Cluster-II: Evolution of the Operations Concept

M. Warhaut, S. Matussi & P. Ferri
Mission Operations Department, ESA Directorate of Technical and Operational Support, ESOC, Darmstadt, Germany

The operations concept for the Cluster-II mission has had to evolve with respect to the original Cluster baseline, due mainly to changes in the spacecraft design and the reduction in the number of ground stations from two to only one for routine mission-operations support. The solutions adopted have allowed the overall impact on the ground segment and mission operations to be minimised, whilst still maintaining the scientific data return at the original level.

Introduction

The preparation of this recovery action for a major space science mission, to be launched four years after the original one, represents a significant engineering and managerial challenge. The need to cap the new mission at less than 50% of its original cost has imposed a rigid discipline in terms of keeping the spacecraft-component and ground-segment facility configurations as close as possible to those used for the original mission. On the other hand, some changes have had to be accepted as inevitable, due for example to a lack of spare parts for the spacecraft, or to keep pace with the continuous evolution in the ESOC ground segment.

Cluster-II also suffers from the fact that it will be launched during what was already an extremely busy period for ESOC, with the launch and control of ESA's XMM mission, and the provision of launch support for other external missions (e.g. Meteosat Second Generation). This results in the need to share the existing facilities, in particular the ground stations. Cluster-II has therefore had to accept to use a single dedicated ground station for the mission's routine science operations phase, instead of the two originally foreseen, which has had a significant impact on the operations concept. An additional consequence of the 'year 2000 peak' is the difficulty in re-utilising staff with Cluster experience, most of whom are already supporting other missions.

Space-segment evolution

In re-building the new Cluster spacecraft, there were from the outset various dilemmas associated with possible or enforced changes in several hardware components. The problem was complicated by the fact that one of the four spacecraft was already completely integrated based on spare parts from the original Cluster programme. This spacecraft, called 'Phoenix' or Cluster-FM5, is identical to the original spacecraft, but slightly different from the next three to be built. The not completely identical spacecraft hardware has meant reduced flexibility during the integration and test phases. In the original Cluster programme, spacecraft units were often exchanged from one spacecraft to another depending on hardware availability and the need to continue specific test activities. This flexibility was one of the keys to the success of the original Cluster integration programme, which ensured the continuation of the complex activities without accumulating significant delays. In addition, it had always been a fundamental assumption underlying the design of the ground segment and the operations concept that all four spacecraft would be indeed identical. The non-availability of original parts already utilised on the Phoenix spacecraft has meant that exceptions have had to be accepted.

The main changes in spacecraft hardware due to unavailability of now obsolete parts are in the telecommunications (TTC) and on-board data-handling (OBDH) subsystem areas. The original TTC high-power amplifier was no longer available and had to be replaced on the three new spacecraft, together with the transponder, by new hardware derived from that developed for ESA's XMM and Integral scientific satellites. A major OBDH change is replacement of the two original solid-state recorders (SSRs) with a single recorder of a new design with a higher recording capacity. No changes in the operating philosophy of the TTC subsystem are required, but the operational database and the related flight-control procedures have been affected. On the other hand, the new SSR allows the way data recording and dumping is managed by the ground to be significantly improved.

As far as the payload is concerned, there will be an identical complement of instruments flying on the four spacecraft, and so at least the instrument hardware will be identical to the original set. The on-board software for several instruments has changed, however, and possible impacts on the ground segment have been carefully analysed, and also checked in the test and verification phase.

It was decided, for cost and schedule reasons, not to change the on-board software of the OBDH central on-board processor, although several patches to improve the final software version were already prepared prior to the original Cluster launch. For Cluster-II, these patches will be loaded on top of the software already burned into the spacecraft PROMs before the launch. For the ground segment, this means safer operations immediately after launch.

The changes in integration approach from the original Cluster programme, introduced to speed up the production work and taking into account the already accumulated experience, had an impact on the testing approach for the ground segment. The traditional final system test for ESOC, the System Validation Test (SVT), in which the ground segment exercises and verifies all command and telemetry functions with the spacecraft flight model, was originally carried out with two spacecraft in parallel. This was done to validate one of the basic features of the Cluster operations, namely the parallelism of control activities on more than one spacecraft. This approach also had the benefit of increasing the test time available to ESOC with the flight hardware. In the original programme, each spacecraft was tested from ESOC for more than 15 working days in total. For the Cluster-II programme, four separate SVT slots were allocated, each with a single, different flight model and for a maximum duration of four days.

