Improving Payload Operations for Science Missions

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A Science Operation System (SOS) aims at generating a detailed and consolidated science operation plan to routinely operate the payload on board scientific spacecraft. In the context of discovery and competitiveness, which are the keywords in Europe's policies and programmes for space, we believe that a permanent mechanism would be beneficial to efficiently and continuously improve SOS performance and productivity. It should monitor and steer the content of the procedures used to design and implement SOS. It should also be run by the science operation community. We therefore propose that the European Space Agency finances a study that will aim to define the requirements of a cost-effective mechanism, such as a Consultative Committee for Science Operation System (CCSOS), allowing for the coordination of the exploitation of current and future SOS experiences. Based on our practical experience of SOS, we provide, in this paper, the requirements of the study. We also discuss the expected key study outputs as well as an example of what could be the CCSOS architecture and outputs. Finally, we are convinced that many elements of this discussion should also be relevant for non-scientific missions, i.e. for missions involving any sort of routine payload operations.

Nomenclature

CCSOS	=	Consultative Committee for Science Operation System
ESA	=	European Space Agency
ESTEC	=	European Space Research and Technology Centre
FD	=	Flight Dynamic
GS	=	Ground Station
MOC	=	Mission Operation Centre
PI	=	Principal Investigator
RAL	=	Rutherford Appleton Laboratory
SOC	=	Science Operation Centre
SOP	=	Science Operation Plan
SOS	=	Science Operation System

I. Introduction and purpose

PAYLOAD operations aim at planning routine payload activities to satisfy the objectives of the space mission within the environmental and spacecraft constraints. In this paper we call a Science Operation System (SOS) the system which aims at performing payload operations for scientific missions. There is one SOS per mission and each SOS generates a detailed and consolidated Science Operation Plan (SOP). A SOP is a timeline of spacecraft usage requests (e.g. like pointing requests) and experiment commands. By definition, an experiment is a set of instruments presenting a unique interface with the spacecraft sub-systems. A SOS is a component of the space (e.g. if the SOP is partially or totally generated on-board the spacecraft) and ground segment; note that the space segment is the interface between the ground station and the payload.

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Currently, ESA (European Space Agency) SOSs have functionalities which are executed by the following ground segment elements:

- The scientific team(s): element responsible for the management of the scientific observations
- Experiment team(s): element responsible for the building and maintenance of the experiments
- The Science Operation Centre (SOC): element responsible for the science operations
- Flight Dynamic (FD): element responsible for the spacecraft trajectory and attitude
- The Mission Operation Centre (MOC): element responsible for the spacecraft operation
- The Ground Stations (GS): element responsible for the communication with the spacecraft

By definition PI (Principal Investigator) driven missions are missions where the PI has total disposition over his/her experiment. Typical PI driven missions include Earth observation missions as well as solar system missions, such as planetary missions. By opposition, non-PI driven missions, also referred as "observatory" missions, are missions where anyone who can satisfy their peers that they can do something useful with the experiments gets to use the latter. Typical non-PI driven mission include astronomy missions. For PI driven mission the scientific and experiment teams are the same and often called the PI teams. Those teams remain distinct for non-PI driven missions.

The above ground segment elements, or sub-systems of those elements, are not necessarily co-located. For instance, ESA SOC and MOC are not collocated. Also, for the Double Star mission, the SOC is divided into a Chinese component, located in China, and a European component, located in Europe.

Discovery and competitiveness are the keywords in Europe's policies and programs for space. This means that effort is required to continuously improve performance and productivity of ESA's activities, including SOS activities. By definition, productivity and performance are quantifiable. Productivity is the measurable ratio between a produced quantity and the means used to produce the latter. Ways of increasing productivity include reducing the cost during:

- design and implementation by, for instance, increasing the generic nature of the SOS
  Note that by definition, a system is generic if:
  - it has clearly separated the fundamental requirements from the mission specific elements
  - it has implemented those fundamental requirements
  - if it inputs mission-specific configurations on top of the same core system for all missions.
- operations by, for instance, increasing automation and diagnostic support

See Ref. 1 for a more extended discussion on what is currently done to reduce SOS set-up and running costs.

