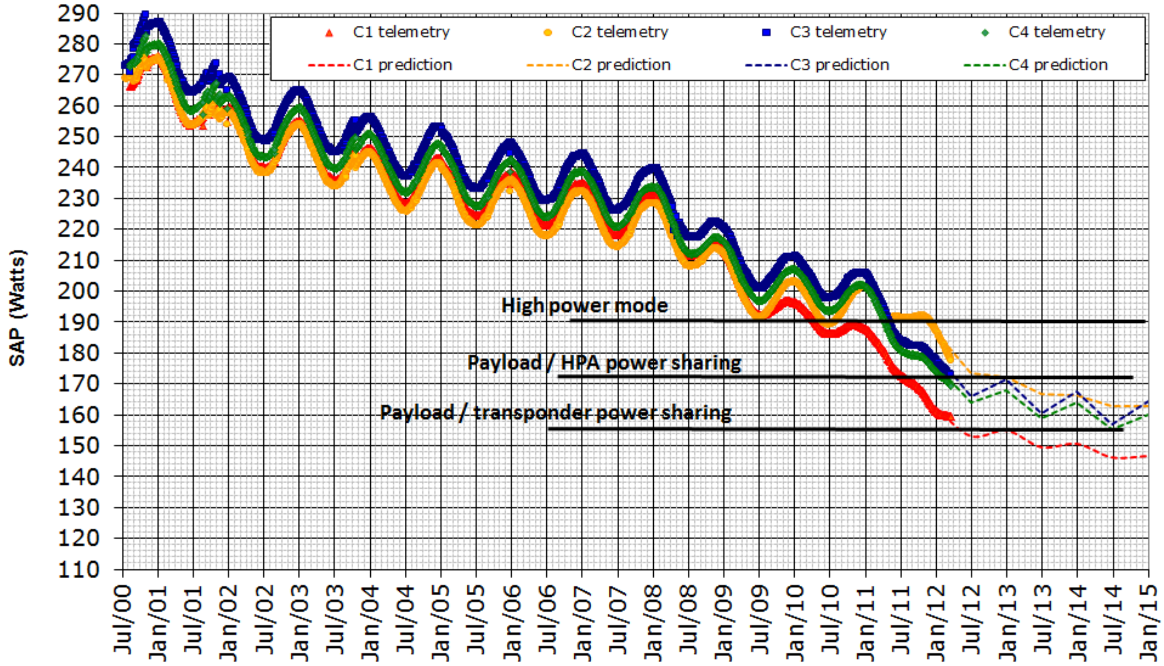


Figure 5. Solar array power degradation and forecast until 2015. *The horizontal lines are indicative for the power needed in the different scenarios. Actual values change from spacecraft to spacecraft.*

Another aspect of the solar array ageing is power drop around perigee. In the early years of the mission, the illumination from the Earth albedo at perigee caused a small SAP increase. Since 2008, this turned into a power drop driven by the rise of the solar array temperature and the change in the thermal behavior of the solar cells. Studies were conducted to define the depth and pattern of the drop[6], and new operational constraints were introduced to limit the overall power consumption in the power drop region.

V. New policies for the ground stations support

Aside from direct consequences on the mission planning implementation, the challenges introduced by the spacecraft ageing and orbit evolution determined an escalation in spacecraft operations complexity, and Cluster started exploiting more and more other ground stations apart from Perth and Maspalomas.

The ESTRACK stations of New Norcia, Kourou, and, despite the short visibility windows, Villafranca are regularly used since 2008 for nominal and special operations. Starting in 2010, the external stations of Dongara and Canberra (DSN) are used for eclipse preparation and recovery when no other antennas are available.