This limited test time imposed the need for a careful trade-off in the selection of subsystems and functions to be addressed, in order to concentrate mainly on those areas in which changes with respect to the original spacecraft were to be expected. This approach relied on the correctness and completeness of the documentation describing the changes, and therefore bore inherent risks. These risks had, however, to be accepted due to the tight project schedule, and were kept within reasonable limits since the overall number of changes introduced into the spacecraft has been small and strictly controlled (Table 1).

Ground-segment evolution

Unlike the problems encountered in re-building the space segment linked mainly to unavailability of parts, the ground segment has had to deal with a continuously evolving infrastructure. This evolution could not be halted for four years to wait for the re-launch of the Cluster mission and then support it with the same systems. Apart from the modernisation of the infrastructure, which is a continuous process and normally only marginally constrained by the needs of the projects using it, one of the problems faced today is rapid obsolescence of computer hardware and software. Workstations, operating systems and, in general, commercial off-the-shelf (COTS) products have an average lifetime of just 18 months, after which the maintenance costs – if maintenance is even supported by the supplier – become far larger than the cost of replacing the item with the latest model or version. This carries with it,

Table 1. Summary of changes to the space segment

Change	Reason	Impact
New Transponder/High Power Amplifier for three spacecraft	Old High Power Amplifier not procurable	Different procedures and databases in the TTC area between Phoenix and the rest of the fleet. Upgrade of ESOC software simulator needed
New Solid-State Recorder (SSR)	Old Solid-State Recorder (SSR) not procurable. New SSR has higher capacity and greater flexibility of use	Positive impact on operations, since the new SSR allows partial dumps. Upgrade of ESOC software simulator needed
Patches to on-board software burned into PROM expensive	Changes in software were necessary, but re-build of full software considered too	Safer LEOP ops compared to original flight (patches to be loaded at launch site). However, no “clean” starting point for software maintenance
New payload software	Evolution of scientific knowledge and targets	Database/procedures changes necessary. Heavy SVT re-testing. Minor upgrade of ESOC software simulator
Sequential spacecraft integration and testing	Acceleration of production schedule	Parallel SVT on two spacecraft not possible. Limited testing time for new features

however, the problem of adapting, i.e. 'porting', the application software to the new tools or platforms, with an inherent, non-negligible cost and schedule impact, and with the related risk of not meeting the original specifications.

The Cluster ground segment suffered this problem in all critical areas: ground stations, control system and simulators. A main component of the on-going upgrading process is the porting of the software to new operating systems: from Sun OS to Solaris 2.6 for the ground-station equipment based on Sun workstations, and to higher VAX VMS versions or Alpha stations for the control system and the simulator. The infrastructure changes dictated by software and hardware obsolescence created significant problems in the area of ground-station interfaces in particular. Compromise solutions, mixing the old and the new interfaces, have been adopted to minimise changes to the old baseline. Figure 1 shows the new baseline for all interfaces between the ground stations and the mission-control system managed by a central computer, the Network Control and Telemetry Routing System (NCTRS), located at the Control Centre.

Ground stations are one of the main infrastructure items of the ground segments for the missions supported by ESOC. They are shared by all missions, particularly for the launch and early orbit phases. For these important shared items, it is essential that identical, or at least compatible, interfaces to the mission control systems are used. On the other hand, the Cluster requirements on telemetry and telecommand interfaces to the ground stations are different from those of the other missions that will be supported in the same time frame, which all utilise packet telemetry and telecommand standards. In the telemetry area, the solution adopted was to port the Cluster telemetry processor software to the new Solaris 2.6 operating system.

The new operating system will allow both the old telemetry processor software (TMP3) and the new software (TMP4) to be run on the same platform, with the required performance. In addition, the change to a new hardware platform (UltraSparc workstations), which very soon became mandatory (maintenance costs for the old Sparc20 platforms were becoming prohibitive) did not imply any additional software adaptation exercise. This solution allowed the installation of identical hardware on all ESA workstations. In order to support different missions, a simple restart of the telemetry processor using different software (TMP3 or TMP4) is required. The telecommand interface to the Control Centre has also changed, but fortunately the solution adopted will allow the utilisation of the new telecommand encoder software and hardware also for the Cluster-II mission, via normal configuration changes.

