CCSDS

The Consultative Committee for Space Data Systems

Report Concerning Space Data System Standards

MISSION PLANNING AND SCHEDULING

INFORMATIONAL REPORT

CCSDS 529.0-G-1

GREEN BOOK

June 2018

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FOREWORD

Mission Planning and Scheduling is an integral part of overall space mission operations. It is an activity that often requires interaction between multiple agencies or organizations. Today no standards exist to facilitate the exchange of the relevant planning and scheduling information. The work of the CCSDS Mission Planning and Scheduling WG is dedicated to specifying such standards. The present document outlines the underlying concepts for specification of Mission Planning and Scheduling information model and the related services.

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1 INTRODUCTION

1.1 PURPOSE AND SCOPE

Mission Planning is an activity that often requires interaction between multiple entities. This may be to support distributed planning, in which the responsibility for different aspects of mission operations planning is spread over multiple entities, including the space segment. It may also be to facilitate collaboration between missions, or to allow the planning of payloads by multiple end-users. Some spacecraft host multiple payloads, in some cases from different agencies, and each with an associated Principal Investigator. Other missions, such as observatories, make a single payload instrument available to a wider user community. Some planning responsibility may be delegated to the spacecraft itself and the corresponding capabilities hosted on board. Currently such interoperable interfaces are defined on a per-mission basis.

The Scope of the proposed standardization work is to define standard CCSDS Mission Planning and Scheduling services, with initial focus on four aspects:

- the submission of Planning Requests, i.e., input to Mission Planning;
- the distribution of Plans (or Schedules), i.e., output of Mission Planning;
- the management of the Planning process;
- the management of the Plan Execution.

Mission Planning and Scheduling are integral parts of Mission Operations and closely related to the other aspects of the overall monitoring and control of space missions. This close relation is recognized in the context of the CCSDS Mission Operations and Information Management Services (MOIMS) Area, by the fact that Mission Planning and Scheduling have been identified and included from the start among the envisaged Mission Operation Services to be specified in the scope of the CCSDS Mission Operation Framework (see reference [1]).

Although the intended standardization will encompass the specification of application-level services for Mission Planning and Scheduling, based on the CCSDS MO Service Framework (reference [1]), the initial emphasis of standardization will be focused on specification of the Mission Planning and Scheduling Information Model and the associated standardized messages exchanged between organizations. As many organizations currently exchange such information through file-based communication, this will include the support of concrete message formats for file-based exchange. It is recognized that a key aspect of standardizing the information model for the services will be agreement on a common definition of terms and their associated semantics.

For this purpose, the work will start with the analysis of current common practices and existing Mission Planning and Scheduling file formats, which are currently in use in the participating agencies. Special focus will be given to the analysis of the Mission Planning and Scheduling file formats, which are currently in use by multi-agency missions with existing cross agency planning scenarios. The analysis will, however, be focused and limited to the Mission Planning and Scheduling information, which pertains to the mission planning boundaries: Planning Request files (input) and Plan files (output).

The intended meaning of the terms Planning and Scheduling in the domain of space operations often differs from their general meaning in the Artificial Intelligent (AI) Planning and Scheduling domain. The common understanding of the difference between the Planning and Scheduling processes in the AI domain is as follows: In planning, decisions need to be made to select the activities that are necessary to achieve an objective or a goal; hence the activities are not fixed and are selected as part of the planning process. In scheduling, the set of activities is known and the process is not concerned with the selection of the activities, but with their arrangement, such that a predefined set of constraints is satisfied.

In the space operations domain, the distinction between the terms Plan and Schedule is not so clear. One of the common interpretations is related to the evolution from a (high-level) Plan to an (executable) Schedule, in which the unknowns are resolved gradually overtime (e.g., events are resolved to absolute times). The interpretation of the term Scheduling also often overlaps with what is generally known as Plan Execution.

For the purpose of this standardization, a common information model is proposed to represent both Plans and Schedules. For this reason, only the terms Plan and Planning are used in the definition of the Information Model and Services. The aspects of the Scheduling in the space operations domain that concern with the execution of Plans will be referred to as Plan Execution.

As part of the subject standardization effort, it is intended that the interaction of the involved entities be specified through standardization of service-based interfaces that define the dynamic interaction between software applications that are providers and consumers of these services. It is recognized that for this to be possible, the initial specification of Mission Planning and Scheduling messages should be ‘service aware’ to allow the message formats to be re-used in the context of service-based interactions.

In this context, it is important to emphasize that the working group believes the main challenges and difficulties pertain to the first task, i.e., the specification of the actual Mission Planning and Scheduling Information Model, regardless of whether the corresponding information is transferred via files or through messages of corresponding service interfaces. Hence the focus of the work and majority of the effort will be dedicated to this task. Once the syntax and the semantics of the messages to be exchanged are formalized, the specification of the corresponding services for their exchange will be straightforward and follow naturally.

As a starting point, the relevant mission planning scenarios, use cases, and deployment architectures have been identified and documented in the current Informational Report. This is to ensure that the resulting Information Model and Services are practical, useful, and compliant to the existing practices, operational concepts, organizational constraints, and security directives of the participating agencies.

Ground station and network planning is an important aspect of the overall space mission Planning and Scheduling. The specification of the Mission Planning and Scheduling Information Model and Services therefore needs to respect these interfaces and related CCSDS standards that are dedicated to ground station and network planning, such as the Simple Schedule Format (reference [4]).

The actual Mission Planning and Scheduling messages and services will be specified in one or more Blue Books. The final list of the Mission Planning and Scheduling Services will be identified as part of the initial concept elaboration work. The currently proposed set of services is:

- Planning Request Service (including associated status tracking);
- Plan Distribution Service (provides access to Plans and their current status);
- Planning Management Service (initiation of planning processes);
- Plan Execution Service (control of the execution of a Plan).

1.2 DOCUMENT STRUCTURE

Following the introductory material, this document is organized into these main sections:

- section 2: Overview;
- section 3: Relationship to other CCSDS Standards;
- section 4: Reference Concepts;
- section 5: Use-Case Scenarios;
- section 6: Information Model Outline;
- section 7: Services Outline;
- section 8: Working Group Standardization Roadmap.

1.3 DEFINITIONS

This Information Report makes use of a number of terms defined in the CCSDS Glossary held in the on-line Space Assigned Number Authority (SANA) registry available at: http://sanaregistry.org/r/glossary/glossary.html. The use of those terms in this Informational Report is to be understood in a generic sense, i.e., in the sense that those terms are generally applicable to the concepts of Mission Planning and Scheduling. Those terms are:

- Application Programing Interface;
- Operation;
- Service Consumer;
- Service Provider;

- Telecommand;
- Telemetry;
- Command Sequence.

For the purposes of this document, the following definitions apply:

AI Planning and Scheduling: In AI, activity selection and assignment of timing or initiation conditions to satisfy timing constraints and resource loading.

NOTE – In the context of this document planning and scheduling are an integrated/ interleaved process that may include both what AI terminology refers to as planning and scheduling.

Goal: The information that can guide the decision-making in the planning process.

NOTE – In common usage this may also be referred to as 'Objective'.

Observation: A type of activity responsible for collecting data, which may require targeted pointing of a spacecraft or instrument.

Opportunity Window: A window during which a previously defined subset of constraints is satisfied for a Planning Request.

Plan: The output of the Planning Process. It contains a set of selected activities associated to time, position, or other event. A Plan may contain additional related information.

NOTE – In the context of the Mission Planning and Scheduling standardization activity, there is no distinction between the terms Plan and Schedule, and only the term Plan is used.

Plan Execution: The process of executing a Plan on board or on the ground.

Plan Period: A Plan specifies Activities for a Planning Period.

NOTE – If time is not the indicator for the initiation of the activities in the plan, the Plan Period needs to be interpreted differently.

Planning: The process of creating one or more Plans (output) from Planning Requests (input).

NOTE – In the context of the Mission Planning and Scheduling standardization activity, there is no distinction between the terms Planning and Scheduling, and only the term Planning is used.

Planning Activity: A Planning Activity is a meaningful unit of what can be planned. The granularity of a Planning Activity depends on the use case; it may be hierarchical. In other words, Planning Activities are the building block for Planning.

NOTES

1 The qualifier ‘Planning’ is used to disambiguate from other uses of the term Activity.

2 In common usage this may also be referred to as ‘Task’.

Planning Constraint: A Planning Constraint is something that limits or restricts the planning of activities. Different types of constraints exist, including resource constraints, temporal constraints, positional constraints, dependencies between activities, and global constraints (that concern the whole plan).

Planning Cycle: An execution of the planning process. A planning process can be executed multiple times and may include a previously generated Plan as its input.

Planning Event: When a condition is met. The condition can be expressed in terms of time, location, or any other Planning Resource.

NOTE – The qualifier ‘Planning’ is used to disambiguate from other uses of the term Event.

Planning Request: A Planning Request constitutes an input to the planning process, which requests one or more activities. Each Planning Request contains all the information that the requester can provide.

NOTES

1 The qualifier ‘Planning’ is used to disambiguate from other uses of the term Request.

2 Typically, the planning process depends on other inputs, which are not provided through the Planning Requests, such as orbital information, or the previous plan.

Planning Resource: Any physical or virtual quantity that either impacts or is affected by the execution of the planned activities.

NOTE – The qualifier ‘Planning’ is used to disambiguate from other uses of the term Resource.

Pointing: The orientation of the spacecraft or an instrument, or any other unit of the system.

NOTE – Pointing is often an important resource in the planning process.

Pointing Request: Part of the Planning Request that constrains the pointing.

Principal Investigator, PI: A specific type of user concerned with the scientific operations of a payload on a space mission.

Replanning: An iteration of the planning process, triggered by an event that may use the previously generated Plan as an input.

Schedule: (See Plan).

NOTE – In the context of the Mission Planning and Scheduling standardization activity, there is no distinction between the terms Plan and Schedule, and only the term Plan is used. In the wider context of Mission Operations, the Term ‘Scheduling’ is sometimes used to refer to Plan Execution. In the Mission Planning and Scheduling standardization activity, this usage is deprecated.

Scheduling: (See Planning).

NOTE – In the context of the Mission Planning and Scheduling standardization activity, there is no distinction between the terms Planning and Scheduling, and only the term Planning is used. In the wider context of mission operations, the term Scheduling is sometimes used to refer to ‘Plan Execution’.

Task: (See Activity).

NOTE – In the context of the Mission Planning and Scheduling standardization activity, there is no distinction between the terms Activity and Task, and only the term Activity is used.

1.4 REFERENCES

[1] *Mission Operations Services Concept*. Issue 3. Report Concerning Space Data System Standards (Green Book), CCSDS 520.0-G-3. Washington, D.C.: CCSDS, December 2010.

[2] *Mission Operations Message Abstraction Layer*. Issue 2. Recommendation for Space Data System Standards (Blue Book), CCSDS 521.0-B-2. Washington, D.C.: CCSDS, March 2013.

[3] *Mission Operations Common Object Model*. Issue 1. Recommendation for Space Data System Standards (Blue Book), CCSDS 521.1-B-1. Washington, D.C.: CCSDS, February 2014.

[4] *Cross Support Service Management—Simple Schedule Format Specification*. Issue 1. Recommendation for Space Data System Standards (Blue Book), CCSDS 902.1-B-1. Washington, D.C.: CCSDS, May 2018.

[5] *Space Communication Cross Support—Service Management—Service Specification*. Issue 1-S. Recommendation for Space Data System Standards (Historical), CCSDS 910.11-B-1-S. Washington, D.C.: CCSDS, (August 2009) June 2017.

[6] *Cross Support Concept—Part 1: Space Link Extension Services*. Issue 3. Report Concerning Space Data System Standards (Green Book), CCSDS 910.3-G-3. Washington, D.C.: CCSDS, March 2006.

2 OVERVIEW

Mission Planning encompasses application-level functions of a Space Mission System that may be distributed across multiple organizations and physical nodes, both in the space and ground segments. The objective of standardization in this area is the interaction between these functions and others at application level, and not standardization of the Mission Planning functions themselves.

The scope of standardization includes both the format/model of data exchanged and the semantics of the interactions for their exchange, captured by the associated service-level interfaces. A generalized view of the functions involved in Mission Planning and their interactions with other functions is given in figure 2-1. The entities shown in blue are in the functional area of Mission Planning. The entities shown in different colors belong to other functional areas of mission operations, such as monitoring and control, navigation, and ground station and communication network.

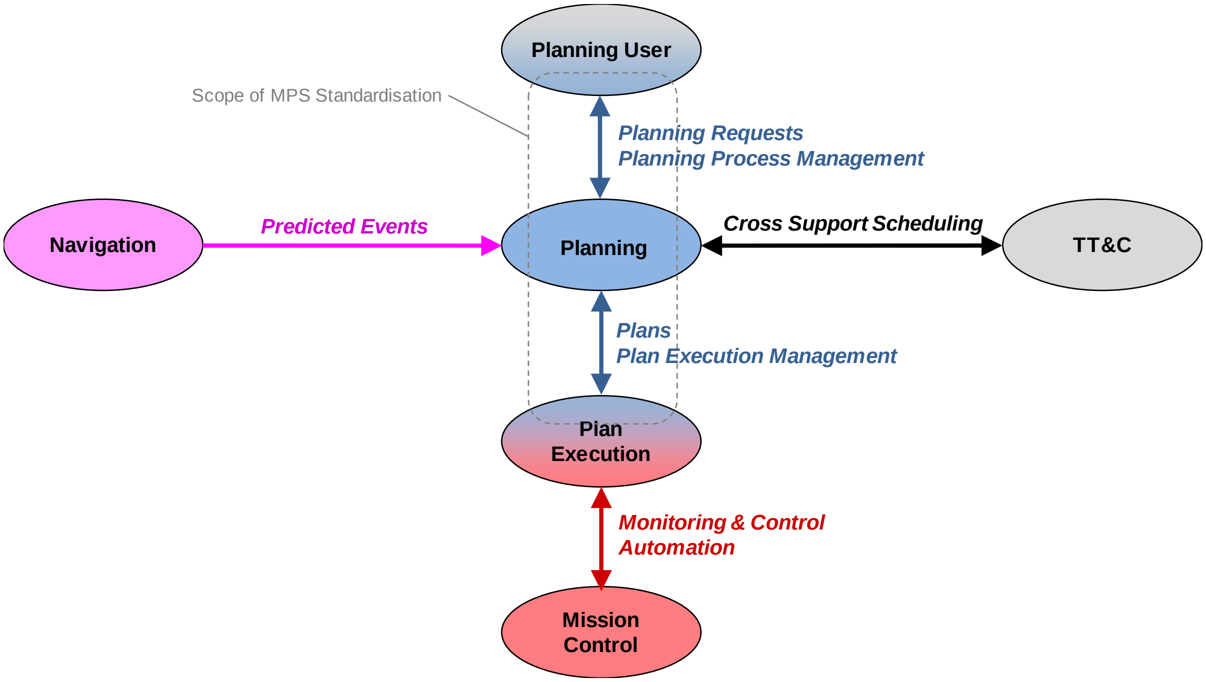


Figure 2-1: Functions Involved in Mission Planning

The following Mission Planning functions are identified:

- **Planning User**: A generic function that is responsible for submitting requests to the Planning function and/or controlling the Planning process. It may also receive feedback on the status of Planning Requests, the generated plans, and the status of the planning process. It is not a Planning function itself, but it is a user of Planning data and services. A real system may contain multiple types of Planning User function, some of which correspond to other mission operations functions within the space mission system.

- **Planning**: The function responsible for performing Mission Planning. Internally, it may be hierarchically organized and/or distributed. Planning Requests are received from multiple Planning Users and feedback on their statuses provided. Planning Users may also perform high-level control of the planning processes supported by the function. The output of the Planning function is plans, which may be retrieved by Planning Users and distributed to Plan Execution functions. Planning may also control the execution of Plans via the Plan Execution functions. Planning is itself a user of the Navigation function and may receive predicted Planning Events related to orbital information, attitude, or slew time information; it negotiates the scheduling of ground station support via Cross Support Services (reference [5]).

- **Plan Execution**: The function responsible for executing a Plan (or part of one). There may be multiple Plan Execution functions distributed between space and ground segments. It is not a Planning function itself, but it does support a common model of the Plan in its interface with Planning. It receives or retrieves distributed plans, allows external control of the Plan Execution process, and provides execution status of the Plan to Planning. Plan Execution may use underlying Mission Control Services to effect the execution of planned activities.

The interactions within the scope of Mission Planning and Scheduling standardization can be grouped into four principal topics, potentially corresponding to services, as follows:

a) **Planning Request, PRS**: Asynchronous submission of Planning Requests, associated responses, and their subsequent management and status feedback;

b) **Plan Distribution and Retrieval, PLS**: Distribution and access to the Plans generated by the planning function;

c) **Planning Process Management, PMS**: Management of the planning process itself—initiation, monitoring and control, and configuration;

d) **Plan Execution Management, PES**: Management of the execution of Plans by a Plan Execution function - initiation, monitoring and control, editing of the currently executing Plan, update of Planning Events and resources, and configuration.

It should be noted that in a specific deployment there might be multiple copies of all the functions identified in figure 2-1.

These functions may be distributed over a number of distinct entities (organizations and systems) within a given space mission system. There is not a fixed set of such entities, but typical examples include:

- User Community / PIs;
- Science/Payload Operations Center;
- Payload Processing Center;
- Mission Operations Center;

- Flight Dynamics / Navigation;
- Ground Tracking Network;
- Unmanned Spacecraft;
- Surface Lander / Rover;
- Manned Space Vehicle.

