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EVALUATING THE NEW CCSDS MISSION PLANNING AND SCHEDULING STANDARD: HOW TGO AND ENMAP COULD HAVE BENEFITTED FROM AN INTEROPERABILITY STANDARD FOR THE EXCHANGE OF MISSION PLANNING AND SCHEDULING INFORMATION

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Abstract

Work on the CCSDS Mission Planning and Scheduling (MPS) standard is currently nearing completion. This paper starts with providing a thorough introduction to the standard and then assesses how the upcoming MPS standard could potentially improve the interoperability of actual space missions. In this respect it will provide an evaluation of how the standard could potentially be applied in two missions currently in orbit, ESA's Mars Trace Gas Orbiter (TGO) and DLR's Earth Observation mission EnMAP. In the meantime, an additional evaluation of ESA's OPS-SAT mission has become available and has been included in the paper.

As part of the analysis, first the most relevant interfaces of each mission will be described. It is then discussed how these interfaces could potentially be mapped onto CCSDS MPS service operations. Finally, it is assessed what would be the advantages of this new approach and where project-specific challenges remain. In addition, shortcoming will be identified, either with the MPS standard itself or in general with related CCSDS standards that are applicable to the mission ground segment.

Acronyms

CCSDS	Consultative Committee for Space Data Systems
CNES	Centre National d'Etudes Spatiales (French Space Agency)
DIMS	Data Information Management System
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Space Agency)
ESA	European Space Agency
ESAC	European Science and Astronomy Center
FDIR	Failure Detection, Isolation and Recovery
FDS	Flight Dynamics System
FOS	Flight Operations System
FTP	File Transfer Protocol
MAL	Message Abstraction Layer
MATIS	Mission AuTomatIon System
MO	Mission Operations
MOC	Mission Operations Center
MOS	Mission Operations Segment
MPS	Mission Planning and Scheduling
MPSS	Mission Planning and Scheduling System
MTP	Medium Term Plan
PGS	Payload Ground Segment
PI	Principal Investigator
POR	Payload Operations Request

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SOC	Science Operations Center
STP	Short Term Plan
TGO	Trace Gas Orbiter
TLE	Two Line Element
UML	Unified Modeling Language
XML	Extensible Markup Language

1. Introduction

In 2015, the CCSDS [1] Mission Planning and Scheduling (MPS) Working Group was initiated, with the aim to define a mission planning interoperability standard. As a first step, the mission planning concepts and interoperability use cases were collected, based on a wide variety of existing missions available at the CCSDS member agencies. The results have been published in 2018 in the MPS Green Book [2]. This Green Book is an informative document that provides the relevant inputs to the eventual MPS standard, to be published in the MPS Blue Book.

Early evaluations of the standard during its development have been made in [15] for the EDRS Link Management System, and also in the scope of ESA's OPS-SAT mission, further described in section 5.

Now the MPS Blue Book specification is in an advanced stage, with the standard currently being completed and the publication pending the final review and approval by the CCSDS member agencies. In order to verify that the standard is complete and correct, ESA and DLR have independently implemented prototypes to demonstrate the interoperability aspects. However, to validate the applicability and usefulness of this standard in actual space missions, a qualitative evaluation of the standard is performed here, based on two missions currently in orbit, ESA's ExoMars Trace Gas Orbiter (TGO) and DLR's Earth Observation mission EnMAP.

2. Overview of the CCSDS Mission Planning and Scheduling standard

This section will provide a brief summary of the current MPS specification. A more detailed description of the specification, including the underlying mission planning concepts, is provided in [3].

The proposed standard is intended to support a wide variety of space missions and interoperability use cases, in line with mission planning concepts typically found in space missions, see also [2]. It is based on an Information Model defining all the data structures, which form the basis for the information exchange by means of the MPS Services.

Although the full standard including the Information Model and Services Specification is quite extensive, for missions adopting the standard it is possible to limit the scope of the implementation. Only a core set of the data structures of the Information Model is mandatory; optional data structures do not need to be supported in a mission. In addition, an entity is free to support any of the Services defined in the standard. For each Service, only a limited number of operations are mandatory, defined with the Service capability sets.

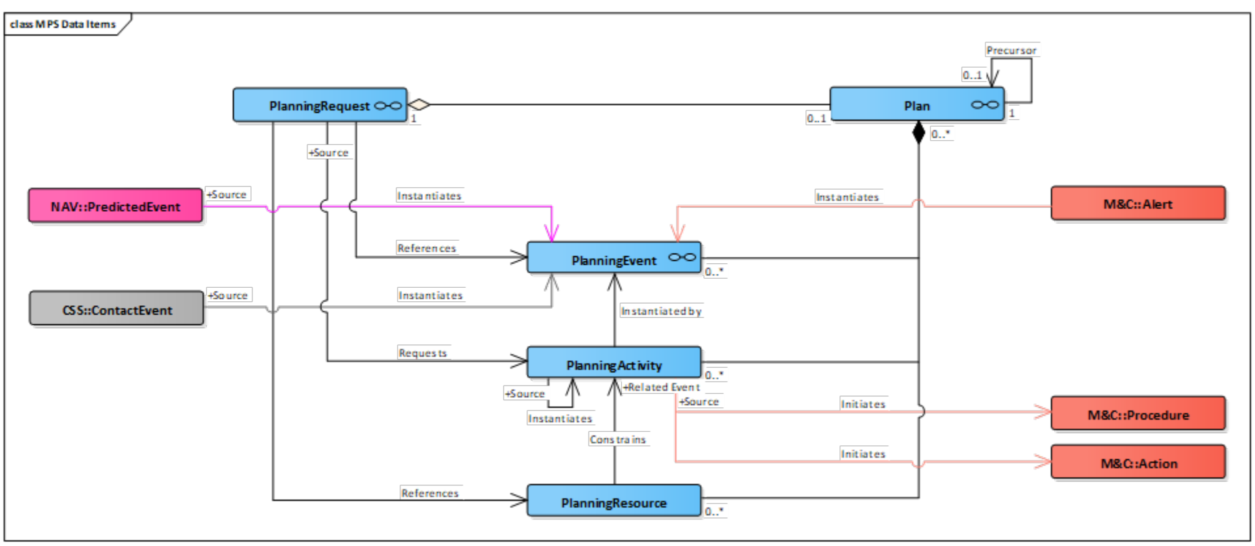

Fig. 1: MPS Data Items

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2.1 MPS Information Model

The MPS Information Model forms the basis for deriving the information exchange between the different entities in a typical space mission ground segment. The Information Model is as such not used to enforce the internal data representation in existing or new Mission Planning systems adopting the MPS standard, but is merely used to derive the detailed data structures used as arguments to MPS service operations.

A high-level overview of the MPS Information Model is given in Fig. 1 above. This shows the principal MPS data items and their interrelationships using standard UML notation. The rectangles in the diagram correspond to standard data items. The lines between them define the relationships between those data items. Mission Planning data items are shown in blue.

