Planning & Scheduling Within a Science Operation Centre Environment: The RAL Practical Experience

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Abstract. Science Operation Centres (SOC) provide the technical support and expertise required to assist the community to plan and operate the payload on-board scientific spacecraft. P&S tools are components of the SOCs. They are essential in the search for increasing performance and productivity. Therefore, this paper aims to describe the environment in which P&S tools are running. It shows the SOC related ground segment areas where improvement can be done and identify some of the key requirements that must be considered while designing P&S tools. In particular, we show that the development of P&S tools should improve SOC performance by increasing their level of automation, functionality and standardisation. We particularly stress for the need for a quick and reliable way of updating the planning (process defining the spacecraft resource sharing) to commanding (process translating the planning data into command data) dictionary, if the direct access to the command data timeline is not granted to the PIs.This analysis is based on the Rutherford Appleton Laboratory practical experience of co-ordinating, for the European Space Agency, the payload operations of 3 missions: Cluster, Mars Express, Double Star (in collaboration with the Chinese Space Agency).

1 Introduction

Advanced planning and scheduling (P&S) tools are essential to improve spacecraft operation planning performance (time saving, quality, reliability...). They are also a condition for spacecraft autonomous activities. Irrespective of how perfect the planning and scheduling tools might be, exploratory space missions are always confronted with various problems such as the difficulty of formulating complex planning rules, technology failure, learning phase of new equipment/technology use or unknown environmental conditions... All these issues require a flexible system which allows human interventions to control the plan generation.

Science Operation Centres (SOCs) provide the technical support and expertise to assist in the formulation and implementation of such human interventions. In addition, an integral component of SOCs are the set of manual procedures to set-up and run the technical elements of the system (setting-up software, data processing & transfer, response to anomalous system behaviour...). In the framework of increasing productivity and performance, both scientific planning and technical issues must be addressed to simplify the human activities, as well as to increase reliability and robustness by decreasing the likelihood of human errors, required to run a SOC (automation, intelligent diagnostics, standardisation).

The Rutherford Appleton Laboratory (RAL) currently has a team of about 15 people co-ordinating, for the European Space Agency, the payload operations of 3 missions: Cluster, Mars Express, Double Star (in collaboration with the Chinese Space Agency). By sharing our practical experience, accumulated over nearly 30 staff years of practice, we would like to discuss what can be done to reduce SOC human resources while keeping, or even improving, the science return. In particular, we are convinced that automation can support such objectives by allowing the users to concentrate on issues requiring human decisions (i.e. by preventing trivial issues from stalling the users). Following this approach we have already developed several tools which automate tedious and potentially error prone activities and, therefore, are well placed to fully support P&S technology effort. We believe that our practical experience can help to show how P&S technology be of assistance to reach such objectives; both in the context of ground and on-board planning.

2 The RAL Science Operation Centres

A SOC is at the interface between the Principal Investigators (PIs) and the Mission Operation Centre (MOC). Using inputs from the PIs and MOC, the ultimate purpose of the SOC is to generate and send, to the PIs and the MOC, the timeline of command data (i.e. commands or command sequences) required to operate the payload (e.g., Hapgood et al., 1997)

