EnMAP MPS: Challenges, Enhancements and Evaluations of the Early Mission Phase

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Abstract

On 1st of April 2022, the EnMAP mission launched. Its satellite carries a space-born hyper-spectral imager with a resolution of 30m, an image width of 30km and a maximum swath length of 1000km. The mission will provide the scientific community with data of the state and evolution of the earth's surface and in particular its eco-system. For instance, the vegetation of areas of interest and its conditions such as moisture and nutrition balance can be identified and monitored. After a brief summary of the most important Mission Planning relevant features of the EnMAP satellite and an overview of the EnMAP Mission Planning System (MPS), this paper comprises a wrap-up of the major challenges the EnMAP Mission Planning team has faced during the first months of EnMAP operations. By design, the EnMAP MPS is a fully automated system. It should have been directly phased in after the LEOP operations had finished. However, some assumptions of the satellite proved wrong, partly because of misunderstandings, partly due to mal-functions. The measures taken to cope with this situation, in particular the semi-automated mode in which the EnMAP MPS survived the first weeks, will be described in detail. The modifications of the Mission Planning System are described, which were necessary to cope with the unexpected limitations of the satellite, before activating the fully automated mode. Being the first mission based on GSOC's generic GSOC Reactive Planning framework, the EnMAP MPS had faced several teething troubles, in particular with respect to memory and runtime. This paper also addresses first experiences with the new "cloud component", which shall improve the collected data of optical missions. The paper also covers the challenges and benefit of the Back-to-Back-Imaging mode, which will allow merging two pictures into the same attitude maneuver, significantly reducing the minimum separation between two consecutive image acquisitions. We conclude with an outlook on how the system may be further enhanced and with lessons we learned during the first months of operations, pointing out what proved particularly helpful and what needs to be avoided or improved in future planning systems.

Keywords: EnMAP, Mission Planning, Reactive Planning

Acronyms/Abbreviations

Deutscher Wetterdienst - German Meteorological Office (DWD)
Environmental Mapping and Analysis Program (EnMAP)
German Space Operations Center (GSOC)
Launch and Early Orbit Phase (LEOP)
Mission Planning System (MPS)
Tele-command (TC)
Telemetry (TM)

1. Introduction

At the German Space Operations Center (GSOC), automated planning was first implemented for the Grace mission. Whereas the Grace planning system comprised a rather simple model for downloading telemetry data only, the combined planning system of the TerraSAR-X and TanDEM-X missions [1] required a highly complex planning model, using almost all features of the GSOC mission planning modeling language [2]. Even though setting up the TerraSAR-X/TanDEM-X planning system required great effort, in the long term, it proved not only fail-safe but also economic, as it has been running now for years without any interference except for extensions and adapting to the ageing of the satellites, see [3][4][5].

In the aftermath of the implementation phase of the TerraSAR-X/TanDEM-X and several other missions, we used our experiences and lessons-learnt to design an even better, generic fully automated planning framework, called

Reactive Planning (formerly known as Incremental Planning System [6]). Until now, we used this as the basis for the TDP-1 [7] as well as the EnMAP Mission Planning system[8][9].

In the following, we describe the major obstacles we faced during the EnMAP commissioning phase and the enhancements and extensions we implemented to resolve them. We also evaluate certain novel aspects of the EnMAP planning system after the first months of operations on how they affect the operators' user experience, the planning results and overall mission output.

2. The EnMAP Satellite and Instrument Characteristics relevant for Mission Planning

The EnMAP instrument consists of a push-broom sensor, which collects the different colors of the 1-dimensional scan line on a 2-dimensional sensor chip. Illumination depends on sunlight, which is why a Sun-sunchronous orbit with equator crossing time 11h (local) has been chosen, see [10]. Clouds block visibility, Sun-glint may disrupt the image when water surface is within the image. Some example pictures and data products are available online, like Fig. 1 and Fig. 2, see EnMAP Image Gallery at [11]. The instrument calibration is performed either by internal procedures or by observing a dark region of the sky, or by observing the Sun through a dedicated filter, see [12].