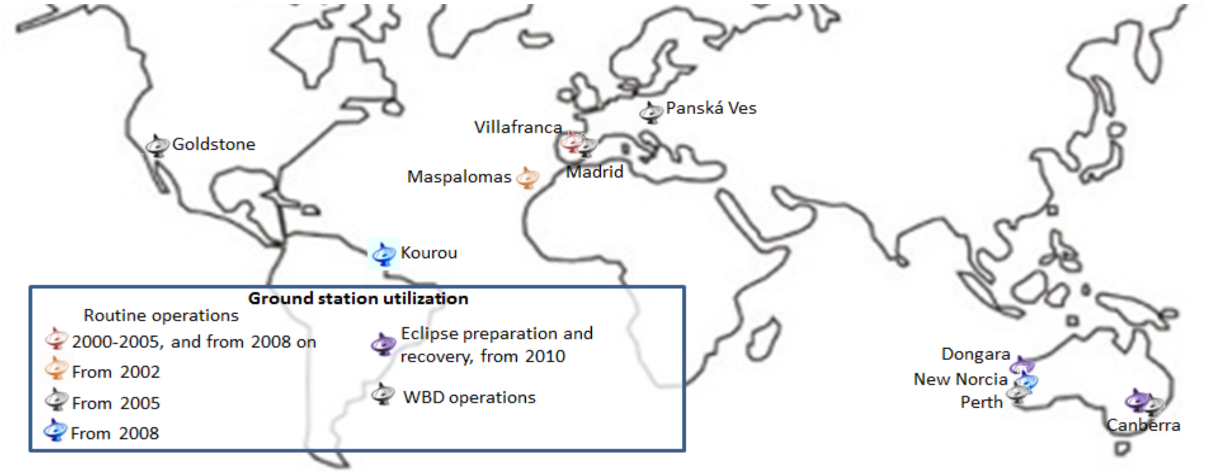


Figure 6. Ground station used by Cluster.

In the same years, the introduction of ESTRACK Planning System (EPS) radically changed the policy of ground station utilization. EPS was designed to optimize the utilization of all ESTRACK resources, core network and cooperative facilities, providing a global plan that complies with the requirements of all its customers (ESA and non-ESA missions). In the EPS perspective, missions do not have dedicated ground stations any longer. Rather, each user submits requests of priority for the usage of one or more antennas, and overall constraints concerning the operations scheduling. Once the global plan is generated, each mission can submit fine tuning requests, if needed. The system will make sure that no conflicts with other customers are triggered, and then update the plan according to the fine tuning requests.

Cluster is one of the most demanding ESTRACK users, as its requirements do not involve only the single satellite pass, like the minimum tracking duration or altitude windows to be avoided, but also multi-spacecraft interaction, such as the ground station reconfiguration time between two different spacecraft passes and the number of spacecraft passes that can take place in parallel, beyond the prohibition to overlap nominal operations with WBD science dumps.

EPS entered service in 2010 as part of an overall evolution of ESOC as a service provision center, which started years before with the introduction of a new recharging policy for ESTRACK facilities. Since 2007, the ground station usage is paid by each mission on an hourly bases[7]. Plan optimization became, therefore, a key issue allowing operations to be conducted in the most cost-efficient way.

VI. Interactive Planning via Cluster Web

The VMS MPS could not handle the new scenarios and operational requirements. Over the years, a series of tools were developed by the Cluster engineers to overcome the MPS limitations, and were finally collected into a web based application called Cluster Web.

Cluster Web consists of a rich and flexible graphical user interface coupled with a data processing and storage facility, giving the Cluster FCT members the possibility to access information coming from different sources (MCS, MPS, JSOC, Flight Dynamics, and EPS) and an immediate overview on the mission activities, together with the capability for an interactive reschedule of the operations plan.

A. Cluster Web architecture

Cluster Web has been entirely developed inside the Flight Control Team as an instrument to assist day-to-day operations. The initial project was built starting from WAMP (Windows Apache, MySQL, PHP), a self-installing web development package. Information were stored in MySQL databases and accessed via webpages coded in PHP.

The choice of WAMP offered several advantages: it came as free software under the General Public License, it did not require any particular hardware (the first Cluster Web prototype was installed in 2007 on a simple personal computer) and, more important, it relied on the intuitive and easy-to-learn MySQL and PHP. This allowed many members of the FCT to participate in developing the project, creating and adding their own tools. Later on the Cluster Web capabilities were further increased exploiting other languages, like JavaScript and Python.

Cluster Web reached the mature stage in 2010, when it was deployed to a Linux SLES-11 server located in one ESOC data center and belonging to the pre-operational LAN. This ensured augmented system stability, enhanced performance, and cleaner access of data pushed from the operational LAN.