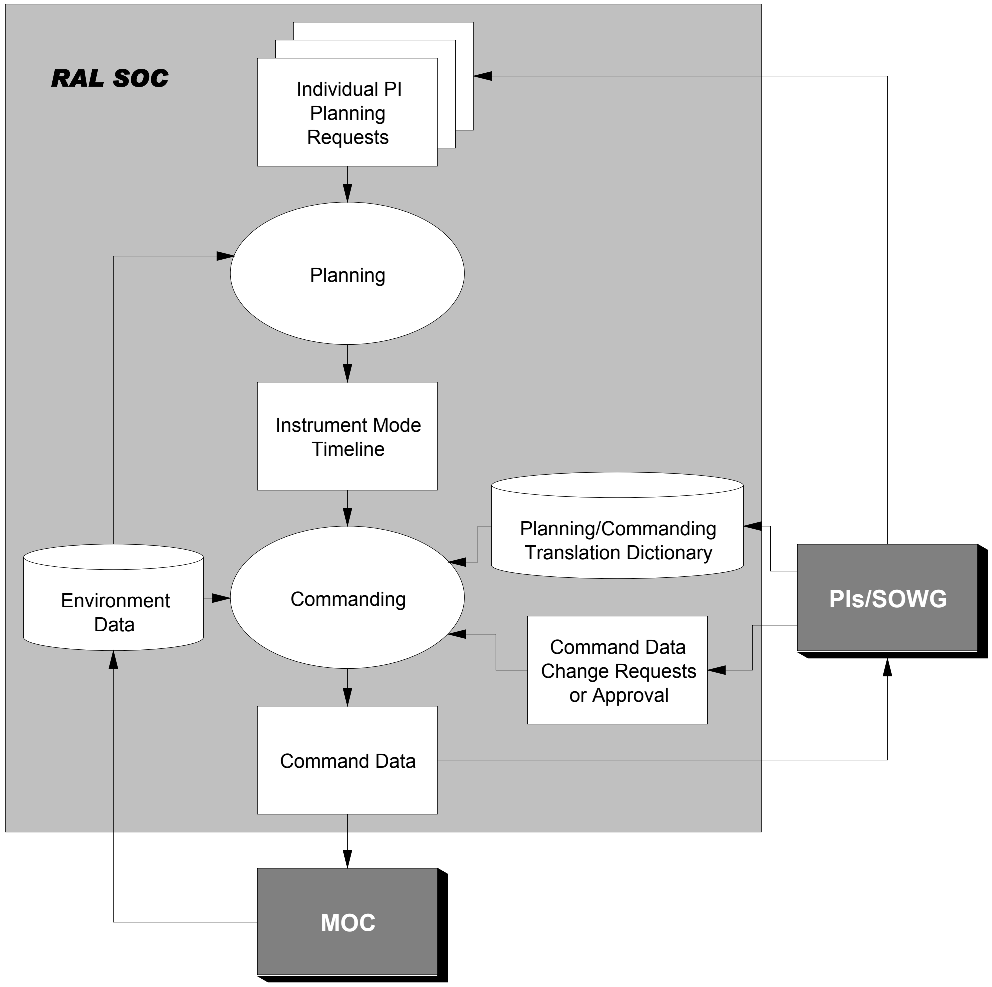

Figure 1: RAL SOC data flow

The following describes some of the fundamental features needed for payload operations of planetary missions; though many features are in common with payload operations for other types of missions. As described in Figure 1 we distinguish two phases of science operations: (a) a planning phase which establishes the activities to be performed and (b) a commanding phase which converts that planning into command data that are uplinked to the spacecraft. Note also that we are concerned here only with operations linked directly to scientific observations; we do not address the operations of the spacecraft except to recognise that it is a source of important constraints that must be respected as the health of the spacecraft is critical to good science return.

The planning sub-system inputs timed observation requests, which have a higher level of abstraction than the command data, sent by each individual PIs. It then checks, finalises and consolidates the initial inputs. The output is a timeline of data having the same level of abstraction as the PI requests; typically instrument modes, i.e. states of an experiment (ESA, February 2003). The planning sub-system is responsible for managing the planning data interface between the SOC and the PIs. In science missions it is usual for the PIs and a Project Scientist Team to form a working group to address science operations issues - a Science Operations Working Group (SOWG). The SOWG typically uses a very high level of abstraction to address