Another change imposed on the ground stations, this time due to hardware obsolescence, was the development of a new Station Computer (STC), the central local control system for all ground-station units. Its repercussions for Cluster-II lie mainly in the area of the interface to the Mission Planning System (MPS), which produces schedules to be transferred to the station computer for automatic station control. The scheme adopted in the MPS software for the generation of the STC schedules is incompatible with the way schedules are handled in the new station

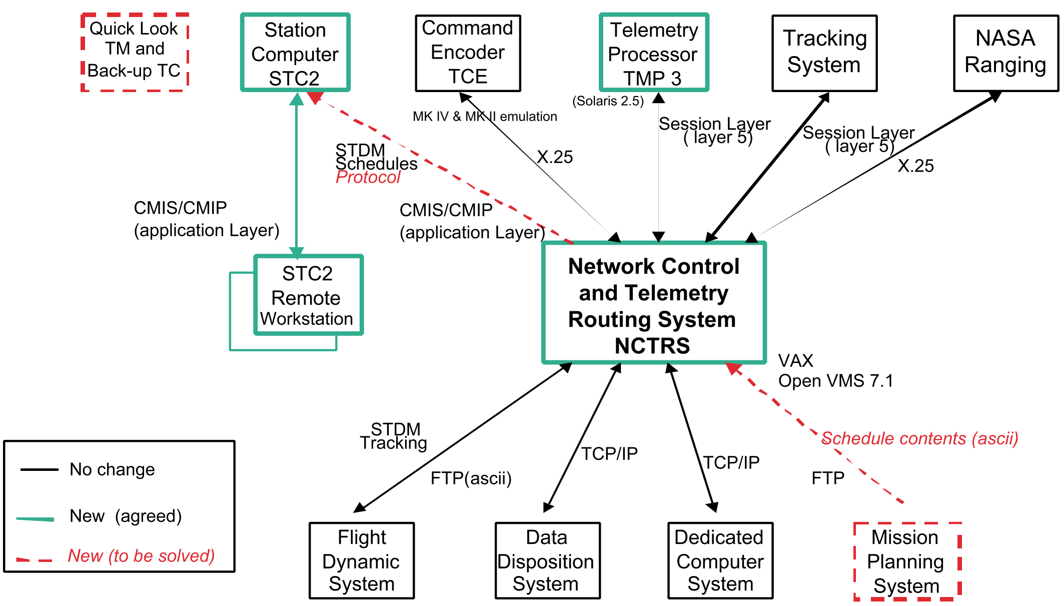


Figure 1. Network Control and Telemetry Routing System (NCTRS) interfaces

computer. The adaptation of this interface involved work on both the STC and the MPS software. The changes in the interfaces between the Control Centre and the ground stations with respect to the original mission are shown in Figure 1.

The fact that one of the two original dedicated ground stations is no longer available triggered a major change in the Cluster-II baseline, which now has only one ground station – at Villafranca, near Madrid (E) – to support the routine science mission phases. A single antenna will therefore be used to control the four Cluster spacecraft sequentially. This change prompted a number of studies and trade-off activities, resulting in an operations concept that provides a significant reduction in operating costs, in terms of both manpower and facilities.

The main antenna to be used at Villafranca, known as VIL-1, is a 15 m dish that operates in S-band at 1.8 – 2.7 GHz (Fig. 2). Formerly used for the IUE and ISO missions, its hardware and electronic equipment have recently been refurbished and upgraded to comply with Cluster-II requirements. Modernisation of VIL-1 involved transporting more than 23 t of equipment from the Odenwald site in Germany, which was a two-week-long road journey. Since its arrival at Villafranca in November 1998, much of the hardware has been replaced, including the 60 dish panels, the subreflector, the antenna equipment room and other parts of the main structure. One of the most significant modifications has been the replacement of the servo and tracking systems, necessary because the Cluster-II satellites will move in a highly elliptical orbit and require high-speed tracking. About 0.8 Gbyte of data will be returned each day from the 44 experiments (11 scientific instruments on each of the four spacecraft). Over two years of operations, this adds up to 580 Gbyte (580 000 000 000 byte) of data – equivalent to 290 million pages of printed text. All of the Cluster-II data exchange between Villafranca and ESOC will be via dedicated communications lines.

Another ‘victim’ of hardware and software obsolescence is the Cluster software simulator. This software tool is based on two computers, a DEC Alpha workstation to simulate the four spacecraft, and a DEC VAX workstation to run the ground-segment models. This separation was needed because of the high computer processing load when simulating four independent spacecraft. The operating system of the VAX used to simulate the ground stations and communication network is no longer maintained by the manufacturer and needed to be upgraded. For this and other reasons, it was decided to port the Cluster ground models also to the new Alpha workstations, upgrading to the latest VMS operating system, rather than maintain the obsolete software. Furthermore, the Cluster simulator had to be updated to follow the spacecraft design modifications and ensure that it is functionally representative of the behaviour of the new Cluster-II spacecraft. The impact of the spacecraft changes on the software simulator was confined to the transponder and SSR. Changes in the payload had only a small overall effect on the simulator.