B. Data visualization

Cluster Web collects and displays information about:

1) Spacecraft positioning and orbital events, supplied by Flight Dynamics.
2) Time-tagged commands executing onboard. Cluster Web ingests the OBRQ coming from JSOC and the DSF generated by Cluster MPS.
3) The EPS ground station utilization plan, i.e. the passes scheduled for Cluster together with information concerning ground station maintenance slots and booking of the ground stations by other missions.
4) Wide Band Data operations, the calendar comes from JSOC.
5) Eclipse operations, the calendar are prepared by Cluster FCT.
6) Spacecraft telemetry, pushed in near real time from the MCS server.

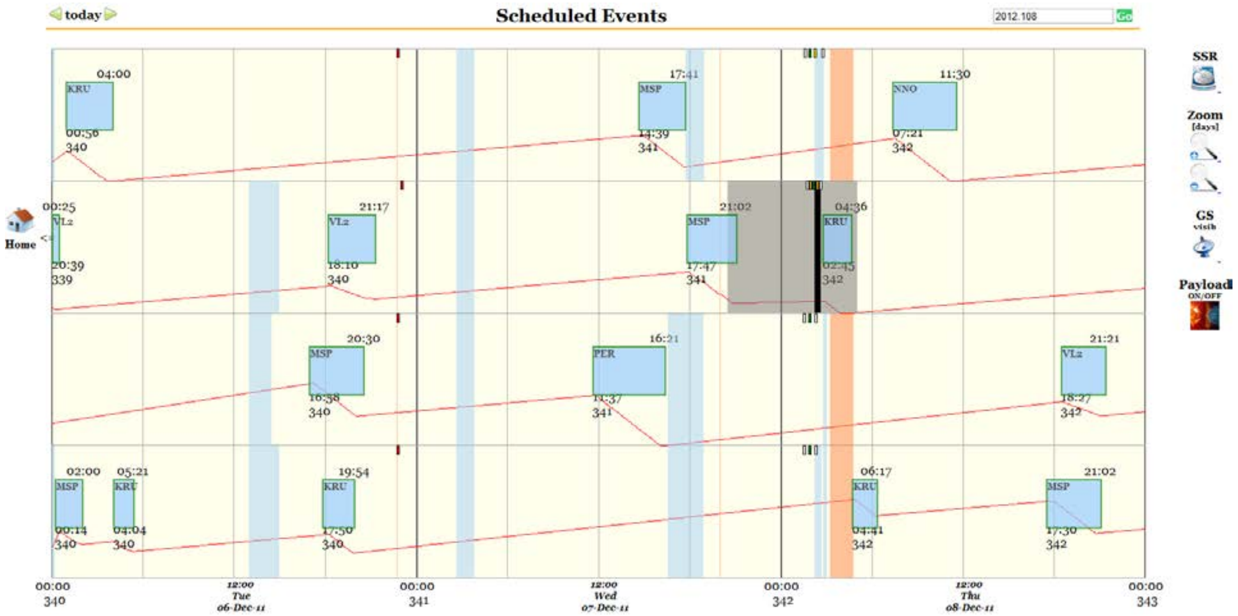


Figure 7. A screenshot of the Scheduled Events overview. *The screen is divided in four lines, one per spacecraft, where are displayed the ground station passes (as blue boxes), the SSR fill level curve, eclipse occurrences (in black) and markers for orbital events. The background colors represent the science modes each spacecraft undergoes. It is also possible to display bars representing the ground stations visibility windows and payload on/off time frames.*

On the scheduled events overview are also shown planning conflicts, such as the wrong onboard antenna selection or the scheduling of a pass outside visibility or over a station which has already been booked by another mission.

C. Forecast of SSR fill level

On the basis of the information about the science mode planned by JSOC and the ground station schedule proposed by EPS, Cluster Web calculates the evolution of the SSR fill level. The SSR fill rate associated with each spacecraft operational mode (science and no science ones) is known from the spacecraft user manual. The SSR fill level change during any ground station pass depends on the possibility to perform high or low bit rate dump. This is forecasted for each pass via calculation of the link budget. The model input includes the relative position of the spacecraft with respect to the ground station (predicted by Flight Dynamics) and peculiar features of all the possible spacecraft / station pairs, e.g. the gain that characterizes a ground antenna with respect to a specific downlink frequency or a certain spacecraft elevation above the horizon. All these data have been collected thanks to measurement campaigns carried out in cooperation with ESTRACK.

D. Dynamic fine tuning of the passes schedule

Using Cluster Web, FCT members have an immediate oversight of the proposed ground station plan. More important, they are able to modify it for a better response to the mission needs, for example extra dumps of the SSR, eclipse operations, or maneuvers.