The following principal MPS data items are shown in Fig. 1:

- **Planning Requests**. Planning Requests are the main input to the planning function. A Planning Request is a container for the information needed to be exchanged between the requester and the planner. It supports the specification of a request to plan one or more planning activities. Alternatively, it can support a request to use an existing Plan (already containing a number of planning activities) as an input to the planning process. It can constitute a one-off planning request, or request the repetitive planning of activities as a "standing order".
- **Plans**. The Plan is the output of a planning process. The Plan is a container of one or more selected planning activities, optionally associated to planning events. In addition, the usage of planning resources may be contained in the Plan. The Plan may contain specific information from the planning process, which applies to the Plan as a whole. In hierarchical and distributed planning concepts, the output of one planning function could be the input of another one. As such, a planning request could refer to an entire Plan.
- **Planning Activities**. A Planning Activity is the basic building block for the planning: a meaningful unit of what can be planned. As such, it has to be understood by the planning function. It could eventually be translated to something that can be executed by a plan execution function; this includes telecommands and automation procedures (that may represent any automated telecommand sequence, operational procedure, on-board control procedure, or function).
- **Planning Events**. A Planning Event marks when a condition is being met. It is not envisaged to use it to express a condition itself, but rather to express the fact that it is fulfilled. Typical conditions, for which events are used to report their fulfilment, are temporal or positional. They may be used to represent predicted or planned events, such as predicted orbital events or planned periods of contact with a spacecraft, which are typically received as an input by the mission planning function, from an external function, such as Navigation.
- **Planning Resources**. A Planning Resource is an abstract status, modelling the state of the system being planned. It may be necessary to model some aspects of system state in order to either trigger the execution of a Planning Activity, to constrain the execution of a Planning Activity, or to define the effect that the execution of a Planning Activity has on the Planning Resource. A Planning Resource is in effect a value of defined type that can evolve over time. A Resource Profile can be used to capture and communicate that evolution over time in the context of a Plan.

In addition, supporting MPS data types are defined, such as Base Data Types, Expressions, Arguments, Constraints, Triggers and Repetitions. Planning Configuration Data is the set of identity and definition objects that together define the set of available data items that can be referenced in Planning Requests and Plans. This configuration data must be available to both communicating parties that exchange planning requests and plans. The transfer of planning configuration data to planning or plan execution functions is outside the scope of the current MPS services.

2.2 MPS Service Specifications

The following MPS Services have been defined:

- **Planning Request Service**. The Planning Request Service is offered by the planning function of an MPS system to enable its users to submit, cancel and modify planning requests, as well as to receive feedback on their status. The service may be used by another planning function in a hierarchical or distributed MPS system, or by an MPS system user. Planning Requests may contain parameters, which may include a set of requested Planning Activities or a reference to an existing Plan (the output of a Planning function in a hierarchical or distributed MPS system).
- **Plan Distribution Service**. The Plan Distribution Service is offered by the planning function of an MPS system to enable its users to obtain the Plans output by it, as well as to receive feedback on their status. The service may be used by another planning function in a hierarchical or distributed MPS system, or by an MPS system user. The service does not provide the capability to control the planning function itself or to generate plans. Submission of Plans to a plan execution function is supported by the Plan Execution Control Service.

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- **Plan Execution Control Service**. The Plan Execution Control Service is offered by an MPS system plan execution function to enable its users to submit (and revoke) Plans for execution; to control their execution at Plan, Sub-Plan and Activity levels; and to receive feedback on their execution status. The Plan Execution Control Service may be used by a planning function, or by an MPS system user responsible for mission operations.
- **Plan Information Management Service**. The Plan Information Management Service is offered by the planning function of an MPS system to enable its users to list and retrieve available definitions for MPS data items, including: planning requests, planning events, planning activities, planning resources and MPS system configuration data. The service may also be offered by a plan execution function. The service does not support the transfer of planning configuration data to planning or plan execution functions, which is outside the scope of the current MPS services. Nor does it support the insertion or modification of MPS data item definitions.
- **Plan Edit Service**. The Plan Edit Service is offered by an MPS system plan execution function to enable its users to modify Plans that have already been submitted for execution. It allows an external user or function to update the status of the Plan, insert, modify or delete planning activity and event instances, update the value of resources, and apply a time shift to a Plan. This may be used for example by expert mission operations users in a non-nominal operational scenario to modify a Plan that is executing or about to execute in order to avert or recover from a failure.

Each service comprises a set of operations that the service consumer can invoke on the service provider. Service operations reference the data structures defined in the MPS Information Model described above.

The MPS services and data types are defined independent of any specific language binding and independent of the lower-level transport protocols and message encoding mechanisms. These parts of the MPS Services protocol stack follow the concepts described in the Mission Operations (MO) service framework [4] and in the Message Abstraction Layer (MAL) [5].

2.3 File Based Exchange

In support of legacy planning systems not able to support services, the MPS standard also envisages the exchange of planning information solely by means of data messages, based only on the MPS Information Model data structures, in particular with the Planning Request and Plan data structures. These data messages can then be encoded in (XML) files and exchanged by any file transfer means (e.g. FTP or email).

3. Evaluation of the MPS standard using ESA’s TGO mission

In this section a comparison will be made between the current implementation of the mission planning systems of ESA’s TGO mission, and the case where the interactions between these systems would have been realized using the upcoming MPS standard. Based on this comparison, the potential benefits and potential drawbacks of using the MPS standard will be identified.

3.1 Mission background

The ExoMars TGO spacecraft performs scientific observations from 400km above the Martian surface while also providing relay support to landed assets on the Mars surface. TGO entered its nominal science phase in April 2018 for an initial duration of 1 Martian year with further extensions approved to provide relay capabilities for the European Space Agency surface assets scheduled to arrive in the late 2020s within a reconfigured ExoMars programme. The TGO Science Operations Centre (SOC) is located at ESA´s European Space Astronomy Centre (ESAC) near Madrid and is responsible for coordinating the science planning activities with scientists based at institutes that provided the scientific payloads and the Mission Operations Centre (MOC) in Darmstadt, Germany.

3.2 Current mission planning concepts and planning system interfaces

The science operations approach on TGO is driven by the mission’s repetitive survey nature combining a high volume of frequently repeating science observations with precise targeted imaging. To cope with an order of magnitude more observations than previous missions, the science planning is constructed following repetitive patterns of measurements designed to satisfy mission goals over an extended time-period that must be interleaved with exclusion windows identified by the Mars relay community to provide a high fraction (around 50%) of the total data relay from Mars.

To execute the above strategy the TGO operations concept relies on a centralized science planning process to interleave a conflict free payload observation timeline with data relay slots. The SOC receives the requested relay slots from the MOC, then generates a baseline plan applying the strategy agreed with the instrument teams, ensuring only compatible observation types can be scheduled in parallel to data-relay operations. This baseline schedule is provided

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to the instrument teams as an event file to proactively avoid conflicts due to pointing, resource limitations or conflicting spacecraft activities and covers a time-period of 4-weeks that correspond to the TGO medium-term planning (MTP) cycle. The baseline schedule also freezes the pointing request file for the full MTP, including all pointing requests derived from the science observation definitions, the required pointing for the relay slots and the necessary spacecraft wheel off-loading slots to remain within momentum management constraints. The final pointing request generated by SOC is an xml file validated using a web-service provided by flight dynamics before submission to the MOC.

The instrument teams update their detailed payload commanding via instrument timeline files that span the 1-week short-term planning (STP) duration. The commanding updates are validated to respect the timing of activities provided through the science event file, maintaining synchronization with the pointing request, and the data-volume budget provided by SOC in the minutes of the planning coordination meetings. The SOC generates a set of Payload Operations Request (POR) xml files that containing the instrument telecommand sequences.