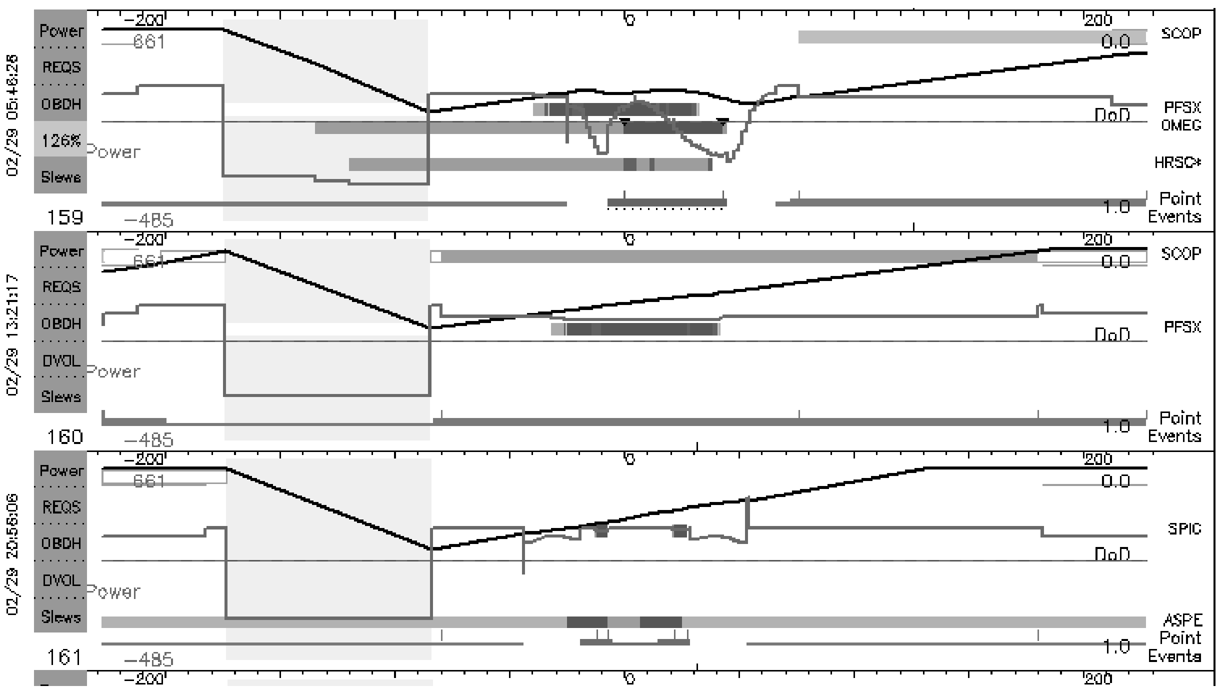

Figure 2: Example of MIRA graphics used in planning MEX payload operations; note that, in reality, the graphic is in colour. The plot shows orbits 159 to 161, with time running from left to right and a long eclipse in the left half. This visual summary shows constraint status and key activities. Constraint status are represented by colour varying flags, on the left. Key activities are represented by coloured horizontal bars (type of observation for each instrument, data downlink period, receiving ground stations and spacecraft pointing). The wiggly grey line shows the predicted net bus power while the black line provides the battery state.

the strategic science issues. A SOC also requires procedural and functional interfaces with this group.

The commanding sub-system inputs the mode timeline. Using a dictionary, stored in a database, it then translates the latter into a timeline of command data. During that process, consistency checking is performed. If required, the mode timeline can be tuned manually to satisfy the constraints. The initial timeline of command data is sent to the PIs for checking.

The command required to execute a specific and regular observation can change in a frequent and unanticipated manner, throughout the entire mission. Such frequent changes are the result of the knowledge, quality and state of the instruments as well as the evolving plans of the PIs to increase the quality of their science return. Therefore, the SOC must be able to receive command data change requests sent by the PIs to modify the initial timeline. Several iterations between the SOC and the PIs can occur before final approval by the PIs. If the changes become permanent then the PI can request an update, performed by the SOC staff, of the dictionary.

The commanding sub-system is also responsible for managing the command data interface between the SOC and the external bodies (PIs & MOC).

It has to be noted that the RAL Mars Express planning sub-system uses two main tools developed by the RAL team. They are called MIRA (the Mars Express Instrument Resource Analyser) and MIRP (the Mars Express Instrument Rule Processor).

MIRA is essentially a tools that filters and checks PI generated requests. It also offers visual display capabilities of the resource status, including constraint violation. MIRP is designed to translate the planning information into command data as well as to insert additional information missing at planning level.

Contrary to the APS (Cf. section 3) , the MIRA or MIRP requirements did not include the capability to automatically generate a science operation plan or execute sophisticated conflict resolutions (which, therefore, must be done manually, by the PI an/or the Project Science Team with the support of the SOC).

MIRA ingests PI requests for each instrument for the planning period; i.e. it does not generate an initial plan from planning rules. It then verifies the feasibility of the PI inputs, taking into account pointing requirements, the available spacecraft resources for power, data storage and downlink, and the mission rules for planning. It provides a graphical overview of the operations on each orbit, as shown in Figure 2, where conflicts are flagged and the details logged. Solutions can be checked interactively by modifying requests, disabling an instrument for an orbit, and so on; updated request files can be output if required. Finally PIs will submit revised request files that meet the resource constraints. MIRA outputs timelines of resource