As soon as a user edits a pass start or end time, inserts a new pass or deletes an existing one, the web engine performs the related conflict checks, i.e. it verifies that the correct antenna is selected onboard, that the pass is inside the correspondent ground station visibility window and that no other mission already booked the station at that time. Also, it calculates the global impact on the plan, as for example the new curves of the SSR fill level. The user is provided an immediate feedback about the consequence of any plan modification he wants to introduce.

Once the plan fine tuning is completed, Cluster Web provides the facility to code it into an EPS-compliant format and forward it to the ESTRACK scheduling office to be implemented in the ground station utilization plan.

Thanks to its features of interactive pass rescheduling, Cluster Web is nowadays the dedicated instrument for the long and medium term planning tasks that have to be performed within the Flight Control Team.

VII. The migration to Linux MPS

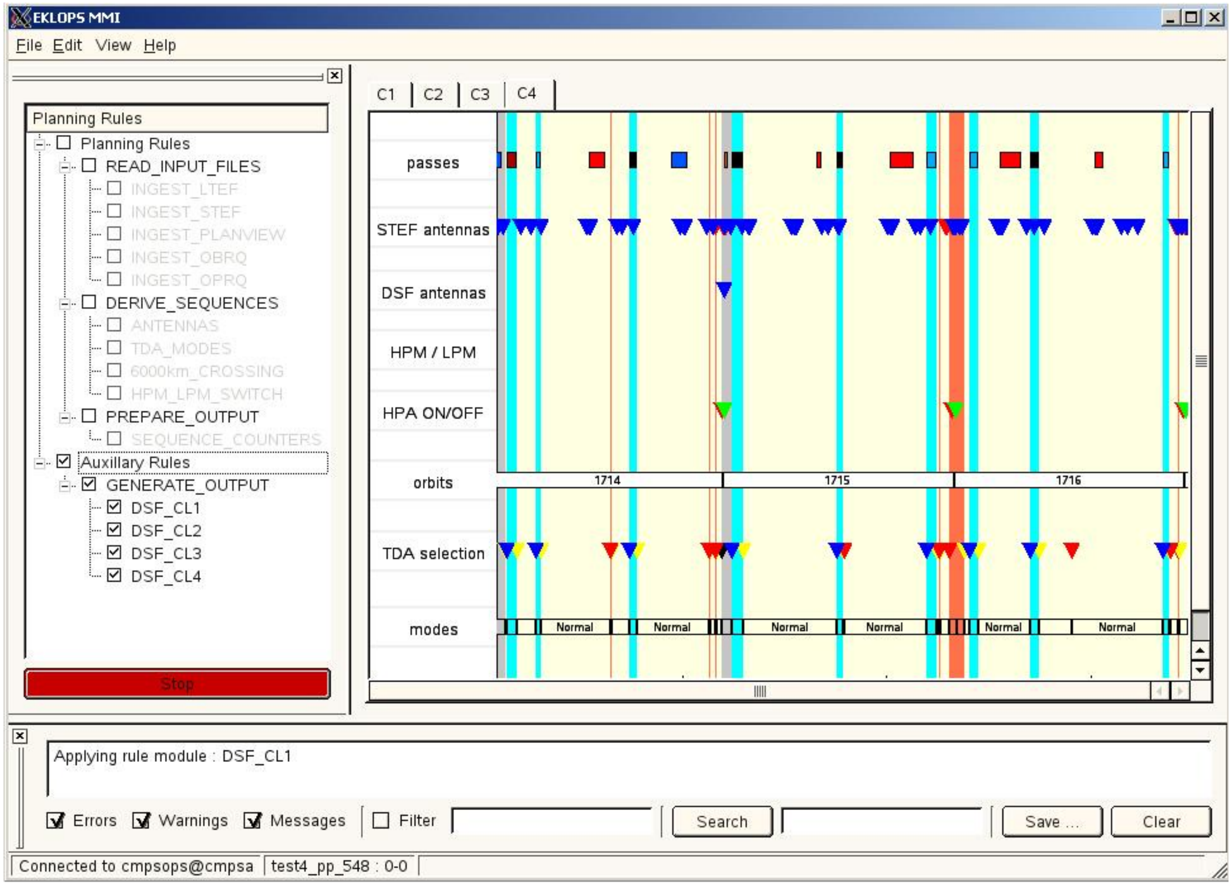
The VMS MPS had been inherited from the 1996 Cluster mission as well as most of the original ground segment components. In preparation for the second mission extension in 2005, several machines, e.g. the ones hosting the Mission Control System and the telemetry long-term packet archive, had been substituted by newer hardware. However, for cost reduction for offline systems like the MPS, the decision was taken not to replace the existing machines, but rely on software upgrades to address changes of the operational needs (as per the Villafranca-Perth swap). This proved to be the right policy for the successful completion of the second mission extension, but could not be sustained as the mission lifetime was extended again to 2012/2014. The concern did not involve just the operational needs depicted in sections IV and V, but also problems of stability and reliability of servers entered in service in the early 90’s.

