IMPROVING SCIENCE OPERATIONS FOR FUTURE MISSIONS

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ABSTRACT

A Science Operation Centre (SOC) provides the technical support and expertise necessary to assist a science community to plan and operate the payload on board a robotic scientific spacecraft. Increasing performance and productivity and, subsequently, decreasing cost can be achieved by increasing the generic nature of the SOCs. It is therefore necessary that the science operation community agrees, as soon as possible, on a definition of "generic". This definition would then provide a conceptual framework to be followed during the design and implementation (including re-engineering) of new SOCs. Therefore, the purpose of this paper is to initiate the discussion aimed at defining this framework. It proposes what are the key elements to be considered to assess and increase the generic nature of SOCs. It is based on the experience accumulated, over the last 12 years, by the Satellite Operations Group (SOG) team, located at the Rutherford Appleton Laboratory (RAL), in designing, implementing and running SOCs for the Cluster, Double Star and Mars Express missions.

1. INTRODUCTION

A Science Operation System (SOS) aims at generating a detailed and consolidated science operation plan and its associated command timeline. The execution of the SOS is done through a mixture of manual, semi-automatic and automatic procedures. The relative proportions and purpose of each of the previous category of procedures is constantly evolving with the complexity of the missions and available technology.

The majority of the SOS procedures are usually physically implemented and executed in the SOC. However, others can be located elsewhere. For instance, some validation processes can be located at the Mission Operation Centre (MOC). Also, occasionally, the main planning activities are shared among various organisations. For instance, the planning of the Double Star (DSP) mission is shared between the Chinese and European space agencies.

The category of SOS referred in this paper addresses missions that require routine planning of operations and to observe scientific targets whose visibility is highly dependent on the spacecraft trajectory. This definition excludes interplanetary missions such as Ulysses (the instruments rarely change their modes) or solar system fly-by such as the Giotto mission (no routine operations). It includes astronomy missions, such as Integral and solar system orbiters such as Cluster or MEX. However, this paper concentrates on orbiter missions because it is the field of expertise of the SOG team.

To increase its performance and productivity a SOC must be generic, i.e. must be able to implement and run, at a minimum cost, only the SOS procedures required by the mission. This means that the SOS must be described as key functions, the content of which, to be generic, must be configurable to match the mission specific requirements. Depending on the mission the SOC will then run some or all the SOS functions. This is why, SOC implementation will also have to consider constraints such as modularity or portability.

All science plans, by definition, must be technically feasible and optimised. An optimised plan is a plan that returns a maximum of scientific information for the resource used. The assessment of the scientific value of the observation is arbitrary and likely to evolve during the mission. The planning and optimisation criteria can require a generation and optimisation of the plan over several months of operations. It is therefore likely that between the generation of the initial plan and the completion of its execution the conditions used to optimise the initial plan will have changed (e.g. change of available resources, instrument failure or degradation) so much that the plan is not meaningful anymore. To cope with those changes the plan will have to be optimised over the planning period but finalised by shorter slices which we call operation periods. For mission such as Mars Express or Cluster, an operation period covers one week of operations and a planning period covers several months. This means that all SOS must have the following two functions: a plan generation function and plan update function.

Therefore, this paper will discuss the following sections:

- Plan generation
- Plan update
- SOS performance and productivity

Please note that hereafter, we define:

- A constraint is a criteria defining mandatory and forbidden situations in the plan (such as a combination of operation requests, e.g. operation A and B cannot be executed at the same time) or the combination of a request with an environmental situation (e.g. operation A cannot

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be executed when the spacecraft is in region of space B).

- A goal is an objective, to which can be given a quantifiable scientific value. An optimised plan is a plan that contains goals returning the highest possible scientific value. Goals can conflict and therefore may not all be integrated in the plan.
- Rules means constraint and goals interchangeably

2. PLAN GENERATION

At the conceptual level, the most important lesson learned, from our multi-mission experience, is to make a distinction between two key plan generation functions:

- A spacecraft usage planning function that establishes the optimised science activities to be performed, called the science plan, and which ensures that the spacecraft can support those activities (e.g. in terms of power, data return to Earth, etc.)
- A command planning function which converts the science plan into the detailed commanding for uplink to the spacecraft. This second stage includes several elements critical to the quality of observations such as detailed instrument configuration to match observing conditions, fine-tuning of instrument parameters in response to latest data on its performance.