As the TGO orbit is actively controlled, the planning is mostly robust to changes between the long-term orbit prediction and the final orbit determination. Any small offsets in absolute time are compensated by generating the operations requests relative to a selected orbital event (the nearest Mars ascending node), for subsequent resolution to absolute time by the MOC based on the final orbit determination before uplink to the spacecraft. The only exception is for high-accuracy imaging which needs to update the timing of images at parameter level based on the STP orbit determination, requiring an extra iteration between the SOC and the PI team once the flight dynamics event file is available.

3.3 Mapping existing interfaces to the new MPS standard

As the TGO SOC was established with very little lead-time before the start of the operations phase, many aspects of the operations concept, science planning processes and interfaces were adapted from previous missions established over a decade earlier, and as a result the interactions are mostly file-based with a more evident mapping to the MPS file-based exchange, with selected examples given in the following sections:

3.3.1 File-based interfaces

The following file-based interfaces are available in the TGO SOC:

- **Relay slots**. To be considered as exclusion windows for SOC to avoid scheduling science observations with incompatible pointing. The relay slots are currently provided as event pairs by the MOC, and the exclusion constraint is passed via documentation. MPS file-based exchange could transmit this information via the MPSPlanFile/Event Instances and the MPSPlanFile/Constraints.
- **Communications Passes**. provided as event pairs by MOC, with a SOC subscription to automatically retrieve any updates to this filetype. File-based request of this information can be provided using the MPSPlanFile/Event Instances. Subscription to receive the updated event file is covered by plan distribution service/monitorPlan (see services below)
- **Bitrate File**. Provided by the MOC as a chronological set of bitrate steps for the entire mission. Covered by Resource Profiles contained under MPSPlanFile structure. Each step in the bit-rate file can be represented as a Resource Profile Segment.
- **Ingestion of Flight Dynamics Events**. The SOC generates the final commanding resolved to the nearest Mars Ascending Node (MASN) event. This information is currently provided the Flight Dynamics over the MOC data dissemination System (EDDS) to provide the absolute time of the events following the last orbit determination, with a SOC subscription to automatically retrieve any updates to this filetype. An MPS file-based approach to provide this information maps to the MPSPlanFile/Event Instances.
- **Propagation of Flight Dynamics Events**. A sub-set of the Flight Dynamics Events, required by the camera team to update the timing parameters for image acquisition.
- **Pointing Request**. The Pointing Request (PTR) file contains a set of pointing blocks that are requested for implementation by the Flight Dynamics team. These pointing blocks are expected to be compatible with the CCSDS Pointing Request Message (PRM) standard from the Navigation Working Group, which is incorporated into the MPS standard.
- **Commanding**. Independent sets of parameterized telecommand sequences, each request file spans 1 week and dedicated to one payload and contains the expected resource profiles for power and data-rate. The Payload Operations Request (POR) files can be mapped to the MPSPlanFile/List of Activities and MPSPlanFile/Plan Resources.

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3.3.2 Potential Migration to MPS services

The unexpected delay of the ExoMars Rover mission will mean that TGO will likely remain in operations until the start of the next decade, and manual processes will increasingly be phased-out to be replaced by automated services where possible. The most obvious candidate for migration to MPS services would be the distribution of events from MOC to SOC (relay events, flight dynamics events), and the further distribution of the subset of flight dynamics events from SOC to the camera team. Event distribution could be handled via the Plan distribution service, PDS/monitorPlan.

3.4 Identified benefits and limitations of the MPS standard

Both the potential benefits and the perceived limitations of the MPS standard are described below:

3.4.1 Potential benefits of the MPS standard

The long lead-in times required to follow a robust TGO operations process that was built on concepts inherited from legacy missions, i.e. that accommodates manual processes executed at each of the planning centers with frequent interactions via file exchange, has an impact on mission performance. For example, planning bottlenecks in the TGO operations process do not allow the latest orbit determination to be used for the image acquisition timing parameters resulting in a loss in prediction accuracy and a degradation of the science data. Moving to the MPS services would drastically reduce most of these margins, allowing for timely propagation of the plan updates and improved targeted imaging accuracy. TGO also participates in coordinated observations with other Mars missions and would obviously benefit if interactions between planning centers followed the same standard.

3.4.2 Limitations of the MPS standard

The TGO planning concept is based on high level segmentation of the mission and synchronization on a set of measurement definitions and robust rules for their inclusion in the planned series of observations. Currently this is achieved before the start of the planning activity through synchronization on a common set of definitions and a framework for plan refinements, effectively configuring the planning entities involved in science planning (the SOC and the various instrument team operations centers) to operate on a common baseline. As previously mentioned, the standard does not currently support the transfer of planning configuration data to planning or plan execution functions.

4. Evaluation of the MPS standard using DLR's EnMAP mission

In this section a comparison will be made between the current implementation of the mission planning systems of DLR's EnMAP mission, and the case where the interactions between these systems would have been realized using the upcoming MPS standard. Based on this comparison, the potential benefits and possible drawbacks of using the MPS standard will be identified.

4.1 Mission background

EnMAP was launched on 1 April 2022. It is a low-Earth orbiting mission carrying a hyper-spectral instrument for monitoring the Earth “in more than three colors” providing the scientific community with data of the state and evolution of the earth's surface and in particular its eco-systems. For instance, the vegetation and its conditions such as moisture and nutrition balance can be identified and monitored.

From its orbit in 640km height, the EnMAP instrument has a resolution of 30m, an image width of 30km and a maximum swath length of 1000km. For envisaged applications, images require sun light and a looking angle of less than 30° (the smaller the better), see [6] and [7]. To achieve best results, the EnMAP planning system includes cloud forecast, cloud statistics and sun-glint predictions which are applied in the planning algorithms, see [8] and [9].

The EnMAP mission aims to provide data to the scientific community. Rather than serving a single paying customer, scientists need to submit a proposal and pass a review process, before their requests are considered, see [10] and [11]. It is to be expected that in many cases, existing data already fulfils the requester's needs. In this case, data from the archive may be delivered to the scientist immediately. Only if new data is required, a new acquisition request is forwarded to the EnMAP Mission Planning System.

4.2 Current mission planning concepts and planning system interfaces

The EnMAP Mission Planning System (MPS) is based upon GSOC's generic Reactive Planning Framework which supports maintaining an up-to-date timeline. In particular, if a new acquisition request is received, an incremental planning run is performed immediately to add the request's acquisition to the timeline. The same happens for any other type of input, details see [8] and [9]. In the following, all interfaces are analyzed regarding whether and how they could have benefitted if the CCSDS MPS service specification had already been available during the design of this mission and its subsystems.