Figure 2. The Cluster-II antenna at ESA’s Villafranca station, near Madrid (E)

The Control Centre facilities at ESOC (Fig. 3) have also been affected in that the original Cluster Dedicated Control Room (DCR) now has to be shared with the XMM project, which is already using it. The original room was designed for a double controller position, each in charge of two spacecraft and with parallel operations via the two Cluster dedicated ground stations. The room included eight identical spacecraft control work-stations and two station control workstations. Thanks to the use of a single ground-station antenna for Cluster-II, it will be possible to use a single station computer workstation in the DCR. Also, fewer spacecraft control workstations will be available. This constraint will be acceptable because only one spacecraft will be in

Figure 3. The Main Control Room at ESOC

visibility of the ground segment at any given moment, allowing a single spacecraft controller to carry out all the necessary real-time operations. In this case, no more than four workstations will be needed for spacecraft-control activities.

The ground-segment changes are summarised in Table 2.

Mission operations concept evolution

The tight budgetary constraints on the mission have imposed many changes on the Cluster-II operations scenarios, including the launches by Russian Soyuz-type vehicles from Baikonur (Kazakhstan). The launch scenario foresees two Soyuz launchers, enhanced with a dedicated fourth upper stage, each carrying a stack of two Cluster spacecraft. There is a four-week interval between the two launches.

Because of the difference in latitude between Baikonur (52 deg) and Kourou (5 deg), the timelines for the Launch and Early Orbit Phase (LEOP) and the Transfer Orbit Phase (TOP) to the final operational orbit look very different from those for the original Cluster mission. For the Cluster-II initial operations phase, the ESA ground stations of Kourou (Fr. Guiana), Perth (W. Aus.), Kiruna (Sweden) and Villafranca (Spain), plus the DSN Canberra (Aus.) station will be available. The LEOP/TOP operations timeline will be defined such that critical activities (such as orbit manoeuvres) on the two spacecraft are not executed in parallel. This reduces the size of the mission operations

Table 2. Summary of ground-segment changes

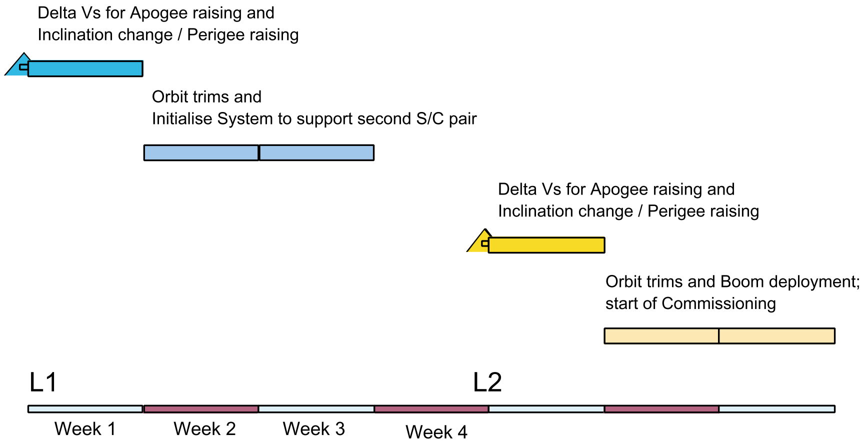
Change	Reason	Impact
MCS VAX software ported to Alpha	Lack of maintenance support for old versions	None expected
TMP software ported to Solaris 2.6 operating system	Compatibility of TMP hardware platform with other missions	None expected
New station computer (STC 2)	STC-1 hardware obsolescence	Changes in mission-planning software to adapt to new STC schedule handling
Software simulator porting from VAX VMS to Alpha	Lack of maintenance support for old versions	None expected
Single ground-station support for routine science ops. phase	Heavy ESOC workload imposes sharing of ground station with other missions; cost reduction	Operations concept modified; upgrade of mission planning software required; ops. manpower reduction.
Reduction of floor space in Dedicated Control Room	Heavy ESOC workload imposes sharing of OCC facilities with other missions	Only possible thanks to revised ops. concept (sequential and not parallel spacecraft control)

team needed and allows a better distribution of the available expertise across the two shifts. Once the first pair of spacecraft have been put into their final operational orbit, the second pair will be launched and a second LEOP/TOP phase will begin. The operations related to the second launch will be complicated by the presence of the first pair of spacecraft, which will need to be monitored and controlled from time to time by the same operations team.