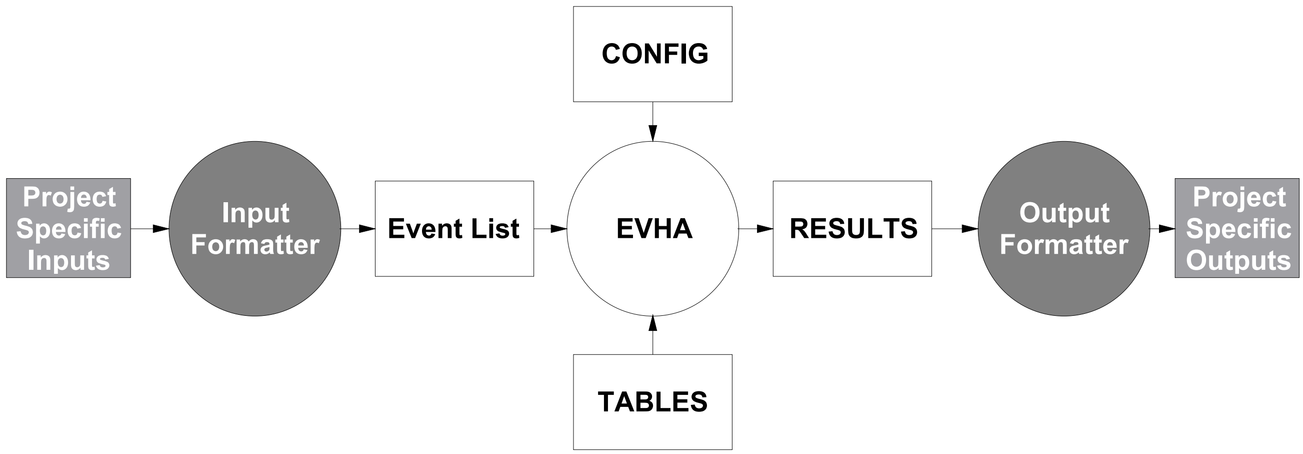

Figure 3: use of the EVHA interpreter within a project specific software. The white and grey symbols represent, respectively, the EVHA and project specific components.

usage, including pointing, power, and data volumes generated and where to be downlinked.

MIRP is a mission specific tool based on a generic tool called EVHA for EVent Handler and Associator. EVHA is a very practical programming language, developed at RAL, designed to easily implement and update complex and well identified conditional statements. It can be used for various purposes, e.g. as a scheduler, a constraint checker, a simulator... and for non-space mission projects. This concept, and its implementation, have been highly successful in their use to co-ordinate complex and variable payload activities on-board scientific spacecraft (Cluster, Mars-Express, Double-Star).

The EVHA interpreter (cf. Figure 3):

- inputs:
  - an event list to be processed by the conditional statements
  - the coded conditional statements called, hereafter, the EVHA tables
  - configuration file (directories, default values…)
- outputs:
  - the results of the execution of the conditional statements

EVHA is a generic tool. Therefore, the content of the event list and the format of the results must be adapted, by the users, to the project specific requirements (Cf. Figure 3).

The MIRP combines EVHA and the output formatter. It will implement rules allowing, for instance, to automatically:

- translate the planning data into a format that can be understood by the mode-to-command data translator of the commanding sub-system.
- add intermediate modes not set at the MIRA level
- calculate parameter values (e.g. from the duration of an observation)
- etc…

Note that for historical reasons, RAL has developed 2 types of instrument rule processors inputting and outputting slightly different products. One type is used for magnetospheric missions (e.g. Cluster and DSP), while the other one is used for planetary missions (Mars Express). However, there is nothing, a priori, that would prevent the use of the same instrument rule processor for all type of missions.

3 Human Procedure Support

ESA is now seeking ways of increasing productivity and cost affordability. Within that context, the Agency has recognised the need to improve payload operations management for planetary missions and, to this end, has issued an ITT for a "space system for on-line flexible sciences operations" as part of the ESA General Studies programme (Cf. ESA, May 2003). This study is expected to start in early-2004 and run for up to two years. The objective of the ITT is to build on-ground, a reusable & modular standard Automated Planning System (APS) for flexible interactive science operations, for future deep space planetary missions (like Venus Express or Bepi-Colombo, etc..).

The manual finalisation of a good plan can be tedious, long, repetitive and error prone. Therefore, automating the planning will increase the reliability and save time, thus allowing the planners to concentrate on issues requiring human decisions. This support will be achieved if the P&S tool, like the APS, aims to produce an initial plan, to raise planning issues to the PIs and to assist the PIs in their manual refinement of the plan.