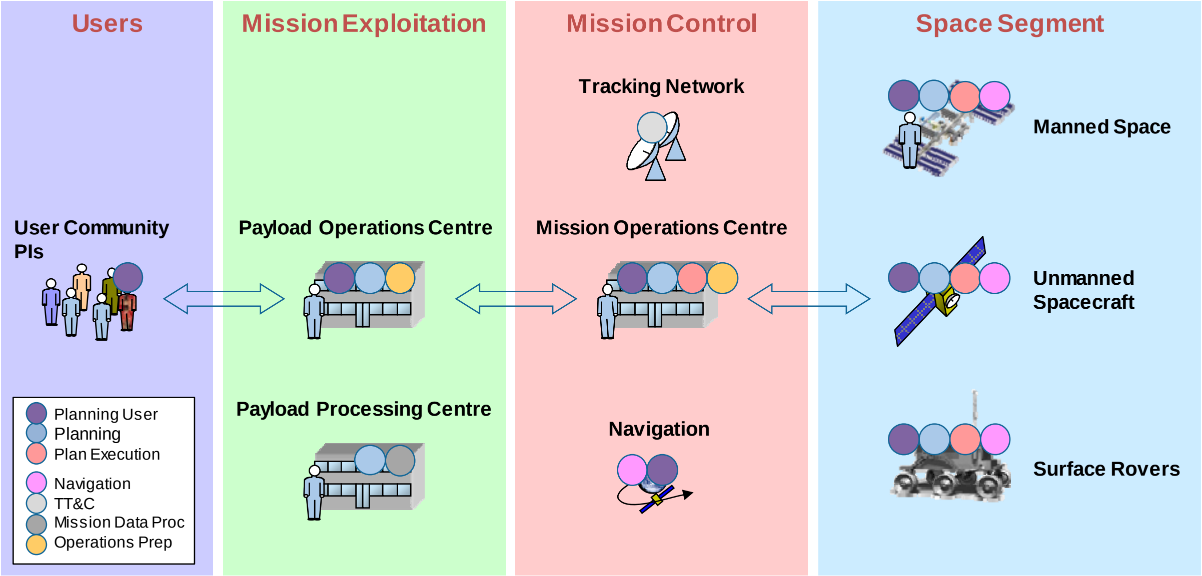


Figure 2-2: Entities and Functions Involved in Mission Planning

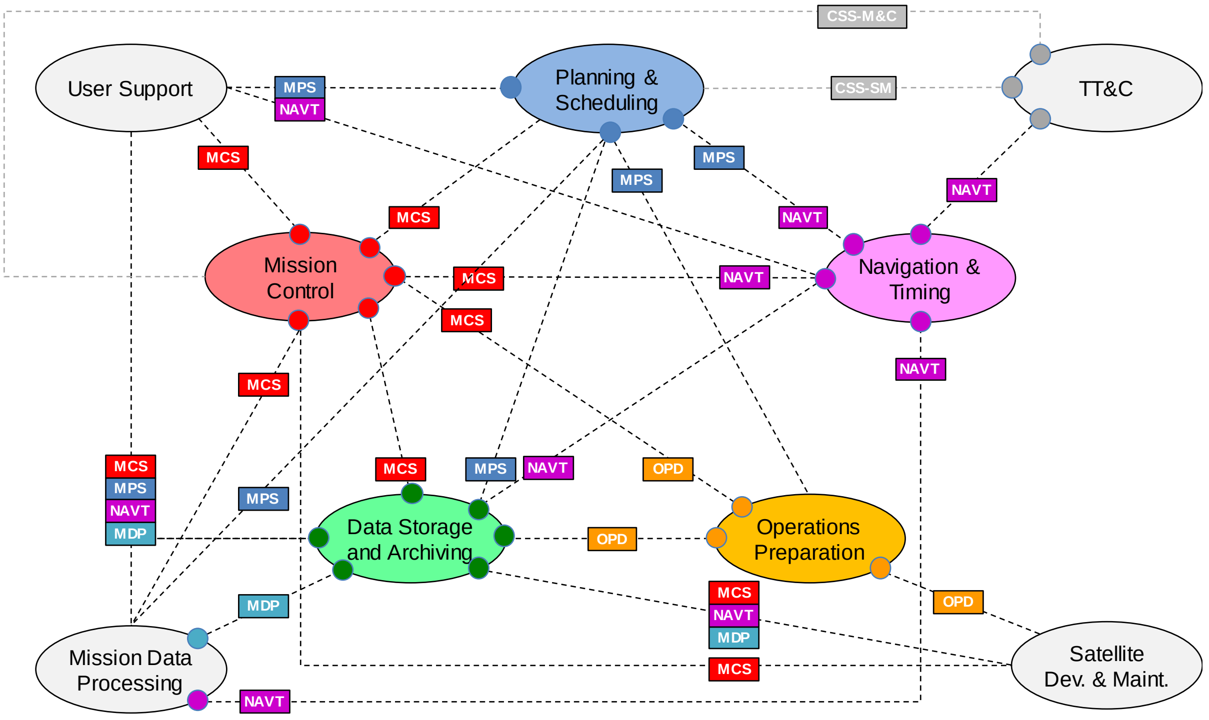
As an example, figure 2-2 illustrates potential deployment of each of the functions identified in figure 2-1 to the entities listed above. The circles indicate where the functions are typically deployed in existing systems, or where they could potentially be deployed in the future. The arrows indicate the interactions in a typical current deployment, but the potential distribution of functions indicated by the circles shows that all the functional interfaces shown in figure 2-1 can be exposed to the boundaries between entities. It is in cases in which the interactions between the functions are exposed across one or more boundaries between entities that there is a need for standardization within CCSDS as a potentially interoperable interface between agencies.

3 RELATIONSHIP TO OTHER CCSDS STANDARDS

3.1 RELATIONSHIP TO CCSDS REFERENCE ARCHITECTURE

CCSDS is currently developing a Reference Architecture in which all CCSDS standards can be identified, together with their roles, and in which it can be shown how CCSDS standards relate to one another and support the deployment and integration of space systems.

Mission Planning encompasses application-level functions whose interfaces fall within the remit of the Mission Operations and Information Management Services (MOIMS) area of CCSDS.



CSS-M&C	Cross Support Services—Monitoring and Control
CSS-SM	Cross Support Services—Service Management
MCS	Mission Control Services
MDP	Mission Data Product
MPS	Mission Planning and Scheduling
NAVT	Navigation and Timing
OPD	Operations Preparation Data

Figure 3-1: Mission Operations Functional Areas and Their Interactions

Figure 3-1 shows the main functional areas that support Mission Operations and their principal interactions and are the potential subjects of standardization by CCSDS. Functions and interactions are color-coded by area (Mission Planning and Scheduling being shown in blue).

The interactions are annotated with text indicating the type of data transferred (MPS indicates Mission Planning and Scheduling data); the circle at one end indicates the function that is the service provider in the case of a service-based interface. At this level, the data types merely indicate the principal function with which they are associated, and so MPS data relates to all data formats that may be standardized for Mission Planning and Scheduling.

This document addresses only the MPS data types and services shown in blue. Interactions with the TT&C function are covered by the CCSDS Cross Support Services (CSS) area of CCSDS. Associated services and data types are shown in grey.

From the perspective of the Mission Planning and Scheduling functional area, interactions are shown with:

- User Support functions (principally for submission of Planning Requests and retrieval of Plans);
- Mission Control (for providing current status and allowing the execution of Plans through Monitoring & Control or Automation services);
- Navigation and Timing (for the provision of predicted events);
- TT&C (for scheduling ground station contacts using CSS Service Management [CSS-SM]).

Examples of Mission Planning users are multiple functions that interact with Mission Planning for the submission of Planning Requests:

- Navigation & Timing for maneuvers;
- Operations Preparation for on-board software and configuration updates;
- Mission Data Processing for payload operations.

Finally, MPS data may interact with Data Storage and Archiving, for the storage of planning data and its transfer to on-board file storage.

Figure 3-2 gives an example of how these functions may be deployed across multiple organizations and physical nodes of a distributed space mission system. Interactions between functions within a deployment node are omitted for clarity; any interactions shown in figure 3-1 may also apply within a node.

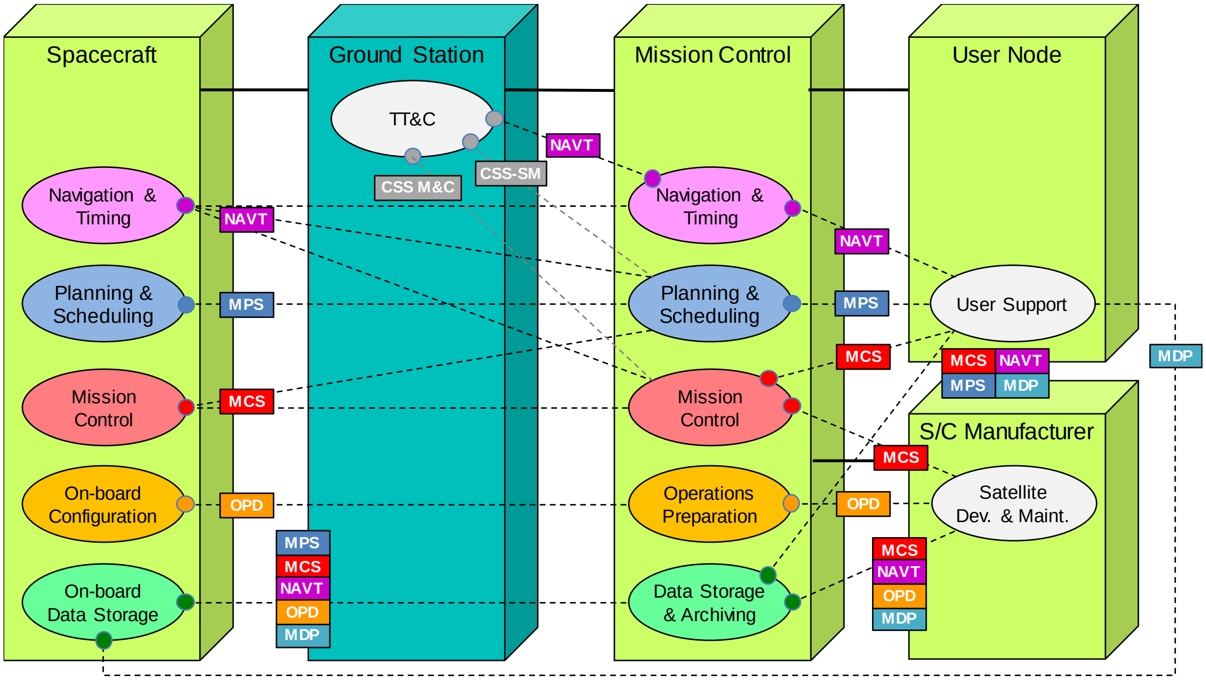


Figure 3-2: Example Deployment of Mission Operations Functional Areas

Figure 3-3 expands the Mission Planning and Scheduling functional area using the same notation. This shows the functions identified in figure 3-1, noting that Operations Preparation, User Support, and Navigation & Timing are all examples of Planning Users. Mission Planning Data is expanded as:

– Planning Requests, PRQ;

– Plans, PLN;

– Planning Process Management Data, PPM;

– Plan Execution Management Data, PEM.

Navigation and Timing Data corresponds to the individual navigation data messages defined by CCSDS, of which the following are relevant to Mission Planning:

– (Predicted Orbital) Event Message, EVM;

– Orbit Data Message, ODM;

– Conjunction Data Message, CDM;

– Spacecraft Maneuver Message, SMM;

– Pointing Request Message, PRM.

Other types of navigation data, such as slew time estimation, can also be an input to the planning function. SMM and PRM may be used in the context of a Planning Request. Planning Requests may similarly reference spacecraft configuration data, including On-board

SoftWare (OSW) images, Actions (Telecommands or Sequences), and Automated Procedure Definitions (APDs), which are managed by the Operations Preparation function.

Interoperable interfaces may be defined as:

a) the semantics of the data exchanged on the interface in form of an information model;

b) the encoding or format of data exchanged on the interface;

c) the expected pattern and sequence of exchanging the relevant data between the two sides of the interface;

d) the expected semantics of the behavior of each side of the interface upon sending and receiving data;

e) non-functional aspects of the information exchange (such as aspects of security, addressing, transaction management, etc.).

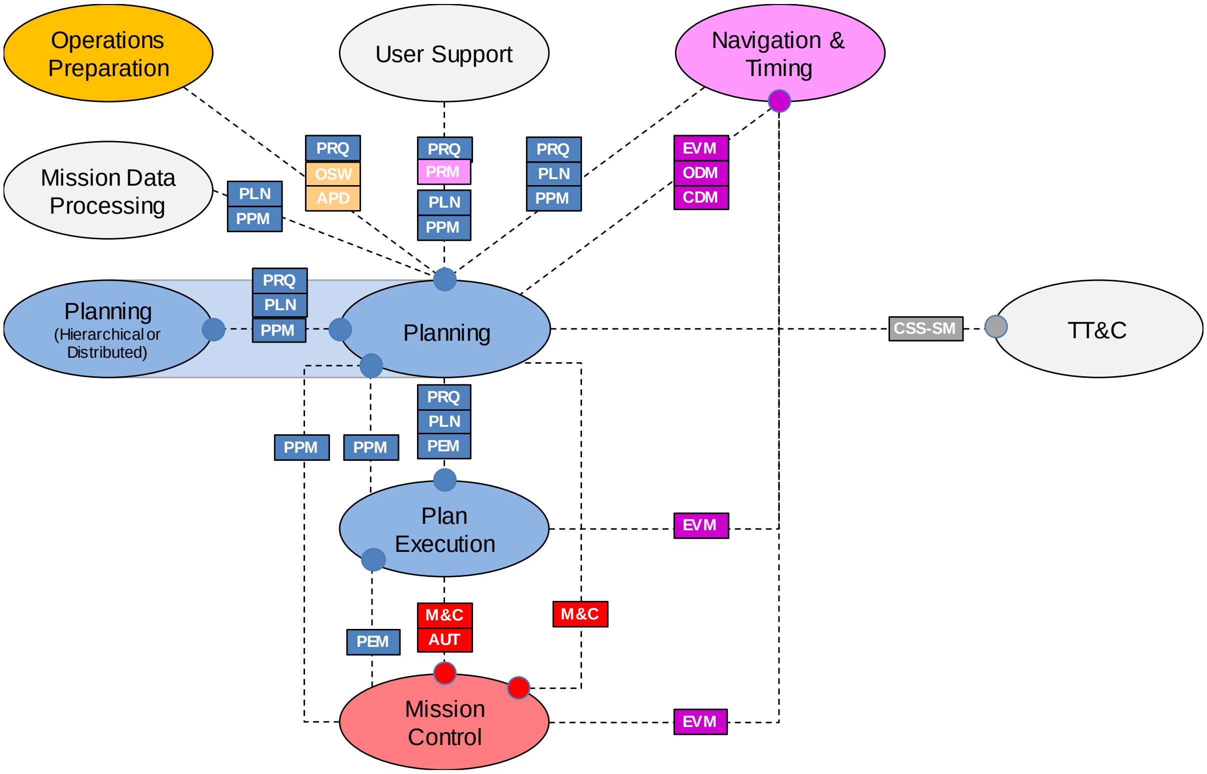


Figure 3-3: Mission Planning Interactions

At a higher level of automation, the above aspects can be realized through machine-to-machine interfaces in the form of service interfaces that define the patterns of interaction between consumer and provider applications. In a more manual interaction, some of the above-listed aspects of the data exchange are delegated to humans. It is the objective of this standardization effort to provide specifications that are agnostic of the selected information encoding and communication mechanism for their exchange.

The objective of the Mission Planning and Scheduling standardization is to enable both file-based interaction using a defined message format and service-based interaction.

Figure 3-3 also shows that there may be peer-to-peer interaction between hierarchical or distributed Planning functions within the same space mission system. In this context, a Plan produced by one Planning function may be referenced or embedded within the Planning Request forwarded to another Planning function, and ultimately to a Plan Execution function. This is illustrated in figure 3-4.

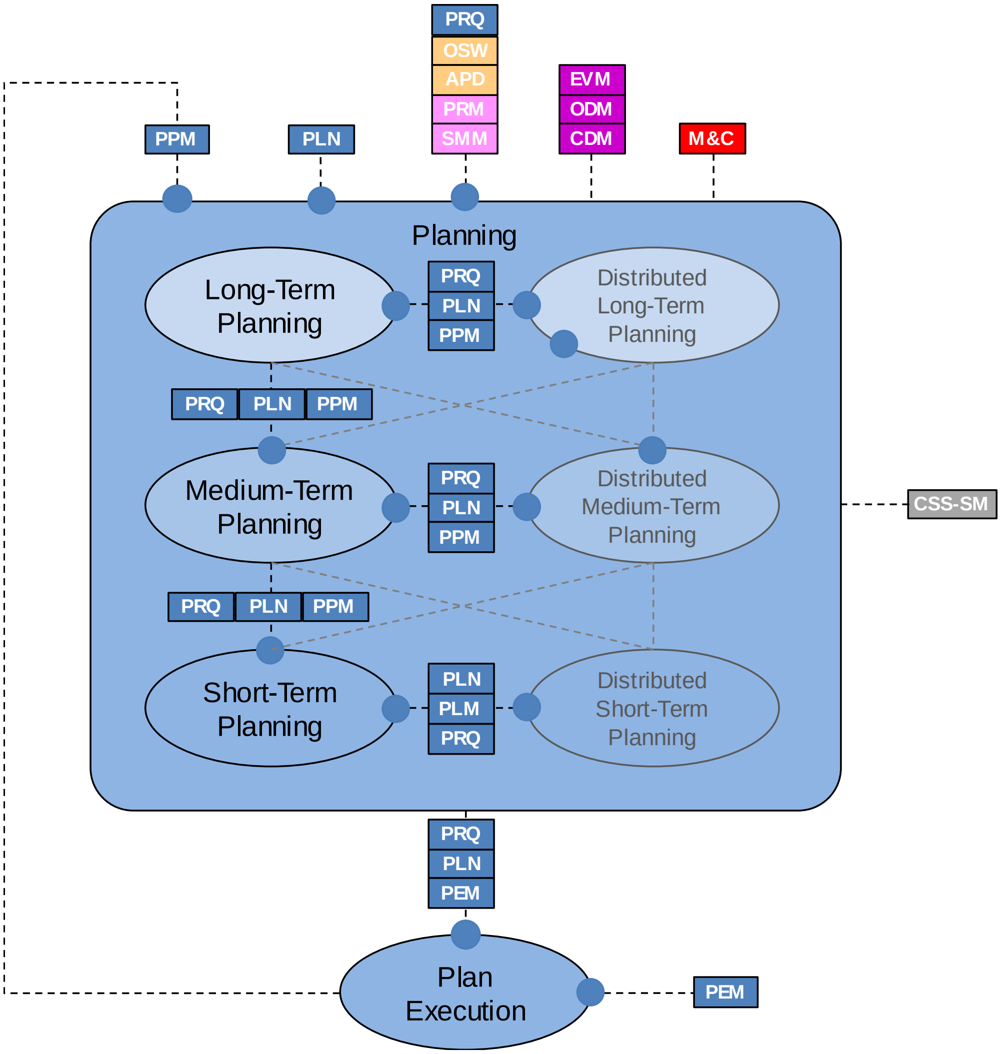


Figure 3-4: Hierarchical and Distributed Planning

Internally within a space mission system, the Planning function may be organized hierarchically. Typically, this is in terms of long-term, medium-term, and short-term Planning, which operate over different planning periods, possibly with different levels of granularity in the plans. Each level of planning may also be distributed over multiple nodes of the space system, or functionally partitioned according to areas of responsibility.

The Mission Planning and Scheduling standards are also applicable to the interactions between distributed Planning functions. The same interactions applicable to the Planning function as a whole can be applied to these peer-to-peer interfaces: Planning Request (PRQ), Plan (PLN), and Planning Process Management (PPM).

