Chapter 5
Mission Planning

5.1 The Planning Problem

Christoph Lenzen

5.1.1 Introduction

Mission planning plays a key role in the operations of a spacecraft, as it ensures that all resources are available and used to an optimal level and the goals of the mission are achieved. There are various ways how to define the exact meaning of mission planning, and different operations centers throughout the world use different definitions.

Within this book, we will consider mission planning as the task of preparing, organizing, and planning all relevant activities that happen during the mission, on board as well as on ground. It is therefore distinct from mission analysis or mission preparation tasks, which serve to analyze and define a mission beforehand and provide the necessary means to execute the mission.

As such, the responsibility of mission planning is to deliver the plan in form of a timeline or so-called Sequence of Events (SoE) right in time for the relevant activities (e.g., before uplink to the spacecraft). This might happen only once (e.g., the actions performed by the lander on an asteroid) or very frequently (e.g., an earth observation satellite fed with customer orders). The plan has to be conflict free, i.e., can under the given on-board and ground constraints be executed on the spacecraft and on ground without any errors. In addition, the timeline should maximize the usage of available resources and ensure that the goals of the mission are eventually met.

C. Lenzen (✉)
German Aerospace Center (DLR), German Space Operations Center (GSOC),
Oberpfaffenhofen, 82234 Wessling, Germany
e-mail: christoph.lenzen@dlr.de

T. Uhlig et al. (eds.), *Spacecraft Operations*,
DOI 10.1007/978-3-7091-1803-0_5,

The overall scope of planned activities that falls into the responsibility of mission planning varies a lot from mission to mission. It can range from a very limited responsibility, e.g., planning only simple transmitter switching for ground station contacts, to almost full responsibility for all spacecraft commands including ground station scheduling.

In this chapter, we will introduce the key concepts for designing and operating a mission planning system and present some examples of planning systems for currently active missions at the German Space Operations Center (GSOC).

5.1.2 General Overview of a Mission Planning System

Since the requirements to a Mission Planning System (MPS) and the tasks that it shall perform vary considerably between different missions, there is not one general planning system that can be used for all different needs. In practice, depending on the nature of the planning problem at hand, one will encounter a wide variety of planning systems, ranging from very large software systems to small mission planning components that might be put to work by a human mission planner.

They can therefore be categorized by their degree of automatism, ranging from fully automated planning software without any necessary user interaction to a completely manual planning process. In most cases the system is somewhere in between these two extremes: A human mission planner is supported by GUI-based software tools, which algorithmically create some aspect of the desired plan and check the overall consistency in the end. This is usually the most economical solution.

An example for a fully automated concept is the combined TerraSAR-X/TanDEM-X (Krieger et al. 2007) mission planning system (Maurer et al. 2010), which creates a timeline including the required telecommands for every payload-related activity on the two satellites and also distributes the generated information to the affected parts of the ground segment.

On the other hand the mission planning system for the GRACE mission (Braun 2002) consists of a small algorithm that is triggered by a human mission planner and creates only the sequence of commands necessary for the downlink transmitter switches. It is therefore an example of a software-assisted planning concept.

The ISS mission planning (see Sect. 5.3)—as a third example—is completely depending on manual creation of the timeline, which is only fed into software tools to display it and to allow further processing.

Another aspect by which mission planning systems can be characterized is the periodicity of the planning process. Some missions have limited duration and the timeline might be created only once before the execution of the mission, e.g., for a lander or planetary probe mission of limited length. For others, a predefined timeline might be adjusted to the current situation in regular intervals, e.g., once per week. Some earth observation satellites are an example where the amount of planning required and frequent customer requests make it necessary to limit the planning horizon and repeat the process very often, e.g., once before every commanding possibility of the spacecraft or even every time new input is available.

The periodicity of the planning process defines the way the timeline is generated. Here we distinguish between three timeline generation modes:

Fixed Plan

This type of mission is planned during the preparation phase from launch until end of mission. There is either no need or no possibility to update the plan during execution. For this approach to work, the mission objective and the approach to reach it need to be known exactly in advance. It also leads to a quite conservative estimation of the available resources.

On the other hand, the plan can be optimized by using sophisticated algorithms with high runtime durations of even days or weeks and by multiple iterations of the results with the customer (usually the scientific community).

Repeated Rescheduling

It allows rescheduling on a regular basis, e.g., each time before a LEO satellite is visible by an uplink station. It allows ingesting updated information about resources, orbit events etc. and new tasks, which need to be performed, in particular new planning requests of the customer.

Major modifications of the timeline are the baseline, especially when trying to optimize the result. Optimization, however, is limited to fast running algorithms. Another drawback is that the user has to rely on the decisions of the automated scheduler: when ingesting a new order, the user will not know about modifications in the timeline until the succeeding rescheduling has been performed. He might also not have time to overrule the decisions of the scheduler, because rescheduling usually is performed just in time.

Incremental Scheduling

The operational concept of this type of mission resembles a booking system. Starting point is an empty timeline, which is filled with each input it gets. In particular when a planning request is sent to the system, the algorithm checks what other requests would need to be (re)moved and send the information back to the user. The user then may decide whether to accept these modifications or to discard the current request.

Of course there are a lot of variations on automatic decisions; nevertheless the incremental scheduling concept is designed to keep the modifications of the existing timeline as little as possible. One will prefer this type in case the timeline shall remain stable or in case the user requires full control over the timeline. Algorithmic optimization, however, is even more restricted due to the performance requirements of the system and due to the fact that optimization usually does not imply minimal modifications on the timeline.

A commonality of most mission planning systems is that they form a central part of ground segment operations, possibly having interfaces to many other ground

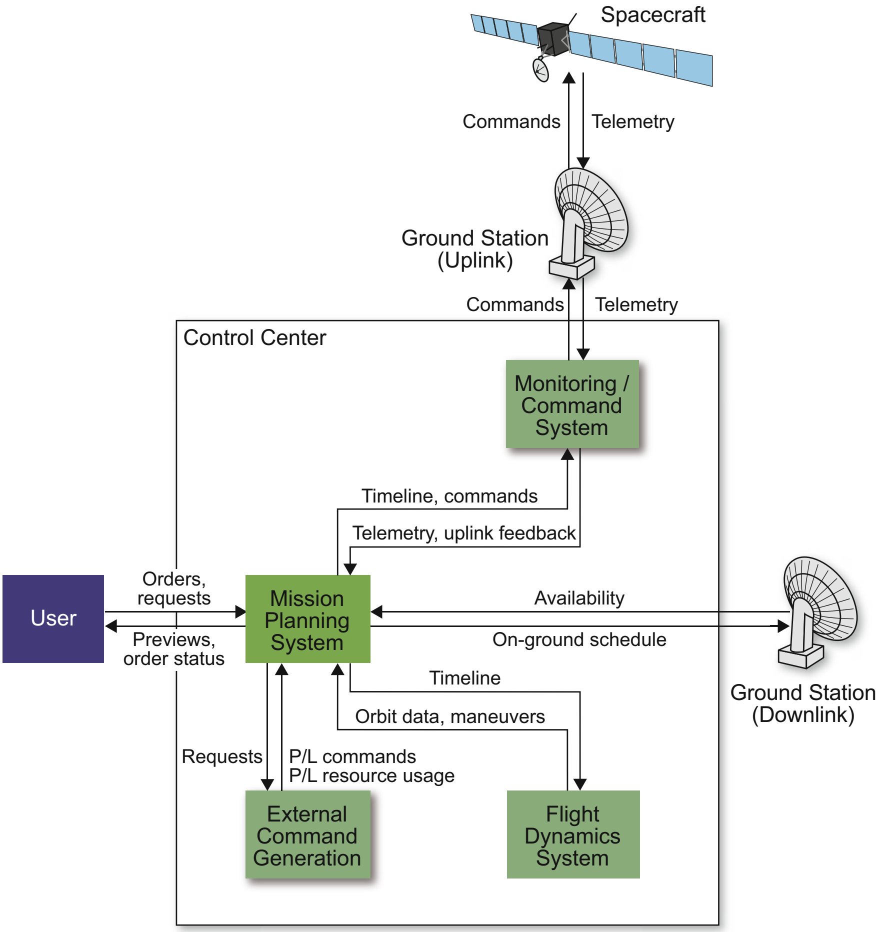


Fig. 5.1 Possible MPS interfaces

segment systems, both inside and outside mission operations. Typical interfaces of a mission planning system are depicted in Fig. 5.1. They comprise input interfaces for incoming planning requests and updated external information like orbit and maneuver information, payload configuration updates, etc. Often the availabilities of external resources have to be fed into the planning system, like ground station availabilities and booking times or astronaut availabilities. Sometimes additional external information will influence the planning result and needs to be fed into the system, for example, the cloud forecast might be used for optimized selection of optical images or evaluating optical downlink opportunities. A mission planning system might already create spacecraft commands by itself, so interfaces to the spacecraft control systems are needed to transfer the created commands and possibly receive feedback whether they were uplinked to the spacecraft and whether the telemetry indicates that they were executed on board. Finally, the output of the planning process needs to be distributed to various customers, e.g., the timeline could be published for the operations personnel, ground stations could be informed which downlinks to expect, and archive systems could be fed with the planned activities. Some mission planning systems offer immediate feedback to customers, which can control the feasibility of their requests, the planning status, and possible alternatives to choose from.

Since different missions impose different requirements, the composition and the size of a mission planning system greatly varies from mission to mission. Completely monolithic specialized mission planning applications would therefore need to be re-implemented for every new mission from scratch again. Instead, it turned out beneficial to maintain a set of loosely coupled generic tools as building blocks that can be extended and tailored to support the mission at hand. This allows for greater flexibility and reusability while allowing an easier development in a team of people. A prerequisite for this is to maintain the MPS-internal interfaces as strict and stable as possible to prevent tedious MPS-internal adaptations for different missions. A general way of expressing the planning problem at hand is needed that can be adapted to the most common planning problems. For this purpose a generic planning language is required; one example is described in more detail below.

One of the components that is required in such a modular MPS is usually a central database that holds the planning model, i.e., the objects which are to be scheduled. Also the latest versions of the timeline are stored in the database. All other components can then interact with the model and perform the necessary manipulations. Ingestion modules will import new data into the model, like planning requests, input from flight dynamics, external resource states, etc. A scheduling engine can be used to generate the plan algorithmically by fulfilling as many requests as possible while considering all constraints and resource states. Various exporting components will access the final plan and produce the desired output formats, like SoE files, command files, or downlink information files for the various ground stations. GUI components can visualize timelines and the current state of planning to the user and allow manually modifying the SoE or start automatic planning tools. Automation components might be included which trigger the planning process upon certain events. As an example, the components of the combined TanDEM-X/TerraSAR-X MPS are depicted in Fig. 5.2. Almost all of the abovementioned components are realized in this system. For the incremental planning concept however a message driven approach outperforms communication via a central database, thus a message passing component must be added.

5.1.3 Techniques for Timeline Generation

5.1.3.1 General Considerations

As mentioned above, there are several characterizations of a mission planning system, which all drive the design of the integration of the planning system into

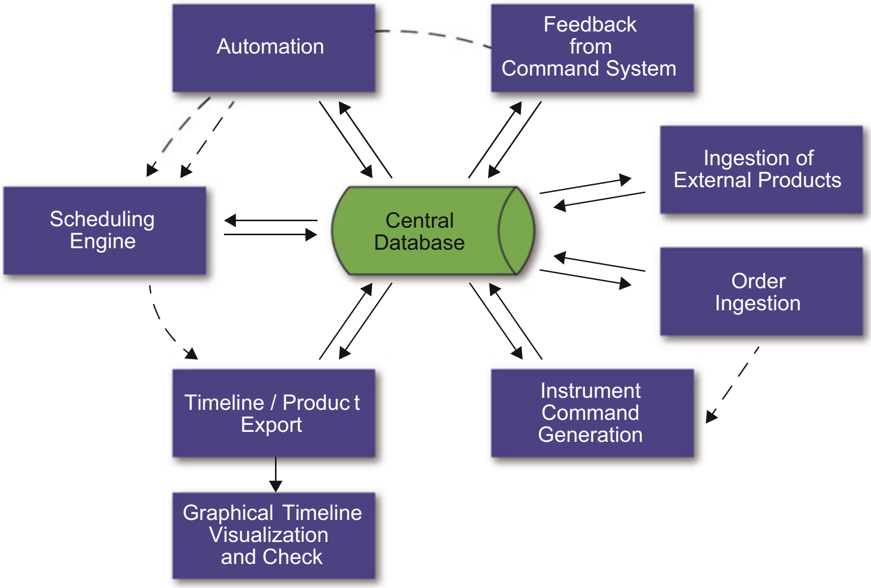


Fig. 5.2 Components of the TerraSAR-X/TanDEM-X MPS

its environment. When looking at its core, however, the objectives of the timeline generation process are the same:

- *Feasibility* and *Safety*: Each subsystem must be able to execute the timeline (feasibility) without being exposed to inacceptable high risk (safety). In particular, the timeline shall not rely on on-board safety mechanisms of a spacecraft. For example it must be avoided to command a timeline which leaves a high energy consumer switched on at the end of the commanding horizon, even if it is to be expected that a later uplink or an on-board safety feature is expected to switch it off at the proper time.
- *Benefit*: The timeline shall serve as many mission goals as possible.
- *Traceability*: In most missions, the user wants to understand why the timeline looks like it does. Since the decisions of what planning requests to include into the timeline are made during the planning run, evidence of it must be supplied by the mission planning system, too.
- *Performance*: The timeline generation process must be sufficiently fast.

Whereas feasibility and safety should be given the highest priority for all missions, the emphasis on the other three objectives may vary significantly in between different spacecrafts and missions. Even during the lifetime of one spacecraft, the goals of the mission may change, e.g., because an instrument of the spacecraft decreases or breaks down, because an additional satellite is added to the existing system (as happened with the TerraSAR-X/Tandem-X satellite twin) or because the user of the satellite changes [as happened for TET-1 (Axmann et al. 2010), which became part of the FireBird mission (Reile et al. 2013)].