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4.3 Mapping existing interfaces to the new MPS standard

The interfaces of the EnMAP MPS with the Mission Operations Segment (MOS) and with the Payload Ground Segment (PGS) is depicted in Fig. 2 below:

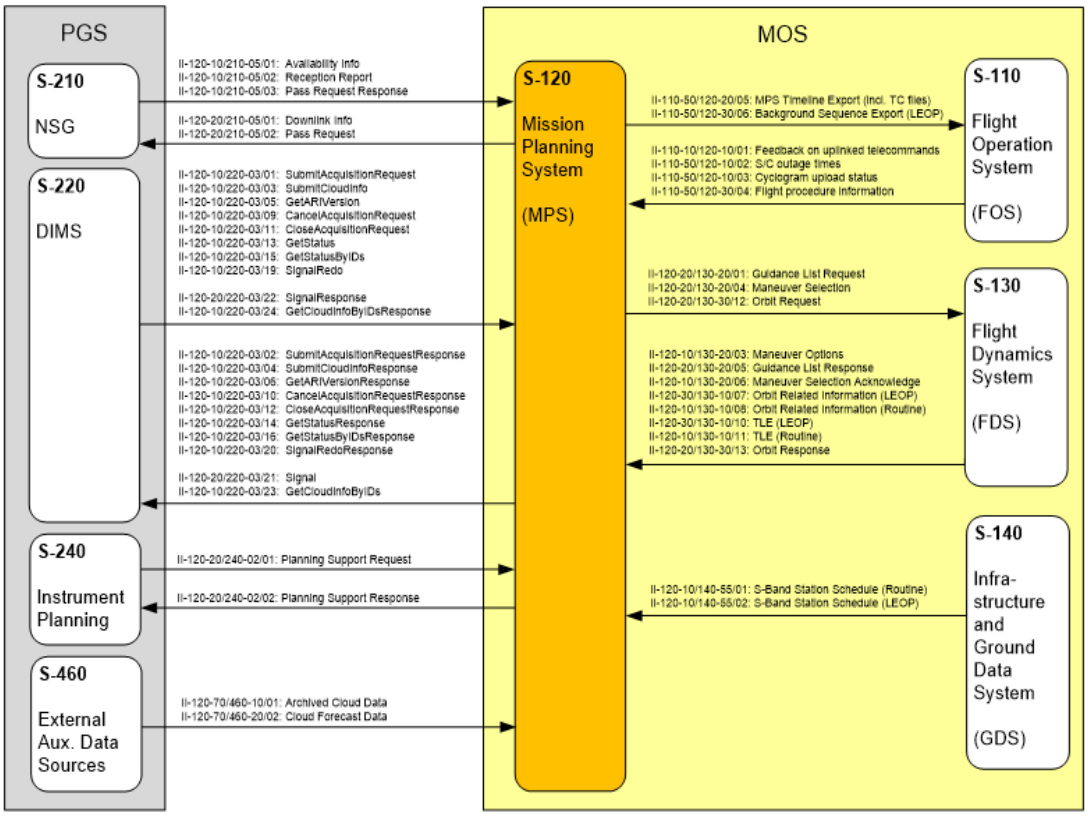

Fig. 2: Interfaces of the EnMAP MPS within the Mission Operations Segment and Payload Ground Segment

4.3.1 Acquisition Request (Submit, Cancel, Close), Status Request, Acquisition Request Status (Signal)

Acquisition Requests (requests to take an image) are transmitted from the interface partner DIMS (Data Information Management System) to the EnMAP MPS via a web-service (based on SOAP). This interface has been copied and adapted from the TerraSAR-X mission (see [12]). In contrast to the TerraSAR-X mission, in case of corrupt data (e.g. a clouded image), a re-do may be triggered to repeat the acquisition during an alternative opportunity. For each status change (e.g. PLANNED, UNPLANNED, COMMANDED, EXPIRED), the respective information is transmitted via a web-service "Signal" to DIMS. In case DIMS needs an update of its database, it may send *Status Requests* in order to trigger the re-export of the status of dedicated Acquisition Requests.

Using the CCSDS-MPS Request service, this interface could be implemented as follows:

- Transmitting a request: EnMAP MPS Planning Request Service – submitRequest operation
  Note that here, the response would only contain an acknowledge of the successful reception of the request, not yet the planning status.
- Receiving updates on a request's status: EnMAP MPS Planning Request Service – monitorRequestStatus
- Triggering a re-export of a status: EnMAP MPS Planning Request Service – getRequestStatus

This interface could be implemented directly using the CCSDS MPS Planning Request service, however only parameters would need to be transmitted within each request, because all information about how the request details should look like are strictly predefined by the type of acquisition within the MPS planning system.

Even for calibration requests, which are also transmitted as acquisition requests, no flexibility in execution shall be supported: If a modification of a certain calibration type is required, the adapted sequence first needs to be validated and only then an update of the model is implemented, and then is available for requests. In any case, the sender of the

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request shall not have the capability to modify the resulting command procedure directly, except via the foreseen, predefined parameters of the request. Within EnMAP, requests may be canceled. For this purpose, the standard defines a dedicated service operation *cancelRequest* within the Planning Request Service.
In addition to canceling, EnMAP allows DIMS to *close* a request, indicating that it will no longer send any status query for this request, allowing the EnMAP MPS to remove the request from the model. This is considered mission-specific and has no corresponding operation within the CCSDS MPS standard.

4.3.2 Outage Requests

To block the timeline for manual operations, members of the Flight Operations System (FOS) may ingest an outage request.

This interface could be implemented using the CCSDS MPS Request service:

- Transmitting a request: EnMAP MPS Planning Request Service – submitRequest
- Receiving updates on a request’s status: EnMAP MPS Planning Request Service – monitorRequestStatus

4.3.3 Orbit correction maneuver

The EnMAP Flight Dynamics system (FDS) sends a *maneuverOptions* message file to MPS, if a maneuver has to be planned. The *maneuverOptions* may contain multiple alternative *maneuvers*, one of which has to be planned by MPS depending on when it fits best the timeline of ground observations. For a collision avoidance maneuver, this *maneuverOptions* may contain just one *maneuver*, which then is considered mandatory. After planning one *maneuver* of the *maneuverOptions* message, MPS sends a *maneuverSelection* message file, informing FDS about the selected *maneuver*, so that their system can initiate further necessary activities.

ManeuverOptions can be transmitted via the Planning Request Service:

- Transmitting a *maueuverOptions*: EnMAP MPS Planning Request Service – submitRequest
- Inform about the selected *maneuver*: EnMAP MPS Planning Request Service – monitorRequestStatus

4.3.4 Uplink Station Interface

The GSOC Scheduling office informs the EnMAP MPS about available uplink contacts via the *schedule.xml* file. Although it is clear, that there exists another dedicated CCSDS standard for covering such an interface [Reference to CSS standard], another solution would be to transmit that information via the Plan Distribution Service:

- Transmitting the schedule.xml file: Scheduling Office Plan Distribution Service – monitorPlan

4.3.5 Downlink Station Interfaces

The Neustrelitz ground station (NST) sends an *availability info* file to EnMAP MPS, listing the contacts of EnMAP that may be used by the mission for data downlink. EnMAP MPS books contacts via *pass request* files, it receives the booking confirmation via *pass request response* files. Just before the downlink, EnMAP MPS informs NST about the to-be-expected data via a *downlink info* file. After the downlink, NST informs EnMAP MPS about the received files via a *reception report* message.