3.2 RELATIONSHIP TO MISSION OPERATIONS SERVICES CONCEPT

The CCSDS Mission Operations (MO) Services Concept provides a standard framework for the specification of end-to-end services between Mission Operations applications (reference [1]). MO Services are defined in terms of a Message Abstraction Layer (MAL) (reference [2]) and Common Object Model (COM) (reference [3]). Together these provide a means of specifying data and service interfaces in an implementation, encoding, and communication agnostic manner. The abstract specification of the service interfaces and data can be mapped to a concrete implementation through:

a) a language binding that transforms the abstract service interface into a concrete API for a given programming language (e.g., Java, C++, or Python);

b) a technology binding that defines how the resulting messages are carried over a concrete message transport protocol;

c) a technology binding that defines how the abstract messages are encoded in a concrete format (e.g., binary, XML, or ASCII).

The Common Object Model of the framework provides the means for uniquely identifying all data entities in a common manner, establishing the logical relation between the entities of the Information Model across service domains, reconstructing a historical view over the evolution of the data in mission life-time, and archiving and retrieval of all mission operation data in a common operational archive. To give a concrete example, the objective is to be able to establish relations at the end-to-end mission operations level to answer questions such as, ‘An Alert (a) was raised because the Check (b) on TM parameter value (c) was violated as a result of execution of Action (d), which was triggered by the Plan Execution function while executing the Plan (e), which contained the Action (d) as a result of the Planning Request (f)’. It will also help to retrieve, e.g., the valid definition of the Planning Constraint (x) at a given time during the mission, when Plan instance (y) was constructed.

An MO application-level service specification comprises a set of operations that the service consumer may invoke on the service provider. Each operation is mapped to a standard interaction pattern defined by the MAL and provides the service-specific body of the constituent messages.

The Mission Planning and Scheduling standards will focus initially on the definition of the core Mission Planning Information Model. At the same time, Mission Planning Services will be specified in terms of the MO framework for exchange of related messages.

3.3 RELATIONSHIP TO CROSS SUPPORT SERVICES CONCEPT

The CCSDS Cross Support Services (references [5] and [6]) define standard interactions between Mission Operations Centers and a Ground Station Complex, which may comprise multiple individual ground stations, and which offer Telemetry, Tracking, and Commanding services to potentially multiple missions. This is a well-established area of interoperability between space agencies.

Conceptually, Mission Planning also involves the planning and scheduling of TT&C services required to support the space-ground interface. However, as this is already addressed by the CSS Service Management standard (reference [5]), it is considered outside the scope of the Mission Planning and Scheduling standards. Mission Planning and Scheduling functions may act as consumers of CSS Service Management in addition to using Mission Planning and Scheduling standards to support the full requirements of a mission. The flow of logic can also theoretically be the other way around; i.e., the network planning entity could consume Mission Planning and Scheduling services to perform its tasks. A simple schedule format exists in the context of CSS Service Management (reference [4]), which may be considered in the context of Mission Planning.

4 REFERENCE CONCEPTS

4.1 OVERVIEW

Some generic concepts applicable to the planning of space missions are described here; they are used as reference information in the following sections of the document.

4.2 HIERARCHICAL PLANNING

An approach to handle the complexity of the planning of a space mission is to divide the planning process over multiple planning cycles, starting with the planning of activities at a lower detail level and then gradually increasing to a higher detail level. This then leads to the concept of a hierarchical planning process.

Planning cycles and so-called planning horizons represent two things: the lead-time by which planning products are computed and the planning process conducted at each level, and the duration or applicability of the planned activities. For example, short-term planning may be conducted every week, covering the next month of planned operations (in this case the planning horizon is one month); or long-term planning may be conducted six months in advance for one week of operations (in this case the planning horizon is one week).

Below, some commonly used planning cycles are described:

- **Long-term Planning**: This planning cycle has a typical duration in the order of several years to several months or even weeks. This planning cycle could be concerned with the overall achievement of the mission objectives, impacted by the long-term spacecraft orbit and attitude planning, and also with performing a first iteration of the resources and constraints.

- **Medium-term Planning**: This planning cycle has a typical duration in the order of several months to several weeks. This planning cycle could be concerned with the more detailed spacecraft orbit and attitude planning and the allocation of resources, such that the different entities involved in the Mission Planning can start the detailed planning, based on more accurate resources and constraints.

- **Short-term Planning**: This planning cycle has a typical duration in the order of several weeks to several days, or even hours (e.g., in the case of robotic surface operations). This planning cycle is typically concerned with the detailed planning of the spacecraft and payload activities based on the final orbit and attitude information, and with checking resources and constraints at the highest detail level, to ensure the output Plan is conflict free and can be executed. It might be noted that similar concepts apply to the detailed planning of the operations of robotic assets.

Typical space missions will be based on all or some of the three planning cycles described above. Additional cycles could be considered, such as a very-short-term planning cycle, which could be arbitrarily short. This in particular is the case for the so-called tactical planning of, for example, robotic assets for surface operations.

This very-short-term planning cycle would allow a fast reaction time on, for example, updated orbit information, environmental events, ad-hoc scientific opportunities, or new information on the state of the spacecraft (or of other space mission assets, such as surface operations elements), including its health status, based on incoming telemetry.

4.3 CENTRALIZED VS. DISTRIBUTED PLANNING

In some space missions, the planning may be centralized in a single function. In other space missions, the planning functions may be distributed over multiple entities on the ground or on board (see also 4.5), where each entity will be involved in a part of the overall planning.

The distribution of functions over different entities may be driven by a number of factors, such as the availability of facilities with unique capabilities, the existence of groups of experts with specific knowledge, or ownership or governance of the asset subject to planning (e.g., a rover, a payload, etc.). With the distribution of functions over multiple entities, the responsibility for parts of the planning may also be distributed, possibly because of organizational, programmatic, managerial, political, or other constraints.

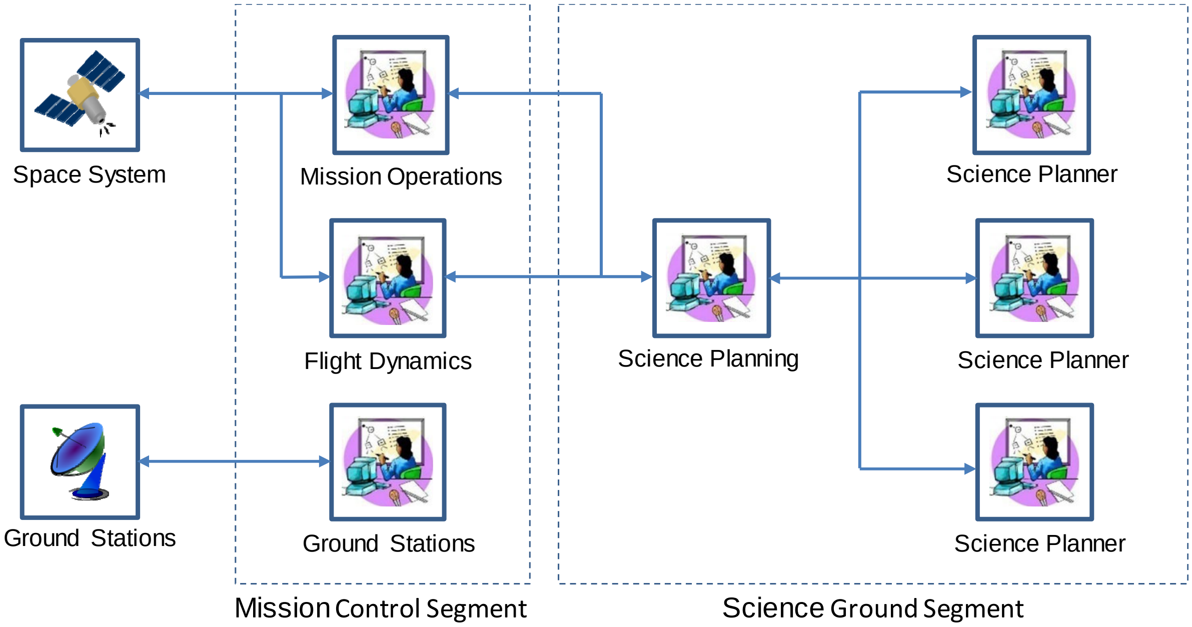


Figure 4-1: Example of Federated Planning for a Science Mission

When these entities are fully autonomous and have their specific knowledge and responsibilities, one may speak of a federated planning concept. An example of a federated planning architecture is given in figure 4-1, depicting a scientific mission with a Mission Control Segment responsible for the spacecraft platform, a Science Ground Segment in charge of the joint Science Planning, and including several Science Planners responsible for the planning of the specific instruments.

In the distributed planning concept, the output of an entity acts as the input of another entity. The latter entity may then combine multiple inputs and produce a consolidated output to be sent to another entity. This then results in a chain of planning processes, in which the scope and fidelity of the planning information increases with each planning function in the chain.

Distribution of the planning knowledge and responsibility across multiple entities typically results in a need for iterations; changes to the planning information, assumptions, or conflicts detected in one node cannot always be resolved locally and require feedback from the source entity in the chain.

In a distributed or federated planning concept comprising multiple independent entities, a specific issue that needs to be addressed is synchronization of the planning information, and especially the related configuration data, between the various planning entities. This may be achieved using automated or service-based methods to exchange and update planning configuration data across the planning entities, including the version control related to this data.

4.4 PLANNING INFORMATION FLOW

Both hierarchical and distributed planning concepts, as described above in 4.2 and 4.3, have an impact on the definition of the Planning Information data elements, in which the output of a planning function could be the (partial) input of a subsequent planning function, either refining the planning over multiple planning cycles in the hierarchical planning concept, or over multiple planning entities in the distributed planning concept. The information flow for these planning concepts is depicted in figure 4-2 below.

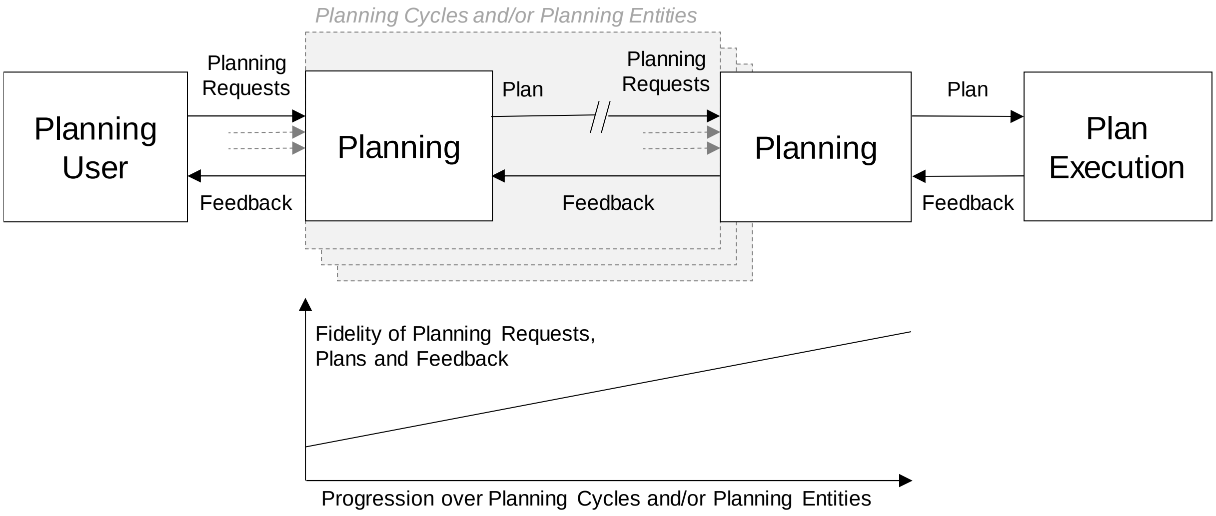


Figure 4-2: Information Flow for Hierarchical and/or Distributed Planning

Examples of increased fidelity of Planning Requests, Plans, and feedback over successive planning cycles and/or planning entities are:

- covering a wider scope with the plan, e.g., more spacecraft subsystems;
- expanding high-level Planning Requests to detailed activities based on the activity hierarchy;
- expanding a single Planning Request into multiple activities based on repeat rules;
- converting default request arguments to specific operations parameters;
- refining a request time range to a smaller time range or a specific time;
- resolving a Planning Event to a specific (predicted) time;
- elaborating Planning Constraints based on a more accurate projection of the usage of resources.

If the output of a planning function is used as the input of the next planning function, it will imply the need for a Planning Request that contains a reference to a previously generated Plan, in which the selected activities will be kept together. In that case, the Planning Service will provide an operation to submit an entire Plan.

4.5 ON-BOARD PLANNING

Mission Planning functions can be migrated partially or as a whole from the ground segment to the space segment. The drivers for such a migration are the need for increased automation and autonomy in the space segment. In particular for Robotic Exploration missions, the required level of on-board autonomy is generally higher because of the long communication delays. Moving Mission Planning functions to the space segment allows for faster replanning, as more accurate information becomes available on board in real-time, and can then be taken into account immediately by the Planning and Plan Execution functions.

An example is Earth Observation satellites flying an on-board Global Navigation Satellite System (GNSS) receiver, in which the Planning Requests could be planned and executed based on the spacecraft position. For imaging satellites, the presence of clouds can be determined on board, and imaging activities could be replanned automatically. Another example is concerning Astronomy Survey missions that can receive Observation Requests (being specific Planning Requests) and plan these on board. In case of a spacecraft anomaly, such as the failure to point the spacecraft towards a target, the Plan can be adjusted on board to optimize the satellite resource utilization. Yet another example is concerning the direct tasking of Earth Observation satellites, e.g., for disaster response from in-theatre field centers, which may result in on-board replanning to accommodate a Planning Request prior to the next mission control center contact.

The important aspects of on-board planning relevant to this standardization effort are the changes of the Information Model and the suitability of the specified Service interfaces to also cover the on-board planning cases.

4.6 GOAL-BASED PLANNING

As opposed to activity-based planning, goal-based planning typically utilizes more objective-oriented Planning Requests. The main difference at the input level is expressed in terms of an objective (what) rather than ‘how’. It is then left to the planning system to come up with ‘how’ to achieve that objective, i.e., with planned activities.

It is the intention of this standardization effort to specify a common Information model, which covers both activity-based as well as goal-based Planning Requests. The same could apply to the ‘when’ part of the Planning Requests, which may not be time or position based, although there may still be specific timing constraints in the goal-based Planning Request, e.g., the time limit by when the goal should be achieved, or the time range during which the planned activities will take place.

4.7 MANUAL, AUTOMATED, AND MIXED-INITIATIVE PLANNING

The planning of individual requests could be performed either manually or in an automated manner by the planning function, or a combination of the two, which is referred to here as mixed-initiative planning. It remains to be decided how to incorporate the support for mixed-initiative planning, in terms of manual insertion or deletion of requests, in the Mission Planning Information Model and Services. One possibility would be to consider these as a special kind of Planning Requests, e.g., exclusion windows in which no other activities may be scheduled by the automated system.

The aspects of the mixed-initiative planning are even more relevant when considering the end-to-end planning process. Typically, the planning is conducted by mission planners, which have dedicated software and tools at their disposal. Although individual planning steps can be automated, the oversight of the planning process as a whole often remains under the control of the planners. Also, the interactions between planning entities can remain under the supervision of individuals, even in cases in which the data exchange is automated.

In fully automated planning systems, the operator involvement is limited to the monitoring of the status of the various planning processes, and possibly to intervening in case of anomalies. These automated systems could be based on service-oriented architectures, allowing for the automated interaction between the various planning entities. The introduction of web-based services will allow external users to interact with the Mission Planning, e.g., to request activities or observations, to monitor the status of any requests made, etc. These services are then implemented by the planning system to function autonomously, potentially serving a larger user community.

4.8 ITERATIVE PLANNING AND REPLANNING

The planning process in a typical ground segment may be highly iterative. This could be driven by a hierarchical planning concept as described in 4.2. Within a single planning cycle, there could be additional iterations due to the need for replanning. The replanning can be triggered by an event, such as new orbit predictions arriving from the Navigation function, or reception of updated knowledge of the space and ground systems, including new configuration data to be used as input to the planning process.

The replanning could start using the current Plan as a baseline and update this Plan based on the new information that has become available, or the replanning could restart without using any past planning information, ignoring the baseline plan.

The envisaged Information Model for Mission Planning will provide for capturing the related aspects of the iterative planning process and replanning. The evolution of a Plan through its lifecycle and maintenance of consistent references to its previous instances therefore need to be incorporated into the data and metadata parts of the Mission Planning Information Model.

4.9 PLANNING SYSTEMS INTERACTION

There are multiple use cases for interaction between the users and a planning function, which need to be taken into account when defining the Mission Planning Information Model and Services. The different use cases address the needs depending on the distribution of the responsibilities and knowledge between the planning function and the users of the planning function, which may be planning functions themselves in a distributed planning concept.

One use case concerns when the planning function receives individual Planning Requests from a single user or from multiple users, and then updates the Plan at set times or immediately every time new requests arrive. The users can then monitor the status of each request until the requests are eventually executed.

This use case results in an interface between the planning function and the users, which is based on individual Planning Requests. Also, feedback is provided for the individual Planning Requests. This approach applies in cases in which Planning Requests are not interrelated; e.g., single requests could be cancelled without invalidating other requests.

Another use case applies to the scenarios in which dependencies between Planning Requests exist. Hence transactional behavior is desired, in order to ensure consistency. In such cases, the user of a planning function is typically a planning function itself, which would first create a partial Plan for the activities under its responsibility and then submit this Plan as a new Planning Request to the next planning function in the chain. This special type of Planning Request consists in this case of a collection of interrelated individual activities. If the planning function cannot accommodate one of the composing activities, the result may no longer be acceptable to the user. In that case, from the user perspective, the complete Planning Request is then considered as rejected.

A combination of the above-described approaches is also possible, in which a planning function in the chain performs detailed planning for some of the subsystems or instruments, and accepts already consolidated Plans for other subsystems or instruments from other planning functions in the chain as a special type of Planning Request. In the end, this is a design choice to be made for the architecture of the ground segment as a whole and for the different planning entities with their specific roles and responsibilities in particular.

4.10 PLANNING EVENTS

The Planning function will organize in its output (i.e., the resulting Plan) the subject activities of a selected subset of its input (i.e., the Planning Requests), taking into account a logic, which is considered as a black box as part of the envisaged Mission Planning and Scheduling standardization work. The organization of the subject activities in the Plan can be based on absolute or relative time, position, or any other ordering logic.

Planning Events are often used for this purpose. Planning Events typically indicate the condition under which a contained activity in the Plan will be executed. The resolution of the events can be delegated to other functionalities, such as the Plan Execution function on the ground or on board. The Planning Events can be resolved to time or position, or to any other condition that may be suitable for ordering purposes in the Plan and for triggering the Activities in the Plan Execution function of a given mission.

Planning Events could be used to abstract the execution time information and base it on a specific condition, typically related to the spacecraft environment or any Planning Resource. Planning Events could be based on events external to the Planning function, such as Orbital Events from the Navigation function.

A Planning Event may have a predicted value that could be used in the planning process, allowing, for example, the assessment of the feasibility of the plan. A range could be used in case there is an uncertainty in the predicted value. Typically, the uncertainty of the predicted event values will decrease approaching the actual execution time of the Plan.