P&S tools offer the promise of significantly reducing the level of human resources required in two important areas. The first is that by integrating the highest possible level of constraints checking it will ensure that virtually all requests sent to the MOC will be accepted, so reducing to near zero the need for iterations between the SOC and the MOC. The second area is that, by providing a generic core system, new missions will not require a new tool but only mission specific adaptations and a reconfiguration of the system variables. This has already been demonstrated at RAL by the re-use of EVHA for Double Star and Cluster.

The experience of RAL is that P&S tools, such as the APS, can be extremely valuable to reduce the need for human resource. However, human resource will still be needed to run such tools. In the following sub-sections we divide such needs into two categories: the human resources needed to produce a payload operation plan and the human resources needed to set up and run the SOC system. We also review how the SOC responsibility can evolve in the context of the search for an optimum use of human resources.

3.1 Human Resources Needed for Payload Operation Planning

Planning automation requires that planning rules are inserted into the system. The P&S tools must therefore be able to interface with the originator of the rules, the PIs and the MOC. The SOC will be responsible for facilitating the insertion of the PI rules into the P&S tools and for implementing the MOC planning constraints. It is of paramount importance that the P&S tools are designed to allow the user to easily implement those rules. In that context, it is highly desirable for the SOC to participate in the definition of interface standards because this will lead to a better integrated system.

The planning rules, defined by the PIs and used to optimise the plan, are generally complex, incomplete and subject to change as already described above. Throughout a mission, the PIs must therefore be provided with the ability to update the planning constraints, the optimisation rules as well as the plan itself, all in a controlled manner. Put simply, the PIs must be able to request timed change requests and this important issue leads to the question of the content of the timed change requests. This content is discussed in the next two sub-sections.

In addition, an improvement of the procedures used to set-up a SOC can save a considerable amount of time. For instance, the SOC should be involved, as early as possible, in the definition of the SOC system configuration variables (such as the definition of the planning rules, the command database etc…). Indeed, the SOC is the repository of an extensive expertise on the use and configuration of the system. Its knowledge should be used to assist the PI and the MOC when defining the mission variables (e.g. by helping with the identification of potential conflicts, by providing interface standards, guidelines and support tools etc…). Such early involvement would prevent fundamental mistakes leading, for instance, to late re-definitions of the configuration or to a planning system with reduced capacity.

Modification of the Plan at High Level of Abstraction. From experience drawn from three operational missions, the PI will certainly want to insert timed requests at a level of abstraction higher than the command data (that is, at the level of instrument modes). The P&S must provide such a facility.

However, as mentioned in Figure 1, from RAL's own experience of Mars Express and other projects, the PIs also have a very strong desire to directly modify the plan at the level of the command data timeline. This can range from a simple update in a parameter value to a change (deletion/insertion) of commands or modification of the timeline.

Modification of the Plan at Lower Level of Abstraction/High Level of Detail. Such modifications are possible if all the planning is done on the ground, but not if it is done on-board. This has clear implications on plan integrity and safety. However, this is a genuine PI need which P&S tools must consider when being designed. Part of the solution, to provide such flexibility, is certainly technical. However, the other part of the solution is also likely to be of a procedural nature which allows the definition of the content of the SOC configuration variables in the best possible way. For instance, a better design of the content of the command database can help to validate PI change requests faster and more reliably; if such a solution is possible then an early collaboration between the SOC, the MOC and the PI will be mandatory.

3.2 Technical Issues

The extensive RAL experience of running SOCs clearly shows that there are also other areas where SOC resources can be saved and reliability increased. These include the setting-up and running of the system. In the framework of increasing productivity and performance this issue should be addressed.

Setting the System-up. A generic SOC system would save human resource and increase reliability. This objective addresses not only mission specific issues (such as the setting up of the mission specific payload operation planning rules) but also the interfaces with the external bodies, particularly the MOC. The SOC would also benefit from a clear policy of use of its services and a standardisation of interface tools; such as a file interchange system or tools for processing the files exchanged with external bodies. As a specific example, Cluster, Mars Express and Double Star uses three different file transfer systems, with different designs and policies of use. The standardisation of a file interchange system would naturally lead to the need for a standardisation of the format and content of the files exchanged between the SOC and the MOC. For instance, it is clear that the pointing request files (PTR) used by the Rosetta SOC and the Mars Express SOC are different. Such lack of standardisation naturally leads to a costly redesign of the interface between the SOC and MOC for future missions.