2.1 Spacecraft usage planning generation

To be generic, the implementation of the SOC must be such that it is able to cope with the various types of science planning that it can be required to execute. From experience, this implementation must be able to cope with all the possible contents of:

- The mission components
- The planning and optimisation rules

The mission components

The criteria to be used to assess the generic nature of a SOC are valid only for certain type of missions. The mission components are therefore key categories of mission features to be considered by the SOS functions. They are “key” categories because they only relate to issues that are mission dependent and impact on the way the science planning is executed (i.e. on the handling of the spacecraft resource usage, ground station visibility and availability, etc…). This is why any change of the list of the mission components and of their associated issues would lead to a redefinition of the criteria to be used to assess the generic nature of the future SOCs.

The key mission components that we have identified so far are:

- The spacecraft manoeuvrability
- The spacecraft trajectory
- The number of spacecraft involved

Spacecraft manoeuvrability

The issue identified here is whether the spacecraft has pointing capabilities. Indeed, whatever the mission, science plans must be generated through an iterative process between the science requests and the spacecraft usage. The spacecraft usage planning can be divided into two dependent activities:

- Spacecraft resource planning
- Spacecraft pointing planning

Those two activities are dependent because the pointing sequence can influence the spacecraft resources (e.g. the pointing of the spacecraft can modify the orientation of the solar panel and, subsequently, the power available). Currently, this SOS iteration requires procedures to be physically executed both at the SOC and the MOC.

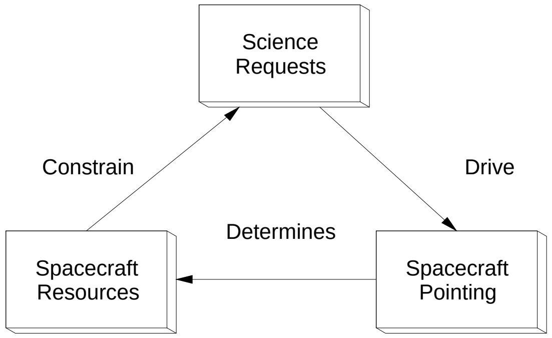

Fig. 1. Science planning iteration for missions with pointing requirements

Missions without pointing requirements, such as Cluster, are particular cases where the pointing is not an issue. It is important to note that, in this case the iteration still exist but is limited between the science requests and the spacecraft resources (e.g. science requests can interfere with uplink/downlink sessions so impacting on the total data volume or quality that can be collected during a given period):

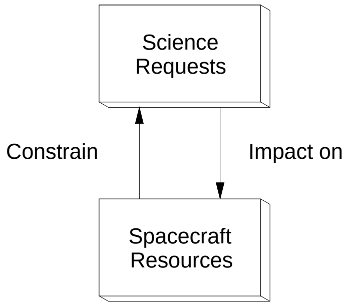

Fig. 2. Science planning iteration for missions without pointing requirements

Spacecraft trajectory

The issues associated to the spacecraft trajectory component, that have been identified, are:

- *Earth occultation limiting ground station visibility*

  For deep space missions, the Sun or the planet (for solar system planetary orbiters) can occult the Earth. Spacecraft orbiting the Earth are particular cases when the Earth is never occulted (unless lunar occultation for elongated orbits occurs).

- *One Way Light Time (OWLT)*

  The main problem for long distance missions is the travel time of the signal between the Earth and the spacecraft, also called OWLT for One Way Light Time. An Earth orbiting spacecraft is a particular case when the OWLT can be negligible.
- *Maximum available power variations*

  Power variations can be due to:
  - Variations in the Sun-spacecraft distance
  - Degradation of the solar panels or batteries
  - Sun occultation

  The SOS system must make sure that the planning satisfies the following constraints:
  - The available power (including safety margins) of the spacecraft is never exceeded.
  - The power available is always sufficient to transmit all the data accumulated into the memory; the downlink/uplink rate is dependent on the available power and distance from the Earth. Within the current technology the data management is far more driven by the downloading/uploading capabilities than by on-board memory limitations.

    Cluster, in its baseline mission concept, is a particular case as there is always enough power, except during Solar eclipses, to operate the payload and use the highest possible downlink/uplink rate.

Number of spacecraft involved

The issue identified here is whether a multi-spacecraft co-ordination of the science operation is needed. Therefore, this component is relevant for missions where:

- The SOS has to co-ordinate the operations on several spacecraft
- The operations on one spacecraft drive the operations on another spacecraft
- The spacecraft driving the operations varies with the circumstances.