In all of these cases, the timeline generation process needs to be adapted and in some cases this has to be accomplished fast. Thus another objective must be defined for the timeline generation process:

- *Flexibility*: it shall be possible to adapt the timeline generation process to meet the modified mission requirements

Whereas the first four objectives might be served best using an individually implemented system, possibly based on a small set of core components, the need of flexibility requires a full generic tool suite, which can be adapted to each mission's needs. A most welcome side effect of such a generic tool suite is that in the long term it can save a lot of manpower.

5.1.3.2 GSOC Modeling Language

The GSOC modeling language is one example of a system which allows modeling the planning problem of a typical spacecraft mission. When modeled properly, a conflict-free timeline will meet the main objective of feasibility and safety. Therefore a modeling language must on the one hand allow sufficiently accurate means to represent the real world and on the other hand it must remain descriptive and rather easy to apply (in order to avoid modeling faults) and of course it also must be manageable by a scheduling engine. It turns out that the following basic elements and features supply a good trade-off in between these three goals; see also (http://www.dlr.de/rb/Portaldata... 2010).

Timeline Entry

A timeline entry describes when to execute a certain task. Consequently the properties of a timeline entry are its start time and its duration.

Task

A task represents something that may be executed some time, e.g., one telecommand or a procedure, i.e., a set of telecommands which are executed in a fixed order. A task is considered to be *scheduled* in case there is a corresponding timeline entry for it. On task level the following properties are defined

Minimum *and* Maximum Duration *of a Task*

These values specify the allowed durations of timeline entries of this task, as illustrated in Fig. 5.3.

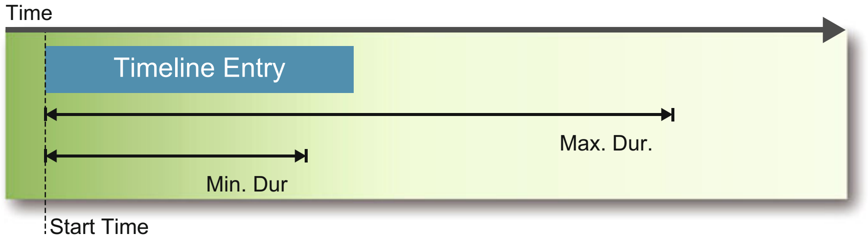


Fig. 5.3 A timeline entry consists of a start time and a duration. The duration can be restricted via a minimum and a maximum duration value

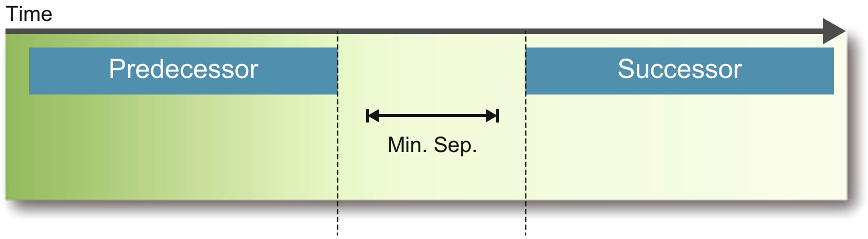


Fig. 5.4 Two timeline entries, separated by a minimum offset in between the end time of the predecessor and the start time of the successor

Time Dependency *with Other Task*

This specifies a minimum mandatory temporal separation in between the timeline entries of two tasks. It can be defined, whether the start or the end time of the timeline entries are used as reference times, as shown in Fig. 5.4.

Also a maximum allowed separation may be modeled that way by swapping the tasks and using a negative minimum separation.

Timeline

A timeline is a set of timeline entries, as shown in Fig. 5.5.

Groups

A group consists of an arbitrary number of tasks ("child tasks") and groups ("child groups"), as depicted in Fig. 5.6. In addition it is defined how many of its children must be scheduled in order to consider this group to be scheduled itself. This allows to collect tasks, which belong together, i.e., which the algorithm should treat as a unit.

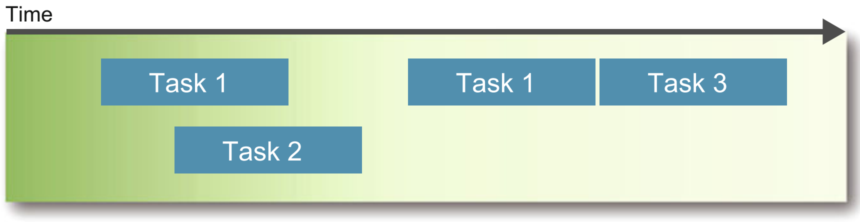


Fig. 5.5 A timeline consists of timeline entries for one or more tasks

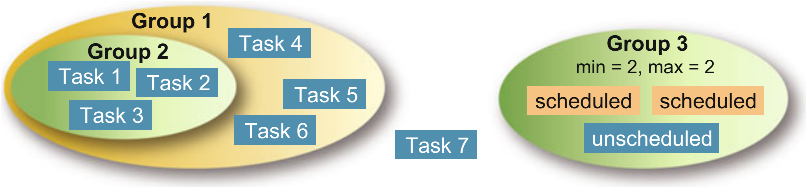


Fig. 5.6 Group 1, task 7, and group 3 are top level; group 3 requires 2 elements to be scheduled

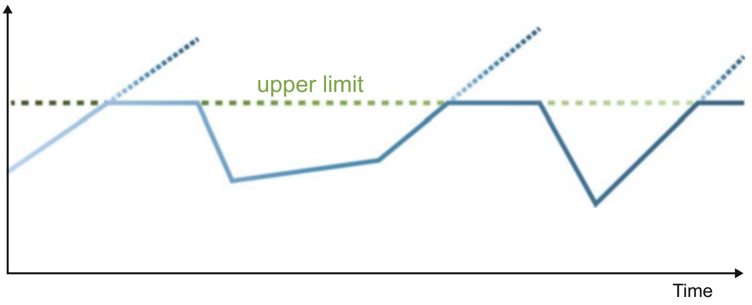


Fig. 5.7 This fill level profile might represent a simplified battery model: when the capacity is reached, the surplus supply gets lost

Constraints on group level:

- Minimum number of children which shall be scheduled
- Maximum number of children which shall be scheduled

Resources

A resource consists of a scalar time profile (*fill level*). Optionally capacity limits can be attributed to a resource: whenever these limits would be exceeded, the surplus is cut off (*lost values*), as shown in Fig. 5.7.

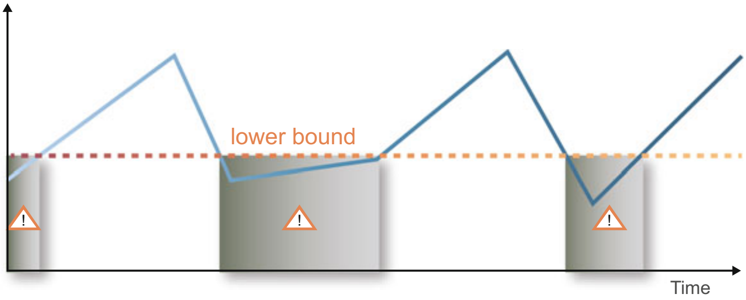


Fig. 5.8 The fill level causes a conflict, when it falls below the lower bound

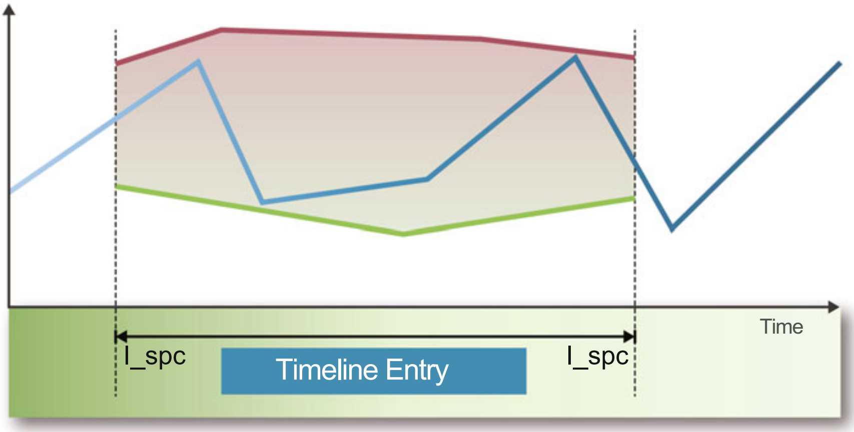


Fig. 5.9 The resource (*blue*) is constrained by upper and lower boundaries (*red*, *green*). The interval where these boundaries apply is derived from the timeline entry via the interval specification (I_spc)

In the following constraints and operations on resources and in between resources and tasks are described.

Resource Bound
A resource bound specifies a globally defined time profile, which the resource's fill level must not exceed, as shown in Fig. 5.8.

Resource Comparison
A resource comparison specifies a local resource bound linked with a task's timeline entry. The resource bound does not necessarily have to coincide with the duration of the timeline entry, but can have a start and end offset with regard to it, as depicted in Fig. 5.9.

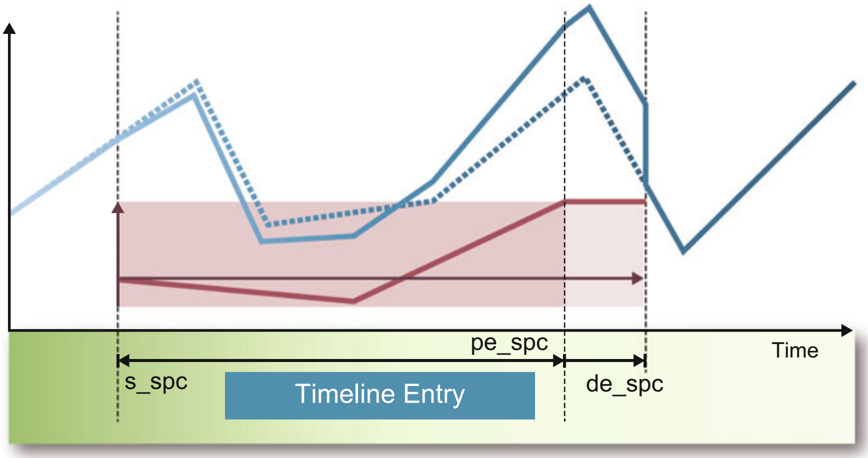


Fig. 5.10 The timeline entry has an active profile (*red*) starting at s_spc and ending at pe_spc, which influences the resource (*blue*) not only during the time frame defined by the duration of the active profile, but also during the extended validity period, which ends at de_spc

Resource Modification

A resource modification specifies how a task's timeline entry modifies the resource. The modification is defined by a change profile, which is mapped to the time axis by adding an offset start (*ActiveProfileStartOffset*, s_spc) to the start time of the timeline entry and which is cut off at the end time, similarly specified by an end offset (*ActiveProfileEndOffset*, pe_spc). However, the modification of the resource can also last longer than the end of the active change profile. In that case you need to distinguish between the end of the active change profile (*ActiveProfileEndOffset*, pe_spc) and the end of the dependency (*DependencyProfileEndOffset*, de_spc): In case the dependency end is greater than the active profile end, the value of the profile at active profile end is extended until dependency end, as shown in Fig. 5.10.

For the special case of accumulating resource modifications like power consumptions the dependency end needs to be set to ∞: After being consumed, the power which was e.g. extracted from a battery for the duration of the timeline entry is never available again.

Suitabilities

A suitability is a special utilization of the resource concept. It is essentially a resource which is used to model the benefit to schedule a task at a given time and thus supplies information about when to prefer the execution of a certain task. A suitability therefore cannot cause a conflict, but it quantifies at what time a task's timeline entry results in what benefit. The benefit of a timeline entry is derived from a resource's fill level around the considered timeline entry,

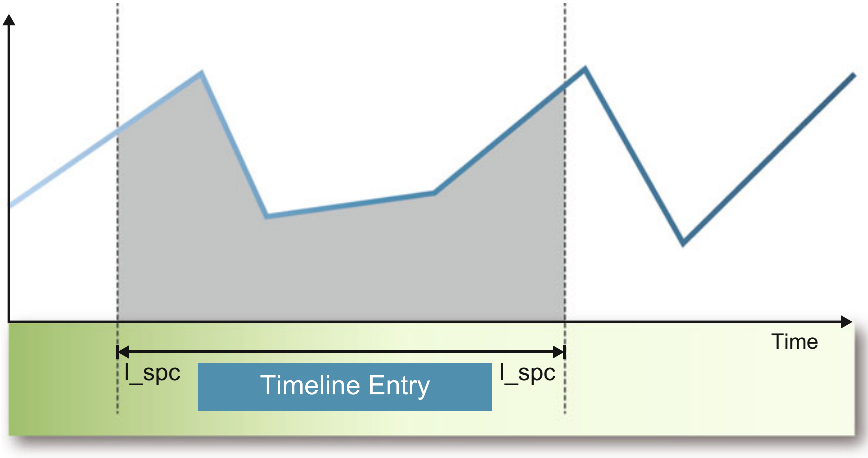


Fig. 5.11 The benefit of scheduling a given timeline entry at a given time can be quantified by a suitable mathematical operation (e.g., the maximum, the integral) applied to the corresponding suitability profile during the time interval defined via the time interval specification (I_spc)

by taking either the integral, maximum, or minimum of the fill level, as depicted in Fig. 5.11. An algorithm may prefer timeline entries with maximum benefit or it may even try to optimize the sum of all benefits of the whole timeline.

5.1.3.3 Application Examples of the Modeling Language

In this section we present a few examples how to apply the above-presented basic building blocks in order to illustrate the flexibility of this modeling language.

Opportunities, e.g., Ground Station Visibilities

In order to avoid scheduling downlinks outside ground station visibility, we define a resource with fill level = 1 wherever the ground station can receive data from the satellite, 0 otherwise, as shown in Fig. 5.12.

Each downlink task on the other hand is given a lower bound comparison, which checks that the opportunity resource has value greater or equal 1.