A Planning Event may be based on a condition other than time, e.g., on the (spacecraft) position, temperature, distance to a target, or visibility of a target under certain illumination conditions. In such a case, the spacecraft may have an on-board navigation sensor providing position information, which can then be used by the Plan Execution function to trigger the execution of the associated activity.

In terms of feedback, the user may be interested in the time when the Planning Event was triggered and the associated activity was executed. This information could be determined on the ground or on board the spacecraft as part of the Plan Execution function and fed back to the Planning function and its users.

4.11 PLANNING REQUEST LIFECYCLE

A Planning Request that is submitted to a Planning function will typically go through a lifecycle managed by this Planning function, which will maintain the state of each Planning Request. Examples of possible Planning Request states are listed below:

- **REQUESTED**: The initial state after a Planning Request has been submitted by the user.
- **ACCEPTED**: State entered when the Planning Request has passed a first consistency check and will be made available to the Planning function.
- **INVALID**: State entered in case the Planning Request is badly formed or contains inconsistent information.
- **REJECTED**: State entered when the Planning Request cannot be planned because of Planning Constraints or any other reason.
- **REVOKED**: State entered when the user has withdrawn the Planning Request.
- **PLANNED**: State achieved when the Planning function has included the Planning Request in a Plan. Additional information may be stored with the state, such as the specific Plan that will contain the Planning Request, the time, event, or other condition defining when the Planning Activity will be executed, other detailed information on the activity to be executed, etc.
- **EXECUTED**: State achieved after a planned event is executed. The actual execution time and other information from the Plan Execution function may be stored together with the state.
- **COMPLETED**: State entered when the executed request is considered to be successfully completed, and may evaluate additional success criteria such as the quality of a scientific observation, the delivery of a mission product back to the user, the achievement of an objective related to the activity, etc.
- **FAILED**: State entered when the Planning Request execution has failed, or in case it is not considered to be successfully completed, according to the criteria as described above.

The set of supported states is typically dependent on the planning system implementation. It remains to be decided if in the eventual Mission Planning and Scheduling standard, the set of possible states will be defined explicitly and exhaustively, including any optional states, and potentially the ability to add user-defined states, all depending on the implementation of the planning system.

Feedback on a Planning Request state may be provided back to the requestor or to any other entity having an interest in a specific Planning Request. Feedback could be provided immediately (e.g., after submitting a request) or when a query for the current state is send to the Planning function. Alternatively, feedback could be provided to registered users of the Planning Request each time the state is updated.

5 USE-CASE SCENARIOS

5.1 OVERVIEW

Use-case scenarios are divided into interoperability scenarios and analysis of typical mission types, identifying commonalities across mission types based on a number of predefined areas of interest. This section ends with a conclusion on the analyzed use cases.

5.2 INTEROPERABILITY SCENARIOS

5.2.1 SPACECRAFT FROM ONE AGENCY HOSTS A PAYLOAD FROM ANOTHER AGENCY

The use case of a spacecraft from one agency hosting a payload from another agency is driven mostly by the dependencies between the payload and the spacecraft platform. These determine the type and extent of the Mission Planning Services required. Typically, they can be:

- structural (supporting the instrument, ensuring stability and stiffness);
- thermal (the platform ensures actively thermal control of instrument);
- attitude (the platform provides instrument the attitude required);
- power (provision of the necessary primary and/or secondary power);
- data handling (including routing of telecommands and HK telemetry);
- instrument data processing and/or transmission (routing of the instrument science data to ground).

The payload requests typically use services from the platform, and in some cases the use of such services implies resource sharing and allocation. This is the case for:

- data storage on board;
- data uplink and downlink;
- power;
- attitude.

The Payload Agency needs from the Platform Agency a set of boundary conditions that shape the Planning Request. These are of a static nature; they may change during the course of the mission but seldom do. Examples are constraints on power, on data volume and downlink, on attitude, slew capabilities, thermal, etc. This helps to better shape the Payload Agency’s Planning Request. The provision of this information could be mission specific but ideally should follow standard data types in order to enable reusability, allowing more than one Agency to fly payloads on the same platform.

The Platform Agency and the Payload Agency also agree on a set of planning policies and processes (including lead times for requests and formats). The information flow from Platform to Payload Agency will typically be in the form of data items or information services.

The planning itself consists of the Payload Agency deriving a set of Planning Requests that meet the operability and scientific or operational aims for the payload. These are then submitted for planning integration by the Platform Agency. The planning process at the Platform Agency deals with solving conflicts and constraints between payloads from potentially multiple agencies and/or the platform. This often means assigning and using priorities (previously agreed upon) for the requests that fall within constraints but are demanding scarce resources.

The nature or extent of the request depends on the former agreement. It could range from direct commanding by the Payload Agency that can be uploaded by the Platform Agency unmodified, to high-level requests that need translation at the Platform Agency. They include timing information, priority information, and resource usage information, plus the set of instrumental activities required.

The result of the planning or Plan is then made visible to the Payload Agency, again through a dedicated data item or a service. The Platform Agency is ultimately responsible for uplink and ensuring on-board execution of the consolidated plan.

Finally, the closure of the planning loop may have been entrusted to the Platform Agency, in which case sufficient visibility of payload operations needs to be reachable, or it is left to the Payload Agency to verify, through received data, the proper execution of the planned requests.

A special case is that in which platform and payload have little or no dependencies (i.e., telecommunication payloads with their own downlink capabilities and with power consumption within platform capabilities). In that case, the Platform Agency’s role is limited to the execution of the Plan, and the Plan definition is entrusted to the Payload Agency.

5.2.2 COORDINATED OPERATIONS OF SATELLITES OF DIFFERENT AGENCIES

Another use case is the coordinated operations of satellites of different agencies. For example, in sensor web operations for disaster monitoring, it is often desirable to ensure spatial and temporal coverage of the affected area. In this case, multiple agencies may have assets with varying capabilities to image, for example, a flooded area. A third-party agency may be the governmental or NGO coordinating disaster relief. In these cases, the Coordinating Agency would provide service requests in the form of either specific observations or imaging coverage requests (such as in the OpenGeospatial Consortium standards).

If the Provider Agencies that own or operate the assets support standardized request status services, then the Coordinating Agency can manage its requests to get the best possible coverage within Provider Agencies' capabilities. Furthermore, as the status of the requests to Provider Agencies change (e.g., previously requested imaging expected to be satisfied by one Provider Agency is suddenly preempted by a higher-priority request), a notification service would enable the Coordinating Agency to pursue other means to have the area imaged.

5.3 ANALYSIS OF TYPICAL MISSION TYPES

5.3.1 GENERAL

The various use-case scenarios applicable to the Mission Planning and Scheduling standardization process have been identified by performing a survey of a number of representative space missions of various CCSDS Member Agencies.

The missions subject to the survey have been categorized into different mission types, in an attempt to identify commonalities in the Mission Planning processes. The list of mission types defined here is not exhaustive; however, within the scope of the performed survey, the current list will cover the most common mission types.

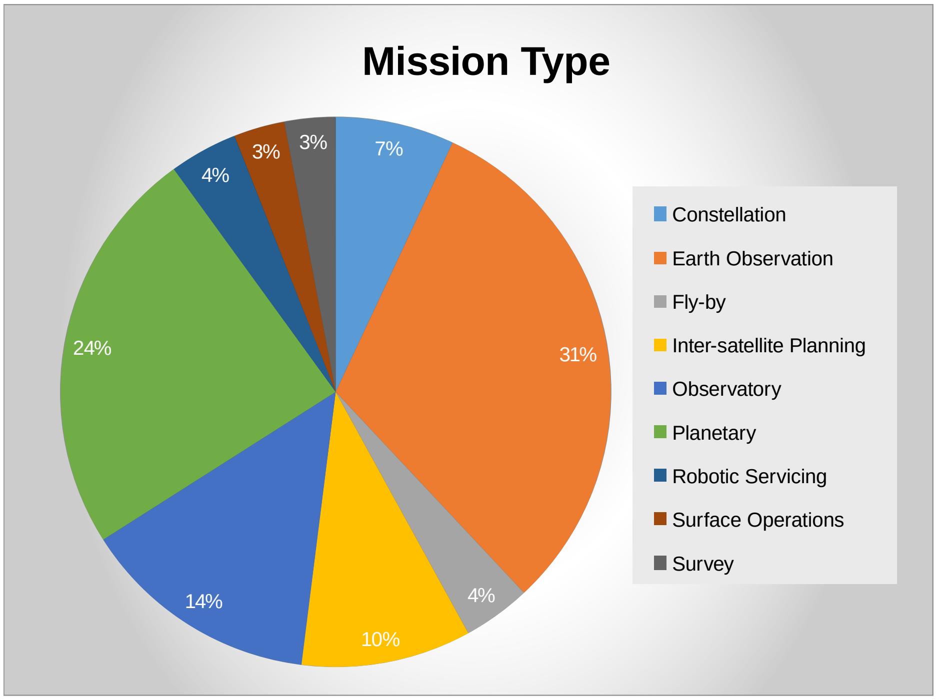


Figure 5-1: Mission Type Classification of Evaluated Missions

Figure 5-1 provides the different mission types and their relative occurrence, based on the survey of 29 missions from 7 different CCSDS Member Agencies. The results of the survey will be described per mission type in the subsections below.

5.3.2 CONSTELLATION

5.3.2.1 General

Inputs from the following missions have been taken into account for this mission type:

Table 5-1: Overview of Constellation Missions

Mission Name	Agency	Status (as of 2016)	Description
Cluster	ESA	In Operation	Constellation of four satellites, studying the interaction of Solar Wind with Magnetosphere from a very high, very eccentric orbit.
Galileo	ESA	In Operation	Global Navigation Satellite System.

Constellation-type satellite missions can be defined as missions that deploy more than one space asset flying in a certain formation in order to meet the mission objectives.

The number of satellite constellations already operational, in their deployment phase or only at a planning stage, has increased significantly over the last decades. These constellations cover the areas of space science, Earth observation, telecommunication, and navigation. Their mission objectives are related to observation of space- or Earth-related scientific phenomena, or the provision of a service to the end user.

An important Mission Planning aspect that is specific to constellation-type missions is the need to cover both the operations planning for the individual spacecraft (often also referred to as a satellite domain) as well the overall planning of the constellation itself, taking into account the higher-level capabilities and services that the constellation aims to deliver.

5.3.2.2 Planning Cycles

Planning cycles for constellations do not necessarily differ from those for single-satellite missions, i.e., long-term being concerned with major event planning such as launches and availability, medium with mission events, and short-term concerned with detailed timeline scheduling.

5.3.2.3 Execution Feedback

Upon Plan execution, feedback from the satellite domains and ground system elements is used to update the state of the constellation plan. It is therefore important that the feedback is standardized, regardless of the source of execution. It needs to be clear from the source which schedule within the constellation Plan is being updated with each feedback message, as well as which instance of planned activity and task the feedback relates to.

5.3.2.4 Navigation Services

A regular update on orbit information from flight-dynamics services for every satellite in the constellation is needed in order to derive the correct timing of orbit related events, ground station visibilities, and inter-satellite related events.

5.3.2.5 Planning Requests

Planning Requests can be raised in all cycles and even arrive as late as one day prior to their requested start date in the case of short-term cycle. They can arrive by file input, user input via an operator, or generated from standing orders defined by planning rules. Peculiar to constellations is the potential need to schedule tasks in several satellite domains, in response to a Planning Request at constellation level. This is needed when the satellites’ detailed tasking needs to be coordinated in time to satisfy the goal of the request.

For constellations providing a (guaranteed) service to an end user, special attention needs to be given to Planning Requests that might impact the service provision if not properly scheduled. For example, the execution of a station-keeping maneuver on one satellite would exclude this satellite from service provision for a certain time span and at the same time require more TT&C resources because of critical operations requirements. This needs to be compensated by the availability of a sufficient number of other in-service satellites and potentially the provision of additional ground-segment resources.

5.3.2.6 Resources and Constraints

For constellation-type missions, special care needs to be given to resources that need to be shared among all the constellation satellites. One typical example is the limited availability of TT&C contact times, which will strongly depend on the amount of TT&C stations available and the required duration of routine or special contacts. Shared resources might therefore significantly influence the overall constellation planning outcome.

Similar to the constellation-specific multi-domain Planning Requests mentioned earlier, there may be constraints between tasks and resources, defined in different satellites domains, that need to be respected for the overall constellation Plan to be considered valid. There might also be inter-satellite-specific geometrical constraints (e.g., distance, phase angle, or collinearities), which would not exist in single-satellite missions.

5.3.2.7 Request Justification

A request justification can be used purely for information or to specify a priority. No constellation-specific properties have been identified in the survey.

5.3.2.8 Planning Phase Output

The outputs of the planning function will be a conflict-free constellation plan. It can be realized either as a single file that contains the activities for all satellites and the ground segment, or as separate files. As constellation-type missions depend more heavily on automated spacecraft operations, the Plan is loaded by the mission control system's automation function for execution.

5.3.3 EARTH OBSERVATION

5.3.3.1 General

Inputs from the following missions have been taken into account for this mission type:

Table 5-2: Overview of Earth Observation Missions

Mission Name	Agency	Status (as of 2016)	Description
Copernicus Sentinel-1	ESA	S1A In Operation S1B In Preparation S1C,D Under Development	The Sentinel-1 mission includes 2 spacecraft phased at 180 degrees, both carrying a C-band Synthetic Aperture Radar (SAR) instrument.
Copernicus Sentinel-2	ESA	S2A In Operation S2B In Preparation S2C,D Under Development	The Sentinel-2 mission provides continuity and further development to services relying on multi-spectral high-resolution optical observations of land terrestrial surfaces.
Copernicus Sentinel-3	EUMETSAT/ ESA	In Preparation	LEO Earth Observation.
Earth Observing One	NASA	In Operation	Earth Observation; repeat orbit, point and shoot.
EnMAP	DLR	In Preparation	Hyperspectral Imaging.
EPS	EUMETSAT	In Operation	EUMETSAT Polar System. Meteorology.
FireBird	DLR	In Operation	The FireBird mission consists of the two spacecraft TET-1 (already in operations) and BIROS (to be launched in 2016) that both carry a combined infrared-optical camera system as their main.
MSG	EUMETSAT	In Operation	Weather satellites.
TerraSAR-X/TanDEM-X	DLR	In Operation	The TerraSAR-X/TanDEM-X mission comprises the two spacecraft TSX and TDX, which are operated mostly in a very close formation, and both carry the same high-resolution radar instrument.

These missions typically carry remote-sensing instruments observing either the Earth's surface or the Earth's atmosphere, but in-situ measurements may also be performed by these missions. Most Earth Observation satellites are located in Low-Earth Orbit (LEO), but weather satellites may also be located in geostationary orbits. Some Earth Observation missions consist of multiple spacecraft working together, possibly with synchronized orbits.

It needs to be noted that most of the payload operations are performed with respect to physical location (either on surface or in-orbit) rather than to timed events. Some Earth Observation (EO) missions use an orbit with a repeat cycle concept (i.e., same geographical location or illumination condition after N orbits), while others do not (drifting Mean Local Solar Time [MLST] or drifting Ascending Node Crossing [ANX] longitude). These concepts impact the way payload planning is done. It might be noted that ESA Earth Observation Payload Planning also includes some planning for ground elements (e.g., X-Band ground station acquisition time and calibration transponder).

5.3.3.2 Planning Cycles

Planning cycles of EO missions differ depending on the type and maturity of the mission. The planning concept generally addresses the diverse needs of both the routine operations phase and the more dynamic commissioning phase. Planning is performed separately for the Payload and for the whole satellite, with the former being the driver for the selection of the cycle length and type.

Planning is also dependent on the orbit type (especially with repeat cycle and without). The traditional time-based planning cycle covers fixed time intervals (e.g., 1 week or 1 month) of time-related operations, Plans are then prepared sufficiently in advance to allow payload and platform planning to be merged, converted into commands, and uplinked. The time extension of the planning period is normally constrained by the accuracy of the orbit prediction. A logic is then defined to implement subsequent Plans as sliding/overlapping time windows or as mutually exclusive ones.

A newer alternative and complementary concept used since GNSS has been available is that of position-based planning (termed Orbit Position Scheduling [OPS]), in which operations are attached to a specific location in orbits and executed automatically on board when the planned position is reached. This OPS planning concept can be defined either within time intervals or statically uploaded on board for the whole orbital cycle in which the operation profile is statically position-fixed, and an orbit with a repeat cycle is used (e.g., always observe Germany on the third orbit of the cycle).

Regarding the extent of the planning interval, a shorter and ad-hoc planning mechanism is defined for periods when intense/dynamic interaction is needed (e.g., in-orbit commissioning) or in case observations are not based on a static or predefined profile but need to take into account user requests, e.g., to observe a specific area for steerable payloads.

5.3.3.3 Execution Feedback

While the concept of open- and closed-loop planning can be implemented (i.e., with and without execution feedback), operational simplification of EO missions and, in particular, the need to avoid short interactive loops, replanning, and 24/7 staffing, has pushed toward open-loop planning approaches. In this context, the execution feedback consists of off-line reporting, based on TC acknowledgement of various operations, that can be used as input to a future planning period but not as an automatic blocking element for the rest of planning.

5.3.3.4 Navigation Services

Navigation services in modern missions rely on GNSS data being available in downloaded data as well as to the on-board OPS system to support, for example, position-based activities (e.g., observation in certain modes when over a specific location or downlink when in visibility of ground station). On-ground planning is performed preferentially, if compatible in terms of accuracy depending on orbit maintenance approach, using a static reference orbit. When this is not possible (e.g., due to maneuvers or loose orbit maintenance approach), a predicted orbit is used instead for the planning.

5.3.3.5 Planning Requests

In general, in EO the Payload Planning Requests define high-level activities that are either time or position tagged. These high-level payload activity requests (related to both payload and associated data-handling system and transmitter) are internally deconflicted and then relayed to the Satellite Mission Planning center that incorporates the Payload planning together with other platform-related planning, expanding it into command sequences and deconflicting it again. These high-level sequences have default parameters. It is possible for some of these high-level activities to introduce parameters to override specific parameters. The requests of Payload data downlink are also forwarded to Payload ground station service operators to request the acquisition of the corresponding data.

5.3.3.6 Resources and Constraints

Earth Observation satellites are designed and sized to allow operation of all their parts, and it is not common that there are resources (e.g., power) that need to be negotiated between the various subsystems. Bearing this in mind, and for operational simplicity, the Rules and constraints are defined separately at the level of instruments planning and platform planning.

This means that the rules and constraints are captured and then used by the payload planning system, which will by design be in conflict. The platform/satellite planning will verify compatibility at the level of interference between the operation (e.g., tranquilization period following an orbit maneuver) and the resource allocation (e.g., power).

5.3.3.7 Request Justification

In Earth Observation, rules and constraints are defined and applied to Mission and Payload planning. This avoids the need of explicit justification requests for the activities, considering that most scientific and operational missions have an observation profile that is not dynamically user driven, as is the case for some astronomy observatory missions.