Performance is the result obtained during the execution of a task; in the context of SOS this can be translated in the type of science that is accessible. Ways of increasing performance include:

- Increasing the data volume (e.g. for better statistics – for instance, the higher the amount of measurements of dynamic targets, such as the interplanetary medium boundaries, the better will be the understanding of the generation and/or the evolution of those targets)
- Increasing the data quality (e.g. plan more accurately the observations of targets requiring high resolution data)
- Increase spacecraft autonomy (e.g. to allow the observation of fast occurring and unpredictable events)

However, SOSs are complex structures, requiring various fields of expertise. As a consequence finding ways of continuously improving performance and productivity is also complicated. This is why we believe that a mechanism to coordinate the improvement is needed for the latter to be performed with efficiency. Such a mechanism can be developed only if its requirements are first well established. This is why we believe that it is in the interest of ESA to finance a study to identify the requirements and pertinence of such a mechanism

Therefore, we propose that the European Space Agency finances a study whose purpose will be to assess the feasibility and requirements of a cost-effective mechanism that will efficiently improve performance and productivity for future SOS.

The mechanism should have a name that is representative of its features, i.e. of its objectives and level of authority. This name will be an output of the study. Meanwhile, in this paper, we have decided to name the mechanism in conformance with what we believe the features of such a mechanism should be, i.e. a "Consultative Committee for Science Operation Systems", or CCSOS.

The Rutherford Appleton Laboratory (RAL) currently has a team of about 11 people coordinating, for the European Space Agency, the payload operations of 3 missions: Cluster, Mars Express and Double Star (the latter in collaboration with the Chinese Space Agency). Based on that experience, we would like to discuss, in this paper, the following issues:

- The study objective and implementation
- The expected key study outputs
- An example of what could be the CCSOS architecture
- An example of what could be the CCSOS output

II. Proposed study objective and implementation

Based on our experience, we believe that the study objectives should be the following:

- To identify the requirements of the CCSOS
- The cost to implement and run the CCSOS
- Whether the CCSOS is cost-effective
- The time required to implement the CCSOS and an initial date to start the implementation
- The initial list of:
  - Organisations that should support the CCSOS
  - Funding authorities

A priori, there is, no limitation on who should be involved in the CCSOS. This means that, the CCSOS could be run by organisations involved in various types of scientific missions, i.e. PI and non-PI driven missions, in order to incorporate a maximum range of expertise. Those organisations should be related not only to ESA, like the SOS ground segment elements, but also to other space agencies, European or not, to further increase the expertise.

The total cost of the study will therefore strongly depend on the number and field of competence of the partners involved. This information is currently unknown and must be an output of the study. We therefore believe that it is necessary to split the study into three phases. One of the outputs from Phases 1&2 will be an assessment of the cost of the following phase. We believe that the content of the phases should be as followed:

- Phase 1: identification of the potential partners that could run the CCSOS
  This phase should include the following activities:
  - Identification of the list of potential partners
  - Assessment of the cost of the second phase
- Phase 2: assessment of the interest of each of the potential partners
  This phase should include the following activities:
  - Drafting of an initial CCSOS feasibility assessment
  - Sending of the draft assessment to each potential partner and assess with the latter, one by one, their interest and funding capabilities. This activity will require several iterations between each partner.
  - Assessment of the cost of the third phase
- Phase 3: finalisation of the draft assessment with the interested partners (involve cross partner iterations)

III. Expected key study outputs

SOS design and implementation are highly dependent on the fundamental requirements of science operations as well as on the always-evolving science objectives (i.e. the purpose) and available technology (i.e. the means). Therefore, we should expect that the CCSOS key requirements include:

- The identification of the SOS fundamental requirements
  The SOS fundamental requirements should be established at conceptual level. This means that they should be static, i.e. independent of SOS design and implementation and, subsequently, of the specific science objectives and technology. They should also be supported by the experience gained during the execution of current as well as past SOS.
- The delivery of a framework to design and implement SOS
  The framework should be dynamic. Indeed, SOS design and implementation are dependent on technology and science objectives which evolve continuously. The framework should provide guidelines to improve SOS performance and productivity. It should also satisfy the SOS fundamental requirements and, finally, determine what will be the SOS architecture, tools and procedures.
- The identification of the domains requiring further research and development to improve SOS performance and productivity; a typical example is research and development in planning tools, particularly to develop automated generic software to generate the SOP.