Mapping this to the MPS services, the workflow could be implemented by the ground station implementing the Plan Distribution and Planning Request services and the EnMAP MPS making use of the following operations:

- Transmitting availabilities: Ground Station Plan Distribution Service – monitorPlan
- Transmitting pass requests: Ground Station Planning Request Service – submitRequest
- Transmitting pass request response:
    - Ground Station Planning Request Service – monitorRequestStatus, OR
    - Ground Station Plan Distribution Service – monitorPlan
- Transmitting downlink info: Ground Station Plan Execution Control Service – submitPlan
- Transmitting reception report:
  Ground Station Plan Execution Control Service - monitorPlanExecutionDetails

4.3.6 Flight Dynamics Events

To provide information when certain calibrations can take place (sun calibration and deep-space calibration) and when the satellite enters and exits the earth shadow, FDS sends MPS an *event file*, whenever a new orbit propagation has completed. Although discussions on this in the CCSDS context are not yet completely addressed, using an MPS service for the transport of this information would be possible here, too:

- Transmitting events: FDS Plan Distribution service – monitorPlan

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4.3.7 Flight Dynamics Orbit

Whenever a new orbit propagation has completed, FDS sends the new *TwoLineElement (TLE)* as a file to the EnMAP MPS. This message not only carries the information about the new orbit data (a more precise propagation is available via a web-service, so the TLE usually is not used further at all), its main purpose is to trigger the orbit update within the EnMAP MPS. That means, that the whole re-plannable, commandable future part of the current timeline is recalculated to fit the orbit again correctly. This workflow however is not specific to mission planning, but rather a general Flight Dynamics one, therefore this interface should be treated as mission-specific until a dedicated standard Flight Dynamics service provides a proper solution.

4.3.8 Guidance List

A dedicated service of FDS provides the *Guidance List*, i.e. a set of hundred quaternions describing the evolving target orientation for the satellite during an acquisition and during a downlink. Such a type of information is necessary for other missions' purposes as well, such as the "guidance"/trajectory of optical communication terminals, however this also is not a topic of Mission Planning; instead, this might also be covered by a standard Flight Dynamics service in the future.

4.3.9 Command Timeline

Before each uplink passage, the EnMAP MPS extracts the to-be-uplinked commands from the master timeline into a dedicated command timeline, which is exported as a sequence of parametrized Flight Execution Procedures and sent as a file to the command system within the Flight Operations System (FOS).

Currently the command timeline is an addendum to the already commanded onboard timeline. This however may change in the future if commands are uplinked covering the timeframe not only until the next but one but until the next but two uplink passage, and a re-commanding of the already commanded timeframe would have to take place then for last-minute updates.

Whereas in the first case, a full plan may be transmitted, in the second case, we need to transmit a patch plan in order to indicate to FOS which commands to add to and which to remove from the onboard timeline.

- Command Timeline: FOS Plan Execution Control Service – submitPlan

4.3.10 Command Feedback

After each uplink, a command feedback informs the EnMAP MPS about the commands which have been successfully sent to the spacecraft and those which failed to be uploaded. In the latter case, the EnMAP MPS automatically adapts the timeline accordingly to reflect the actually upcoming onboard operations and their effects, e.g. regarding the resources to be monitored and considered in the future planning process.

This information could be transmitted if the Flight Operations System (FOS) implemented the Plan Execution Control service:

- CommandFeedback: FOS Plan Execution Control Service – monitorPlanExecutionDetails

However, as long as this remains a purely GSOC internal interface for both partners, we probably will not convert it to a standardized CCSDS interface.

4.3.11 Planning Support

The frontend 'Instrument Planning' requires the latest target visibility prediction in order to provide a comfortable and reliable interface to the end user. This interface is served by a dedicated MPS component at GSOC, the SCOTAService [14]. However, considering a more generalized breakdown of responsibilities and functionalities, it is rather a Flight Dynamics interface than a Mission Planning service and therefore has no mapping to CCSDS MPS service operations.

4.3.12 Cloud Data

Both, archived cloud data and cloud forecast data, are specific to the cloud prediction functionality within the Reactive Planning framework of GSOC and have no correspondence within the CCSDS MPS services.

4.4 Identified benefits and limitations of the MPS standard

As described above, a majority of the interfaces to and from the EnMAP MPS could be covered using CCSDS MPS service operations. Most of these however have not been invented from scratch for the EnMAP mission but have been copied from existing missions, in particular from the TerraSAR-X/TanDEM-X missions (see [13]). We therefore had only little effort to implement these adapted interfaces. For future missions however, a standardized interface would provide this benefit for both interface partners, even if they do not yet know each other. Besides, even if the

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interfaces had been quickly agreed upon and implemented, there are many of them. Saving a few days on each of them may still sum up to a significant amount. Furthermore, quite a lot of interfaces are still file-based. When replacing these with a service-based architecture, migrating to the CCSDS MPS standard might even save additional effort, due to the fact that an implementation of the MAL (see [5]), on which the CCSDS MPS standard is based upon, is already available for Java and C++.

In contrast, it is obvious that still some of the main generic interfaces of a regular Earth observation mission are not yet fully specified as services within the CCSDS system architecture and that therefore still gaps and ambiguities exist regarding which standard specification to use. Other CCSDS services in turn do not rely on the MAL, which again limits the ad-hoc applicability of the whole architecture. Here, the process of finding solutions for overall systems via CCSDS is currently not available.

Another aspect to consider is the following: although different services and operations of the standard would be used, only a limited part of the information model would be applied within the EnMAP mission. In particular, none of the CCSDS constraints is relevant for EnMAP, because only validated procedures are allowed to be used and all planning rules were required beforehand and are implemented within the planning system and its configuration capabilities. Any remaining flexibility for the requests therefore can be modeled by pre-defined parameters, leaving the definition and propagation of constraints completely to the planning system. Additionally, due to the centralized planning approach, there exists no need to define requests which include plans. So, implementing the whole range of a Service specification including all options for the service operations could mean a big overhead in comparison to what is really needed for a dedicated "conventional" Earth observation mission with an operations approach, design and system architecture as for the EnMAP mission. The mission, and thus interface partners, would have to do a thorough analysis and find agreements on a tailoring in terms of which services and which Service capability sets shall be used and are expected to be served/requested by the respective interface partner, as described in section 2 and the standard's Blue Book. The same applies for the content of the operations' message contents, which optional/nullable operations or message contents will be used or not. This then limits the effort for integration testing, and/or even implementation in case the involved applications of the interface partners had not yet implemented the CCSDS standards already beforehand, but start with that for preparing a certain mission.

However, this of course is viable, and the main purpose to provide interoperability and thus realize interaction as quickly as possible would be fulfilled anyway first when having involved subsystems already supporting the standardized services somewhen in the future. For now, it is good know that in principle most of the non-specific or internal interfaces of the EnMAP MPS could be mapped to CCSDS MPS service operations, and to have identified where decisions within our own control center for the future generic system architecture, but also clarifications and extensions within the overall CCSDS landscape are still needed and have to be agreed upon in the future.

5. Evaluation of the MPS standard using ESA's OPS-SAT mission

In this section a comparison will be made between the current implementation of the mission planning systems of ESA's OPS-SAT mission, and the case where the interactions between these systems would have been realized using the upcoming MPS standard. Based on this comparison, the potential benefits and possible drawbacks of using the MPS standard will be identified.