At the end of 2010, the decision was taken to move to a new system based on EKLOPS (Enhanced Kernel Library for Operational Planning and Scheduling), which represented the planning standard already used by several ESA missions: Envisat, Mars Express, and Venus Express[8]. After one year of development and validation, the new Mission Planning System was declared operational in November 2011. As the new system run on Linux servers, it is since then commonly referred to as the Cluster Linux MPS.

A. Linux MPS architecture

Linux MPS is composed by three software packages: the mission planning engine itself, the man-machine interface, and the Validator. The latter is a component inherited by VMS MPS which acts as a gateway for the data supplied by JSOC and Flight Dynamics. The use of the Validator ensures compatibility between Linux MPS and its data input interfaces: it made possible the replacement of VMS MPS with Linux MPS without any implementation effort on external parties (JSOC and Flight Dynamics systems remained untouched).

The planning engine uses the same input data that were taken by VMS MPS, i.e. OBRQ, STEF and operational requests generated by Cluster FCT; additionally, it ingests the ground station utilization schedule proposed by EPS. All these information are parsed into the plan database as entities characterized by a definite start time and end time.



Planning Rules

- ☐ Planning Rules
  - ☐ READ_INPUT_FILES
    - ☐ INGEST_LTEF
    - ☐ INGEST_STEF
    - ☐ INGEST_PLANVIEW
    - ☐ INGEST_OBRQ
    - ☐ INGEST_OPRQ
  - ☐ DERIVE_SEQUENCES
    - ☐ ANTENNAS
    - ☐ TDA_MODES
    - ☐ 6000km_CROSSING
    - ☐ HPM_LPM_SWITCH
  - ☐ PREPARE_OUTPUT
    - ☐ SEQUENCE_COUNTERS
- ☑ Auxillary Rules
  - ☑ GENERATE_OUTPUT
    - ☑ DSF_CL1
    - ☑ DSF_CL2
    - ☑ DSF_CL3
    - ☑ DSF_CL4

```
Applying rule module : DSF_CL1
```

☑ Errors ☑ Warnings ☑ Messages ☐ Filter

Connected to cmpsops@cmpsa | test4_pp_548 : 0-0

Figure 8. A screenshot of the Linux MPS man machine interface.

The man-machine interface allows a visual inspection of the plan database. The user is presented the planning rule tree and graphical displays of the spacecraft plans; each display can be configured independently. A message log is also provided, together with the possibility of a table representation of selected plan entries.

B. Overall consequences of the introduction of Linux MPS

Being Cluster Web the preferred instrument for medium and long term planning tasks, Linux MPS is dedicated to the short term planning job, i.e. the generation of the spacecraft commands schedule.

The time-tagged sequences to be uplinked are derived from the content of the plan database on the basis of planning rules written in the Language for Mission Planning[9] (LMP). LMP rules can be edited directly by Cluster FCT members without the need for external software support expertise. This allows quick implementation of new rules and short turnaround time for the modification of the existing ones, in order to adjust the Mission Planning System to respond new mission requirements.

Thanks to the flexibility of the LMP language and the additional input that was possible to process (i.e. the EPS ground station schedule), the migration from VMS to Linux MPS made possible the implementation of new planning features such as the optimization of the onboard antenna selection (depending on the spacecraft attitude with respect to the ground station that is tracking it) and a logic for detection and notification of planning conflicts, as for example WBD operations very close to an ESTRACK pass, or inside the perigee power drop window. The objective is to release the mission planner from the need to check manually the entire content of the plan, as it used to be necessary with VMS MPS. Instead, the attention of the planner is driven towards those conflicts which have to be investigated and solved individually.