Equipment Resources, e.g., Downlink Antennas of a Certain Ground Station

In order to model the antenna availability of a certain ground station, we define a resource with

- Initial fill level = 0, representing the number of antennas in use

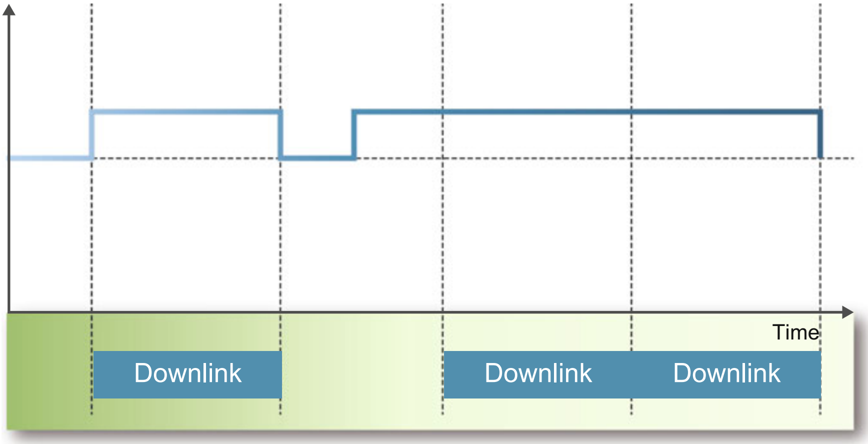


Fig. 5.12 The fill level of the opportunity resource (*blue line*) indicates where downlinks may be scheduled

- Upper bound = number of available antennas

Whenever a downlink for one satellite shall be scheduled, we also need to allocate one antenna of the respective ground station. The downlink therefore increases the fill level of the antenna availability resource. Wherever the number of available antennas is reached (= upper bound), no further downlink may be scheduled anymore, as depicted in Fig. 5.13.

Renewable Resources, e.g., Battery Discharge Level

In order to model the battery of a space craft, we define a resource with

- Initial fill level = 0
- Upper limit = battery capacity
- Lower bound = 0: you cannot take energy from an empty battery

Besides we define resource modifications:

- For consumer tasks, we define a resource modification with
  - Change profile defined in the interval $[0, \infty]$, usually with constant negative slope
  - ActiveProfileEndOffset = 0, which means that the change profile is only considered in the time interval of the timeline entry
  - DependencyProfileEndOffset = ∞, which means that the final consumption at ActiveProfileEnd applies to the whole future (accumulating resource consumption).

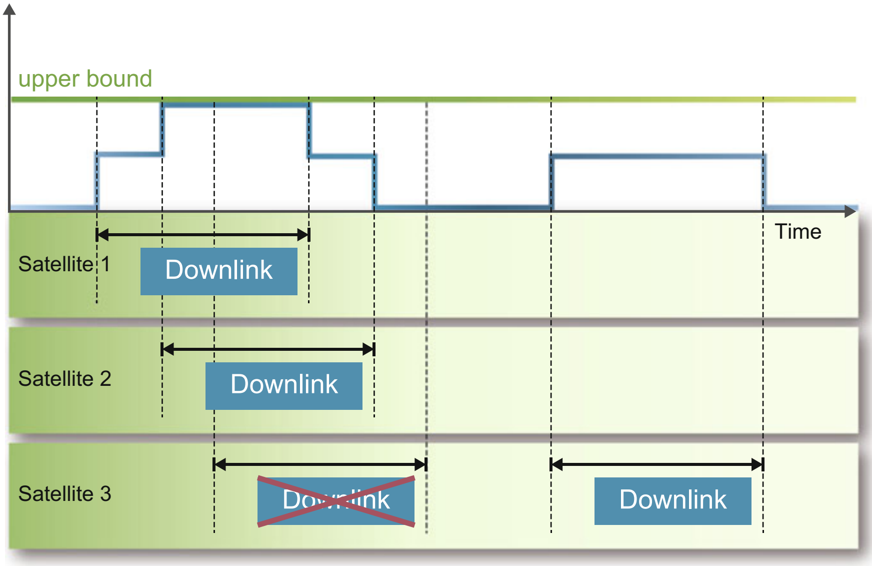


Fig. 5.13 Scheduling a downlink increases the number of antennas in use, including an offset for preparation and cleanup

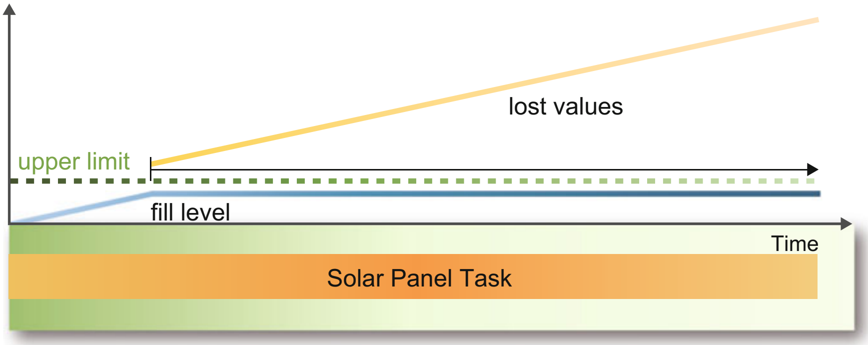


Fig. 5.14 Without satellite activities, much energy is lost, because it cannot be stored

- As supplier task, we define the solar panel task with a similar constraint, but with positive slope on the change profile. This task is scheduled all the time where the solar panels collect sunlight.

In the beginning, as soon as the battery is full, the surplus power supply is lost, as shown in Fig. 5.14.

However, the more consumer tasks are scheduled, the less power is lost, as illustrated in Fig. 5.15.

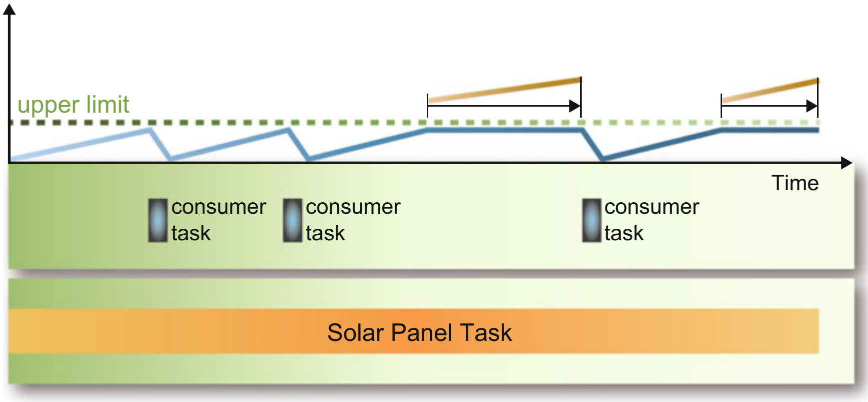


Fig. 5.15 With scheduled consumers, only little energy is lost

Gliding Windows (in Between Equipment and Renewable Resource)

Thermal constraints usually are too complex to be modeled directly. However, they may be described in constraints like "Don't turn on the instrument for more than 10 min per orbit." In order to model such a constraint, we define a resource with

- Initial fill level = 0
- Upper bound = 600 [s]

For each task, which needs the instrument to be switched on, we define a resource modification, with

- Change profile has slope = 1 [per s]
- Active profile end offset = 0
- Dependency profile end offset = 1 orbit

The effect of this modeling is visible in Fig. 5.16. Each scheduled task increases during its duration continually the "clock resource," and this modification is kept for the duration of one orbit, before it is reset to zero. The "clock resource" has an upper bound of 600 s, which corresponds to the requirement to keep the overall "clock count per orbit" below 10 min.

In order to make this model precise, a release slope may be defined which replaces the ending step of the modification profile by a ramp (not displayed in the picture).

Combining Resource Types

In the above examples, we have specified different resource types (opportunity, equipment, renewable resource). Although the resources may differ in having

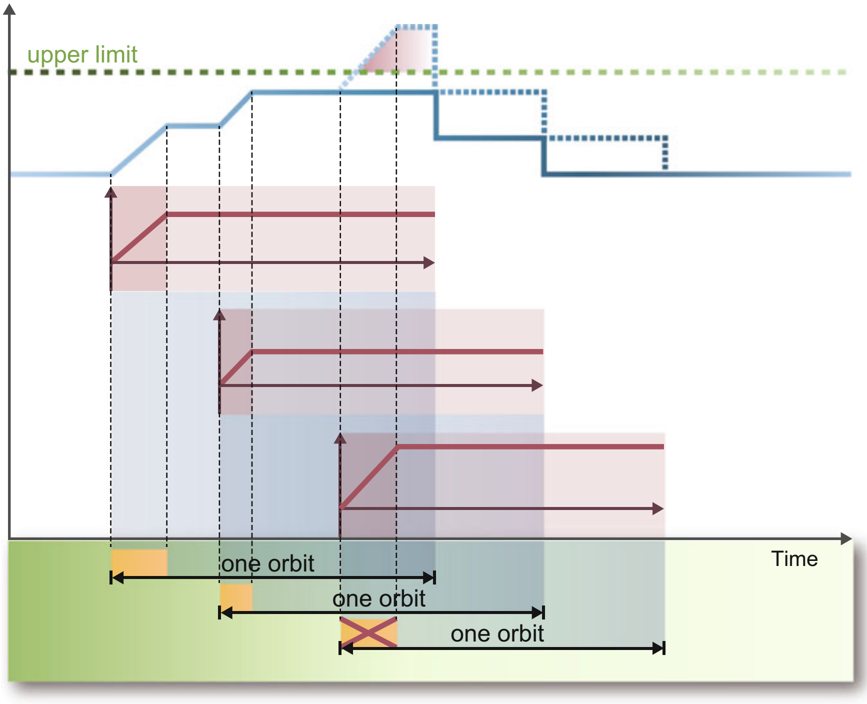


Fig. 5.16 The "one-orbit gliding window" assures that only a limited amount of on-board activities may be scheduled during any time interval of size one orbit

upper and lower limits, the distinction of the resource types depends mainly on the constraints which are defined on them. Given the fact that the GSOC modeling language does not explicitly distinguish these resource types, they can be combined arbitrarily.

For example, one may introduce a resource comparison on a resource, which models the battery's state of charge in order to assure that a certain on-board experiment is executed only if the battery's voltage exceeds a certain level.

Another use case are unavailabilities of equipment: It is possible to schedule an unavailability task, which is given a Resource Comparison with upper bound = 0. This adds a local upper bound of value 0 on the equipment resource during the time of unavailability, so no task may be scheduled there, which needs (i.e., would increase) this resource.

Besides it turns out useful to define all initial fill levels of resources to have constant value = 0 and to avoid modeling any upper or lower bounds on resources. Instead it is recommended to introduce setup tasks, which are scheduled during the whole timeline horizon. A nonzero initial fill level of a resource can be supplied by a resource modification of one setup task and a comparing resource dependency will replace the upper or lower bound of a resource. This way one may prepare different configurations by specifying different sets of setup tasks and easily switch in between these configurations just by scheduling the desired set of setup tasks.

In fact, resource bounds may be implemented using hidden tasks.

5.1.3.4 Scheduling Algorithms

Having translated the mission into the modeling language, we can now focus on generating the timeline entries, i.e., the execution times for the different activities. This can be done by a human operator using interactive software such as GSOC's planning tool Pinta. When using such software, the operator will be presented with possible timeline entries for each task he or she wants to schedule and he or she will be warned against existing conflicts in the timeline. However, this manual approach may be quite work-intensive; therefore it may be a good idea to support the process by supplying subalgorithms, which the operator may apply to certain tasks or groups. This approach can be enhanced by more and more complex algorithms, until the only remaining task of the operator is to start the algorithm and check its result. This kind of planning has been implemented within the TET-1 mission (Axmann et al. 2010).

In the end, when the same type of scheduling is required again and again or when the dependencies are too complex for a human operator to survey, the operator may be excluded completely from this process, ending up in a fully automated scheduling system. An example for such a fully automated planning system is described in Maurer et al. (2010). In this example, a priority-based Greedy algorithm (Korte and Vygen 2005) is used, i.e., the existing planning requests are considered one by one in descending order of their priorities and included into the timeline if this is possible without causing a conflict. However, there exist more sophisticated algorithms, which perform global optimization on a given quality criterion. If such an alternative algorithm was implemented and proved to be superior to the existing one, exchanging the algorithm would be quite easy as long as both algorithms use the same model.

The question of how much automation should be implemented and how much should be left to a human operator depends on the kind of mission.

Fixed Plan

For less complex instances of this type, it may be best not to write an algorithm at all but to let an expert generate the timeline manually. In case the planning problem has already been modeled, this manual timeline generation may be supported by graphical planning tools, which suggest conflict-free timeline entries for selected tasks and highlight existing conflicts and their sources in order to support fast manual conflict resolution.

For less complex but voluminous instances of this type, the manual approach may be accelerated using generic (i.e., off-the-shelf) algorithms. In this case a simple configuration will be sufficient to generate a first version of the timeline, which thereafter may be checked and improved by the operator.

On the other hand, complex missions of this type may require a highly specialized optimization algorithm. You will not find a generic algorithm for such a mission. However, modeling the problem in the standardized way still has advantages, which may be worth considering:

- Conflict check of the final timeline using generic tools
- Display of the final timeline using generic tools
- Simple integration of the specialized algorithm with existing scheduling software

Repeated Rescheduling and Incremental Scheduling

These operational concepts support ingestion of new information during the mission execution phase. This usually implies that new requirements to the planning process evolve during the execution time. Therefore using a generic algorithm not only saves implementation effort in the preparation phase but also increases the flexibility to react on such new requirements. So unless there are good reasons to implement a specialized algorithm it should be attempted to configure a generic one.

The main challenge of a generic algorithm is to design it sufficiently flexible to cover the typical demands of future problems and to keep it extensible such that the unexpected demands may be covered by generic or project-specific add-ons to the preexisting generic system.

On the other hand the algorithm and its configuration must remain simple. In case the algorithm's functionality is hard to understand or in case it has too many configuration items, it is likely not to be understood by any other than the developer himself, which makes it unlikely to be reused in the future.

The naïve approach would be to define some basic generic algorithms and to extend them whenever new features would be required. Although in the course of time these algorithms will cover most requirements, one will find them very soon hard to understand and to apply. A better approach to extend the basic algorithms is to decompose them into their very basic parts and to allow combining them, as described in Lenzen et al. (2012). This way, small and easy-to-understand "algorithm snippets" are generated, which can be combined in the desired way. Following this approach, an extension of the generic algorithm should result in adding a new algorithm snippet.