In case specific observations are required outside the nominal mission profile (e.g., to support disaster charter), the discussion and agreement is performed off-line with the relevant mission authorities, and then the corresponding activities are performed either via the nominal Payload Planning System (if possible) or directly by the Mission Control center (outside of the planning loop).

5.3.3.8 Planning-Phase Output

Planning-phase output is captured in a set of (generally XML) files dictating the requested activity for the payload and the satellite. Sometimes, a restituted Plan in the form of an XML file is produced, including execution success as observed by the individual command execution.

5.3.4 FLYBY

5.3.4.1 General

Inputs from the following missions have been taken into account for this mission type:

Table 5-3: Overview of Flyby Missions

Mission Name	Agency	Status (as of 2016)	Description
Cassini	NASA/ESA/ ASI	In Operation	Mission to explore Saturn and its complex system of rings and moons.
Rosetta	ESA/NASA/ DLR/CNES	Post-Operations	Comet Orbiter including a Lander.

These missions may apply to the flyby of any Solar System objects; the spacecraft follows a trajectory bringing it close to the target body, but not into orbit around the target body. A flyby may be part of a larger space mission, in which it only concerns a specific mission phase.

5.3.4.2 Planning Cycles

A flyby mission is characterized by the typically short duration of the science opportunity windows around the closest approach. Therefore the activities are usually preplanned for a single cycle around the estimated time of closest approach (e.g., from a distant position through closest approach and back to a distant position from the target).

5.3.4.3 Execution Feedback

In most flyby missions, execution feedback is not available within close portions of a flyby, thereby necessitating that the critical close flyby be pre-planned and generally executed open loop. Examples of this are the Cassini flybys, the New Horizons Pluto flybys, and the Rosetta flybys of asteroids Lutetia and Steins and low-gravity flybys of comet Churyumov-Gerasimenko.

5.3.4.4 Navigation Services

Navigation measurements and updates are usually performed during far approach phases and adjustments made relative to closest approach. Mission Planning (sequencing) is usually performed relative to navigational landmarks (e.g., closest approach) to facilitate updates to planning/sequencing due to navigation updates.

5.3.4.5 Planning Requests

All types of science observation, as well as engineering activities, would be Planning Requests. Because in flybys the target viewing geometries and distances are changing constantly, geometry is often a critical part of Planning Requests (e.g., to view targets with specific distance, illumination, and viewing geometries).

5.3.4.6 Resources and Constraints

Because of the rapidly changing geometries, observation time with specific geometries is often considered a resource, as is spacecraft pointing.

5.3.4.7 Request Justification

No specific information has been compiled here.

5.3.4.8 Planning Phase Output

Because of the rapidly changing geometries, observation time with specific geometries is often considered a resource, as is spacecraft pointing.

5.3.5 INTER-SATELLITE TELECOMMUNICATION

5.3.5.1 General

Inputs from the following missions have been taken into account for this mission type:

Table 5-4: Overview of Inter-satellite Telecommunication Missions

Mission Name	Agency	Status (as of 2016)	Description
Alphasat	ESA	In Operation	Geostationary satellite that carries a commercial communication payload and four Technology Demonstration Payloads (TDPs) provided under ESA responsibility. Mission Planning responsibilities comprise the coordination of possibly conflicting payload operations of the Technology Demonstration Payloads that are provided by different research institutes, which are in charge of defining in-orbit demonstration tests of these new technologies.
EDRS-A	DLR, for DPCC (Devolved Payload Control Center)	In Preparation and IOT Operation	Geostationary data relay system for other, low-Earth orbiting satellites. Mission Planning responsibilities comprise link management for optical and Ka-band inter-satellite and satellite-to-ground links and related tasks
TDP-1	DLR	In Operation and further Preparation	Geostationary relay satellite payload for laser communication. Mission Planning responsibilities comprise planning optical communication between the geo- and LEO-satellites, in-between LEO-satellites as well as optical and Ka-band downlink.

These missions are typically located in a geostationary orbit with a fixed location relative to the Earth's surface. The communication services provided could be from ground to space and back, but could also be from space to space in the case of a data relay mission. Communication may be based on radio signals or on optics using laser.

The Mission Planning of telecommunication missions may be more service based than opportunity based, when comparing, e.g., to the Planetary or Earth Observation mission types.

5.3.5.2 Planning Cycles

Inter-satellite communication by nature involves at least two spacecraft. Thus the frequency and duration of planning cycles is dependent on the planning cycles of the involved single satellites. For instance, for the TDP-1 mission, Plans that result from the inter-satellite communication planning system have to be provided as input to the ground segments of the LEO satellites in advance to their own Planning Activities and to the ground segment of the

GEO satellite, in accordance with the other TDPs and the commercial partner on Alphasat. Therefore a daily planning is performed to be able to give early feedback about the feasibility of Planning Requests to the user community with a final planning run once a week to create the final, reliable Plan for the upcoming week.

On the other hand, when being responsible for only one of the involved spacecraft, as for EDRS-A, the according ground segment part can make full use of the possibility a geostationary satellite with everlasting commanding availability over the same ground station provides: A planning run is initiated with every new relevant input received, either customer-initiated Planning Requests (including deletion or update requests) and orbit products, or telemetry and execution feedback from the spacecraft, and a replanning and adjustment of the Plan takes place each time the newest possible information basis is available. This results in planning cycle durations of some minutes only, with ‘order deadlines’ of up to only 25 or even 15 minutes, depending on the request.

5.3.5.3 Execution Feedback

Depending on the mission, there can exist multiple types of feedback from the spacecraft or an optimistic approach without a feedback loop to the Mission Planning system. For example, for EDRS-A, telemetry feedback showing the on-board memory content, as well as preprocessed confirmations about the status (uplinked, uplink failed, execution in progress, executed, execution failed) for the commanded activities, is received by the Mission Planning system and is to be analyzed and included in the next version of the Plan as well as forwarded to other ground segment entities.

5.3.5.4 Navigation Services

By nature, inter-satellite communication missions demand precise orbit and satellite and instrument attitude determination, and thus the necessity exists for the respective planning systems to include them. Therefore, on the one hand, orbit information has to be considered in the planning and the spacecraft knowledge about its/their own position(s) has to be ensured and managed as well. To serve this, products from flight-dynamics services are to be received and processed regularly.

On the other hand, flight-dynamics services are actively invoked to receive additional information for Planning Requests, either to determine the pointing to be acquired for every new communication session from an initial position or in dependence of the pointing for the previous and next communication session, without a parking position in-between. Furthermore, the pointing vectors to be acquired during the communication sessions have to be calculated and included into the planning results for the commanding. If applicable, in this context the flight-dynamics services also deliver the information if a Planning Request cannot be performed at all because of the given orbital geometries or instrument pointing capabilities.

5.3.5.5 Planning Requests

The Planning Requests for inter-satellite communication planning systems primarily comprise requests for communication link sessions on one of the involved satellites, in-between two of them, or in-between one of them and an antenna on ground. In addition, general operations such as instrument parking or un-parking, or other maintenance tasks, are requested. For EDRS-A, another type of Planning Request contains the data to be transferred during the execution of communication sessions from ground via the relay-satellite to another satellite, which has to be uploaded in advance of the actual link.

In general, the Planning Requests contain requests for high-level activities that are processed as dedicated command sequences. However, Planning Requests for EDRS-A, for example, can also contain such command sequences directly as a request from the customer, and, furthermore, slots for manual, real-time commanding are also requested via Planning Requests.

5.3.5.6 Resources and Constraints

Typical resources to be monitored by the Mission Planning systems and constraints to be included in the planning result calculation for inter-satellite communication missions are related to the pointing capabilities and opportunities of the spacecraft and communication terminal(s) or antenna(s) involved in the link sessions, and the on-board memory buffer(s) status for storing commands and data to forward.

As with any other mission, this is complemented by the duty cycles of the instruments and the rules regarding which activities are or are not allowed to be performed in parallel.

5.3.5.7 Request Justification

This information is contained in the Planning Requests, either explicitly or derivable from the content type by applying given mission-specific rules. Priorities, as one of the rules, can be given via simple request parameters as well as determined from various components, such as parameter values in combination with current circumstances.

5.3.5.8 Planning Phase Output

As with any other mission type, the result of every planning run is a new or updated overall Plan for a predetermined timeframe in the (near) past and future. Out of this, different export interfaces are served, depending on the mission: One or more export files containing the respective telecommand sequences for the commanding interfaces are created, as well as several other output files containing anything from parts of the information from the created plan, e.g., status messages for single requested activities that were contained in the Planning Requests, to lists of information excerpts of Plan contents of the same type.

5.3.6 OBSERVATORY

5.3.6.1 General

Inputs from the following missions have been taken into account for this mission type:

Table 5-5: Overview of Observatory Missions

Mission Name	Agency	Status (as of 2016)	Description
James Webb Space Telescope (JWST)	NASA	In Preparation	L2 science mission to explore the early formations.
Solar Orbiter	ESA	In Preparation	Deep Space Solar observatory mission, operating at close Sun distances for a period of 3-7 years.
Spitzer Infrared Space Telescope	NASA	In Operation	Orbital observatory.
XMM	ESA	In Operation	X-Ray Observatory in 48h elliptical orbit around the Earth.

A space-based observatory is normally located in a high Earth orbit or Lagrange point, to reduce the effects of the Earth’s environment, although LEO missions are also to be considered. It may carry one or more instruments observing the celestial sky.

The Mission Planning of an observatory is driven by the science community behind the mission. Individual scientists may request observations to be performed in observation campaigns and managed by a central planning entity.

5.3.6.2 Planning Cycles

The planning cycles are composed of some mission-long planned activities (i.e., routine calibration plan, recurrent high-priority targets) that are not movable or, if so, take higher priority versus others; long-term planning cycles typically defined by the announcement of opportunity to the scientific community (i.e., release of a given time frame along which observers may request specific observations, time bound or freely allocatable); medium-term planning cycles defined by the horizon of certainty of mission conditions (i.e., orbital stability forecast, availability of Spacecraft Maintenance Windows, others); and short-term planning cycles that represent the Plan Request to the Mission Operations Center for execution. On top, there is the figure of the Target of Opportunity, which could involve a fast replanning.

Long-term cycle planning resolves the conflict of multiple requests for a given time window, stating which user requests to the Planning Service take priority and which ones are discarded or left for later cycles. The process may also involve a top-level assignment of times per request, thus creating effectively a top-level Plan for the period, or simply allocating the requests to a pool of available entries for later planning. The planning typically spans months up to one year in some examples.

Medium-term planning involves allocation of requests and activities for the timeframe covered, considering available pointing/visibility and Spacecraft Availability. A preliminary optimization is implemented to minimize dead times (slews, instrument reconfigurations, and others). Medium-term planning covers one or several weeks in advance.

Short-term planning involves the extraction of the selected subset of products from the medium-term planning and the final optimization given the latest updated knowledge of the environmental conditions. The short-term planning product covers one or several days.

Finally, Targets of Opportunity (i.e., dynamic astronomical objects in position, time, or other characteristics) may trigger a fast replanning to accommodate these targets, this fast replanning being either a re-run of the short-term planning or an ad-hoc planning process focused just on the new target.

5.3.6.3 Execution Feedback

The execution feedback to the Planning Service consists of a preliminary accept/reject status of the Plan, followed by use of TM and TC history or activity reports to confirm execution. This needs to allow identification of the different original requests in the sequence of performed or failed activities, down to a level of detail that can allow triggering the scientific product generation. It contains execution status not only for the requested instrument configuration and commanding steps, but also for the pointing and stability information and for environmental conditions (radiation, thermal, others) that could impact the original request. Frequently, several Plan Requests Activities belong to higher-level Plan Requests that make a consistent observation request; therefore the capability to get feedback on the higher entity is also requested.

5.3.6.4 Navigation Services

By nature, observatory missions are demanding in terms of navigation and pointing/slewing. The instrumental activity requests are linked to attitudes of targets in the sky and/or avoidance of given regions. The services typically include stable pointing requests to given targets, the computation of visibilities and avoidances of regions or targets, the slew time predictions, and the slew paths.

The availability and access to the Planning Service of the navigation solution or access to its computation often saves iterations in the planning process. These dynamic services exist in 3 out of 4 example missions in use.

5.3.6.5 Planning Requests

A typical Planning Request consists of a petition for instrumental (one or many) activity at a fixed time/fixed target/open time/open target in the sky, given a subset of environmental conditions and constraints are met and avoided respectively. It always contains a section dealing with instrument configuration and activity, either in the form of direct commands to the instruments or meta-blocks that are translated by Mission Control Center. In most cases it contains pointing information, either in the form of celestial coordinates or as quaternion information that performs translation from a previous attitude or reference frame. In given cases (i.e., dark calibrations, other activities), the attitude is open, as long as given conditions (illumination, stray light, others) are met. It also may contain a fixed time for execution (i.e., coordinated activities with other observatories, celestial activity), a range of times for execution, or an open window for the request. Finally, it may contain as part of the request a link to others (forming a Plan) and a link to the applicable set of constraints.

The requests in the example missions use template structures or fixed upper-level constructs that simplify the definition of lower-level TCs needed. The timing involved can be either at a repeated pattern (e.g., for calibration activities) or using a reference (not earlier than, after activity, etc.).

5.3.6.6 Resources and Constraints

The planning process in these missions is driven by different types of resource and constraint considerations:

- **Self or Inter-instrument Constraints**: Activities performed by one instrument that prevent others from happening (i.e., mechanical or electrical interference, nonaligned fields of view), or activities that cannot be performed by one instrument (i.e., number of filter wheel rotations, CCD/detector persistence avoidance, others).
- **S/C Resource Utilization** (i.e., power, memory, downlink bandwidth, attitude, slewing times and capabilities, antenna pointing) and limitations.
- **Pointing Constraints**: typically, Sun and other object illumination avoidance or targeting, defining at any given time allowed regions of the sky, or, given a region of the sky, allowed observing times.

The planning process often consists of the optimization of the priority of the pool of the selected observations for the long-term Plan versus the resources and constraints, ensuring local medium-term planning highest optimization that maintains a good level of overall optimization in the long-term process. Furthermore, the optimal use of multiple instruments in missions carrying more than one instrument is another factor to consider. The resource and constraints may be globally defined (implicit) or an explicit part of the Plan Request.

5.3.6.7 Request Justification

The request justification may be part of the request, especially in such cases as the Targets of Opportunity. Otherwise, the justification is typically used at Science Operations Center (SOC) or Scientific Planning side to assign priorities by allocation committees, not directly involved in the planning process but rather selecting ‘candidates’ to be used, as well as other planning considerations, but is not propagated to the Plan.

5.3.6.8 Planning Phase Output

The output is a request to the Mission Operations Center consisting of a Plan covering the short-term period. This Plan addresses either activities (i.e., higher blocks) or TC sequences directly, and can be time based or event based. It is typically composed of a pointing subset of information linked to another subset dealing with instrumental configuration.

5.3.7 PLANETARY

5.3.7.1 General

Inputs from the following missions have been taken into account for this mission type:

Table 5-6: Overview of Planetary Missions

Mission Name	Agency	Status (as of 2016)	Description
BepiColombo	ESA/JAXA	In Preparation	Interplanetary mission to Mercury, including a Planetary Orbiter and a Magnetospheric Orbiter.
Cassini	NASA/ESA/ ASI	In Operation	Mission to explore Saturn and its complex system of rings and moons.
ExoMars 2016	ESA/NASA/ IKI	In Operation	Mars Surface Relay and Science Mission (Trace Gas Orbiter)
JUICE	ESA	In Preparation	Exploration of Jupiter and its Icy Moons.
Rosetta	ESA/NASA/ DLR/CNES	Post-Operations	Comet Orbiter including a Lander.
Smart-1	ESA	Post-Operations	Lunar mission; technology demonstrator including electric propulsion.

The spacecraft of a planetary mission typically carries multiple scientific payload instruments. Depending on the mission objectives, imaging instruments are characteristic for these types of missions; but non-imaging instruments are also often on board planetary spacecraft.

5.3.7.2 Planning Cycles

The planning process of planetary missions typically follows a three-phase planning approach with long-term, medium-term, and short-term planning. All reference missions have these three planning cycles.

The typical duration of the long-term planning cycle is months. At this stage the planning is performed based on key geometric parameters, such as the distance to the planet and illumination condition (e.g., local solar elevation). Depending on the mission needs, the planning can be kept on high-level planning (e.g., assignment of time slots or orbits to instruments) or go into detail planning at activity level.

A typical duration for medium-term planning cannot be stated as it varies from days to weeks and months for the reference missions. The common aspect is, however, that the medium-term Plan is typically detailed at activity level. The planning is often based on events, which can be resolved to time.

The short-term planning cycle is days to weeks. The main input being updated information regarding the constraints and more accurate orbit files.

5.3.7.3 Execution Feedback

The execution feedback is typically provided for Science operations in form of TC history. For relay operations, in addition to the TC history, a ‘Planning Result Response (PRR)’ file is provided for some missions (e.g., ExoMars) to the relay user at different planning levels (mid- and short-term planning). It provides, for example, feedback on whether the forward-link bit-patterns (rover commands) were successfully uplinked to the relay orbiter.

5.3.7.4 Navigation Services

For most payload instruments of planetary missions, the spacecraft orientation (pointing) is an important resource/constraint. Consequently, satisfying pointing requirements and avoiding pointing conflicts is one of the main challenges of the planning process for this type of mission. In order to evaluate the slew time between two subsequent requested spacecraft attitudes, the Mission Planning system needs to interact with the Navigation capabilities (of the ground segment or, in case of on-board automated planning, with similar functionality on board the spacecraft). This interaction can be manual or automated.

In the iterative planning process, the Mission Planning functionality exchanges as part of the planning process dedicated Mission Planning products (e.g., pointing requests) with the navigation functionality and asks for their validation. In order to reduce the number of iterations, simplified rules based on worst-case boundary assumptions are often taken as the baseline by the planning system.

In more automated approaches, the Navigation function may expose a dynamic service interface to the Mission Planning function (in the form of a Web service, an API, or even a tool or library).

The results of the conducted survey have indicated that the majority of the inquired missions make use of dynamic interfaces between their Mission Planning and Navigation functionality.

5.3.7.5 Planning Requests

Typically, the Planning Request contains:

- references to operations templates for the requested activity;
- information about resource consumption either as explicit information or implicitly through use of operational templates; as part of the request: global constraints, geometric constraints (e.g., distance, phase angle), and dependency constraints on other activities (e.g., not in parallel with S/C maintenance slots);
- scientific justification or rationale for the requested activity (half of the surveyed missions include this kind of information);
- information related to the priority of the request is provided in different formats, e.g., a numerical priority level, a prioritized target list, etc.