A major step forward is the implementation of planning rules to manage the available solar array power via the payload/HPA power sharing. Knowing the calendar of the science operations (and the specific payload commands associated to them) and the schedule of the ground station passes, Linux MPS is able to pinpoint the time window over which the payload, or at least part of it, can be switched off to allow the HPA operating in high power consumption mode, and consequently dumping the content of the SSR at the highest data rate. The relevant commands are then inserted in the spacecraft time-tagged schedule in an automated way, whilst so far the on-call engineer had to take care of this job him/herself.

The better performance of the Linux system with respect to the VMS one and the decrease in the amount of iterations and manual checks to be performed allowed to bring down the time needed to complete a short-term plan from an entire working day to less than two hours.

C. Further development of Linux MPS capability

The scheduling of payload/HPA power sharing operations is an example of how Linux MPS allows a lowering of the workload on the Cluster FCT and provides a partial optimization of the plan. Such a capability is going to become crucial in the final years of the mission, when the further decrease of the available solar array power will force to the operation of the spacecraft in the scenario described before as payload/transponder power sharing.

The LMP rules for payload/transponder power sharing will be obtained adjusting the ones currently used to perform power sharing between payload and HPA (i.e. the sequence to set the HPA in low power mode will be replaced by the one to switch off the transponder). What is important to underline is that, by the time the payload/transponder power sharing will have to be used, the FCT members will have been using this for months, if not years, with the concept of operations timing introduced by the current power sharing policy.

Furthermore, the Linux MPS core architecture is common to the mission planning system adopted by several other ESA missions, and this allows for cross training and exchange of knowledge and solutions coming from different operational experiences. On the example of what was done by interplanetary mission’s flight control teams[9] the possible implementation for a medium/long term plan optimization algorithm is currently under study.

VIII. Conclusion

The extension of the lifetime of a mission not only has impacts on the space segment, but also on the ground systems and instruments used to ensure extended operational capability of the spacecraft.

Of all the changes faced in the last twelve years by the Cluster ground segment, this paper depicted the gradual innovation process that involved the fundamental problems of mission planning.

In the original Cluster planning philosophy, VMS MPS represented the central node of a structure comprising on one side JSOC, Flight Dynamics and Cluster FCT as input sources, on the other side the Mission Control System (thus the spacecraft) and ESTRACK (thus the ground stations) as output destinations for the command sequences and the ground station schedule. The planning approach was rigid, and advanced from the master science plan proposal, to the definition of the precise observation time and commands, to the implementation of the ground and space segment operations timeline. This was possible thanks to the high margins of operability granted by the spacecraft performance and by the ESA ground station allocation policy.

The definition of an optimized and budget oriented ground station management system on one side and the overall degradation of spacecraft performances on the other required in time a gradual enhancement in the mission flexibility and defined the need to rely on fast adapting planning strategy and on tools that allowed it.

The solution was found into the combination of two new tools, Cluster Web and the Linux MPS.

Cluster Web, an instrument created by the Flight Control Team for the Flight Control Team, provides the facility for a dynamic, interactive optimization of the operations plan to the mission needs.

Linux MPS, relying on a solid basis of technology already successfully used inside ESA, allowed overcoming the deficiencies of the original Mission Planning System and opened the way for innovative planning solutions focused on the optimization of the available resources.

The interaction between these new systems is a clear mark of how a high degree of flexibility and the possibility of fast adaptation are crucial to lead the mission in a successful way through its final years.

Appendix A
Acronym List

BM	Burst Mode for science acquisition
DSF	Detailed Schedule File
DSN	Deep Space Network
EKLOPS	Enhanced Kernel Library for Operational Planning and Scheduling
EPS	Estrack Planning System
ESOC	European Space Operations Centre
ESTRACK	European Space Tracking Network
FCT	Flight Control Team
GEO	Geostationary Earth Orbit
HPA	High Power Amplifier
ITU	International Telecommunication Union
JSOC	Cluster Joint Science Operations Centre
LAN	Local Area Network
LMP	Language for Mission Planning
LTEF	Long Term Event File
MCS	Mission Control System
MPS	Mission Planning System
NM	Nominal Mode for science acquisition
OBRQ	Observation Request file
SAP	Solar Array Power
SSR	Solid State Recorder
STEF	Short Term Event File
VMS	Virtual Memory System
WBD	Wide Band Data

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