5.1.4 Summary

The current algorithms of the GSOC scheduling suite restrict to heuristics, which find good results in rather short time. Using this approach, one may freely combine the features of the modeling language. Implementing an optimizing algorithm on the other hand will require some restrictions on the planning model. For example the lost values calculation of a resource is hard to translate into the model domain of an optimizer. However, one may find approximations of the model, which may be covered by an optimizer.

5.2 Mission Planning for Unmanned Systems

Tobias Göttfert and Falk Mrowka

5.2.1 Introduction

Space missions without human beings on board are often suited for automated planning systems, since the mission objective and duration is usually known beforehand. Additionally the "human factor" is not present and the complexity of the vehicle's subsystems is lower than the one of e.g. a manned space station. There is usually a finite list of tasks that can be planned, depending on the features of the spacecraft, and a finite list of resources which have to be modeled. However, the requirements and operations scenario of non-manned spacecraft missions can vary a lot and no single Mission Planning System (MPS) fits up to now all missions that are flown in one control center. In general, the more complex and more agile the planning problem gets, the more work can and should be invested into automation and a sophisticated software system. For comparatively simpler planning tasks, which have to be performed less often, regular manual creation of the mission timeline is often the more economical solution (see also Sect. 5.3). However, in both cases, a set of common software tools for planning and scheduling is highly beneficial.

T. Göttfert (✉) • F. Mrowka
German Aerospace Center (DLR), German Space Operations Center (GSOC),
Oberpfaffenhofen, 82234 Wessling, Germany
e-mail: tobias.goettfert@dlr.de

5.2.2 Mission Planning System Example

As an example for the application of the generic scheduling language which was presented in Sect. 5.1, the combined MPS for the TerraSAR-X and TanDEM-X missions (TSTD-MPS) at the German Space Operations Center (GSOC) shall be described (Lenzen et al. 2011). This system is at the moment the most evolved and feature-rich MPS at GSOC, having grown from a single-satellite, single-mission automated planning system into a dual-satellite, dual-mission planning system that takes various correlations between the spacecrafts and the missions into account (Mrowka et al. 2011). The TerraSAR-X and TanDEM-X spacecrafts are described in more detail in Krieger et al. (2007). For here it is relevant to know that both carry a Synthetic Aperture Radar (SAR) instrument that is able to capture either two-dimensional imagery via one satellite or three-dimensional radar-based digital elevation models that make use of both spacecrafts simultaneously in an interferometric mode.

Therefore, the two satellite missions need to be considered as tightly linked in terms of planning.

Additionally, the mission is operated in a public–private partnership, where several parties can place planning requests for radar imagery, which all have to be collected at the MPS side.

In total, the TSTD-MPS has to model more than 300 resources and their constraints which are associated with the two satellites and is responsible for the scheduling of all payload-related activities, both on board and on ground. This means that not only the radar instrument activities need to be scheduled, but additionally mass memory and bus-related activities, like X-Band downlink of the radar data. In addition, an on-ground schedule is created that allows the participating ground stations to control their antennas accordingly, as well as the data processing centers to properly file the incoming payload data. The GSOC generic scheduling language (see Sect. 5.1) provides all the building blocks that are needed to describe the planning problem for this mission and the implementation of a priority-based scheduling algorithm.

For example, the simple addition of one 2D radar image is modeled via a timeline entry of a task with certain duration on the timeline. When scheduled, this timeline entry affects several resources, e.g., the power or time usage of the radar instrument, which of course is only possible if none of the resource limits is violated. In addition, scheduling the data take is only possible if there is no danger that the partner spacecraft is illuminated with the SAR instrument during that data take, modeled via another resource. The data take also necessitates file handling tasks and their timeline entries, like creation and deletion of data files for the image, which in turn affect the mass memory resource usage. On top, data downlink tasks have to be scheduled during a ground station contact, which in turns triggers the scheduling of antenna switch-on and switch-off tasks.

Pinta 3.5.3 - [unnamed - StartTime: 16:05:00 - Duration: 00:45:00]

RecalculateProfileState for Timeline 'unnamed' finished.

UTC

None

16:05:00 16:22:49 16:50:00

WorkSpace: Not Set

Project: [unnamed]

Fig. 5.17 Graphical view of parts of a TerraSAR-X/TanDEM-X timeline within Pinta. A short time period (approx. 45 min) and a limited set of activities are displayed on a horizontal time axis. Tasks and resources of the TerraSAR-X satellite (TSX) are shown in *green*, and for the TanDEM-X satellite (TDX) in *blue*. Note how the algorithm schedules instrument activation for the data takes and the switchover of X-Band downlinks when passing over several ground stations. 3D data takes are scheduled in parallel on both satellites

Within the scheduling process, the algorithm looks at every planning request in a defined order, based on request priority, and decides if all these conditions can be met. Only then, the data take is planned together with all additional tasks, and the resources are modified accordingly. In the end, an export tool creates telecommands for the spacecraft from the tasks on the timeline, which are then uplinked and executed. Further data files are generated for the various shareholders on ground. Figure 5.17 shows a simplified example of a TerraSAR-X/TanDEM-X timeline, taken from the GUI tool for timeline analysis, called Pinta, in which some important tasks and resources can be seen in a graphical view.

The planning process within the TSTD-MPS is performed in a regular scheme which is strictly coupled to the ground station contacts for command uplink (repeated rescheduling). On average, this results in a planning run every 12 h, where every time a new version of the timeline with a planning horizon of three days into the future is generated. However, each upload contains time-tagged spacecraft commands only for the next 24 h, still leaving 12 h of overlap from each command upload to the next one. This ensures that one failed uplink contact will not stop the mission execution.

5.2.3 Considerations on Designing a Mission Planning System

Mission planning systems for nonhuman missions are software systems, where the degrees of automation and human interaction depend on the mission requirements. Therefore creating an MPS is strongly coupled to software engineering. The design of such a system is influenced by the following key factors:

- How to map mission objectives and capabilities to the planning model and planning algorithms
- How to interact with the rest of the ground segment and serve its interfaces
- How to design the system as robust, failure tolerant, and automated as needed
- How to maximize the amount of reuse of existing components

During the mission development phases A to C (c.f. Sect. 2.1), the baseline and the complexity of the MPS are already defined and small changes on the mission design and/or requirements can influence the needed effort on mission planning side considerably.

Therefore it is advisable to analyze the mission design as early as possible also from a mission planning point of view. A number of aspects need to be taken into account, of which a few examples shall be given.

For a mission with several spacecrafts it needs to be evaluated, whether it can be dealt with by using independent planning models for the spacecrafts, or whether they are inherently coupled to each other. For example the TerraSAR-X and the TanDEM-X spacecrafts are inherently coupled in their formation flight because of synchronized data taking for 3D images, and therefore one common MPS is needed because of the common planning model for both satellites and both missions.

The level of intelligence of the on-board software needs to be taken into account, e.g., whether the telecommands available to MPS address high-level or rather detailed low-level functionalities. For TerraSAR-X spacecraft the MPS has to command also instrument activation and instrument standby in several levels, whereas other spacecrafts perform these tasks on their own if data takes are commanded.

It needs to be checked whether the command uplink scheme is very rigid and well defined or whether there is a lot of flexibility involved. In some cases even a constant uplink is possible, as it is the case for geostationary satellites. As example, the MPS for the GRACE mission (Braun 2002; Herman et al. 2012; Tapley et al. 2004) is built on a fixed scheme of weekly planning runs and incremental uplinks of the resulting commands every day, the TSTD-MPS on the basis of specific ground stations contacts.

The flexibility and optimization requirements from the user's side need to be analyzed: It makes a huge difference whether frequent replanning and thus possible changes of the plan are desired or discouraged.

It is crucial to clearly define which resources have to be modeled to what extent. For some resources a detailed model is required; for others approximations are sufficient. For example for the TerraSAR-X spacecraft, memory usage is modeled exactly; the battery level is modeled in a linear approximation; thermal resources are modeled by a simplified heuristic using a predefined time window approximation.

Also the modeling of the ground segment needs to be investigated. It can be built very complex, but often a simplified representation is good enough. For example, shall certain ground stations be preferred for data downlink because of a network connection with higher bandwidth?

Last but not least the complexity and safety of the commanding concept needs to be taken into account, e.g., for the TerraSAR-X spacecraft, for safety and autonomy reasons, every 12 h the next 24 h are commanded to the spacecraft, which needs sophisticated delta-commanding capabilities.

5.2.4 Mission Planning at Various Time Scales

Mission Planning is a task that happens on a wide variety of timescales, from years down to sub-seconds. This chapter shall give an overview about the work of the mission planners and their results on these timescales.

During all of phases of the mission, starting already in the analysis phase A, i.e., *years* before the launch, mission planning needs to be involved in the process. The mission planning team provides consulting and participates in the analysis and mission definition process. It collects mission and user requirements and ideas about the goals of the mission and prepares concepts for planning and scheduling. It defines the design of the mission planning system and the necessary components, which either can be taken from existing components or have to be newly developed. In the end, a concept for the MPS and its operation and the mission planning requirements are created and the MPS is developed and integrated, together with all necessary tests.

Activities that happen in the timescale of *months* are usually major changes in the mission, e.g., major orbit-configuration changes. Other changes might lie in the operational concept, e.g., changes in the uplink or downlink schema, different usage of the payload, and introduction of new requirements. The mission planning team gives consulting to the mission management and ensures that the feasibility of the change is given.

For planning systems that handle stable and predictable scheduling problems, a long-term preview of the timeline can also be given, which covers the timescale of months. Of course, this preview is subject to changes, depending on input of planning requests, but can serve as a valuable tool to enable the coordination between different parties that have influence on the timeline. For example, flexibility in the execution of orbit maneuvers can be used to schedule them at a time that minimizes the disturbance on nominal mission execution; different users can coordinate their requests, etc. Also a coarse preplanning of activities is sometimes performed months ahead.

Normally, the planning horizon of a nonhuman mission is in the order of *days*. Within this time frame, all relevant nominal input shall arrive at the MPS, well ahead of execution time. Those inputs are e.g. planning requests, the ground station availabilities, orbit and maneuver information, or other flight dynamics input. Also planned maintenances fall in this category.

The timeline is then usually generated some *hours* before uplink, depending on the mission planning concept, degree of automation, and requirements on the reactivity of the MPS. This short-term planning can take into account the latest status of flight dynamics data for products with a high requirement on accuracy and a limited time span of validity. The point of timeline creation also determines the order deadline, after which no late planning requests can be considered anymore.

Usually, only during the LEOP phases, activities can be planned *minutes* before their execution time, since only in this phase extended real-time operations with human personnel in the form of mission planning and flight operators are carried out.

The activities that have to be scheduled also happen on different timescales, depending on their nature. Hereby, both duration and required timing accuracy can vary a lot, from days and hours down to the *second* and *sub-second* range. A few examples are maintenance phases, which can last hours and days and usually start at manually chosen times, ground station contacts, which have durations in the range of minutes for low-earth orbiting satellites and need to be scheduled with a few seconds precision, or maneuvers, which usually last a few seconds and also need a precision in the range of seconds.

Most satellite buses provide an accuracy of execution of time-tagged commands in the range of one second, normally sufficient for most activities on board.

For applications that require a more precise control over their execution time, special provisions have to be made: First, the on-board hardware has to support this, usually via GPS-supported time correction features in the affected subcomponent of the satellite, and second, the MPS has to be able to fine-tune the start time and duration of the activity when the latest orbit information with the required accuracy is available. A prominent example is the scheduling of imaging data takes for low-earth orbiting satellites, which require a timing accuracy of less than 1 ms for a ground track accuracy in the range of meters.

Figure 5.18 shows zoom-ins into a timeline of a fictitious satellite mission to demonstrate the various timescales of activities that the MPS encounters.

5.2.5 Conclusions and Outlook

Mission planning for nonhuman missions has to cope with many different types of spacecrafts and operational concepts, leading to a variety of MPS designs. However, the well-known set of plannable activities and their potential frequent repetition usually make some sort of automatic scheduling feasible. The surrounding tools that complete the MPS are then crafted to the automation and operational

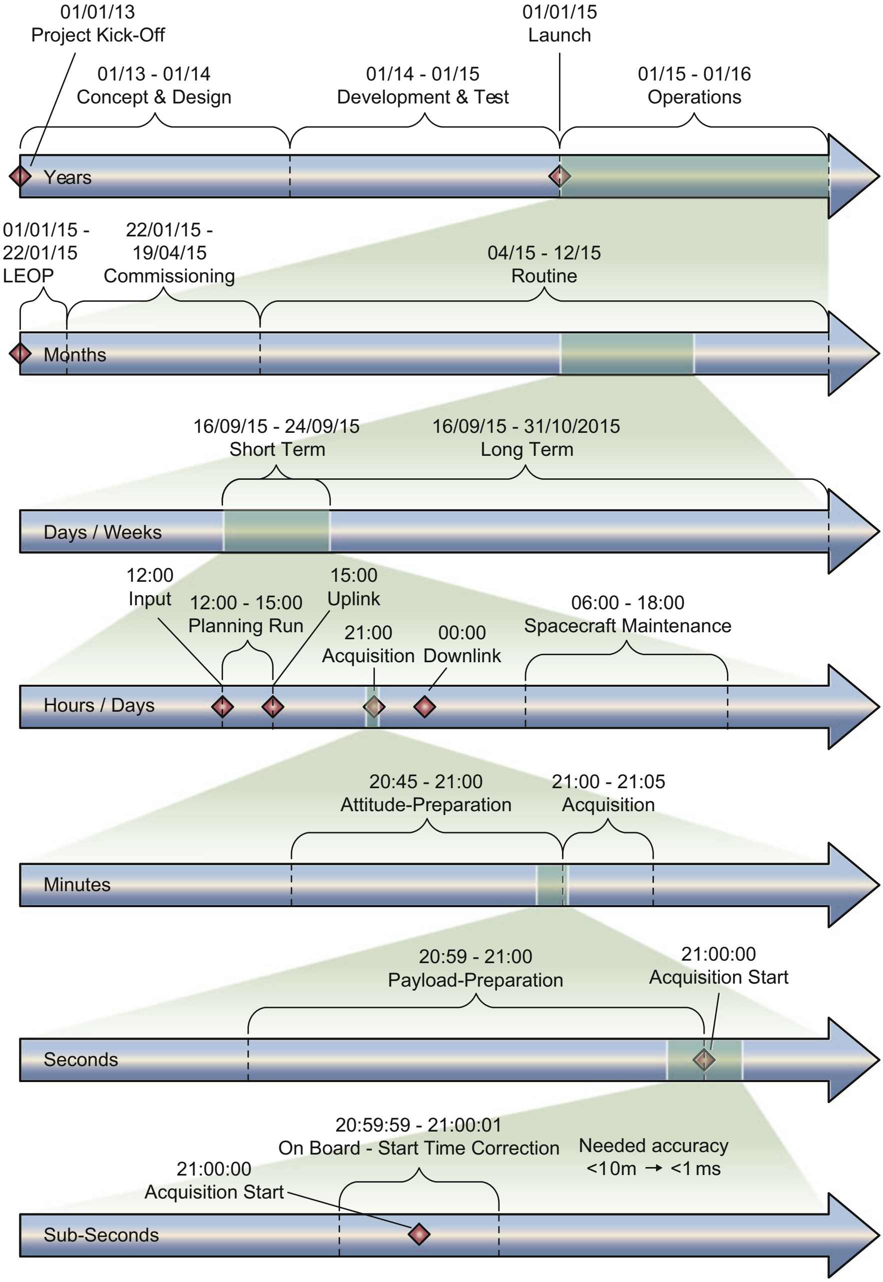


Fig. 5.18 Timeline with example activities of a fictitious satellite mission. The various levels of zoom exemplify the different timescales on which the mission planning processes and scheduled activities take place

needs of the mission. For this, a proven set of planning tools that supports all relevant scheduling functionalities and easy inspection of the resulting timeline is a crucial prerequisite.