Figure 4 is a schematic of the LEOP/TOP operations timeline, and how these critical phases for the two launches are connected. L1 is the time of launch of the first spacecraft pair, L2 the second launch, nominally four weeks later.

The deployment of spacecraft appendages (instrument and lower-antenna booms) and the start of payload-commissioning activities for all four spacecraft only takes place once the full constellation has been achieved, i.e. all spacecraft are in the initial operational orbit. The reduced ground-station availability has imposed a major change in the Commissioning and Verification Phase (CVP) operations. Originally these operations were to be executed in parallel for two spacecraft, using the two dedicated ESA ground stations. For Cluster-II, the single mission-dedicated station in Villafranca (E) will be used, augmented by the DSN Canberra station. As the ground coverage of the two stations is almost complementary, CVP operations for the four spacecraft will be executed sequentially, but covering almost 24 hours of real-time activities per day. The new mission plan for this phase is still being finalised, but it is expected that all activities can be covered in a time comparable to that assumed for the original mission (12 to 14 weeks). The current baseline is to start CVP operations on the first pair of spacecraft only after the second pair have completed their LEOP/TOP activities.

Figure 4. The LEOP/TOP timeline



As already mentioned, during the Mission Operations Phase (MOP) in which the scientific observations will be performed, only one ground station (Villafranca) will be used for science data recovery, and the baseline is to use a single antenna to serve all four spacecraft. This is a major change in the operations scenario compared with the original mission, which used two ground stations, each one permanently dedicated to two spacecraft. It implies that, on average, each spacecraft is visible from the ground station for only half of the time that was previously available. Studies have been performed to analyse how much science data can be recovered with this new configuration, and what on-board storage is required for the new Solid State Recorder (SSR) in order to compensate for the reduced spacecraft visibility. The results show that it will still be possible to recover the same quantity of science data that was specified in the original Cluster Master Science Plan (MSP). However, some changes must be implemented in the ground segment to cope with the reduced visibility periods, such as the doubling of the data-link capacity between the station and the Control Centre, and the possibility to execute partial dumps of the SSR stored telemetry data. With the latter possibility, it is feasible to exploit every single visibility slot, thereby maximising the science data return. Partial dumps can only be performed in forward mode, i.e. older data first, to avoid the need for reconstituting the temporal sequence of science and house-keeping data. This is also a change from the original Cluster approach, which was to dump all data from the SSR in reverse order, involving a modification of the ground software that processes the dumped data.

An advantage of using a single ground station controlling the four spacecraft in sequence is that routine mission operations can be executed by a single spacecraft controller position, compared to the two of the original mission, significantly reducing costs. Defining the size and timing the recruitment of the mission control team for a recovery mission is always difficult. The danger is to underestimate the unavoidable changes required in the operational documentation, such as the flight control procedures, and the modifications to the control system, and therefore implement a late build-up of a, perhaps undersized, flight control team. The case of the Cluster-II mission is complicated by the fact that only 3 of the original 23 members of the Cluster control team will participate in the new mission. The problem of maintaining the expertise and skills that were available in the original team is partly mitigated by the fact that many of the initial team members are still available at ESOC, having moved to other projects. Part-time involvement of some experts from the original Cluster mission is therefore already a reality, and will continue until the critical phases of the mission are over.

Conclusion

The preparation of a ground segment and mission-operations concept for the Cluster-II recovery mission, heavily affected by severe cost and schedule constraints, was driven by the basic premise of trying to avoid any change to the original baseline. At the same time, the unavoidable 'environmental' changes, such as the replacement of obsolete parts in the spacecraft or the adaptation to the new ground-segment infrastructure items, have had to be taken into account.

In some cases, changes were imposed purely by the need for cost savings, including the change to a single ground station for controlling the routine phases of the mission. Thanks to the upgrades to spacecraft data-storage capacity and functionality and to an improved mission control concept, significant cost reductions in terms of manpower requirements and facilities utilisation have been achieved without impacting the overall science data return.

Acknowledgements

The work described in this article was carried out on all sides – science, industry, project and operations – by small teams of 'veterans' of the original Cluster mission, using their reservoir of skills and knowledge accumulated over several years of being dedicated to this project. The realisation of a recovery mission within the limited resources assigned to the Cluster-II project is only possible thanks to the work of many more people – the hundreds of scientists, technicians and engineers who originally developed, integrated and tested the Cluster spacecraft, payload and ground segment, and who left the project for many different reasons after the failed launch. To these people in particular the authors are sincerely grateful.