The SOS architecture establishes the list of the SOS sub-systems and the relationship between the latter and the ground and space segment elements. It is worth noting that ESA is currently implementing a structural modification of its ground segment by co-locating some of the SOCs at Villafranca del Castillo, near Madrid (Spain).

SOS tools are typically used to reduce the amount of human resources required, to perform tasks that human cannot do and/or to increase reliability. They are very sensitive to the progress made in various technologies including:

- Planning technology: for instance, the generic nature of a constraint based planning algorithm is a function of the categories of rules that are accessible to the users.
- Computer technology: for instance, faster computers can allow the implementation of previously prohibitive CPU consuming algorithm.

- Spacecraft technology: for instance, one can imagine that, in the future, spacecraft technology would allow for more flexibility in the choice of spacecraft trajectories; the latter would then become another planning parameter to be included in the SOP in addition to, for instance, spacecraft pointing and experiment operations.

Currently, the execution of all current SOS is done through a mixture of manual, semi-automatic and automatic processes. The relative proportion and purpose of each of the previous category of processes is constantly evolving with the complexity of the missions and available technology.

Finally, SOS procedures describe the timeline of activities that lead to the generation of the SOP.

IV. Example of CCSOS architecture

This section provides an example of CCSOS architecture that could be implemented in order to satisfy the possible CCSOS requirements discussed above. The CCSOS architecture could be built in relation with the CCSOS key requirements. This means that the CCSOS architecture could include the list of following sub-systems:

- A SOS fundamental requirements sub-system to identify and issue the SOS fundamental requirements. Its outputs could be recorded in, for instance, a paper or a book (e.g. chapter in a wider purpose book). Its implementation could include brain storming sessions with the participants being co-located or not.
- A dynamic framework sub-system to manage the evolving content of the SOS design and implementation framework. Its output could be recorded in, for instance, papers or reports. Its implementation could include:
  - one component to monitor the evolution of technology and science objective
  - one component to issue proposals (e.g. via brain storming sessions)
  - one component to validate the proposals

  The validation process is important as weaknesses or faults in the proposals are likely to be detected when using the framework to design and implement new SOS. Those problems needs to be identified and fixed. Note that they are different from well-identified maintenance issues such as bugs or upgrades of computers or commercial software. The handling of such issues can be a constraint (for instance defined in the framework) on the SOS design and implementation. For instance, the SOS implementation can include a specific sub-system dedicated to maintenance issues.
- A research and development sub-system: to identify the areas to be developed to improve SOS performance and productivity
- An administrative sub-systems to manage:
  - The content of the CCSOS variables such as:
    - The list of organisations which should support the CCSOS (e.g. the space agencies to be involved, the current SOCs and MOCs etc…)
    - The platform used to execute the CCSOS sub-system (e.g. brain storming sessions could be executed through a series of workshops)
    - The list of funding authorities
  - The CCSOS interfaces with the external bodies such as, for instance:
    - the contractual bodies to define, for instance, how to report, to get instructions or some funding
    - similar mechanisms dealing with non-scientific payload operations

V. Example of CCSOS outputs

This section provides an overview of what could be the content of the fundamental requirements that would need to be identified, by the CCSOS. This discussion could potentially be used as a starting point for the CCSOS but also illustrate the complexity inherent to the generation of SOP. Based on our extensive experience, we believe that it is possible to categorise the purpose of the SOS into the following activities:

- Generation and implementation of the planning inputs
- Generation of the SOP based on the content of the planning inputs

A. The generation of the SOP

The SOP generation can be divided into two main activities:

- The initial SOP generation
- The SOP update

1. The initial SOP generation

From our experience, the SOP is a plan which is optimised according to the planning rules (Cf. the section Planning rules below). It also requires to distinguish between the two following activities:

- A spacecraft usage plan

The spacecraft usage planning establishes the optimised science activities to be performed, called the spacecraft usage plan, which ensures that the spacecraft can support those activities (e.g. in terms of power, data return to Earth, etc.).

- A command plan
  The command planning converts the science plan into the detailed commanding for uplink to the spacecraft. It is called the command plan.