Following the development of highly automated mission planning systems and the increasing computational capabilities of on-board hardware, new approaches increase the flexibility of mission planning systems even further to cope with the growing demands of reducing overall reaction times of the satellite system. One example are the investigations for moving parts of the planning algorithms onto the spacecraft, making it possible to invoke last-minute planning processes without contact to ground (Wille et al. 2013; Wörle et al. 2013).

5.3 Mission Planning for Human Spaceflight Missions

Thomas Uhlig, Dennis Herrmann, and Jérôme Campan

5.3.1 Introduction

Planning is a key part of human spaceflight operations, was already part of the first Mercury flights, and has significantly developed ever since. While the first flight plans were text-based tables on paper, today's plans are displayed graphically with dedicated applications, have sophisticated possibilities to include or extract information, and are available via the Internet. In the meantime, the terminology "timeline" is commonly used to describe the schedule of the astronauts and the related ground activities.

In this chapter, planning for human spaceflight operations is described using the International Space Station as a model case. This confined focus might sound like a loss of generality; however, all human spaceflight endeavors undertaken so far cumulate in the ISS project. In that sense, the ISS planning processes, phases, and tools can be considered as the heritage of the American Mercury, Gemini, Apollo, Skylab, Space Shuttle, and the Russian Восток (Vostok), Восход (Voskhod), Салют (Salyut), and Мир (Mir) planning processes. All that experience and lessons learned were used to design the mission planning for the International Space Station.

It needs to be highlighted that a number of planning and scheduling processes and products exist for the ISS in various areas: Planning is being done for example for the station attitude, for robotic tasks, for Extravehicular Activities (EVAs), for consumables, and for critical resources like water, as shown in Fig. 5.19. This article only focuses on the crew and ground activity planning—the process

---

T. Uhlig (✉) • D. Herrmann • J. Campan
German Aerospace Center (DLR), German Space Operations Center (GSOC),
Oberpfaffenhofen, 82234 Wessling, Germany
e-mail: Thomas.Uhlig@dlr.de

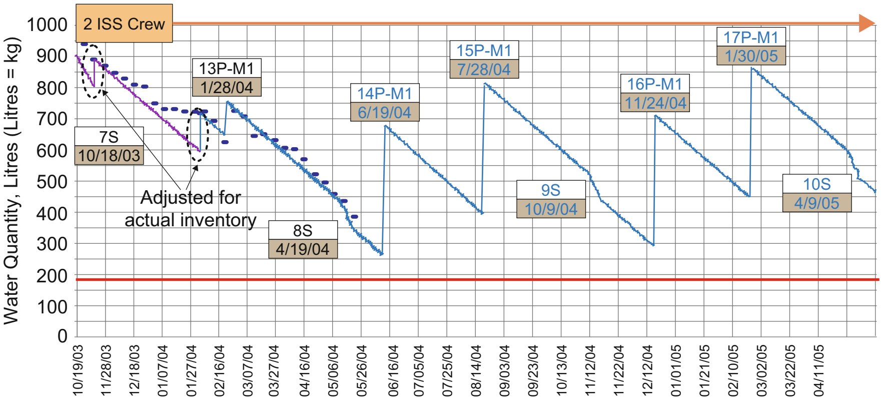


Fig. 5.19 Planning is done in various forms for human spaceflight missions. Here, an example for the on-board water availability planning is given (Reprinted from Kitmacher et al. (2005) with permission from Elsevier)

which is commonly referred to as "mission planning." All other aspects are not covered here.

Although the terminology and the planning theory are similar to mission planning for unmanned missions, the automatization of planning for the ISS is marginal. In principle, it would be possible to model activities, to define exactly the constraints, relationship to other activities, and dependencies of resources, as described in Sect. 5.1. But since the mission goals for ISS operations cannot be broken down to a few science objectives, like it is possible for a satellite (i.e., "earth observation"), the number of resources and conditions to be modeled would be immense. If the goal of a mission would be earth observation only, the conditions could be limited to some parameters concerning the position and attitude of the spacecraft, the orbital constellation with respect to the sun, if sunlight is required for optical pictures. The resources could be the available power, the data stowage situation on board, and the downlink paths.

But ISS mission goals include not only earth observation, but also experiments of almost all scientific disciplines. The experiments might have requirements for special microgravity conditions, temporal constraints on a variety of different time scales, interdependencies to "private" crew tasks (like fasting or blood sampling), priority orders, and even international or political dimensions. Figure 5.20 gives an overview about the most important resources and constraints.

Although it might be possible in theory to produce a complete list of all thinkable resources and conditions, and a state-of-the-art computer system with a corresponding algorithm could predict these parameters continually, the effort to link each activity to its related resources and conditions and thus to model it correctly would outweigh the benefit of an automated planning system. This is in particular

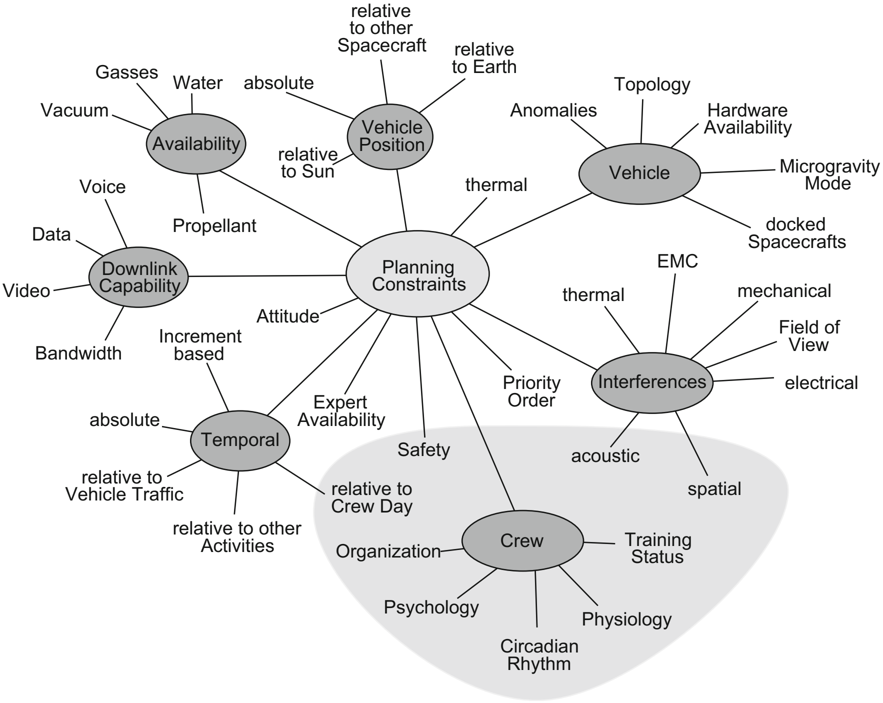


Fig. 5.20 Planning for human spaceflight can be constrained by a variety of factors. The most important ones are shown here; the ones directly linked to human presence are summarized in the *shaded area*. A mathematical modeling of them to support automatic planning algorithms is not feasible

true, since a large fraction of the activities which are on the timeline occur only once.

Also the human factor has to be taken into account, which is difficult to put into a mathematical model. Astronauts have personal preferences, which need to be respected and incorporated into the planning, if possible. There are medical and psychological aspects, which only appear if the integrated schedule is checked by an expert, e.g., there might be concerns to do more than one blood draw per day.

Due to the internationality of the ISS and multiple participants, the planning has also a political dimension, which might influence the final planning product, but definitely needs to be reflected in the corresponding processes.

For those reasons, the human spaceflight planning is still a manual process and involves different teams around the world to accomplish it. The multitude of influencing factors, which can easily change in near real time, also makes the mission planning a highly dynamic endeavor.

5.3.2 Basic Considerations

Planning for projects like Apollo or the early Space Shuttle flights is fundamentally different than planning for the Mir or the International Space Station. If the planning is done for short duration flights, the preparation and the execution phase are clearly separated. The optimization of such plans has to be very high to make best usage of the limited flight time, and due to the abovementioned separation, this goal can also be accomplished (Popov 2002).

For long-term missions like the ISS, which is continuously manned for several years, the plan preparation and the plan execution processes need to be run in parallel, which adds complexity to the planning, but also decreases the need for high optimization, since overall crew time is no longer a limiting factor (Korth and LeBlanc 2002).

However, to better be able to cope with continuous ISS operations, it was decided to break down the Space Station timescale into smaller pieces, which can then better be worked with methods comparable to project management. Those timescales are called "increments" or "expeditions", are driven by the ISS crew rotation, and have numbers assigned; currently (March 2014) the ISS is in increment 38. An ISS increment has a duration of 2–4 months; each Soyuz undocking event triggers the start of a new one. Since two Sojuz crew alternate, this translates into a crew stay on board of approximately 6 months, which is compatible with the time a Soyuz spacecraft is designed for and approved to remain in space under the very harsh environmental conditions, which are described in more detail in Sect. 1.1.

The planning processes are therefore adapted to the increment concept, as described in more detail in Sect. 5.3.5. For historical reasons two increments are always treated together in one combined planning effort—so all the considerations below are applicable for double increments, e.g., increment 37/38.

The elementary planning items in human spaceflight planning are activities (sometimes also referred to as Planning Requests, PR), which are either executed by the ground team or by the astronauts on board. The heart piece of each activity is normally a procedure (or parts of a procedure), which are called Operations Data Files (ODFs). They contain a detailed description of what has to be done using well-defined formats and standards.

These procedures also define the required resources to conduct the activities. To complete the set of planning data required for the scheduling and a proper execution of the activity, some additional info is attached to each planning request, partially detailing the data already contained in the Operational Data File (ODF), and partially adding new planning information like the resource utilization. The relationship between the ODF and the planning request is depicted also in Fig. 5.21.

The planning requests are maintained in a database at each participating control center (see Sect. 5.3.3) and are then fed into the common planning system.

During the planning process the limited ISS resources like crew time or data bandwidth need to be shared between the different international partners. It was

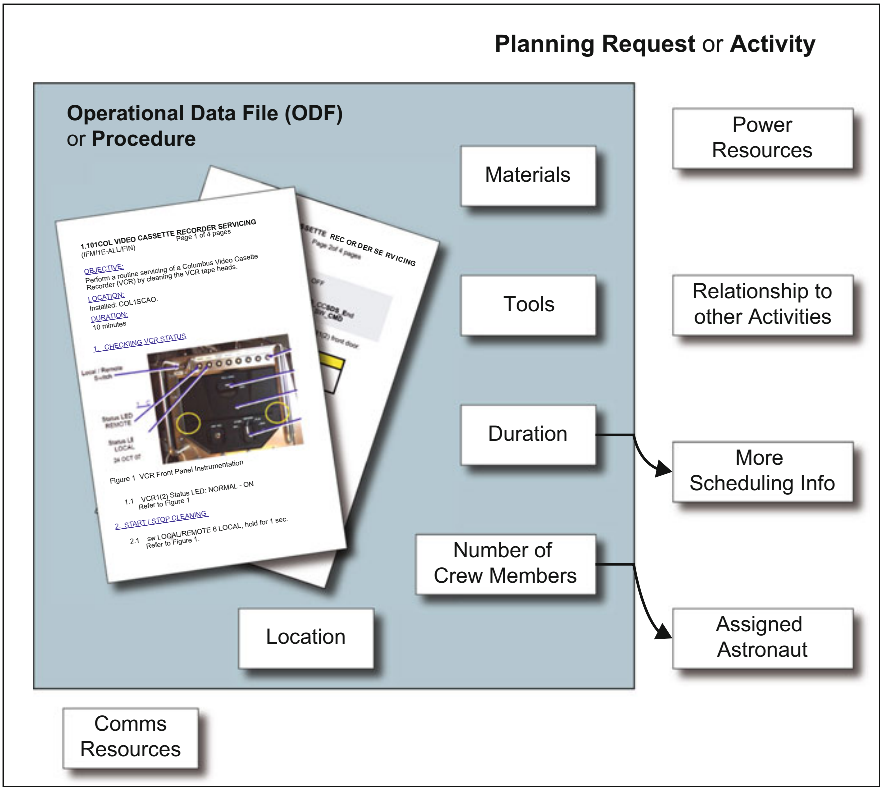


Fig. 5.21 An activity definition or planning request as elementary planning item contains as basis a procedure called Operational Data File (ODF), which defines the actual task to be performed. It contains also various information about the task like the materials or tools required for execution. The procedure is supplemented by some additional information, like the assigned astronaut—often referred to as planning attributes—which complete the set of data required for proper planning of the planning request

agreed that the ratio every partner is eligible to use is directly related to its overall contribution to the ISS program. This leads e.g. to an ESA utilization share of 8.3 % of all common ISS resources, including crew time.