5.3.7.6 Resources and Constraints

The following resources can be identified:

- **Pointing**: Satellite orientation is one of the main characteristic resources in Mission Planning for this type of mission.
- **Power**: Because of the long distance from the Sun, power is typically a challenging resource for planetary missions.
- **Data Storage Capacity**: There is a limited storage capacity on board the spacecraft. The downlink speed of planetary missions is typically lower than, for example, Earth Observation missions. The combination of these two factors makes the data volume another important resource for planetary Mission Planning.

The following constraints can be identified:

- **Geometric Constraints**: Illumination conditions (solar local elevation, phase angle, distance, etc.);
- **Thermal Constraints**: Maximum illumination period of certain areas of the spacecraft and its instruments;

- **Logical Constraints**: Scientific objective can only be achieved by performing a series of activities of one or more instruments (potentially in a particular order);
- **Timing Constraints**: Repetitive activities.

5.3.7.7 Request Justification

5.3.7.7.1 Payload Activities

The high-level scientific objectives of a planetary mission are often specified at very early phases of the mission selection and design (e.g., characterization of the composition of the atmosphere of the target planet, high-resolution mapping of the target planet surface, search for certain elements in certain areas of the planet, etc.). The payload instruments of the mission are then selected/designed, ensuring that their activities (observations/measurements) can contribute to the achievement of the defined scientific objectives of the mission.

This gives a high-level rationale for establishing a hierarchical network of scientific objectives and relating them to the activities of the payload instruments. To what extent this network of scientific objectives and its relation to individual payload activities is systematically defined and maintained varies from mission to mission.

Some planetary missions establish rules for providing information about the scientific rationale of a requested activity, as part of the Planning Request. This allows tracing the requested payload activities to the scientific objectives of the mission. In practice, such high-level information is not always sufficient to drive the decision-making logic during the Mission Planning process; hence not all missions make systematic use of such networks of scientific justification in their Mission Planning process.

The planning of planetary missions is conducted as federated planning, in which the knowledge and responsibility for the activities of each payload instrument is with a separate team, led by a Principal Investigator. In this setup, it is not unusual for justification for payload activities to be done at phase/period level rather than for each Planning Request. In this approach, as part of the long-term planning, high-level geometrical conditions (e.g., illumination conditions, phase angles, solar local elevation, distance to the surface, etc.) are analyzed and suitable periods of mission are accordingly assigned to individual lead instruments to achieve their scientific objectives (e.g., per week, per orbit or even portions of an orbit).

If this approach is adopted, the sub-sequent Planning Requests at medium and short-term planning cycles may not include complementary information about their scientific justification, and the tracking of payload activities to scientific objectives of the mission may be conducted orthogonal to the planning process.

5.3.7.7.2 Platform Activities

The justification for Planning Requests that relate to spacecraft platform activities are often more tangible and hence easier to specify in a systematic manner when compared to scientific justification of payload activities. These types of Planning Requests are typically related to routine and repetitive activities that are necessary to maintain the spacecraft health, conduct communication with the ground, or perform orbital corrections. In the federated planning process, which is typical for planetary missions, the responsibility for platform activities is with a different entity (MOC) from the payload activities.

The rationale for many platform activities can often be formalized as planning rules, which are incorporated in the planning system. Accordingly, some of the related Planning Requests are periodically submitted or even auto-generated based on defined rules. Since the justification for these activities is implicitly given, it is less common to provide complementary justification information as part of the Planning Request for these types of activities. In case of conflicting requests for payload and platform activities, it is not unusual to also revisit the justification for the conflicting platform Planning Request for trade-off analysis.

5.3.7.7.3 Request Justification Summary

Planning Requests for payload activities of planetary missions often (but not always) include complementary information about their scientific justification.

Planning Requests for platform activities of planetary missions do not typically include complimentary justification information. The rationale behind the Planning Request is, however, often captured through keywords (e.g., the name of the activity) that allow tracing to operational rules, defined as part of the planning process.

5.3.7.8 Planning Phase Output

No specific information has been compiled here.

5.3.8 ROBOTIC SERVICING

5.3.8.1 General

Inputs from the following missions have been taken into account for this mission type:

Table 5-7: Overview of Robotic Servicing Missions

Mission Name	Agency	Status (as of 2016)	Description
Orbital Express	DARPA, U.S.	Post-Operations	Technology demonstration of in-orbit autonomous rendezvous and robotic servicing.

These are special missions, in which the spacecraft performs dedicated activities on another spacecraft that is the subject of the servicing mission.

The Mission Planning of these missions may be very specific and may require real-time operations with the ground segment in the loop, or may be based on more autonomously operating servicing vehicles. An example of such a mission is the Orbital Express mission, a robotic servicing-technology-demonstration mission in which autonomous rendezvous, module replacement, and refueling were demonstrated.

5.3.8.2 Planning Cycles

These missions often have traditional hierarchical planning cycles with long-term, medium-term, and short-term planning cycles. Long-term planning might include allocation of times to high-level activities such as refueling. Short-term planning might include low-level robotics commands and allow for execution uncertainty for retries and closed-loop control.

5.3.8.3 Execution Feedback

Because of robotic activities, lower-level activities are likely to require execution feedback. In some cases, feedback from these lower levels ‘leaks’ into higher levels in terms of uncertain execution times and failures.

5.3.8.4 Navigation Services

For robotics activities that may require specific approach vectors and angles, such as autonomous rendezvous and robotic manipulation, spatial reasoning and therefore navigation may be central to the mission.

5.3.8.5 Planning Requests

Planning Requests can take the form of many robotics actions, such as manipulation, exerting force/delta-v, or higher-level refueling or module replacement.

5.3.8.6 Resources and Constraints

In addition to the typical power and data volume, other ‘robotic’ resources may be relevant such as occupation of certain areas of free space.

5.3.8.7 Request Justification

[No specific information has been compiled here.]

5.3.8.8 Planning Phase Output

Planning Phase Output can vary from abstract activities for long-term planning to detailed command sequences at lower levels of hierarchical planning.

5.3.9 SURFACE OPERATIONS

5.3.9.1 General

Inputs from the following missions have been taken into account for this mission type:

Table 5-8: Overview of Surface Operations Missions

Mission Name	Agency	Status (as of 2016)	Description
Mars Science Laboratory	NASA	In Operation	Surface operations for a complex rover.

This mission type includes the utilization of rovers on Solar System objects, particularly on Mars and the Moon. Surface Operations missions typically consist of multiple mission elements, such as an orbiter providing the data relay to Earth from the rover on the surface. In addition, there may also be a dedicated landing support subsystem.

The planning of these missions may be divided into a dedicated surface operations planning and the planning of the other elements, especially of the data relay function. Eventually, the individual planning of all of these elements will be aligned.

5.3.9.2 Planning Cycles

These missions typically do have multiple hierarchical levels of planning. For example, the Mars Science Laboratory rover has long-term planning (allocation of sols to major science objectives or locations), supra tactical (which looks several sols in advance to manage downlink cycles and operations restricted sols), and tactical planning (which addresses one-to-several sols handled in a single uplink cycle).

5.3.9.3 Execution Feedback

Execution feedback includes rover position and robotic (arm placement) and available per tactical cycle (one to several sols). This also includes energy and data volume state.

5.3.9.4 Navigation Services

Navigation services include rover location (see above) and arm position estimation.

5.3.9.5 Planning Requests

Planning Requests can include both remote sensing measurements and robotic placement requests, such as for contact or hover instruments, as well as drive requests.

5.3.9.6 Resources and Constraints

In addition to the typical time, energy, and data volume resources, the rover and arm position can also be considered resources.

5.3.9.7 Request Justification

No specific information has been compiled here.

5.3.9.8 Planning Phase Output

Long-term planning output for the Mars Science Laboratory (MSL) is meant for abstract resource forecasting (e.g., sols to driving). Supra-tactical planning output is meant for baseline activities, to manage uplink and downlink cycles and schedules. Tactical planning output is meant for actual commanding.

5.3.10 SURVEY

5.3.10.1 General

Inputs from the following missions have been taken into account for this mission type:

Table 5-9: Overview of Survey Missions

Mission Name	Agency	Status (as of 2016)	Description
GAIA	ESA	In Operation	Surveyor of the Galaxy to determine position and velocity of stars.

A survey mission is normally located in a high Earth orbit or Lagrange orbit, to reduce the effects of the Earth’s environment. Alternatively, it may be in a dedicated Solar System orbit to be in a more favorable position with respect to the target body of interest, such as the Sun. It is a typical mission type in space astronomy missions but might be used as well for Solar System exploration missions.

The Mission Planning of a survey mission is usually based on predefined rules or scanning laws, which determine how the celestial sky or target of interest is being observed in an optimal way and how a full systematic coverage can be obtained.

A particular set of missions that could be understood as surveys are those in which the regions of the sky or targets are identified from the start and are applicable for the whole mission duration, even if the way to conduct the survey is not implemented through scanning laws but through a collection of stable pointing requests. This could be the case for cosmological missions or exoplanet finder missions. Therefore the main characteristic of a Survey Mission is the (apparent) predictability of its targets and its sequence.

5.3.10.2 Planning Cycles

The planning cycle is based on a mission-long planning rule (scanning law, overall pointing sequence, etc.). This determines the mission behavior, although it may be the case that short-term refinement is required using the latest available knowledge of the environment and conditions (thus creating a medium-term cycle in the range of weeks), or to accommodate last minute changes or updates (i.e., requests for instrument calibrations or engineering activities, correction of anomalies).

5.3.10.3 Execution Feedback

The execution feedback is confirmed through the availability of TM and TC history as well as all the HouseKeeping TeleMetry (HKTM) and ancillary products, such as attitude and orbit history.

5.3.10.4 Navigation Services

The example mission used does not foresee dynamic navigation service. Typically, these survey missions are not demanding in terms of quick determination of pointing or by repetitive use of these services. The existing interfaces make use of some Flight Dynamic routines available at the planning service side (SOC) to explore or identify visibility windows. There are no SOC to Flight Dynamic interfaces.

5.3.10.5 Planning Requests

The Planning Requests are one-off timing types of activities, in which blocks are defined in a SOC DB and requests are based on them. Exceptionally finer granularity sequences could be composed for instrument-specific activities.

5.3.10.6 Resources and Constraints

Resources and constraints are implicit in the definition of the scanning law or overall planning rule, and also through the use of operational templates. They are described as global constraints (geometry, alpha or beta angles, thermal).

5.3.10.7 Request Justification

The Plan Requests are mostly based on a pre-agreed overall survey rule or law; therefore there is no science justification accompanying the requests. However, this could be required for medium-term corrections or deviations, in order to allow the planning entity or SOC to assign priority to them.

5.3.10.8 Planning Phase Output

The planning output is, for the mission-long planning, either a scanning law in the form of a mathematical construct or a repetitive or deterministic set of targets and instrumental activities for the whole mission duration. For the modifications, it is a time-driven set of telecommands or recognized block templates implementing one or more activities.

5.4 CONCLUSION

The results of the systematic information gathering survey of representative space missions of various CCSDS Member Agencies has shown that, despite the difference between the mission categories and the way each mission organizes the Mission Planning information, common concepts exist between all analyzed missions and similar types of information are involved. This underlines the possibility of defining a generic and common information model for Mission Planning and generic interfaces for its exchange, which is the objective of the work of the CCSDS Mission Planning and Scheduling WG.

6 INFORMATION MODEL OUTLINE

6.1 OVERVIEW

This section provides an outline of the Information Model applicable to the Mission Planning and Scheduling standard, introducing and describing major data elements in line with agreed terminology, used throughout this document.

A division can be made between Planning Information and Supporting Information. Planning Information directly concerns the Information exchanged at interfaces of the identified Mission Planning functions. The Supporting Information encompasses information supporting the execution of these functions but not necessarily exchanged between the identified interfaces.

For this reason, Planning Information pertains more to the interfaces of a Mission Planning system, in terms of input and output, while Supporting Information is more internal to a Mission Planning system. It is acknowledged that the borderline between these two sets of information can move, depending on the adopted Mission Planning processes, implementation choices, and organizational drivers.

Following a stepwise approach, the first envisaged Mission Planning Services Blue Book will focus on the common denominator of typical Mission Planning scenarios and capture the Mission Planning Information that crosses the interfaces of such Mission Planning systems.

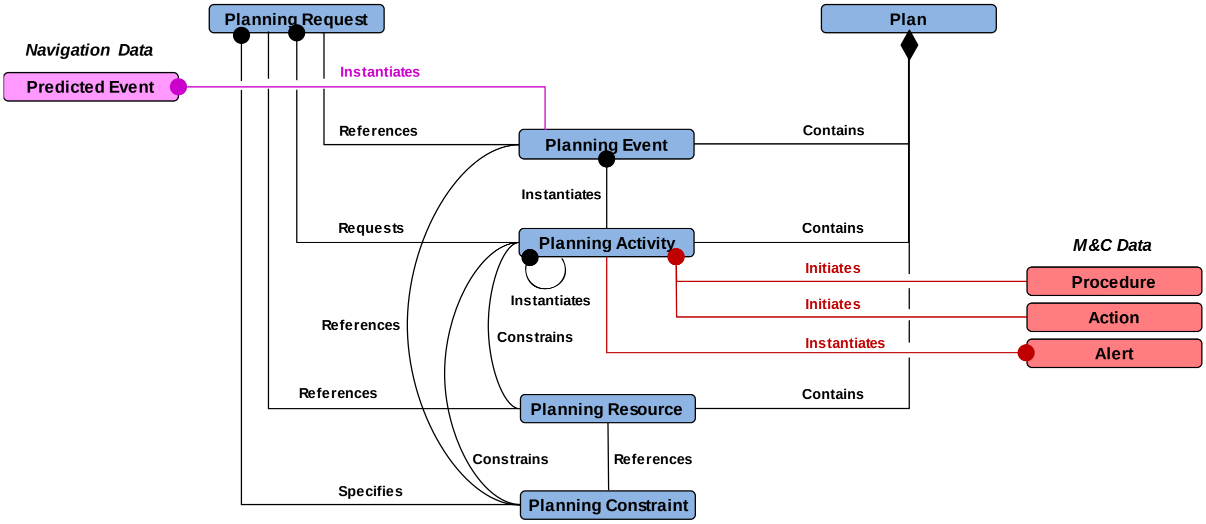


Figure 6-1: Mission Planning High-Level Data View

6.2 HIGH-LEVEL DATA VIEW

6.2.1 GENERAL

The Mission Planning high-level data view is depicted in figure 6-1. The rectangles in the diagram correspond to standard data objects; the lines between them define the relationships between those data objects. Data objects are color-coded by functional area, consistent with figure 3-1; Mission Planning data objects are shown in blue, Mission Control in red, and Navigation in magenta.

Relationships shown in black are within the scope of Mission Planning standardization, others are color-coded by their respective areas. A diamond shaped terminator on a relationship indicates a composition relationship (for example, a Plan may contain Planning Events, Planning Activities, and Planning Resources). A circle shaped terminator on a relationship indicates a source relationship, consistent with the CCSDS MO Common Object Model.

The external data items, such as the Predicted Event data from the Navigation domain and the Procedure, Action, and Alert data from the Mission Operations Monitoring and Control (M&C) service domain, are defined in other CCSDS standards. This is in line with the CCSDS Reference Architecture, as introduced in 3.1, which describes more exhaustively the relationship between the Mission Planning function and other Mission Operations functional areas.

The internal data items (i.e., the blue boxes) are defined inside the Mission Planning function. Planning Requests and Plans are both container objects whose content relates to a set of planning data items: Planning Events, Planning Activities, Planning Resources, and Planning Constraints. For each of these types (or classes) of planning data, there is a defined set of items that can be referenced or instantiated within Planning Requests and Plans.

6.2.2 PLANNING REQUEST

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 is envisaged that this will support the specification of different types of requests:

a) request to plan an activity or a set of activities;

b) request to achieve a goal;

c) request to use a Plan as an input to the planning process;

d) request to modify the content of a Plan.

The main characteristic of the Planning Request is that, being a container, it needs to hold references to, or instances of, the constituent information items that are required by the planner and agreed to by the interacting parties for exchange at interface level. It has one or more Planning Activities as the basis of the request and, in addition, optionally references Planning Events. Information about constraints on when a requested activity can or will be planned may be exchanged as part of the Planning Request by referencing constraints on the time, the position, the state of Planning Resources, or any other Planning Activities.

6.2.3 PLAN

The Plan is the output of a planning process. The Plan is basically a container of one or more selected Planning Activities, optionally associated with 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 the hierarchical and distributed planning concepts, the output of one planning function could be the input of another one. In that case, a Planning Request could refer to an entire Plan.

Plans may be iterative and therefore overlap with the previous Plan. This introduces the notion that a Plan may have an identified predecessor, and also that if a planning data item is contained in multiple iterations of the plan, then it should have the same unique identity in each successive iteration of the Plan to avoid ambiguity and duplication.

6.2.4 PLANNING EVENT

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. There may be more Planning Event types defined, which will be decided during the implementation of the standard.

A Predicted Event is the specific instantiation of a Planning Event with its associated value, which may be used during the planning process and in the generated Plan. The Predicted Events are typically provided externally from the planning function (for example by a Navigation function); therefore these elements are not part of the Plan but only referenced from the Plan. Predicted Events could also be determined internally, in which case the event information will be contained inside the Plan.

The Predicted Event time or position could be extended with an additional delta range, describing the uncertainty in the event time or position. This uncertainty will typically decrease over evolving planning cycles when getting closer to the actual event taking place, allowing for more accurate predictions of the event.

Planning Events may support more advanced concepts, such as multiplicity, for example, to support the planning of repeated observations at given time offsets.

6.2.5 PLANNING ACTIVITY

A Planning Activity is the basic building block for the planning, being 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.

Planning Activities support hierarchy; a Planning Activity may be composed of one or more subordinate Planning Activities. A Planning Activity may define arguments (parameters), which could be used to instantiate a specific Planning Activity in a Plan, based on its generic definitions. Arguments of a Planning Request or Planning Event can be passed through to the arguments of Planning Activities resulting from these. Arguments can then similarly cascade down through a hierarchy of Planning Activities.

A Planning Activity has a definition. The definition of a Planning Activity may evolve over time. It is important to maintain a unique and unambiguous relationship between the Planning Activity and its evolving definitions. This allows reconstitution of the history of any Planning Information. The definition of the Planning Activity at the level of the interface needs to be known to both interacting parties (i.e., the requester and the planner of the Planning Activity). It is possible to have a self-describing interface in which the definitions are also included in the request or the plan. This only works for limited deployment cases; in general, it would be preferred to separate the provision of definition data, for which the MO Common Object Model (COM) and the associated COM Archive Service provide a mechanism.

6.2.6 PLANNING RESOURCE

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:

- trigger the execution of a Planning Activity;
- constrain the execution of a Planning Activity.

If an event or constraint on a Planning Activity needs to be expressed in terms of the state of the system (rather than just time or position), then this corresponds to the state of Planning Resources. This is considered not internal to the Planning function if it forms part of the Planning Request or Plan.