5.1 Mission background

OPS-SAT is a 3U CubeSat launched by ESA on 18 December 2019. It is the first nanosatellite to be directly owned and operated by ESA. The spacecraft is a flying platform that is easily accessible to European industry, institutions and individuals, enabling rapid prototyping, testing and validation of their software and firmware experiments in space at no cost and with no bureaucracy. The spacecraft is equipped with a full set of sensors and actuators including a camera, GNSS, star tracker, reaction wheels, high speed X-band and S-band communication, laser receiver, software defined radio receiver and an 800 MHz processor with a reconfigurable FPGA at its heart. Conceived to break the "has not flown, will not fly" cycle, OPS-SAT has spearheaded many firsts, both internally in ESA [16][17][18] and for external experimenters [19][20][21].

Currently OPS-SAT has 236 registered experimenters, every day multiple new experiments are scheduled and executed on-board. This experiment-centered approach forms the concept of operations and the mission planning activities. Generalities about MO services deployed onboard OPS-SAT are described in detail in [22].

5.2 Current mission planning concepts and planning system interfaces

OPS-SAT does not have a complex constraints model, but a complex operations model instead. The operational concept depends on rudimentary FDIR, robustness of the flight model and a reliable and "safe" safe mode, which works as a preferred option in case of unpredictable problems with an experiment.

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The current mission planning concept is based on the following points:

- The planning process is complex due to multiplicity of experiments, this complexity is mainly automated by the tools. For the same reason, the planning activity is critical for the mission.
- Short planning span (1-4 days) and frequent re-planning is required due to the diversity and low predictability of experiments. For example, it is not worth to schedule a new experiment for multiple days, as it can fail already on the first run, requiring troubleshooting and a new version.
- Planning modification re-triggers the full process of MPS;
- File-based planning using the Mission AuTomatIon System (MATIS) tool;
- LEO passes give 7-9 minutes of commanding maximum per pass, with 2-3 attended passes per day. This requires very quick operations, both manual and automatic, with responsive tools capable to support this load.

In general OPS-SAT operations are based on a mixture of the execution of schedule and live manual operations (procedures) executed via MATIS or the manual TC stack. An example of the OPS-SAT 1-day planning cycle is given in Fig. 3 below:

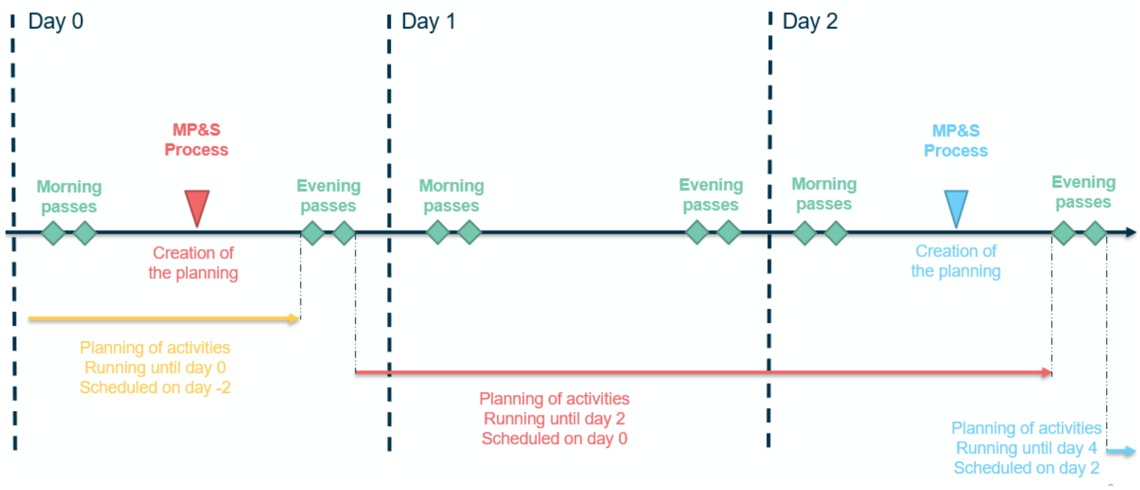

Fig. 3: OPS-SAT 1-day planning cycle

With the current mission planning process an example of the Planning Request for OPS-SAT looks as shown in the Fig. 4 below:

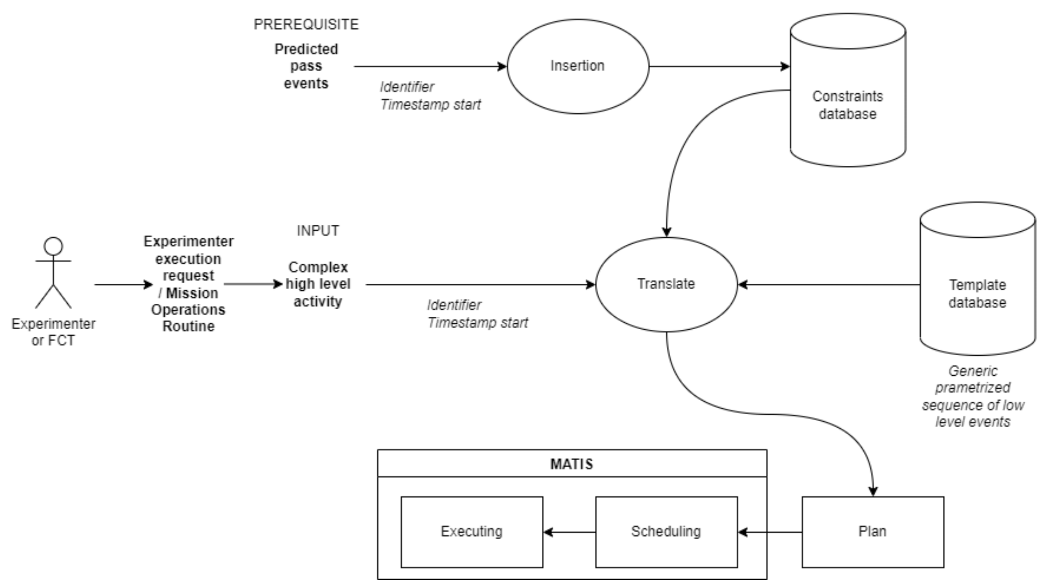

Fig. 4: OPS-SAT Current Planning Request

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The final schedule of operations is loaded into MATIS as a set of files that is resolved to absolute time on-ground using the final orbit determination. During a pass they are uplinked to the spacecraft, containing 1-4 days of operations.

5.3 *Mapping existing interfaces to the new MPS standard*

The planning process of OPS-SAT can be split into the following steps:
- Planning of activities;
- Creating the machine-readable schedule to be uplinked and executed;
- Uplink and execution of planning.

Planning of activities is described in Fig. 5. The important point to mention is that the planning input and constraints also come from experimenters and operational requirements change at a very fast pace (every two days or so). This makes a planning request a complex task to process, making a planning possible only for a few days forward due to rapidly changing mission status.