Therefore, this excludes cases when the co-ordination with another independent platform (e.g. from another mission). For those cases the other mission features are an input to the planning, as this planning system has no authority to plan the operation of the other missions.

For such multi-spacecraft co-ordination the SOS must be able to handle:

- Simultaneously the relevant orbital events of all the spacecraft involved
- The concept of:
  - Reference spacecraft (to segment the planning periods)
  - Centroid (when operations are linked to the location of the fleet and not to one spacecraft of the fleet) – the centroid can have different definitions according to the needs.

A single spacecraft mission is a particular case when the reference spacecraft is the spacecraft itself and the location of the centroid the location of the spacecraft.

Requirement relevance for the RAL missions

Table 1 describes the relevance of the various issues associated with the mission components, described in the previous sections, for the Cluster and Mars-Express SOCs.

Table 1. Relevance of the mission component issues for the RAL missions.

Components	**Issues**	**Cluster**	**MEX**
Spacecraft Manoeuvrability	*Pointing*	Not Relevant	Relevant
Number of spacecraft involved	*Multi-spacecraft coordination*	Relevant	Not Relevant
Spacecraft trajectory	*Earth occultation*	Not Relevant	Relevant
	OWLT	Not Relevant	Relevant
	Maximum available power variations	Relevant	Relevant

Note that DSP is not mentioned in this table because the spacecraft usage plan is generated by the Chinese SOC and not by the RAL one.

Planning and optimisation rules

To have a generic system, a generic syntax of planning and optimisation rules is required. This generic syntax can then be used to enter the mission specific rules into the system. Its definition is a complex issue currently under study. Experience shows that there are two main sources of rules used to build the plan:

- The mission planning constraints established by the MOC ensure that planning respects the capability of the space and ground segments as well as the safety of spacecraft and payload (these rules shall include instrument rules derived by MOC from PIs input).
- There can be more than one science plan satisfying the mission planning constraints. This is why another type of rules, called the mission policy, are required to identify which of the possible science plan is to be selected. In other words, the mission policy, established by project scientist team, is used to optimise the mission scientific return and to allow resolution of conflicting science requests.

2.2 Command planning generation

This section addresses the translation of the spacecraft usage plan into the command plan. The implementation of the command plan generation system is independent of the mission components previously described. This is because the interface between the spacecraft usage planning and command planning generation is independent of the mission components. However, the content of the mission components is likely to appear as an input to the command plan generation function.

The spacecraft usage plan is a timeline of operations to which is associated spacecraft usage. Those operations can be instrument specific (e.g. an observation mode of a given instrument) or relevant for the full payload (e.g. the Normal or Burst data rate mode for Cluster). The translation of the timeline of operations into a timeline of command sequences and associated parameter values can be straightforward; e.g. execute the set of telecommands A with the set of parameters B each time operation C is required. However, our experience has shown that, in reality, the translation rules can be far more complex. Those rules cannot be applied during the generation of the spacecraft usage plans because they apply to the spacecraft usage plan itself. This means that they apply to the types as well as to the start and end times of the operations and potentially combine the latter with the environment (e.g. operation with respect to the location of the spacecraft along its trajectory, or to spacecraft resource numerical values, etc…). The rules vary with various factors including the payload technical design and performance, the scientific objectives, the choices made by the scientists, etc…

For example:

- Some technical adjustments, not changing the spacecraft usage plan, can be inserted only when the time when the experiment is switched on is known and only within certain environmental conditions; for instance:
    - Once every three observations use red filter instead of green filter
    - For observation type A use blue filter only above region B otherwise use yellow filter
    - Etc…
- Observations can be stopped by a command sequence or automatically after a given period of time controlled by one of the parameters of the command sequence which switched the experiment into its observation mode. The value of the parameter can be known only after the start and end times of the operations have been adjusted following the optimisation process. This means that it must be possible to calculate dynamically the values of some parameter and not just pick up those values from a database.
- Etc…

In any case, the translation rules must lead to a command timeline that must never violate the spacecraft usage plan. Also, this implies that the rules do not change very often. If they do then only a manual translation is possible. The Cluster SOC trades this off by performing an automated translation that can be manually adapted by the PIs (see Plan Update section).