A Planning Resource could in principle be considered as information that is internal to the planning system. However, some resources may be shared across multiple planning entities. As a result, information regarding a resource could be communicated between entities and therefore would have to be referenced as part of a Planning Request, or of the Plan, in terms of requested or consumed resources, respectively. This may include the initialization or synchronization of Planning Resource values at specific points in the Plan.

6.2.7 PLANNING CONSTRAINT

A Planning Constraint is something that limits or restricts the planning of activities. A Planning Constraint could be based on Planning Resources, with their specific allocation and consumption. A Planning Constraint is not specifically associated with a Planning Request, but rather applies generally to a Plan. Different types of constraints exist: time constraints, resource constraints, geometric constraints, sequencing constraints, exclusion constraints, etc. Also, assigned priorities may imply constraints on the planning.

A Planning Request does not necessarily have to reference any Planning Events, but could only define Planning Constraints, resulting a in pure constraint-based planning for the request. Some Planning Constraints are internal to the planning system and therefore will not appear in the interface between planning entities.

6.3 DATA ITEM CHARACTERISTICS

The generic characteristics of the Planning Data Items are depicted in figure 6-2. Each Planning Data Item can hold references to its configuration data (definitions) and the instances of data objects that are contained within Planning Requests and Plans.

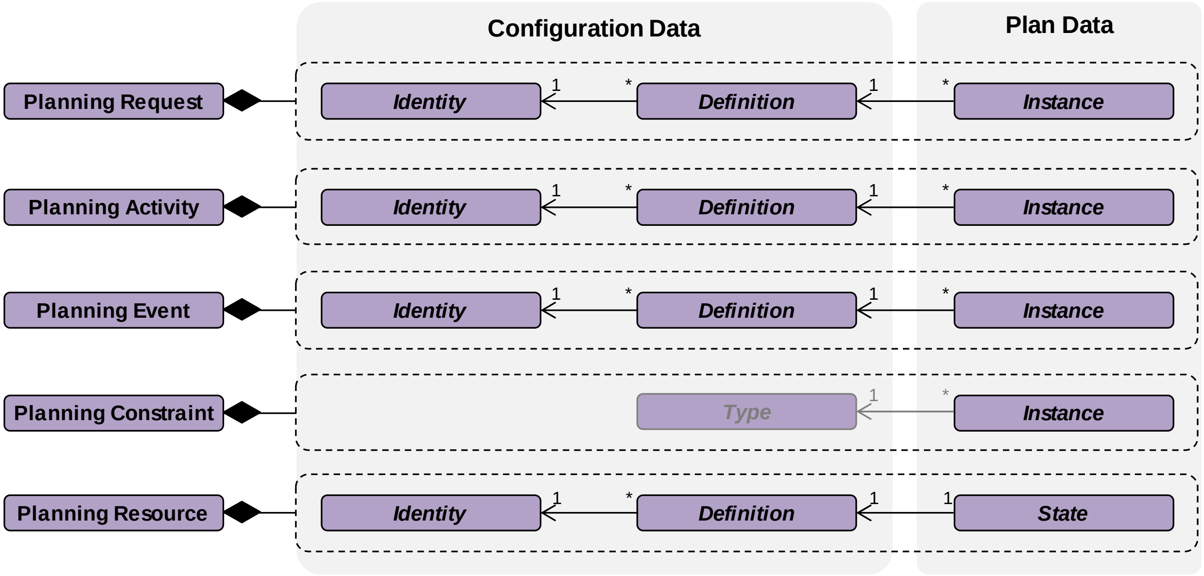


Figure 6-2: Characteristics of Mission Planning Data Items

Planning data items have three characteristics:

a) A unique identity that is associated with a data item throughout a mission lifetime.

b) A definition that is associated with that data item and that may be updated in the course of the mission lifetime. The definition contains static information about the data item, potentially including a description, a set of variable parameters, a hierarchy of contained data items, and any fixed constraints.

c) The instances of a data item, including the value of parameters, relationships to other data item instances (parent, children, and potentially siblings), and any dynamic constraints.

The use of the MO Common Object Model (COM) for the specification of the Mission Planning Information Model provides the framework for capturing these concepts, supporting the reconstruction of the history of the Mission Planning information at any given time in a mission.

Planning Data definitions form the Configuration Data that Planning functions need to share in order to interpret the content of Planning Requests and Plans. Planning Data instances are exchanged at Planning function interfaces within Planning Requests and Plans.

Some classes of Planning Data, including both Planning Activities and Planning Events, may be instantiated multiple times. In this case, there may be multiple instance objects associated with the same definition, each requiring its own unique identity in addition to that associated with the definition. Planning Requests themselves could also have this structure if a simplified interface for users supports the concept of predefined templates for Planning Requests.

Planning Resources are singletons with a current or predicted state. Stand-alone Planning Constraints have no associated definition, but may appear in the context of a Planning Request or Plan.

6.4 FEEDBACK AND TRACEABILITY INFORMATION

The planning function may provide feedback on the status of a Planning Request. The Planning Request life cycle has been described in 4.11, where a number of possible Planning Request states have been proposed, including specific information that is maintained in relation to the current state of the request.

Feedback on a Planning Request state may be provided back to the requestor or to any other entity having an interest in a specific Planning Request. Feedback could be provided immediately (e.g., after submitting a request) or when a query for the current state is sent to the planning function. Alternatively, feedback could be provided to registered users of the Planning Request, and will be provided each time the state is updated. Feedback does not necessarily have to be provided at the same level as the original request; feedback could be provided at a lower level, e.g., by including the execution details of the request.

Traceability is concerned with information that will identify the requester, and will be moved ‘forward’, so that at a later stage feedback can be provided to the original requester. It will also serve a broader purpose, e.g., when produced Plans are inspected, the originators of Planning Activities can be identified.

The interaction between the planning function and the user entities, being recipients of the feedback information, will be described in more detail in section 7. The provision of feedback will be incorporated into the specification of the related Mission Planning services as part of the envisaged information exchange patterns based on the MO Services concept (see 3.2). The use of the MO Common Object Model provides the means for establishing the required links and capturing of the metadata needed for this purpose.

6.5 SUPPORTING INFORMATION

In 6.3 above, a generic data item structure is proposed, which distinguishes between configuration data and planning data, the latter being the specific instantiations of the data items that are identified and defined with the configuration data. The planning data will be the main information as input to and as output from the Planning function and therefore subject to the current standard.

However, to keep consistency in the definitions of this data when multiple entities are involved in the Mission Planning, it is anticipated that the configuration data should also be covered by the standard. Typically, the configuration data changes at a slower pace and in general will not change as the result of the execution of the planning process itself. Still, ad-hoc changes could take place, so the management of this data should be supported by the standard to ensure consistency across ground-segment entities in the use of this data.

Planning Resources and Planning Constraints have been described above, and are in some cases subject to the current standard, e.g., in the case of Planning Resources shared across multiple entities involved in the Mission Planning, or in the case of constraints being defined at the level of the Planning Requests. Other resources and constraints may only be defined internally in a planning function. In this case, the information will not be subject to the standard.

In support of computing resources and constraints, various models of the space and ground systems may exist in the different planning functions. These models can be regarded as internal to the planning systems; however, there may be the use case in which models, software programs, mission or spacecraft parameters, etc., are shared between planning entities to ensure consistency in the modelling.

At a later point in time, the Mission Planning and Scheduling standard could support the exchange of any kind of information, including modelling data, without being concerned about the actual contents of the information. In that case, the standard could provide a set of generic exchange services including identification, traceability, configuration control, etc., without the need to standardize the contents of this information.

7 SERVICES OUTLINE

7.1 GENERAL

As stated in the Introduction, the initial focus of standardization for Mission Planning and Scheduling will be on the development of standard Mission Planning Information Model, agnostic to encoding and selected communication protocol for its exchange. The specified Mission Planning Information Model can then be instantiated and, for example, encoded as XML or ASCII and exchanged in the form of files between collaborating organizations or functions. This will primarily concern the exchange of Planning Requests, Plans, and the associated status feedback.

In order to achieve interoperability between the involved parties, it is, however, also necessary to standardize the semantics of the information exchange in terms of the expected pattern and sequence of information exchange; the functional and non-functional requirements on the sending and receiving side, upon transmission and receipt of the respective information; the expected feedback, including possible errors; and the handling of aspects such as security, addressing, and transaction management of the information exchange.

It is therefore envisaged to specify a set of Mission Planning and Scheduling Services, reusing the already existing CCSDS Mission Operation framework (see 3.2). These Services will define the behavioral aspects of the concerned interfaces, building on the specified abstract Mission Planning Information Model.

7.2 SERVICE USE CASES

The service interface has two roles associated with it, that of the service provider and the service consumer. The provider functions for the Mission Planning Services correspond to the one of the abstract functions identified in figure 2-1: Planning or Plan Execution. The consumer functions may in principle be any other function; however, figure 3-3 identifies the consumer functions anticipated by the CCSDS Reference Architecture (see 3.1), which include:

- User Support;
- Navigation and Timing;
- Operations Preparation;
- Other Planning functions;
- Monitoring & Control.

The Mission Planning interactions required by these functions can be further analyzed to identify a set of use cases which correspond to particular types of required interaction, as follows:

a) **Submission of Planning Requests** and receipt of status feedback on the progress of those Planning Requests. This is required by:

    1) **User Support**: For the submission of end-user Planning Requests (e.g., for observations or other payload operations). This may be via a Planning GUI, gateway, or portal used directly by human users of the system.

    2) **Navigation**: For the submission of Planning Requests for spacecraft maneuvers, pointing, and other Attitude and Orbit Control Systems (AOCS) operations.

    3) **Operations Preparation**: For the submission of Planning Requests to perform on-board configuration management operations (e.g., updates to on-board software or procedure definitions).

    4) **Planning**: The Planning function may itself be hierarchical and/or distributed. In this context, Planning may also act as a consumer of the service (submitting Planning Requests to another Planning function).

b) **Submission of Plans** and receipt of status feedback on the progress of those plans, at the level of its contained planning items (e.g., Planning Activities). This is principally required by distributed Planning functions and may equally apply to:

    1) submission of Plans to another Planning function;

    2) submission of Plans to a Plan Execution function.

    This is in effect a specialization of use case a), in which the body of a Planning Request corresponds to a Plan, high-level Plan, or partial Plan previously output by a Planning function.

c) **Access to Plans** and/or Plan status for reference purposes or display. This is required by various third-party functions, including User Support, Navigation, and Mission Control, outside the context of the submission of a Planning Request or Plan. It may support a Planning GUI, gateway, or portal used directly by human users to view the status of a plan. Specific deployment considerations may require both pull (request) and push (subscribe) patterns of interaction to be supported.

d) **Management of Planning Processes**. This enables a consumer function to configure, monitor, and control a Planning function, including the invocation of planning processes. It may be used by:

    1) **Planning**: to coordinate planning processes in a hierarchical/distributed planning context;

    2) **Mission Control** and/or **Plan Execution**: to enable integration of planning processes into automated operations, including automated re-planning in response to anomalies;

    3) **Navigation**: to invoke re-planning following submission of a maneuver Planning Request or generation of updated predicted Planning Events;

    4) **Mission Data Processing** or other third-party function: to update the status of a Planning Activity.

e) **Management of Plan Execution**. This enables a consumer function to configure, monitor, and control a Plan Execution function. This includes both control at the level of a Plan (start/stop, pause/resume execution of a plan) and editing of the content of an executing Plan (insert, update, or delete Planning Activities, Planning Events, and Planning Resources). Although it is desirable to perform the latter through the full cycle of planning processes, it is recognized that there are times when it is operationally necessary to intervene at a lower level, particularly when Plan Execution is delegated on board the spacecraft. This interaction may be used by:

    1) **Manual** control over the execution of a (remote) Plan Execution function via a Plan (or Schedule) Execution GUI;

    2) **Planning**: to effect direct control over a Plan Execution function;

    3) **Mission Control**: to enable integration of Plan Execution into automated operations, including automated response to anomalies.

7.3 SERVICE IDENTIFICATION

The services are concerned with the exchange of information related to Planning Requests (PRQ) and Plans (PLN), in accordance with the Information Model outlined in section 6. However, to ensure uniqueness of terms which may already be used in the context of the MO Service Framework, the qualifier ‘Planning’ is used for some terms (i.e., for Request, Activity, Event, and Resource).

In section 2, four principal topics were identified that correspond to potential standardized services:

a) Planning Request Service, PRS;

b) Plan Distribution and Retrieval Service, PLS;

c) Planning Process Management Service, PMS;

d) Plan Execution Management Service, PES.

These are derived from the use cases outlined in the previous section. Each service corresponds to one of the identified use cases, with the exception of the Planning Request Service, which addresses both the Submission of Planning Requests and the Submission of Plans. This approach has been chosen to enable end-to-end support of planning submissions and the associated feedback from the Planning User through various stages of hierarchical or distributed Planning to Plan Execution as illustrated in figure 7-1.

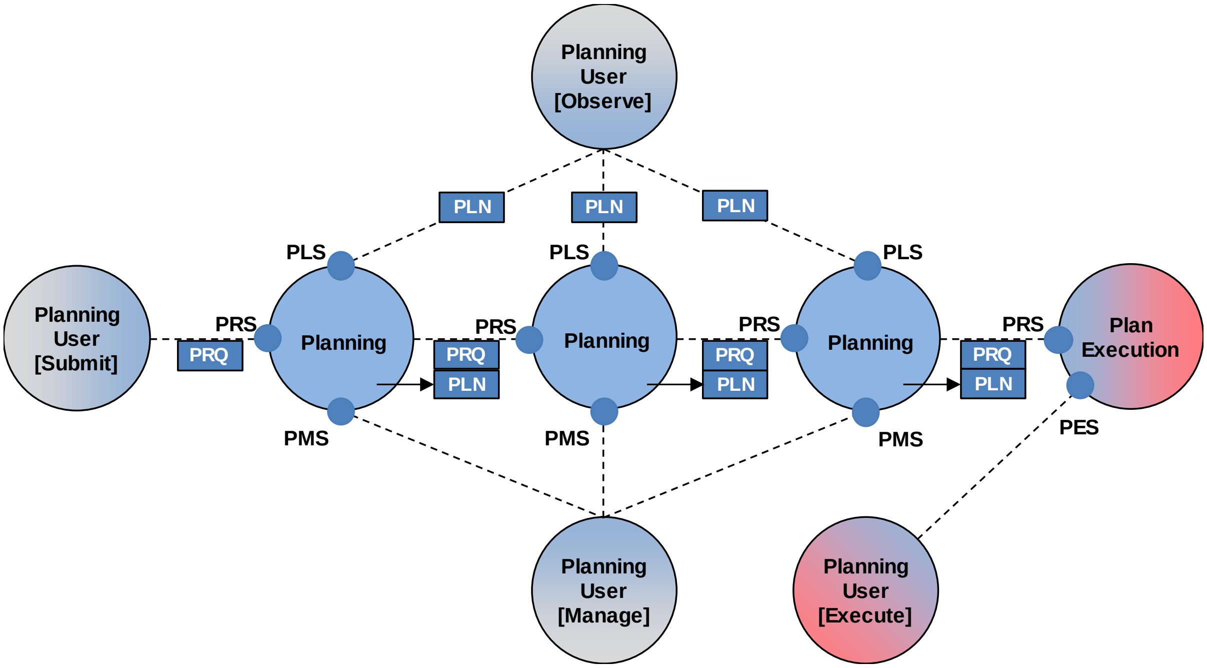


Figure 7-1: Correspondence of Planning Use Cases to Services

The Planning Request Service may also be used to forward a Plan (as the body of a Planning Request) to another Planning function. The feedback provided in this case is at both Planning Request and Plan levels.

The Plan Distribution and Retrieval Service may be used by another consumer to obtain a Plan or associated Plan Status for reference purposes. Table 7-1 summarizes the identified services, their main capabilities, and referenced data objects. Each service is discussed more fully in a dedicated section below.

Table 7-1: Summary of Mission Planning Services

Service *Provider*	Capabilities	Data	Description
Planning Request, PRS ***Planning***	– Submit Request – Update or cancel Requests – Edit Plan content – Update Planning Events and Resources. – Provide Request Status feedback – Manage Request Definitions	– Planning Request – Plan – Planning Activity – Planning Event – Planning Resource – Planning Constraint	Asynchronous submission of Planning Requests, associated responses, and their subsequent management and status feedback. Update (editing) of the executing Plan at activity level. Update of Planning Events and resources. A Planning Request may reference a Plan (output from an earlier planning process), in which case the provided feedback includes the status of the Plan in terms of its contained activities and other items.
Plan Distribution & Retrieval, PLS ***Planning***	– Retrieve Plan or Plan Status – Subscribe to Plan or Plan Status	– Plan – Planning Activity – Planning Event – Planning Resource – Planning Constraint	Provides distribution and access to Plans generated by the planning function.
Planning Process Management, PMS ***Planning***	– Initiate, Monitor and Control Planning Processes – Update Plan Status – Manage Planning Definitions	– Plan – Planning Activity – Planning Event – Planning Resource – Planning Constraint	Management of the planning process itself - initiation, status feedback and control. Also supports provision of Plan status updates by a third party.
Plan Execution Management, PES ***Plan Execution***	– Initiate, Monitor and Control execution of a Plan – Manage Planning Definitions	– Plan – Planning Activity – Planning Event – Planning Resource – Planning Constraint	Control and management of the execution of a plan, including actions to Start/Stop and Pause/Resume execution.

Each service supports a number of capabilities, each of which will be defined as a set of service operations. These operations are typically initiated by the service consumer and carried out by the service provider. Each operation may require bidirectional communication, with multiple messages being exchanged, and will normally relate to data objects identified in the information model.

7.4 USE OF THE CCSDS MO SERVICE FRAMEWORK

7.4.1 GENERAL

The CCSDS MO Service Framework comprises several elements:

- The Message Abstraction Layer;
- Technology (Transport Protocol and Encoding) Bindings;
- Language Bindings;
- The Common Object Model;
- Common Services.

7.4.2 MESSAGE ABSTRACTION LAYER AND ASSOCIATED BINDINGS

The Message Abstraction Layer (MAL) provides a standardized abstract way of specifying data and service operations and the messages they comprise. This is independent of the service implementation in terms the underlying messaging protocol, the encoding of data within the messages, and the programming language. MAL messages are defined in terms of data elements of standard types and comprise standard headers and a body that can be specialized for each MO service.

MAL operations also follow one of a limited set of standard interaction patterns:

- SEND;
- SUBMIT;
- REQUEST;
- INVOKE;
- PROGRESS;
- PUBLISH-SUBSCRIBE.

The first five represent increasingly complex Request-Response patterns that are initiated by the Consumer. With SEND, there is no response from the Provider. With SUBMIT, there is only a standard acknowledgement. With REQUEST, the provider gives a single synchronous response containing the return data. INVOKE gives an initial acknowledgement with an asynchronous response at a later date, while PROGRESS allows any number of asynchronous responses.