5.3.3 *Planning Teams*

The increment concept allows also to better assign key personnel and to ensure a task and responsibility rotation with a frequency of approximately half a year.

The first steps of defining the content of the increment are done on a management level by every international partner during the strategic and tactical planning phases described further below.

Each ISS control center (see also Sect. 7.1) then facilitates its own planning department, whose experts are assigned for the increments. For a given increment, there are usually a number of individuals involved in the preparation phase. The terminology Long Range Planner (LRP) is used by NASA, ESA calls them Columbus Lead Increment Planner (CLIP), and the Japanese supply the 3PO (Planning, cPs, iPs Officer). We will see later that the preparatory phase does not end with the start of the increment, but the plans have to be fine-tuned again, if the actual execution day comes closer due to the highly dynamic environment of human spaceflight. To minimize the handovers and to facilitate the knowledge which was built up by the planners who worked the preparation phase, in all ISS control centers this near-real-time processing of the timeline is done by the same individuals who already prepared the first draft timelines.

One week prior to execution, the timeline for a given day is handed over from the planning personnel in the backrooms to the Flight Control Team (FCT) on console. Also within each flight control team a planning function is implemented, partially a dedicated position staffed by an expert from the planning group (like the OPSPLAN at the Johnson Space Center in Houston, partially merged with a technical position (like the COL OC at the Columbus Control Center in Oberpfaffenhofen). These real-time planners coordinate and process late formal changes to the timeline and can assist the Flight Controllers in case real-time replanning of activities “on the fly” is required.

5.3.4 Concept of Crew Flexibility

It is part of the human nature that an astronaut prefers to have certain freedom in his working day. Thus the timeline is generally considered as a proposal from the ground teams only, and the crew is generally allowed to deviate from the plan or to adapt the schedule to their individual preferences.

Some effort is currently spent within the ISS community to group activities into different categories. Activities marked as *flexible* in the timeline can be performed by the crew at their discretion—these tasks are not dependent on anything else. The daily exercise of an astronaut is a typical example.

Team Activities are tasks with constraints that are expected to be executed as scheduled. However, it may be performed differently than scheduled, but in this case a prior ground and crew coordination is required. Such activities might be dependent on special resources or conditions or are requiring support from the ground teams.

Time Critical activities need to be executed exactly at the time when they are scheduled. If this is not possible, it needs to be canceled for that day. In the timeline viewer those activities appear with a blue frame. Typical examples are live public affairs events.

In case some activities are related to each other and have to be conducted in a certain sequence, those activities are marked with the same color in the timeline viewer. Thus the astronaut still has some degree of freedom in the timeline execution, as long as he respects the given sequence of events.

Weekends and pre-agreed holidays are kept free of work if somehow possible. However, on crew request a concept of voluntary science/maintenance was established in the last years. In case the crew expresses their interest prior to their mission, the ground team put together tasks which can be autonomously executed by the crew on weekends or holidays. For each weekend, the crew then receives a pick list approximately 2 weeks in advance, from which they can select their preferred activities. These are then put into the timeline of the crew-off days; however, crew always reserves the right to resign from the tasks and protect the free days.

All activities, which appear scheduled in the timeline, are called "hard scheduled" and the time required for their execution is budgeted to the corresponding space agency. However, there is an alternate concept in use, which is called job jar or task list. The task list is populated each week with possible candidate activities which can be performed by the crew at any time. The idea behind the task list is to provide the crew a repository of activities which need to be executed sometimes, but are (at least for the moment) not anyhow critical. Typical examples are stowage audits. In case the crew has some "gray space" on a dedicated day they might consider to check the task list for further work and get ahead with the increment goals, if they wish.

5.3.5 Planning Phases Overview

Different planning phases need to be distinguished for the ISS project. The phases range from very generic planning of vehicle traffic and crew rotation far ahead to the very detailed daily planning of activities. As shown in Fig. 5.22, three phases can be distinguished. The strategic planning phase goes far into the future, and becomes tangible approximately 5 years before the execution phase. It directly transitions into the tactical planning phase, which is initiated around 1.5–2 years prior to start of the double increment.

The strategic and tactical planning phase follow an annual schedule rather than an increment-based one; therefore the temporal relationship to the start of the increment is by nature only an approximate value.

One year prior the increment the Execute planning processes are entered, which can be split into two subphases: the pre-increment and the increment execution planning. Since the planning products (see below) of the increment execution have a lead time of 17 days, this phase is started about 2 weeks prior to increment start. This phase runs throughout both increments. After the increments, corresponding reports need to be generated by the planning community, which are not further detailed here.

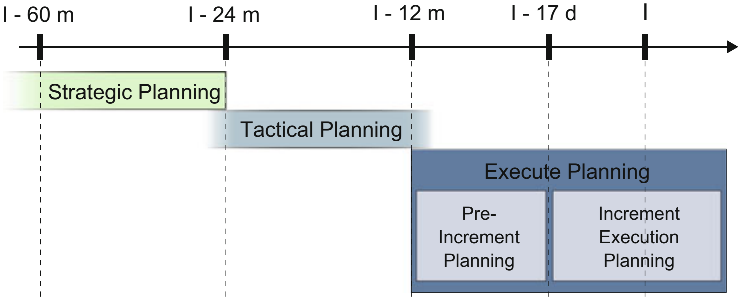


Fig. 5.22 The planning process for a dedicated increment can be split into different phases. These phases use the start of the increment (denominated as "I") as time reference. The strategic planning phase concretizes approximately 60 months prior to the increment start, the tactical planning about 24 months before. The Execute Planning phase is entered at I—12 months and can be split into the pre-increment time frame and the increment execution. The latter begins 17 days prior to the increment with the generation of the first execute planning product (see below) and lasts throughout the increment

5.3.6 Planning Products and Processes

5.3.6.1 Strategic Planning

The strategic planning phase is also referred to as multi-increment planning, since it covers a longer time frame; its planning horizon is 5 years in advance (Leuttgens and Volpp 1998). It is—like all planning phases—a multilateral process and defines the ISS assembly sequence, all visiting vehicle traffic, and the crew rotation on ISS and ensures that the corresponding resources and consumables are available which are required to reach the high-level operations and science objectives, which are also defined in that planning phase.

The most important documents which are generated during this planning phase are depicted in Fig. 5.23.

The Operations Summary is used for the generation of the Composite Operations Plan (COP), which contains projections of the utilization capabilities allocated to each international partner, and the development of the Composite Utilization Plan (CUP), which contains the utilization plans of all ISS partners. These two documents are combined and harmonized in the Consolidated Operations and Utilization Plan (COUP), which is also published once per year. The COUP covers five consecutive years of ISS operations, of which the first is the just completed one, for which a utilization report is provided, and the second is the one in the tactical/ execute planning phase. The subsequent years are in strategic planning: Years three and four were already contained in the last issue of the COUP, whereas year five is the newly added outlook five years ahead.

From the Consolidated Operations and Utilization Plan (COUP) and other source documents the Multi-Increment Planning Document (MIPD) and the Multi-increment Payload Resupply and Outfitting Model (MIPROM) are derived.

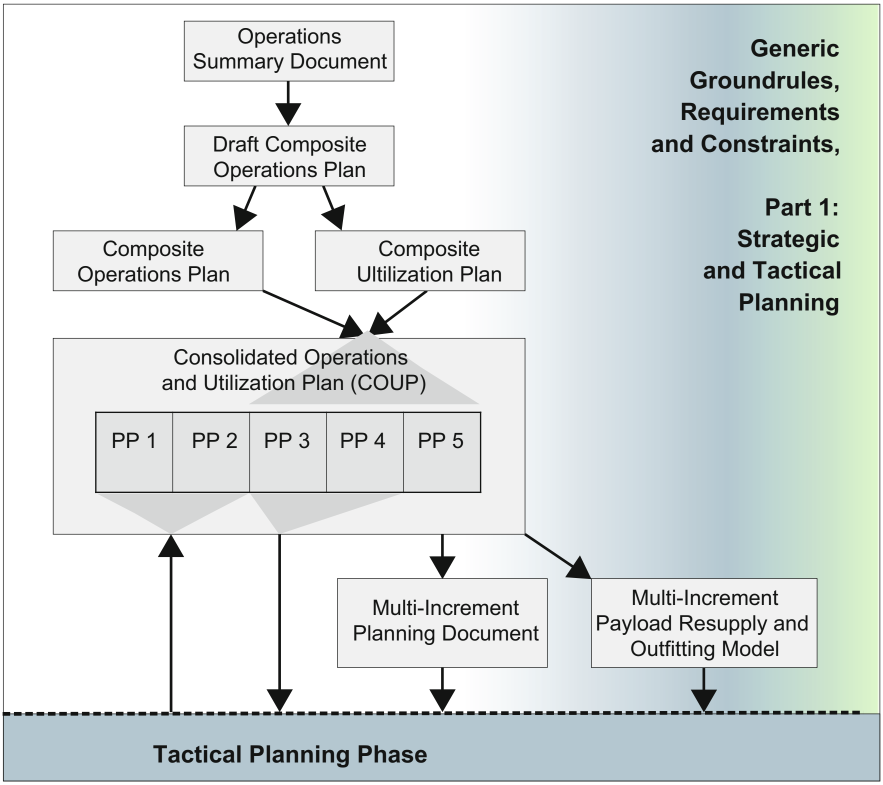


Fig. 5.23 The strategic planning process involves the generation of multiple documents which are iterated several times prior to final publication once per year. The Multi-Increment Planning Document, the Multi-increment Payload Resupply and Outfitting Model, and the COUP document feed the tactical planning phase. Results of the tactical planning are fed back into the COUP. The Generic Groundrules, Requirements, and Constraints, part 1, sets the rules and standards for the planning process (Simplified schematic)

The first one defines the ISS program tactical content and flight definition required to allow consistent planning and resource control. In addition, it identifies the projected ISS resources, accommodations, and supporting services available to the operations and utilization communities.

The latter provides long-range facility-class payload launch and disposal plans and the topology of the external payloads installed on ISS.

Both documents are also published on an annual basis and have the same outlook horizon like the corresponding COUP.

All documents described above are governed by a set of rules called the Generic Groundrules, Requirements, and Constraints (GGR&C), which accompany the entire strategic and tactical planning efforts.

Several groups are involved in the strategic planning process and the products are approved by high-level ISS program panels like the Program Integration Control Board (PICB), the Space Station Control Board (SSCB), and the Multilateral Payloads Control Board (MPCB). The strategic planning documents give directions to the subsequent planning process, the tactical planning.

5.3.6.2 Tactical Planning

Tactical planning is a multilateral ISS Program function that defines and documents the major program requirements, priorities, resource allocations, vehicle traffic, research objectives, the system-related assembly, logistics and maintenance work to be accomplished, and the payload manifest down to a sub-rack level for each increment 1.5–2 years ahead.

The tactical planning phase starts approximately 1.5–2 years before the start of the corresponding double increment. The high program level documents of the strategic phase need to be translated into requirements which can be implemented by the execute planning experts. Figure 5.24 summarizes the most important products of this planning phase.

The main document which is developed in that phase is the Increment Definition and Requirement Document (IDRD) including its annexes, which are in fact self-standing documents as well.

However, before the increment definition can start, the strategic considerations which are based on an annual timescale need to be broken down to double increments. All transportation systems capabilities and schedules, the ISS capabilities and available resources, and the operations and utilization requirements are now assigned to a dedicated increment and related flights.

The Increment Definition and Requirement Document (IDRD) Annex 5, also known as Payload Tactical Plan (PTP), marks the transition from the multi-increment-based planning to a double increment driven approach. It also details the payload planning down to a sub-rack level, and provides the corresponding up- and download manifest information including mass, volume, and additional resource requirements of each item during the transport phase. The research goals for the increment time frame are clearly defined and the required resources for each experiment are compared with the available amounts. This includes also the usage of common station items like tools, disposable gloves, wipes, and tapes. The topologies of the experiment hardware on board are laid out, which means that the configuration of the entire space station is described down to a locker or rack insert level and changes to that configuration during the increment are defined. A table lists all requirements for cold stowage of items. For each research crew activity it is already documented what time has to be allocated for it and the details of the training which has to be delivered to the astronauts on ground are documented. All special agreements between the international partners which are in place for the increment are also referenced.

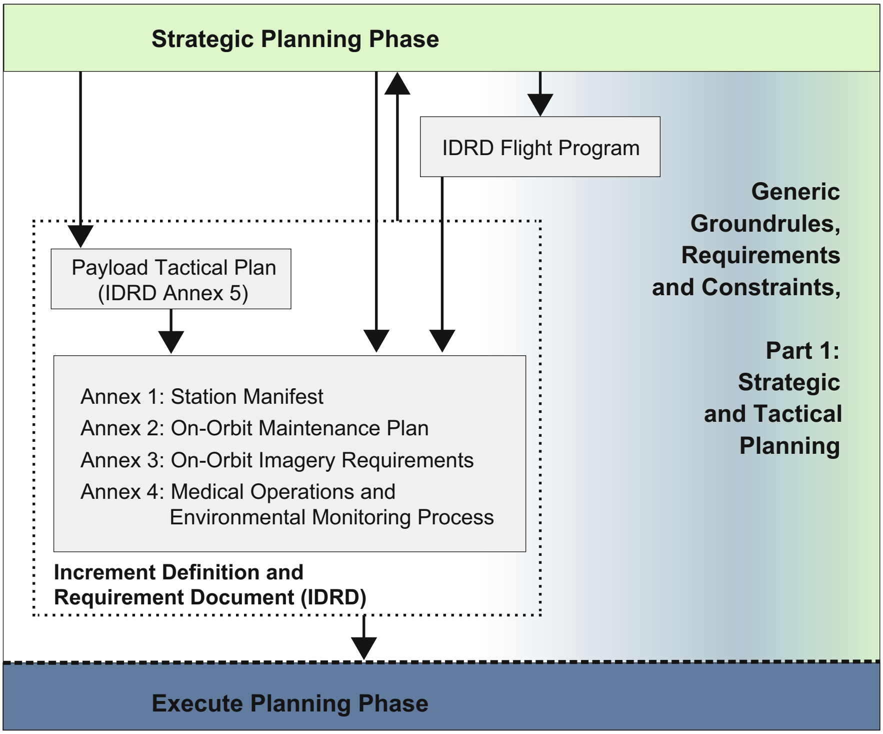


Fig. 5.24 During the tactical planning phase the outcomes of the strategic processes are translated into the Increment Definition and Requirements Document (IDRD) and its annexes, which then serves as input for the execute planning

The document generation process cumulates in its baselined version approximately one year prior to the start of the corresponding double increment.