3. PLAN UPDATE

Updating the plan implies that the modification of the spacecraft usage plan is under control. This means that the implementation of the update mechanism must take into consideration the mission components previously mentioned. A plan can be updated by:

- Regenerating the plan, i.e. by executing a full (from scratch) or partial (i.e. repairing) re-planning. The optimisation process will have to be able to consider the past operation period without changing them (one cannot change the past).
- Adapting its content directly (i.e. without re-optimising the full plan) following specific requests by the scientific community; this automatically raises the issue of controlling the changes, including the tracking of the changes (to reapply previous adaptations following a re-optimisation), the configuration of the types of change allowed (controlled by the scientific community) and the validation of the changes (they still must be technically feasible and safe).
- Both (i.e. a plan re-optimisation followed by an adaptation), e.g. to finalise each operation periods.

It is clear that the re-planning is possible only if there is enough time to execute the latter. If there is not enough time then, depending on the circumstances, either the plan is left unchanged or modified according to the mission specific contingency procedures (usually delete the plan).

The typical conditions leading to the regeneration of the plan includes:

- Event time changes. Note that this is about major time changes not small ones. Small changes can be easily dealt with by expressing the time tag of the command sequences with respect to specific events rather than to absolute times.
- Unpredictability (the occurrence of an unpredicted scientific events, a problem of execution etc…)

The typical condition leading to a post-optimisation adaptation of the plan include:

- The need to fine tune an instrument
- The need to react to an urgent situation where a well known specific action is required – it is faster to “hack” the plan rather than to modify the planning and optimisation rules to get what is wanted.

Since the spacecraft usage plan and the command plan do not handle the same type of information the scientific community may want to be able to update both types of plans.

4. SOS PERFORMANCE AND PRODUCTIVITY

The SOC can improve its effectiveness and cost by developing software and/or procedures which limit human errors, speed-up the execution of the tasks, limit the repetition of time consuming tasks, avoid tedious, long, repetitive and error prone tasks (thus allowing the planners to concentrate on issues requiring human decisions).

Set-up and running costs increase with the time required to perform the actions as well as with the required level of experience and performance (i.e. grade) of the staff.

Increasing performance and productivity requires to design and implement mechanisms speeding up the actions required to set-up and run SOCs. This means improving not only the intrinsic performance of the tools and procedure but also their ease of use.

4.1 Set-up Improvement

Currently the SOC set-up includes systematically the requirement analysis, the design, development, installation and configuration of the SOS for each new mission.

A clear way of increasing set-up performance and productivity is to minimise the design and development phases and to simplify the installation and configuration phases. The design and development phases can be minimised by designing and developing generic SOS (architecture, tools, interface, etc…). The simplification of the installation and configuration can be achieved by developing, as much as possible, appropriate tools and procedures.

The following sections provide examples of what is being currently done to improve set-up performance and productivity.

System architecture at RAL

First, there is a clear distinction between the spacecraft usage planning and payload command planning within the SOC system architecture at RAL. This modularity allows for flexibility across missions. For instance, the payload command plan generation is very similar for the Cluster and Double Star missions but the spacecraft usage planning is very different. For Cluster, the spacecraft usage planning is done by the RAL-SOC, while, for Double Star, the Chinese SOC does it. Secondly, RAL tries to re-use and re-engineer as much of existing SOC systems to operate new missions. Thirdly, whenever possible, the re-engineering is done in a way that increases the generic nature of the system.

Interface

There is currently an attempt, driven by ESA, to produce a common SOC-MOC interface control document across the planetary missions, currently Rosetta, Mars Express and Venus Express.

Tools

The current SOCs have developed a series of tools that can be readily re-used across missions after reconfiguration. The main ones include the Experiment Planning System [1], or EPS (command plan), the Event Handler & Associator (EVHA) (command plan) [2]. ESA is also commissioning the development of the Automated Planning System [3], or APS, to help the generation of both the spacecraft usage and payload command plans.

4.2 Running Improvement

Running costs include the execution and re-execution of the tasks required to generate the plan. The reasons why re-executions happen include the changes of conditions, leading to a plan update, and the pertinence of the data exchanged between the components of the iterative planning described in the Spacecraft manoeuvrability section. It is worth noting that the pertinence of the data exchanged is not about syntax or formatting issues. Such problems can, usually, be sorted out relatively easily using software. It is about making sure that what is requested is technically feasible before it is validated.

To increase running performance and productivity, ways must certainly be found to speed-up the execution of the tasks, i.e. to increase the performance and functionality of the tools and procedures that are used to execute those tasks. However, ways must also be found of avoiding the recurrence of certain activities, particularly the ones requiring the longest execution time.