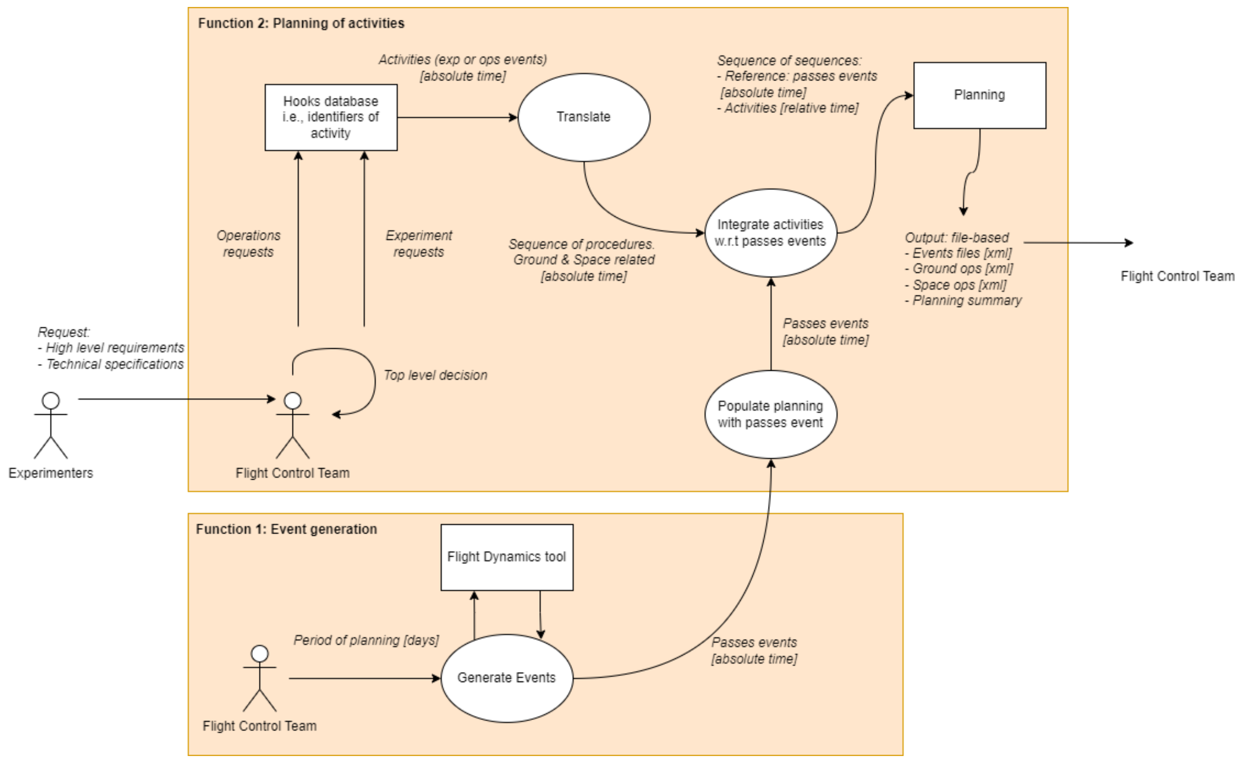

Fig. 5: OPS-SAT Planning of Activities

Opposite to planning, the scheduling in OPS-SAT means the process of creating a machine-readable schedule to be uplinked to the spacecraft as well as for ground activities, e.g. booking of ground stations. It is based on planning, the particularities are:
- The passes events timeline is expressed in absolute times whereas the activities, planned w.r.t these events, are expressed in relative times.
- The absolute time is the effective time in the end.

Several files serve as an input for this process:
- Events file: orchestration on absolute time;
- Ground operations: configuration file;
- Space operations: time tag commands;
- Summary of pass times: for human operator.

The OPS-SAT scheduling process is shown in Fig. 6 below.

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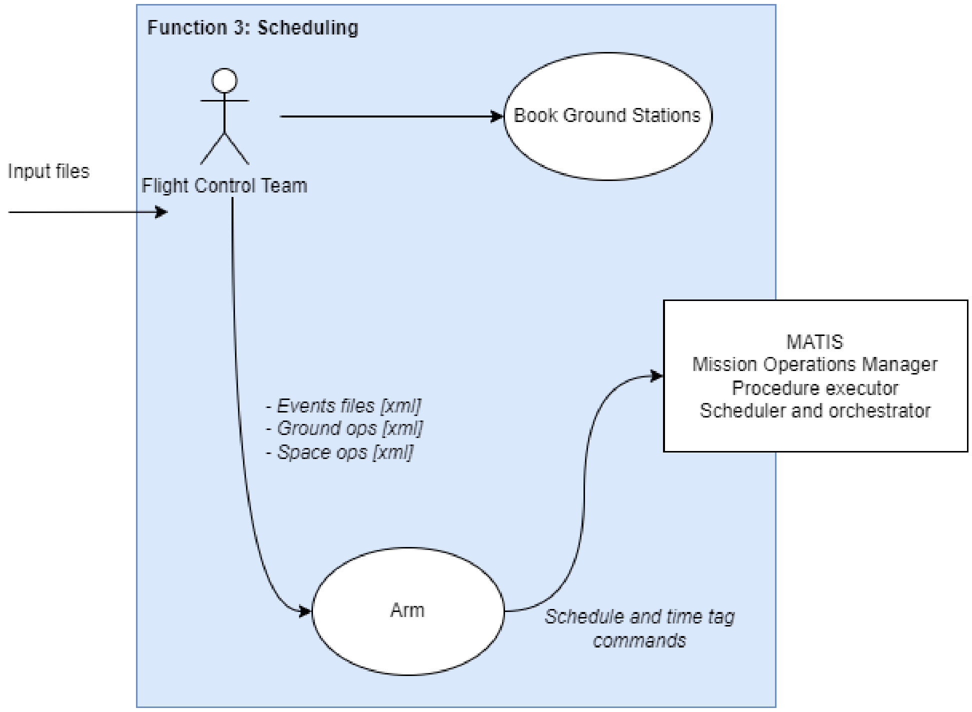

Fig. 6: OPS-SAT Scheduling Process

The final step is the executing of planning. The produced schedule is released from MATIS via SCOS as telecommands. They are confirmed on-board and re-uplinked automatically if necessary, using in-house developed MATIS procedures and scripts. Live operations are also executed via MATIS and its procedures. Real-time procedures follow the same template as the one implemented in the planning function. The process is described in Fig. 7 below:

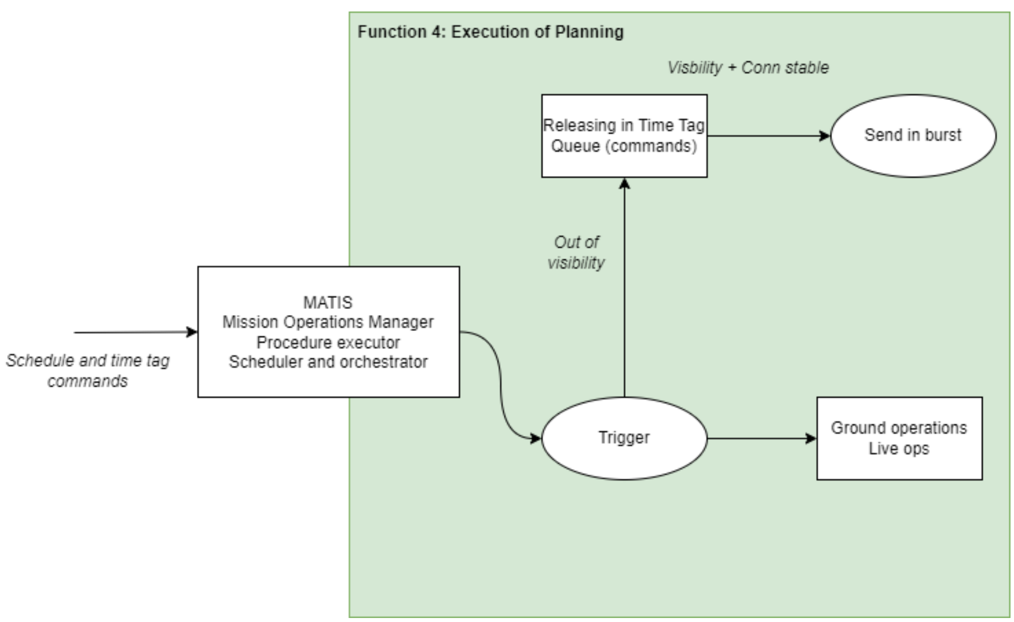

Fig. 7: OPS-SAT Execution of schedule

To compare the current situation with the new MPS standard, the planning system is almost there in terms of data and functionality. Many interfaces described in the standard would not be implemented, as the mission only needs a small subset of capabilities.