The Increment Definition and Requirement Document (IDRD) Annex 5 is one major driver of the further planning, which is laid out in great level of detail in the other annexes of the IDRD. These annexes follow their individual development schedules and are under the control of different working groups and decision boards. Annex 1 (Station Manifest) is essentially a detailed inventory list of all planned vehicle "flights" to the space station and retour to earth. This includes not only payload items, which have been identified in Annex 5, but also system or assembly parts, resupply, propellant, cryogenics, water, or crew items. Annex 2 (On-orbit maintenance plan) of the IDRD lists all maintenance activities which are required in the double increment time frame to ensure that the station remains in a good shape. In general it is distinguished between corrective and preventive maintenance and the corresponding requirements are derived from the various design documents of all station hardware. Annex 3 (On-orbit imagery requirements) documents the requirements of on-board imagery, which might come from generic requirements, or payload or system driven requirements, or other sources. Both still and video imagery are listed. Finally, all medical requirements and the guidelines and rules for ISS environmental monitoring and control are summarized in Annex 4 (Medical operations and environmental monitoring).

The Increment Definition and Requirement Document (IDRD) serves as the main input for the next planning phases, which is commonly referred to as Execute Planning. Since the IDRD contains also a priority ranking for all activities, it also serves as important document in that regard during the increment. There might be the need for changes of the content which is driven by the latest real-time developments. Therefore the document is translated into an operational document, the so-called Current Stage Requirement Document (CSRD), which is then maintained by a common effort of the management and operations community and serves as a guideline document for task priorities.

5.3.6.3 Pre-Increment Planning

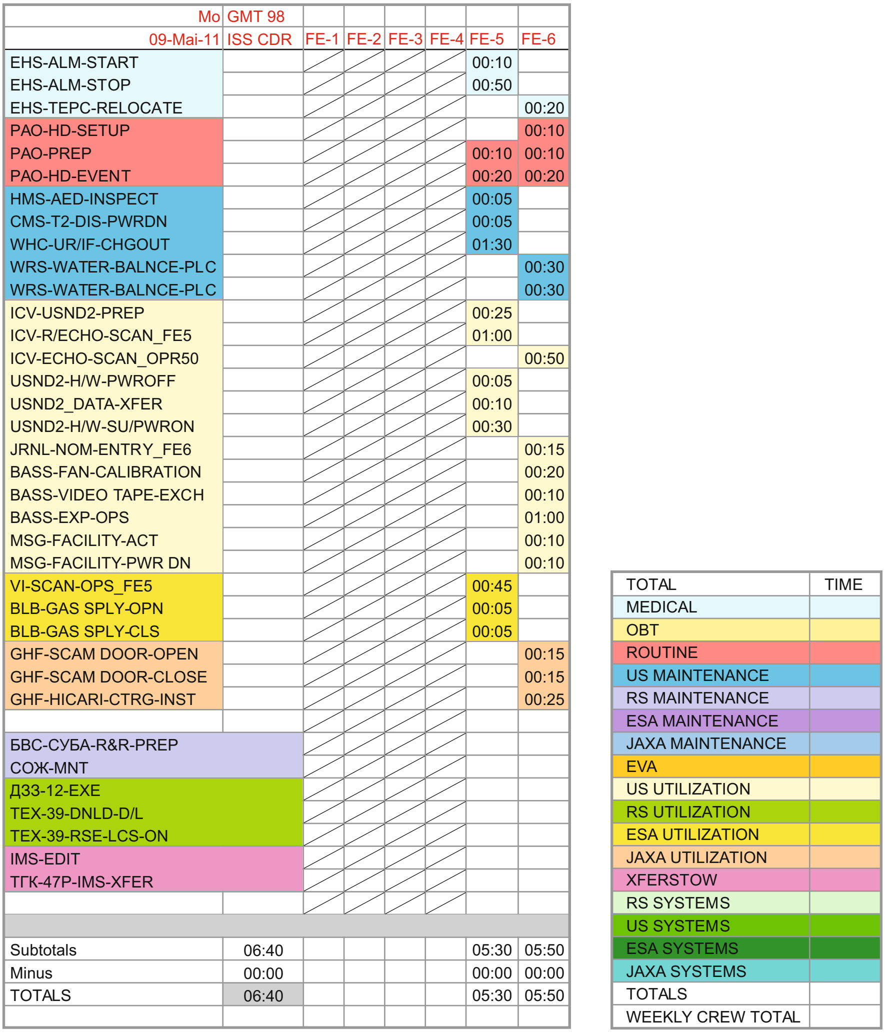
The transition into the Execute Planning phase also marks the point in time, when the planning is handed over to the actual planning teams, which then proceed with building more and more detailed executable planning products.

The two main planning products, which are developed during the Pre-Increment planning phase, are the On-Orbit Operations Summary (OOS) as a rough outline of the future Timeline (see Fig. 5.25) and the increment-specific Ground Rules and Constraints (Gr&C), which comprises a set of planning rules, which apply for the activities of the increment. Both products are generated by the Execute Planning Teams in a common attempt, which cumulates in two Technical Interface Meetings (TIM), the so-called OOS TIMs. Here, the planning for the corresponding double increments is consolidated among all international partners.

The On-Orbit Operations Summary (OOS) is the first product which has a clear planning character in its literal meaning: It assigns dedicated activities to a dedicated crew member and already puts them into a temporal context. The duration of each activity is already known and thus the planning to a granularity of one day can be accomplished.

The planning teams not only take the requirement documents of the tactical planning phase into account, but they also get the actual activity definitions from the corresponding activity owners (i.e., the payload expert centers), which already comprise of all information which is required for the planning process, as laid out in Fig. 5.21. This technical information contains the duration of the activity, the assigned and trained crew members, any requirement for resources (e.g., power) and conditions (e.g., Ku-band coverage for video or data transfer), the associated procedure, and correlations or interferences with other activities.

The international ISS partners work their contributions for the On-Orbit Operations Summary (OOS) and the Ground rules and Constraints (Gr&Cs) independently, but in close contact with each other. 19 weeks prior to the increment start (I—19w), the payload parts of OOS and Gr&Cs are collected by the Payload



Mo	GMT 98						
09-Mai-11	ISS CDR	FE-1	FE-2	FE-3	FE-4	FE-5	FE-6
EHS-ALM-START						00:10	
EHS-ALM-STOP						00:50	
EHS-TEPC-RELOCATE							00:20
PAO-HD-SETUP							00:10
PAO-PREP						00:10	00:10
PAO-HD-EVENT						00:20	00:20
HMS-AED-INSPECT						00:05	
CMS-T2-DIS-PWRDN						00:05	
WHC-UR/IF-CHGOUT						01:30	
WRS-WATER-BALNCE-PLC							00:30
WRS-WATER-BALNCE-PLC							00:30
ICV-USND2-PREP						00:25	
ICV-R/ECHO-SCAN_FE5						01:00	
ICV-ECHO-SCAN_OPR50							00:50
USND2-H/W-PWROFF						00:05	
USND2_DATA-XFER						00:10	
USND2-H/W-SU/PWRON						00:30	
JRNL-NOM-ENTRY_FE6							00:15
BASS-FAN-CALIBRATION							00:20
BASS-VIDEO TAPE-EXCH							00:10
BASS-EXP-OPS							01:00
MSG-FACILITY-ACT							00:10
MSG-FACILITY-PWR DN							00:10
VI-SCAN-OPS_FE5						00:45	
BLB-GAS SPLY-OPN						00:05	
BLB-GAS SPLY-CLS						00:05	
GHF-SCAM DOOR-OPEN							00:15
GHF-SCAM DOOR-CLOSE							00:15
GHF-HICARI-CTRG-INST							00:25
БВС-СУБА-R&R-PREP							
СОЖ-MNT							
Д33-12-EXE							
TEX-39-DNLD-D/L							
TEX-39-RSE-LCS-ON							
IMS-EDIT							
ТГК-47P-IMS-XFER							
Subtotals	06:40					05:30	05:50
Minus	00:00					00:00	00:00
TOTALS	06:40					05:30	05:50

TOTAL	TIME
MEDICAL	
OBT	
ROUTINE	
US MAINTENANCE	
RS MAINTENANCE	
ESA MAINTENANCE	
JAXA MAINTENANCE	
EVA	
US UTILIZATION	
RS UTILIZATION	
ESA UTILIZATION	
JAXA UTILIZATION	
XFERSTOW	
RS SYSTEMS	
US SYSTEMS	
ESA SYSTEMS	
JAXA SYSTEMS	
TOTALS	
WEEKLY CREW TOTAL	

Fig. 5.25 The On-Orbit Operations Summary contains already a full list of all payload and system activities, assigns them to a dedicated day of the increment and to a crew member

Operations and Integrations Center (POIC) in Huntsville/Alabama and are integrated by the NASA experts within 2 weeks. Next, the integrated payload OOS and Gr&Cs are delivered to Houston 17 weeks prior to the start (I—17w) and combined by their planners with the system inputs, which are at that point also provided by all international partners.

The integrated, preliminary On-Orbit Operations Summary (OOS) and Ground rules and Constraints (Gr&C) documents are thus ready 4 months prior to the double increment start and are now discussed in the already mentioned Technical Interface Meeting (TIM) between all planning teams to detect and resolve any conflicts.

A second iteration of the OOS and Gr&C integration then follows: All payload inputs are again collected by the Payload Operations and Integrations Center (POIC) at I - 11w and forwarded to Houston 2 months prior to increment start, where the final OOS/Gr&C document is compiled. A final planning Technical Interface Meeting (TIM) is held, which cumulates in the approval of the final planning products for the upcoming double increment.

The On-Orbit Operations Summary (OOS) plans for each day of the two increments do not yet contain the actual scheduling times of the activities nor are the standard elements of a crew day (e.g., exercises, meals) included. This level of detail is only reached in the next planning step.

The increment-specific Ground rules and Constraints (Gr&C) contain special planning rules, which have to be followed by the planning teams to ensure that all activities are planned in a proper way compliant with all scientific, technical, or medical constraints and can be executed on a non-interference base.

The Gr&Cs are used throughout the increment for the subsequent planning processes and planning product developments.

5.3.6.4 Increment Planning

During the increment planning phase, the On-Orbit Operations Summary (OOS) is successively translated in more detailed planning products, until the final On-Orbit Short-Term Plan (OSTP) is attained, which serves as the final product which is executed by the operations teams. The temporal relationship between the different products is shown in Fig. 5.26.

Each week of the increments, a seven days time period (Monday to Sunday) is extracted from the On-Orbit Operations Summary (OOS) and is transformed by the Long Range Planners (LRP) into the Weekly Look-ahead Plan (WLP). This timeline usually already contains for all activities the exact timing, and the daily crew tasks are also already included. A full working week is dedicated for the generation of each WLP.

For the Weekly Look-ahead Plan (WLP) development, which is again decentralized by all international partners and finally integrated in Houston, the Payload Operations and Integration Center (POIC) derives from the OOS a payload planning template, adds the communications resource availability, and ensures that the crew sleep cycle is adapted to the latest agreements. This template is used by all control centers to fine-tune their corresponding payload part of the week under consideration. Then the info is fed back to POIC who builds a preliminary payload WLP.

The preliminary payload Weekly Look-ahead Plan (WLP) is then further integrated with the system inputs from all partners by the planning team in Houston and finally results in an integrated preliminary Weekly Look-ahead Plan (WLP), which is available mid of the generation week. The remaining week is dedicated to discuss the preliminary product, to resolve any conflicts within the WLP, and to generate a

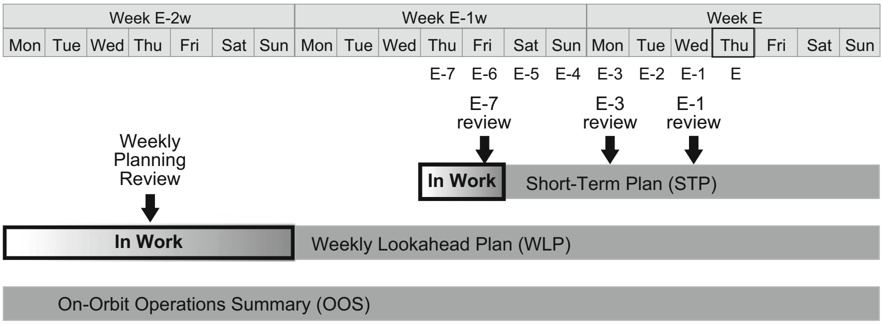


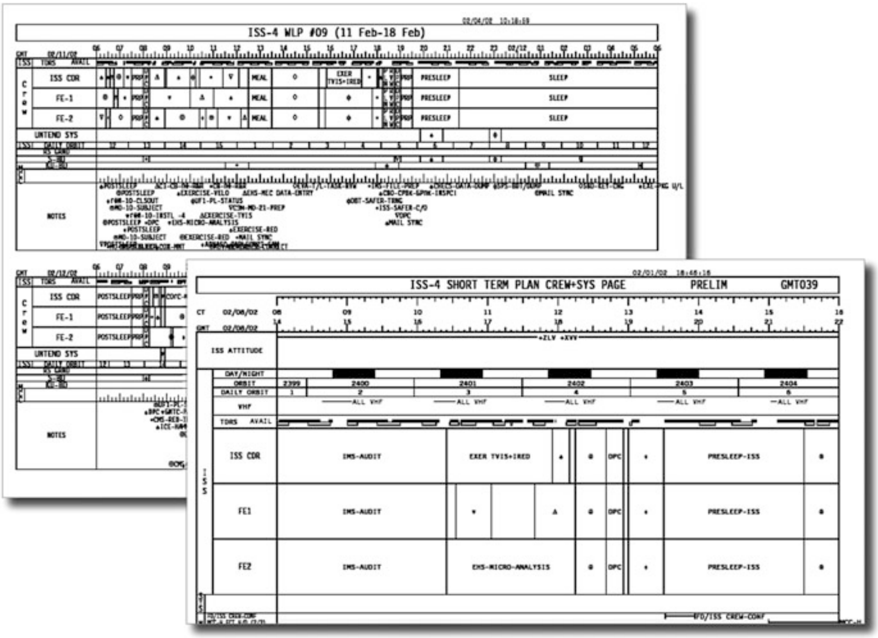
Fig. 5.26 The Execute planning phase is illustrated for a given increment day, the execution day E. A first version of the planned activities for that day is already contained in the OOS, which is prepared and approved prior to the increment start. Two weeks prior to day E the Weekly Lookahead Plan (WLP) for the corresponding week is prepared using the OOS as baseline, which contains already a more detailed schedule for E. From the WLP the STP is derived seven days in advance (E-7) and finalized at E-6. This product is reviewed by the console teams three more times ("E-7", "E-3" and "E-1"), before it is executed finally

final WLP, which is available on Friday. The formal approval of the planning product is due on Monday of the following week, during which already the translation of the WLP into the next planning product, the Short-Term Plan (STP), starts.