The combination of the spacecraft usage and command plans makes the SOP. The spacecraft usage plan is a timeline of operations to which is associated spacecraft usages. 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 mode or Burst mode data rates for the Cluster mission). 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 plan because they use the spacecraft usage plan as an input. 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 the spacecraft available resources etc…). The rules vary with a number of 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 X otherwise use yellow filter (relevant only if the identification of the time of the observation is independent of the region)
  - 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 switches the experiment into its observation mode (e.g. PFS on Mars Express). 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 select 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 change randomly then only a manual translation is possible. The RAL SOCs currently carry out a trade-off by performing an automated translation that can be manually adapted by the PIs.

It is worth noting that, at implementation level, this distinction between spacecraft usage and command plans should have an impact on the content of the procedures. Indeed, there is a three-phase terminology (Long-, Medium- and Short-Term planning) which is used on ESA missions to describe the gradual refinement of plans for payload operations, typically over a period of six months leading up to execution. RAL experience shows that the meaning of this terminology is mission dependent and that it would be beneficial to ensure consistency across missions and clearly identify the classes and content of the dynamic components. For instance, it may be beneficial to introduce more functional division of the SOP generation such as:

- A strategic spacecraft usage planning phase (identification of the planning rules – see Planning rules section below), where long-term trends, such as those set by orbit dynamics of the planet and of the spacecraft, are used to develop an outline plan of possible scientific activities. This plan is an excellent place to establish a framework for balancing different scientific activities because it provides the overview that can identify the best periods for each activity.
- A detailed spacecraft usage planning phase (generation of the spacecraft usage plan and of the planning data – see Planning data section below), where a viable timeline of instrument activities and resource usage (including pointing) is established. For missions such as Mars Express, because of the need to point the spacecraft in response to scientific requests, there is a strong feedback between activities and resource availability. With the current technology this requires that an iterative process is executed whereby instrument activities are added, deleted or modified until a consistent timeline is obtained. This phase can include the handling of requests to change the timeline of instrument activities in response to newly identified opportunities.
- A command planning phase, where the detailed plan is converted to time tagged commands for uplink to the spacecraft. It includes not only the derivation of commanding but also the setting of the many parameters that are independent of the detailed plan (i.e. they have no resource implications) but must be

set correctly to obtain high quality scientific data. We note that obtaining this quality is critical to the achievement of world-class scientific objectives.

2. The SOP update

It implies that the modification of the spacecraft usage plan is under control. A plan can be updated by:

- Re-optimisation of the plan, e.g. by executing a full (from scratch) or partial (i.e. repairing) re-planning. The optimisation process, currently done manually (although using software support tools) for Mars Express, has to be able to take into consideration previous operations 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 of these (i.e. a plan re-optimisation followed by an adaptation).

It is clear that the re-planning is possible only if there is sufficient time to execute it. 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, also called target of opportunities, a problem of execution etc…)

The typical condition leading to a post-optimisation adaptation of the plan, which are likely to require a re-validation of the plan, include:

- The need to fine tune an instrument's planned operation modes
- 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, currently, wants to be able to update both types of plans.

As an example of the need for a dynamic nature of the CCSOS framework content, one could imagine that, in the future, the SOP is entirely generated on-board the spacecraft. In that case, the SOS architecture would have to evolve, since on-board planning:

- Would forbid any manual intervention between the different components of the planner as currently done between the various processes executed at the different SOS ground segment elements (as the plan is not available).
- Would require not only events and times that are predicted but also derived from measurements.

B. The Planning Inputs

The SOP generation requires the SOS to input science objectives as well as the spacecraft and payload constraints; i.e. the planning rules. Planning rules relate the payload and spacecraft operations to environmental conditions when the latter occur. Therefore the SOP generation requires the timeline of events representative of the occurrence(s) of the relevant conditions; i.e. the planning data. Finally, technical information about the experiment is required to establish a link between the spacecraft usage plan and the payload activity as well as between the payload activity and the command plan. They are called hereafter the experiment data.

This is why in this section we discuss:

- The planning rules
- The planning data
- The experiment data
- Example of planning inputs usage

1. Planning rules

They are used to control the quality and validity of the SOP during its generation. They are the constraints, goals and optimisation criteria. The planning rules can be divided into the following components:

- The mission planning constraints
- The mission policy

The mission planning constraints ensure that planning respects the capability of the space and ground segments as well as the safety of spacecraft and payload. Examples of planning constraints include:

- The available power (including safety margins) of the spacecraft must never be 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 sufficient power, except during Solar eclipses, to operate the complete payload and use the highest possible downlink/uplink rate.