The following sections provide examples of what is being currently done to increase SOC performance and productivity.

System architecture

The likelihood of having a change of condition which would impact the plan reduces with the decrease of the duration between the start time of the finalisation and the start time of the execution of the operation period. One may then think that improvement can be achieved by concentrating a high amount of staff resource as close as possible to the execution start time, because the chances of having a change of conditions will be lower. However, usually the cost increases with the decrease of the time between the start of the finalisation and execution of the operation period. This is simply because staff working during the weekend or nights are more expensive than staff working during traditional working hours. Therefore, the right balance must be found between the staff resources needed to pre-emptively limit any change of conditions and those required to react, afterwards, to a change of conditions.

Moreover, staff resources required to implement updates are decreased by limiting the need for re-validation after an update so speeding-up the planning process. This is particularly useful when some validations take a long time to execute. At RAL examples of such separation include:

- The possibility for the PIs to iterate the spacecraft pointing and resources and propose a solution which is then checked for thermal constraints. The former takes a few minutes to a few hours to execute but the latter takes about 1 week. In other words, having to check the thermal and power constraints each time the pointing is changed, e.g. due to a spacecraft resource violation, would be extremely time consuming.

- The possibility for the PIs to update the payload command plan without having to change the spacecraft usage plan if the necessary updates do not require a change of the spacecraft usage plan.

Finally, the pertinence of the data exchanged in between the components of the iterative planning are usually improved by defining empirical rules that are then used to formulate the science requests. Such rules can limit the likelihood of rejection of the requests very significantly.

Tools

Tools are used to speed-up the generation and improve the quality (by reducing human error) of the data exchanged with, and within, the SOCs. They include the generic tools mentioned in the set-up cost section. They also include more mission specific tools such as [2]:

- For spacecraft usage planning, the Mars Express Instrument Resource Analyser (MIRA)
- For file processing and management:
  - Cluster: Joint Science Operation Centre Control Centre (jcc)
  - Double Star: Double Star Control Centre (dcc)
  - Mars Express: Payload Operation Service Control Centre (pcc)

5. SUMMARY AND CONCLUSIONS

ESA has financed the design and implementation of two types of SOC, at ESTEC and RAL, to co-ordinate the science operations of similar missions: e.g. Mars Express at RAL and Rosetta, Venus Express and SMART 1 at ESTEC. This provides a unique richness of expertise. However, we believe that to develop further this richness, for the current and future SOCs, and to capitalise on it, some centralised co-ordination is required. We are convinced that allocating some resources for such a co-ordination would, ultimately, save very significant amounts of money in the funding required for SOCs for future missions.

As already stated in [4] we believe that the generic nature of SOCs must be increased in order to improve performance and productivity (i.e. reduce cost) of science operations. This means that the first step is to define and agree what "generic" means. This definition should then provide a framework and should be followed whenever a new SOCs is being designed and implemented. This framework should be discussed and agreed within the science operation community as soon as possible. Its implementation as well as the evolution of the technology will lead to a modification of the SOC (and probably MOC) requirements. Therefore, to be efficient in the search for increasing productivity, one needs to define and agree the future and evolving roles of the SOCs as well as a methodology to identify the best ways for the SOCs to move efficiently towards their future roles. This could be achieved, for instance, through a set of workshops. Note that the science operation community involved should not be restricted to the Solar system one; i.e. it could also include other communities such as the ESA Astronomy and Earth Observation science operation communities.

This paper is therefore aimed at initiating the discussion about the content of the above framework. It has concentrated on Solar System missions and proposed an initial list of key functions, and associated configurable elements, which should be considered during the design and implementation of each new SOCs (Cf. Table 2).

Table 2. Summary of the initial list of key functions.

Function: Plan Generation

Function: Spacecraft Usage Planning
Implementation must consider:
 * Mission components
  + Spacecraft manoeuvrability
  + Spacecraft trajectory
   - Earth occultation
   - OWLT
   - Maximum available power
  + Number of spacecraft involved
 * Planning and optimisation rules

Function: Spacecraft Command Planning
Implementation must consider:
  *Translation rules

Function: Plan Update
Implementation must consider:
 * Types of required updating
  + Plan regeneration; i.e.:
   - Full replaning (from scratch)
   - Partial replanning (repairing)
  + Post-optimisation plan adaptation

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