Publish-Subscribe is a well-known interaction pattern in which an intermediate Broker acts as go-between. The Provider publishes data to the Broker, while Consumers independently subscribe to that data, which is then forwarded by the Broker as it becomes available.

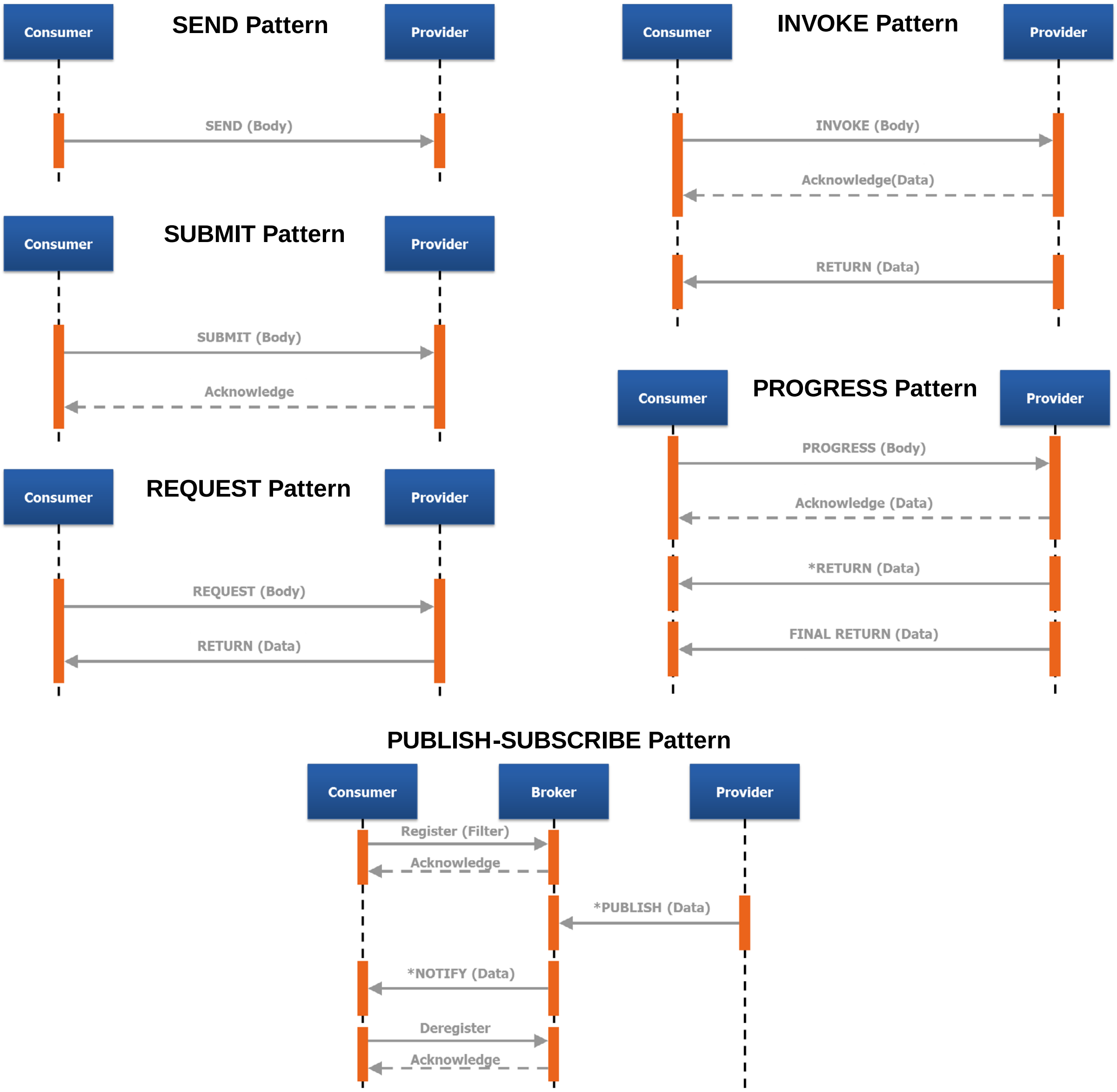


Figure 7-2: MAL Interaction Patterns

When defining an MO-compliant service, each operation is defined as following one of these standard interaction patterns (see figure 7-2), but then the body or data contained in the extensible messages of that interaction pattern is also specified. The key advantage of this approach comes with the associated technology and language bindings.

Technology bindings specify how the MAL interaction patterns and messages are mapped to an underlying messaging technology, both in terms of messaging protocol and message encoding. Providing that bindings exist covering both protocol and encoding for a given messaging technology, any service expressed in terms of the MAL can be deployed over that technology. The result of applying the technology binding to a MAL compliant service is effectively an interoperable wire protocol for the service, providing both provider and consumer are using the same messaging technology. Technology bindings are available for both space link (CCSDS Packets) and terrestrial (e.g., ZeroMQ) technologies.

Language bindings specify how a service expressed in terms of the MAL can be exposed as an API for a given programming language. The same language binding can be applied to all services defined in terms of the MAL. This approach also lends itself to auto-coding, as the bindings correspond to standard transforms that can be used to auto-generate code for a specific implementation technology and language for any service defined in terms of the MAL.

Theoretically it is also possible to build a ‘MAL Bridge’ that provides a gateway between systems that use different messaging technologies, enabling all MAL compliant services to operate transparently across that bridge. To ensure compliance with the MAL, each Mission Planning & Scheduling service operation is specified in terms of a MAL interaction pattern, with the extended message elements being specified as abstract MAL messages.

Compatibility with concrete XML file formats can be ensured by using a standard XML encoding of service message elements. A self-standing XML file may need to contain more information in a single file than would normally be transferred in a single service message. The XML file format may therefore be an aggregation of several service message elements, and it is important that these are defined such that they can be used separately in the context of service messages.

7.4.3 COMMON OBJECT MODEL

The MO Common Object Model (COM) provides an extensible standard for basic MO service data objects (see figure 7-3). It provides a standard way to identify data uniquely and to express relationships between data items. It provides ‘out of the box’ standard capabilities for any service data object derived from the COM, including:

- Archiving (or service history);
- Activity Tracking;
- Event Reporting.

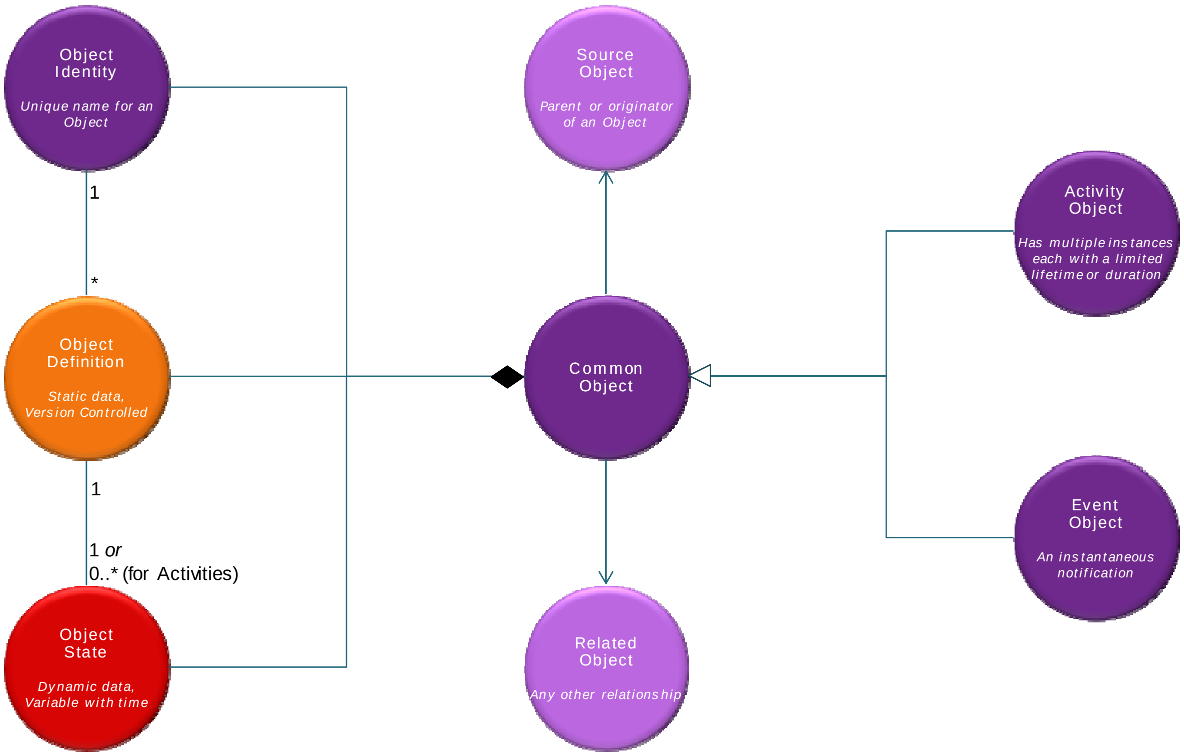


Figure 7-3: Common Object Model

The COM Object is a base class that services can use to derive their own data objects. COM objects have two references available to capture relationships with other objects. One is its ‘source’, or a reference to the object that is considered its parent or originator; the other is available to express any other relationship applicable to the data object.

In the context of a Mission Operations service specification, many of the service data items are actually compound structures comprising three elements (each a COM object in its own right): a unique Identity; the Definition, which is version controlled but can be changed when necessary; and its State, which contains the information that dynamically updates over time. The set of object Definitions for a service constitutes a major part of its configuration. Recording timestamped object States over time provides a history, or archive, of the service.

The COM includes two specializations of the basic COM object:

- **An Activity** (not equivalent to a Planning Activity): Any data object that has a limited lifespan and may have multiple instances (State objects) created from the same Definition. This corresponds to objects such as Commands that may be invoked multiple times.
- **An Event** (not equivalent to a Planning Event): An instantaneous notification of something that happens in the system at a given point in time. Services will usually have a set of possible Events defined as part of the service configuration.

The COM standard also includes standard services that can be reused or extended in the context of an MO application service:

– **Archiving Service**: A generic archive service for service data objects defined in terms of the COM;

– **Activity Tracking Service**: A mechanism to report progress/status of an Activity object, which itself uses the COM Event service;

– **Event Service**: Delivery of COM Events to service consumers.

Mission Planning data objects can be defined in terms of the COM, which will bring the benefit of use of these standard services. Figure 7-4 extends the high-level view of Mission Planning data given in section 6 to show the relationship to COM object patterns.

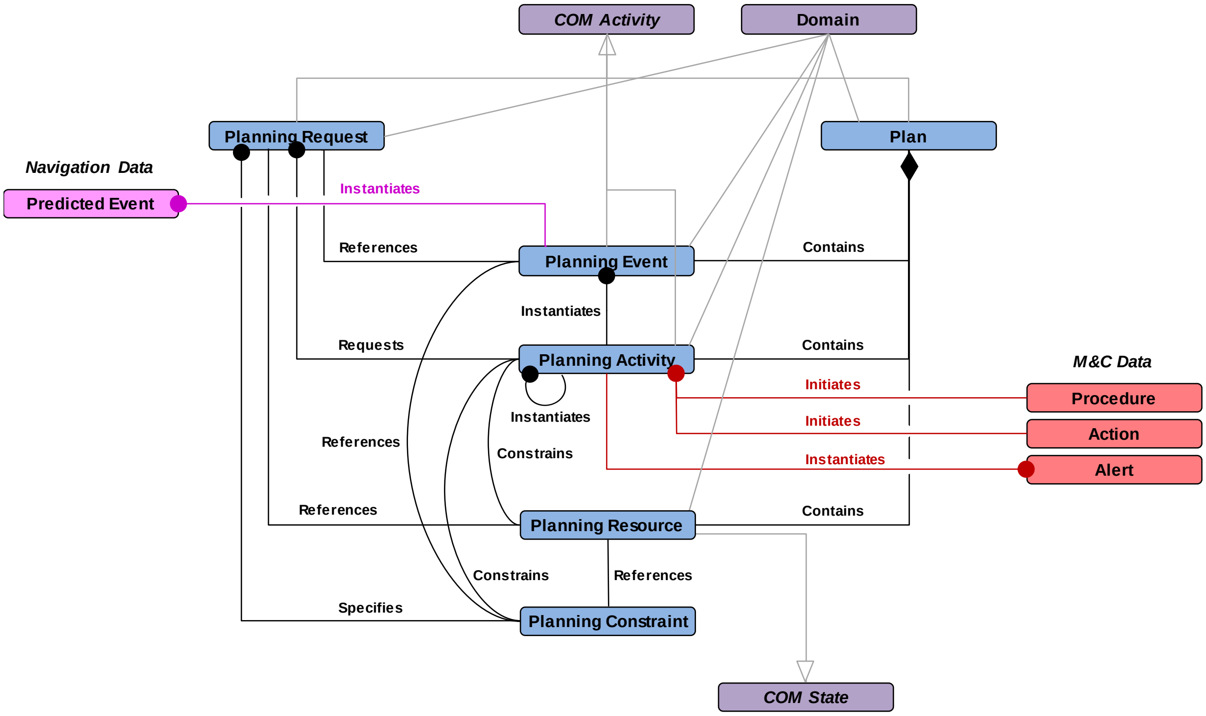


Figure 7-4: Relationship of Planning Data to MO COM

Planning Requests, Planning Activities, and Planning Events are all data objects that can be invoked multiple times from the same Definition and which have a limited duration or lifetime. They can therefore be defined as specializations of the COM Activity pattern, which means that the Activity Tracking Service can be used to provide their progress/status.

The ‘source’ of a Planning Activity will correspond to the Planning Request or Planning Event that resulted in its invocation, or in the case of a nested Planning Activity, its parent Planning Activity. That of a Planning Request will correspond to the organization or user who raised it.

The body of a Planning Request may contain details of the requested Planning Activities or indeed contain a Plan output by a higher-level Planning function. As Planning Activities can be hierarchical, the Planning Request only needs to reference a root node Activity, which can then be expanded by the Planning function.

Planning Resources may be derived from the COM Object base class, as they do not in principle have a limited duration.

The extension of the COM Object classes means that the COM Archiving Service can be used to support access to archived Planning Request history. Similarly, it may be used to provide access to the consolidated execution history of Planning Activities, Events, and Resources in the context of Plan Execution (this is sometimes referred to as Schedule History).

Plans are composite data structures. There may be a COM derived Plan object to contain information applicable to the Plan as a whole, but it will also contain a set of Planning Activity, Planning Event, and (potentially) Planning Resource objects.

An iteration of a Plan typically has a predecessor, of which it represents the next planning period. Plans may be contiguous with or overlap with their predecessors. In order to allow for efficient referencing and updating of plans, it is recommended that planning object occurrences that appear in multiple iterations of a Plan retain the same identity (at occurrence level) across all iterations of the plan. Additionally, planning objects contained within a Plan may have an optional attribute that indicates their change status with respect to the predecessor plan: New, Modified, Unchanged, Deleted.

7.4.4 MO COMMON SERVICES

MO Common Services are supporting services provided by the MO framework. Three services are currently identified:

- Directory;
- Login;
- Configuration.

The Directory service can be used by a service consumer to locate a service provider and obtain XML service descriptors. The Login service provides a standard method for login and authentication through a deployment-specific security system. It is integrated with the access control aspect of the MAL.

The Configuration service provides a standard way of accessing and managing service configuration data (including data object Definitions). Configurations can be hard-coded or use bespoke configuration data, but in situations in which data is derived from the COM, there is a greater level of standardized support.

Service consumers can activate predefined configurations of a service provider and list, get, add, remove, and store current configurations. It also defines a standardized XML representation for configurations.

7.4.5 MO MONITORING AND CONTROL SERVICE

The MO M&C Service provides a standard set of services supporting control Actions, monitoring Parameters, and asynchronous Alert notifications. In principle, any function can expose an M&C service to enable its automation.

The identified Mission Planning services include Planning Process Management and Plan Execution Management. A core capability of both services is to support the monitoring and control of the Planning and Plan Execution functions, respectively, to enable their automation. It is probable that this capability can be satisfied as either an instance or a specialization of the MO M&C Service.

8 WORKING GROUP STANDARDIZATION ROADMAP

The present document describes the high-level concepts which will be used as the basis for specifying Mission Planning Services and Data Types. The CCSDS Mission Planning and Scheduling Working Group (WG) will adopt a stepwise approach. It will focus initially on producing a specification that captures the needs of the most common Mission Planning use cases and leaving more specific use-case scenarios to later stages of standardization.

Following this logic, it is planned to produce in the first step one Mission Planning Blue Book, which will provide the formal specification of:

- the underlying Mission Planning Information Model, as it is outlined in section 6 of this Green Book;
- the set of Mission Planning Services, as they are outlined in section 7 of this Green Book.

The Information Model will define all data types as required in the definition of the Mission Planning Services. In addition, the Information Model will allow deriving data formats for non-service-oriented (e.g., file based) exchanges.

In a later stage, the WG may continue with production of other Blue Books to cover more specific aspects of Mission Planning, such as:

- extended information model, to cover resources and constraint information;
- extension of services, in order to address the needs of more specific planning use cases such as tactical planning of surface operations.

All Mission Planning Services and Data Types will be specified in an implementation, encoding, and communication agnostic manner, by using the abstract service and data description language of the CCSDS Mission Operation Framework.

In order to address the immediate need for concrete message formats, which can be transferred by means of files, the Mission Planning and Scheduling WG will also create one concrete XML Schema for all Mission Planning Data Types, to be defined in the Mission Planning Services Blue Book. This will facilitate the adoption of the standard by adhering to current practices of mission operations in the CCSDS participating agencies.

ANNEX A

ACRONYMS AND ABBREVIATIONS

The complete list of official CCSDS Abbreviations can be found in the SANA CCSDS Abbreviations Registry. Any acronyms and abbreviations used in this document that are not contained in the SANA Registry are listed below.

AI	artificial intelligence
ANX	ascending node crossing
AOCS	attitude and orbit control systems
APD	automated procedure definition
CDM	Conjunction Data Message
CSS	Cross Support Services
CCS-M&C	Cross Support Services—Monitoring and Control
CSS-SM	Cross Support Services—Service Management
DPCC	devolved payload control center
EO	Earth observation
EVM	event message
GNSS	Global Navigation Satellite System
HK	housekeeping
HKTM	housekeeping telemetry
MCS	mission control services
MDP	mission data product
MLST	mean local solar time
MPS	mission planning and scheduling
NAVT	navigation and timing
NGO	non-governmental organization
ODM	Orbit Data Message
OPS	orbit position scheduling
OSW	on-board software (image)
PEM	plan execution management (data)
PES	plan execution management service
PLN	plan (data)

PLS	plan distribution and retrieval service
PMS	planning process management service
PPM	planning process management (data)
PRM	Pointing Request Message
PRQ	Planning Request (data)
PRS	planning request Service
SMM	Spacecraft Maneuver Message
SOC	science operations center
TDP	technology demonstration payload