However, there can be more than one SOP satisfying the mission planning constraints. This is why another type of rule – the mission policy – is required to identify which of the possible science plans is to be selected. In other words, the mission policy is used to validate the SOP and to optimise the mission scientific return. Planning constraints are mostly driven by technical issues while mission policy are more driven by scientific choices. This is why mission policies are likely to evolve more frequently than the planning constraints. In any case both types of rules will evolve during the mission.

2. Planning data

They are used to generate the SOP and/or assess the feasibility of the science requests. They relate to information that is independent of the content of the SOP. Planning data which are dependent on the SOP must be assessed dynamically during the SOP generation. The typical planning data that are relevant for current orbiter missions include:

- Orbit related events
- Key space and ground segment activities
- Ground station visibility and availability
- Maximum available power variation; power variations can be due to causes that are independent of the content of the SOP such as:
  - Variations in the Sun-spacecraft distance
  - Degradation of the solar panels or batteries
  - Sun occultation
- Multi-spacecraft mission specific data

  A mission can require the multi-spacecraft co-ordination of the science operation. The planning of the operation of experiments located on more than one spacecraft is more complex but, fundamentally, no different than planning the operation on one single spacecraft. However, it requires that the SOS be able to handle the fleet of spacecraft as a single object and, therefore, concepts such as:
  - Reference spacecraft (to segment the planning periods – SOP can be optimised by segments called 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

3. Experiment data

This describes the operation of an experiment, e.g. experiment modes and attributes such as power, constraints on experiment operation, the sequences (and associated parameters) needed to command various mode transitions.

Experiment data can be static or dynamic. Static data vary rarely during the mission. They are typically the sequences required, for instance, to switch the instrument on and off. Dynamic data, on the contrary, are data which vary frequently. A good example of dynamic data is the MARSIS experiment on-board the Mars Express orbiter. For MARSIS, command sequences have nothing to do with its resource usage, except in a very indirect way. MARSIS is a table-driven instrument. The sequences first load data into tables where the data specifies a relative time-line of observations (i.e. using some generic load-data-into-memory sequences, with start address and data values as parameters). The final sequence tells MARSIS when, in the future, it should start execution. The relative time-line contains details that match the resolution of the radar to the scale-size of surface features being probed. So those details must be derived with knowledge of both instrument performance and target regions. The PI team has models to do this. The execution start time is provided by the PI as offset from pericentre and converted to UTC by the MOC just before uplink, using latest orbit predictions. So the resource usage is determined by the details of the data uploaded to the instrument.

4. Example of planning inputs usage for PI driven missions

At detailed level the content of the planning inputs are mission type dependent. Table 1, below, provides two examples of such dependencies.

Components	Issues	Cluster	Mars Express
Planning rules	Pointing constraints	Not Relevant	Relevant
Experiment data	Dynamic data	Not Relevant	Relevant
Planning data	Multi-spacecraft coordination	Relevant	Not Relevant
	Earth occultation	Not Relevant	Relevant
	Distance to the Earth (e.g. to calculate the one way light travel)	Not Relevant	Relevant
	Maximum available power variations	Relevant	Relevant

Table 1: Example of planning inputs relevance for the Cluster and Mars Express missions

The SOS architecture establishes a relationship between the ground segment elements and the SOS sub-systems. **Table 2** below provides an overview of such the current ESA SOSs relationship:

		PIs	**SOC**	**MOC**	**FD**	**GS**
Generation and Implementation of the Planning Inputs	Planning rules	X	X	X	X	X
	Planning data	X	X		X	X
	Experiment data	X		X		
Generation of the Operation Plan		X	X	X	X	X

Table 2: Overview of the current relationship between the ESA SOS ground segment elements and sub-systems.

VI. Summary and conclusion

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 further develop this richness, for the current and future SOCs, and to capitalise on it, some centralised coordination is required. We believe that this coordination should take the shape of a CCSOS, run by the science operation community, whose aim will be to increase SOS performance (i.e. better quality or new science) and productivity (i.e. cost reduction).

We are therefore convinced that allocating some resources to study the feasibility of such a CCSOS is mandatory to increase the chances of improving efficiently the future SOS performance and productivity.

Finally, it is worth noting that, despite the fact that the discussion concentrates on the payload operations for scientific missions, we are convinced that many elements of this discussion should also be relevant for non-scientific missions as well.

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