However, the reality of large and complex software systems is that they are always confronted by weaknesses in their design and implementation and by the evolution of the underlying technology. Therefore, standardisation will not lead to a complete suppression of the need for software development but it will be an important factor in allowing for a re-direction of resource for improving existing systems rather than developing quasi-new systems.

ESA is ideally positioned to co-ordinate such a search for standardisation and would greatly benefit from the participation of the current SOCs.

Running the System. For historical reasons, the RAL-SOC manually triggers the software processing of the files interchanged with the external bodies. Operational experience shows that such manual intervention is not really required and can be automated. However, such an automated system will still require interface(s) for human intervention to accommodate technical system failures. Such human interventions can be very significantly reduced if the system (including file processing software and file interchange software):

- Is made more reliable
- Provides efficient diagnostic support
- Is made easy to use (efficient man-machine interface)

For instance, failure of the data interchange management system can lead to files not being delivered or, potentially even more harmful, only partially delivered. The origin of such failures can be from software bugs, network problems, change of the software environment on the server (e.g. due to human handling), etc… The time required to recognise the existence of a problem, to link the problem to the data transfer system, through to analysis and final solution can be extremely time consuming. Potentially, it can jeopardise the reliability of the system and even the ongoing science operations.

Again, standardisation will help redirecting the resources to improve and develop such type of systems.

3.3 SOC Responsibility

The reduction of the need for human resource for planning science operations leads to a redefinition of the role of the SOC. Up to now, SOCs were in charge of designing, implementing and running payload planning operation systems. In the search for reducing human resource, the role of the SOC might be restricted to setting-up, running and improving the system. This new role would be true for both on-ground or on-board payload operation planning systems. It could include the following activities:

- Installing and testing the system and its configuration
- Assisting the PIs in providing their inputs, for instance, by providing advice on how to format their inputs and resolving conflicts (for example, between instruments or other technical constraints); an early involvement of the SOC during this phase would be crucial to increase efficiency.
- Implementing the MOC planning rules into the system.
- Acting as an repository to collect data in order to improve the system (including tools and procedures). Note that if SOCs are run in different locations, the collection of the data should be organised and centralised by a body like the ESTEC SOC.
- Participating in the design and development of new tools/procedures (including P&S tools) or improvement of the existing tools/procedures.

4 Conclusion

We have shown that P&S tools can save time and increase reliability, when preparing payload operation plans, by allowing the users to concentrate on areas where human interventions are required with the system taking care of tedious, well identified and controlled, issues. However, throughout the full duration of the mission (for both on-ground and on-board planning), the system must also allow the PIs to be able to reconfigure the variables of the planning system (for example, database, planning rules, scientific targets etc...) as well as to insert timed requests into the plan. Therefore, to be efficient, P&S technology must propose fast and reliable ways of providing such updates. In particular, due to the uncertainties inherent to space exploration (technology failure, learning how to use new equipment/technology, unknown environmental conditions...), the PIs must be able to update the outputs of the planning-to-commanding translation (either by updating directly the timeline of command data or the planning-to-commanding translation dictionary). The flexibility, for such PI change requests, will be more limited for on-board planning than for on-ground planning. However, procedures and technical solutions can be used to help reduce such restriction to a level that would be considered acceptable by the PIs.

We have also shown that attention must be given to the procedures used to set-up and run a SOC. For instance, in the search for increased efficiency and cost reduction, it is crucial to involve the SOC as early as possible in the definition of the content of the SOC system configuration variables.

Finally, the systems handling the SOC's external interfaces, particularly the interface between the SOC and the MOC, should be automated and standardised as much as possible (e.g. event file, payload request files, file interchange system...). Such standardisation would allow future design and development efforts to concentrate on improving the system rather than to quasi-redesign it for each new mission. Such improvements would lead to human resource saving by, for instance, simplifying the setting-up and use of the SOC interface sub-systems and by helping to diagnose failures when running the system. It will also reduce the SOC processing times so allowing PI requests to be received closer to their delivery times to the MOC.

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- Mars-Express Payload Operation Service (MEX-POS): http://www.pos.rl.ac.uk/
- Double-Star European Payload Operation Service (EPOS): http://www.epos.rl.ac.uk/