The WLP development phase is each week supported by regular telecons (International Execute Planning Telecon, IEPT) between all international planning teams on Monday (approval of last week's final WLP, discussion of first issues), Wednesday (discussion of preliminary WLP), Friday (discussion of final WLP) and the Weekly Plan Review (WPR), which is a high-level meeting which involves management, various increment lead functions, and the planning community.

The approved Weekly Look-ahead Plan (WLP) is in the following used to generate the Short-Term Plan (STP). Each day of the week a new development cycle for the day one week in advance is initiated: One separate day is extracted from the WLP one week prior (E-7) to execution; each partner generates its input for the STP and sends it to Huntsville and Houston. At the Payload Operations and Integration Center (POIC) in Huntsville, the payload part of the STP is integrated and then sent to Houston, where the final integration takes place. The preliminary, integrated STP is then compiled into the On-board Short-Term Plan (OSTP) format, which can be considered the executable version of the STP, and published via dedicated software, the OSTP Viewer (OSTPV), for a review of the flight control teams on console.

This review, also called "E-7", is conducted by all three console shifts and all change requests for the STP/OSTP are collected in an electronic document, called Flight Note. The planning team on Houston side then implements all changes requested by the Flight Controllers, which leads at E-6 to a final, integrated STP for the execution day E. Also this final plan is converted into an OSTP and published in OSTPV. At that time, the STP is considered consolidated and



ISS-4 WLP #09 (11 Feb-18 Feb)

ISS-4 SHORT TERM PLAN CREW+SYS PAGE PRELIM GMT039

Fig. 5.27 The level of detail in the Weekly Look-ahead Plan (WLP) and the Short-Term Plan (STP) are practically almost similar

approved—the actual planning work is completed for day E and the final product, the OSTP, was handed over to the Flight Control Teams and the astronauts for execution.

The Short-Term Plan (STPs) are also subject of discussion in the above-mentioned International Execute Planning Telecons (IEPT), which are conducted every other working day (Mon, Wed, Fri). The STPs for the weekends are usually easy to produce, since Saturday and Sunday are usually “crew off days”; thus they are developed together with the STP of the corresponding Friday.

For the time of a visiting vehicle launch and subsequent days the planners may decide to develop in addition to the nominal STP a dedicated slip STP, which is then put into effect when the launch and thus the docking with the station is delayed. This is usually only done if the launch slip is likely and if a slipped launch has significant impacts on the crew timeline.

The format of the Weekly Look-ahead Plan (WLP) and the Short-Term Plan (STP) is quite similar, as Fig. 5.27 suggests.

5.3.6.5 Real-Time Planning

For the flight control teams the first time they get to see the so-called timeline on console is the publication of the preliminary Short-Term Plan (STP) seven days in advance. The publication is done via the OSTP Viewer (OSTPV) and appears as

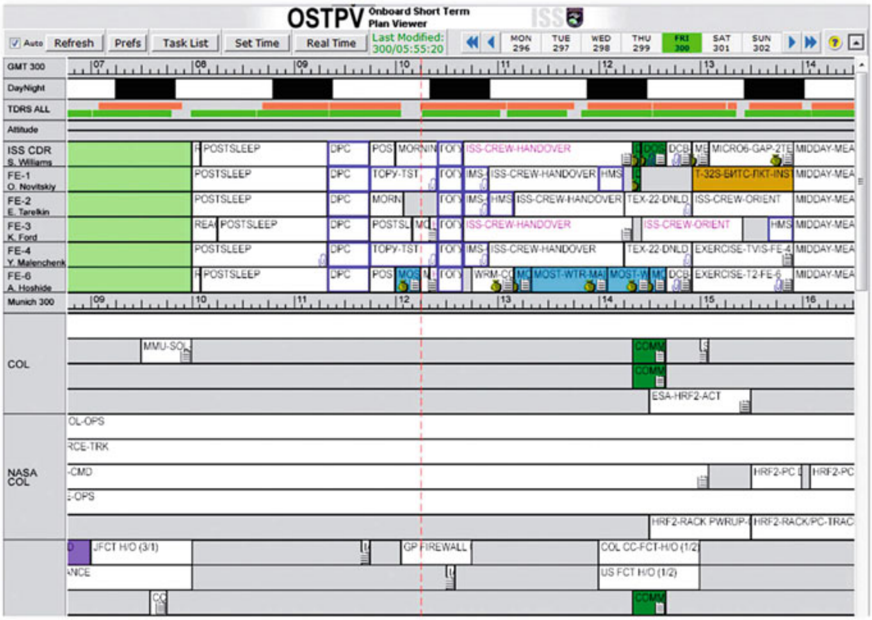


Fig. 5.28 The On-Board Short-Term Planning Viewer (OSTPV) displays the timeline on board as well as in the control rooms

shown in Fig. 5.28. As already described, the team performs a common “E-7” review of that STP and puts any change requests into a corresponding, dedicated Flight Note. The subsystem experts thus help to consolidate the final STP, which is then published in a corrected version on the subsequent day. The responsibility for the timeline is at that point also transferred from the long-range planners to the planning function within the flight control team.

As the execution of a given day comes closer, the flight control team performs two additional reviews of that timeline: The “E-3” review three days in advance and the “E-1” review the day before. The agreement for those timeline reviews foresees that only substantial errors with a potential major impact if not corrected can be subject of change. Should there be a need for a modification of the timeline a formal change request process is triggered, which requires the concurrence of all international partners.

Also outside of the formal reviews, changes to the timeline can be requested via this process, if e.g. the latest developments on board or any issues on ground would require an adaptation of the final, approved planning products.

Although the timeline is worked and optimized over weeks or even months and has passed various reviews, the astronauts still have a certain degree of freedom to deviate from the plans, as explained in Sect. 5.3.4.

The responsible control centers survey the activity execution of the crew and can, with respect to the timing, take appropriate measures in real time, in case the crew is not able to work the prepared timeline as planned. In this case the planning functions of the control centers work in the background on proposals how to reschedule the remaining crew day, to identify activities which can be postponed to another day or shifted to another crew member without impact, or—with the help of the corresponding Flight Director—to cancel planned activities with lower priorities.

5.3.7 Planning Tools

Being an international and distributed effort, the execute planning is highly dependent on computer and web-based tools which are used by the affected parties.

Some tools are used to collect the planning data, which is required to build the corresponding plans and schedules. Every ISS partner has currently its own processes and pieces of software, which reflect the requirements of their internal organization. Then the data is exported in a defined data format to a dedicated NASA tool called Consolidated Planning System (CPS), which is then used by the planners to generate the Weekly Look-ahead Plan (WLP) and the Short-Term Plan (STP).

When the On-board Short-Term Plan (OSTP) is ready to be published, the web-based OSTP Viewer software (OSTPV) is utilized which provides an easy-to-use and effective visualization of the schedule, and which is not only used by all ISS control centers, but also by the astronauts on board ISS (at least the non-Russian crew—Russian cosmonauts are required to execute the so-called Form 24, which is a tabular representation of the STP).

OSTPV allows not only a graphical representation of the schedule, but also access to the additional information, which is related with each activity, as shown in Fig. 5.20. The corresponding procedures are linked as well and can be opened by utilizing another piece of software, the International Procedure Viewer (IPV). The corresponding Stowage Notes, which list all tools and materials required for a crew procedure execution together with their stowage location, are also attached.

The process to change one of the approved planning products (WLP, STP) is also supported by a web-based tool, the Planning Product Change Request (PPCR) software. This interface grants all partners access to a “from to” form, which is used to provide all the info required to process the change request. The tool also provides a functionality which allows to seek formal concurrence of all international partners for the requested change.

The tools are currently under rework by NASA in an effort to generate a more integrated tool suite, include more automatization, and enhance the efficiency. Several years of ISS operations have resulted in many innovative ideas to improve the user interfaces, to better connect the various tools with each other, and to implement new functionalities.

5.3.8 Conclusion

Planning is a key element for mission success. Planning for human spaceflight missions is in many aspects comparable to the corresponding processes of unmanned missions, but also areas of significant differences exist. It is a manual and thus more process-oriented endeavor, whereas for unmanned missions also a high degree of automatization is possible, which requires a good mathematical modeling of the planning problem. The fact that no board computers but human beings are subject of the scheduling introduces an element, which requires also "men in the loop" for the various planning processes.

Acknowledgement The authors gratefully acknowledge the kind support of Hilde Stenuit and Eric Istasse of the ESA Mission Science Office, who contributed to this article with their knowledge about the strategic and tactical ISS planning phases.

References

References to Sect. 5.1

Axmann, R., Mühlbauer, P., Spörl, A., Turk, M., Föckersperger, S., Schmolke, J., Operations Concept and Challenges for 11 different Payloads on the TET-1 Mini-Satellite, 4S Symposium - Small Satellite Systems and Services 2010, Funchal, Madeira, Portugal.

Braun, A., Grace Mission Planning: Application of the Linear Programing Method to On-Board Memory Management, Proceedings of SpaceOps 2002.

Krieger, G., Moreira, A., Fiedler, H., Haynsek, I., Werner, M., Younis, M. and Zink, M. "TanDEM-X: A Satellite Formation For High-Resolution SAR Interferometry", IEEE Transactions on Geoscience and Remote Sensing, Vol. 45, Number 11, pp. 3317 -3341, November 2007.

Korte, B., Vygen, J., Combinatorial Optimization. Issue 3. Springer, 2005, ISBN 3-540-25684-9.

Lenzen, C., Wörle, M., Mrowka, F., Spörl, A., Klaehn, R., The Algorithm Assembly Set of Plato, SpaceOps 2012

Maurer, E., Mrowka, F., Braun, A., Geyer, M.P., Lenzen, C., Wasser, Y. and Wickler, M., "TerraSAR-X Mission Planning System: Automated Command Generation for Spacecraft Operations", IEEE Transactions on Geoscience and Remote Sensing, Vol. 48, Number 2, pp. 642 - 648, February 2010.

Reile, H., Lorenz, E., Terzibaschian, T., The FireBird Mission – A Scientific Mission for Earth Observation and Hot SpotDetection. Small Satellites for Earth Observation, Digest of the 9th International Symposium of the International Academy of Astronautics. Wissenschaft und Technik Verlag, 2013. ISBN 978-3-89685-574-9.

DLR RB-MIB "Planning Modelling Language", July 2010 – [cited 20.01.2014]. Available from http://www.dlr.de/rb/Portaldata/38/Resources/dokumente/gsoc_dokumente/mb/GSOC_Modelling_Language.pdf

References to Sect. 5.2

Mrowka F., Geyer M., Lenzen C., Spörl A., Göttfert T., Maurer E., Wickler M., Schättler B., "The Joint TerraSAR-X / TanDEM-X Mission Planning System" Symposium Proceedings, pp. 3971-3974. IGARSS 2011, July 24-29, 2011, Vancouver, Canada. ISBN 978-1-4577-1004-9.

Lenzen C., Wörle M. T., Mrowka F., Geyer M., Michael P., Klaehn R., "Automated Scheduling for TerraSAR-X/TanDEM-X". IWPSS 2011, 08-10 June 2011, Darmstadt, Germany.

Braun A., "Application of Linear Programming to On-Board Memory Management", SpaceOps 2002 Proceedings, AIAA DOI 10.2514/6.2002-T3-10

Herman J., Davis A., Chin K.B., Kinzler M., Scholz S., Steinhoff M., "Life with a weak Heart; Prolonging the Grace Mission despite degraded Batteries.", 12th International Conference on Space Operations (SpaceOps 2012), 11-15. June 2012, Stockholm, Sweden.

Krieger, G., Moreira, A., Fiedler, H., Haynsek, I., Werner, M., Younis, M. and Zink, M., "TanDEM-X: A Satellite Formation For High-Resolution SAR Interferometry", IEEE Transactions on Geoscience and Remote Sensing, Vol. 45, Number 11, pp. 3317 -3341, November 2007.

Tapley B. D., Bettadpur S., Watkins M., Reigber C.," The gravity recovery and climate experiment: Mission overview and early results", Geophys. Res. Lett., 31, L09607, doi:10.1029/2004GL019920.

Wille B., Wörle M. T., Lenzen C., "VAMOS – Verification of Autonomous Mission Planning On-board a Spacecraft", 19th IFAC Symposium on Automatic Control in Aerospace, 2.-6. Sep. 2013, Würzburg, Germany.

Wörle M. T., Lenzen C., "Ground Assisted Onboard Planning Autonomy with VAMOS", International Workshop for Planning and Scheduling in Space, March 25-26, 2013, Moffett Field, CA, USA

References to Sect. 5.3

Korth, D., LeBlanc, T.P., International Space Station Alpha Operations Planning. Proceedings of the International Workshop on Planning and Scheduling for Space, Houston, TX., 2002.

Kitmacher, G.H., Gerstenmaier, W.H., Bartoe, J.F., Mustachio, N., The international space station: A pathway to the future. Acta Astro 57: 594-603, 2005

Leuttgens, R., Volpp, J., Operations Planning for the International Space Station, ESA, ulletin 94, 1998.

Popov, A., Mission Planning on the International Space Station Program. Concepts and Systems. IEEEAC paper #1439, 2002.