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The team has identified these main challenges for re-implementing the current MPSS in accordance with the standard:

- Even though we need a subset of MPS, the mapping is not obvious to design and implement. For instance, the Request as defined by the standard cannot be straightforward mapped into the OPS-SAT MPSS concept.
- MPSS has no service-oriented interfaces – wrapping certain actions and file-based planning inputs/outputs to a service-oriented API is not straight forward. It is possible to use the file-based backwards compatible interfaces instead.
- The current system is very centered around manual actions by operator, and difficult to automate further.
- Currently used NMF-based onboard applications already allow to expose MO MPSS interface.

Possible improvements would be a better-defined interface for Experiment Execution Request and its feedback, as it is currently done via email. Also, an automation of more Mission Routine Operations inputs (via a feedback loop from the current S/C state) would be feasible.

Complete automation of (re)planning would be difficult. Removing the operator from the decision making is not feasible (too many edge cases to take into consideration, as the system state changes rapidly). But there are compromises which can be made. Automation can address the most common anomalies. If the planning cycle is kept shorter, it could minimize discrepancies between assumed and actual state of the system.

5.4 Identified benefits and limitations of the MPS standard

An example of a very high level first step of how OPS-SAT could work towards MPS data model and interface adoption is shown in Fig. 8. It describes the complete process of scheduling a single complex activity from definition to execution.

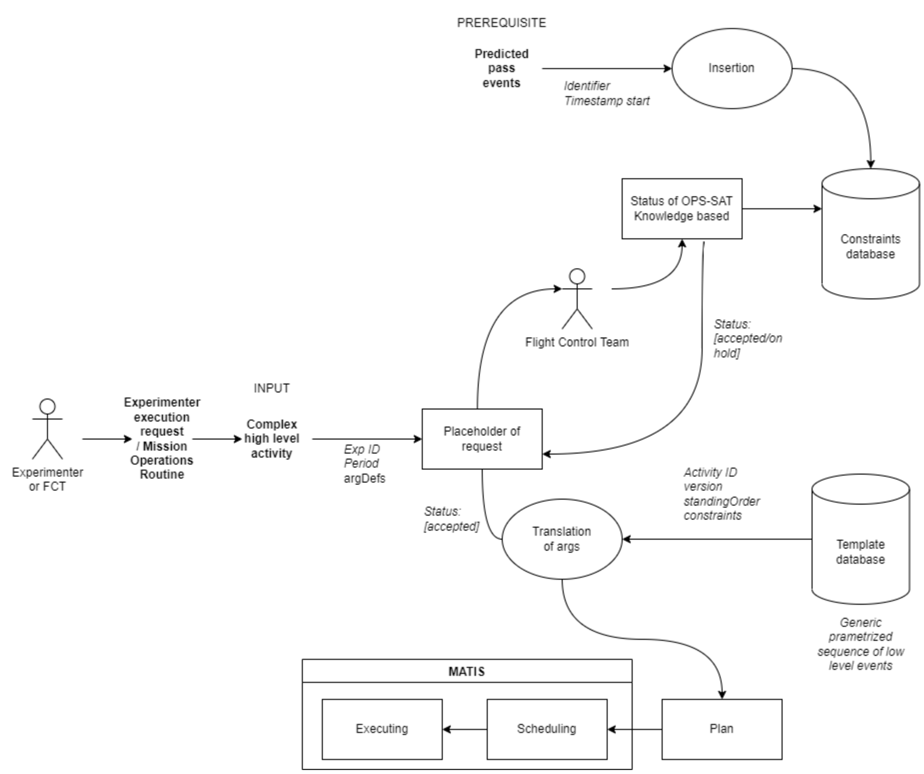

Fig. 8: OPS-SAT Planning Request in OPS-SAT using MPS

We can identify the following benefits of the new MPS-based approach for the mission:

- MPS can provide the mission with rich, formalised interfaces for interactions across the system, both manual and automated.
- If the entire planning cycle becomes MPS-compatible, it could easily integrate not only the core operations planning, but also payload application planning.

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The overall observations would be that the system design requires very in-depth study of the book to derive a sensible application. The next OPS-SAT Space Lab mission OPS-SAT-2, currently in design phase, and its derivatives could be a very good validation environment for the complete adoption of the MPS standard.

6. Next Steps

The preliminary results of the comparisons performed in sections 3, 4 and 5 above have already been taken into account in the current MPS specification and have led to generic improvements, not only to the benefit of the evaluated missions, but potentially to the benefit of any space mission wanting to adopt the MPS standard.

Currently, the MPS Blue Book is ready for review by the CCSDS member agencies. In addition, the prototyping work by two independent agencies (ESA and DLR) is ongoing. The current expectation is that the MPS standard will be available for publication during the second half of 2023.

In order to further improve the current draft standard, additional validation efforts could be foreseen, e.g. with missions of other CCSDS member agencies, or to evaluate the File Based Exchange for a specific mission such as ExoMars TGO, where some of the data contained in bespoke TGO planning file formats could be converted to the MPS File Formats based on XML, to validate some of the detailed capabilities of the MPS standard.

7. Conclusions

The clear benefit of a service-oriented standard such as MPS over a file-based approach is that it will allow for automation and a shortening of the planning cycles, as in particular valid for the ExoMars TGO mission. In addition, the MPS provides a rich set of services and related information model. Using a set of standardized services will in particular benefit missions with multiple independent or distributed entities in the ground segment, where no ad-hoc interfaces will have to be agreed between each of entities.

The current MPS services and related information model is quite extensive, and not all missions may need the full complexity that is currently available in the standard. However, many parts of the standard are optional, at the level of services, service operations and data items (the MPS constraint model for example is complex, but could be omitted complete in case not required in a specific mission).

A current shortcoming of the CCSDS architecture is that beyond the use of the MPS standard, other interfaces (e.g. with the Navigation function) are not (yet) based on services, but these are still file-based. As such, the CCSDS architecture does not provide a single complete solution for the implementation of a mission ground segment.

In addition, the MPS standard does not provide a means to disseminate the mission planning configuration data in an automated manner. However, this issue has already been identified and it is planned to add the services related to the configuration data in a next version of the standard.

Finally, once the standard is published, a next step would be the actual implementation of a ground segment based on the MPS services. This would then truly be a demonstration of the validity of the MPS standard.

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