The instrument is mounted on the satellite bus in a fix position, which means that the whole bus has to turn to point the camera to the target. Similarly, the X-band antenna needs to be pointed to the ground station during a downlink pass. Between two such attitude maneuvers, the solar panels are pointed to the Sun, which implies an image acquisition and downlink preparation time of about five minutes. Since EnMAP's sensor is a push-broom sensor, observations take place while the satellite passes the target area: the scan-line is always orthogonal to the satellite's flight direction. Standard observations specify a center coordinate and the image size. The center coordinate determines the constant roll angle during the observation, which must lie between -30° and +30°, and the acquisition's start and end are derived from the image size.

To assure that the satellite keeps this looking angle, it must be provided with a time series of quaternions, which specify the desired target orientation during the data acquisition. The calculation of the GuidanceList is done by a dedicated tool which is provided by our Flight Dynamics team as a microservice.

The design of the satellite, the instrument and the ground station scenario require a vast amount of flexibility of the planning model. Currently we have about 400 simple parameters in addition to further constraint parameters, which are also part of the EnMAP configuration. Propagation of onboard resources, in particular of memory and power, is also crucial for seamless and safe, yet productive operations of the satellite. The use of GSOC's planning library Plains (see [13]) was therefore never questioned.

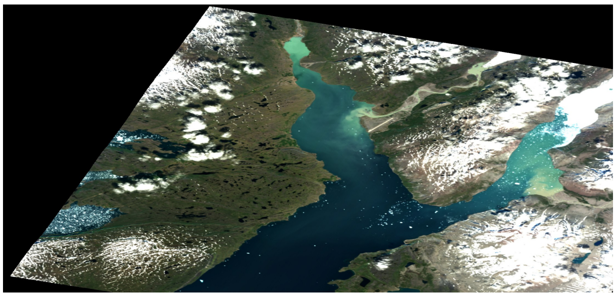

Fig. 1 Narsarsuaq, Greenland, 2022-06-22

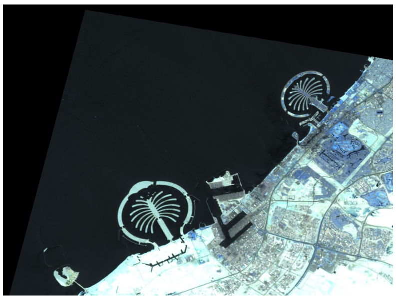

Fig. 2 Palm Islands, UAE, 2022-06-12, false-color

3. The EnMAP Mission Planning System

To provide the best possible service for the user community and the operations team, the EnMAP Mission Planning System is based upon GSOC's generic Reactive Planning framework and as such continuously collects new input and applies each input immediately. Thus, the user (payload data requesters as well as satellite operators) always can obtain an up-to-date view of the planned timeline and new requests may be considered even shortly before the uplink passage, because no full planning run is required before the respective command export, see [6][8][9].

To reduce the complexity of the different parts of the system and to limit effects of malfunctions, we split up the functionality into different components, see Fig. 3: The MasterProcessor maintains the planning model and the master timeline. It persists its state via event sourcing ([14]), other components which need access to the model receive a replicate of these events and thus stay up-to-date. The TimelineManager keeps track of the commands onboard the satellite and exports the commands for an upcoming uplink passage. The Timer is the only component to access the real-time; it triggers command exports for upcoming uplink passages and other time-dependent activities such as saving snapshots at midnight. The StatusReporter notifies interface partners about any changed status (e.g. of requests or planned data transmission), it provides a health report for monitoring the consistency of the model and it exports snapshots and patches which can be transported over network boundaries so they can be collected by PintaOnWeb ([15]), which allows for inspecting the timeline and the model via web-browser outside the control room. SCOTA provides orbit calculation functionalities, for which it can use a standard two line element or the high precision orbit provided by GSOC's Flight Dynamics system, see [16]. The InputManager collects and sorts all input and forwards them to the MasterProcessor one after another. During maintenance phases, the InputManager may also withhold input until the maintenance is completed. Further components connect the EnMAP MPS to the various interfaces, see [8][9][17].

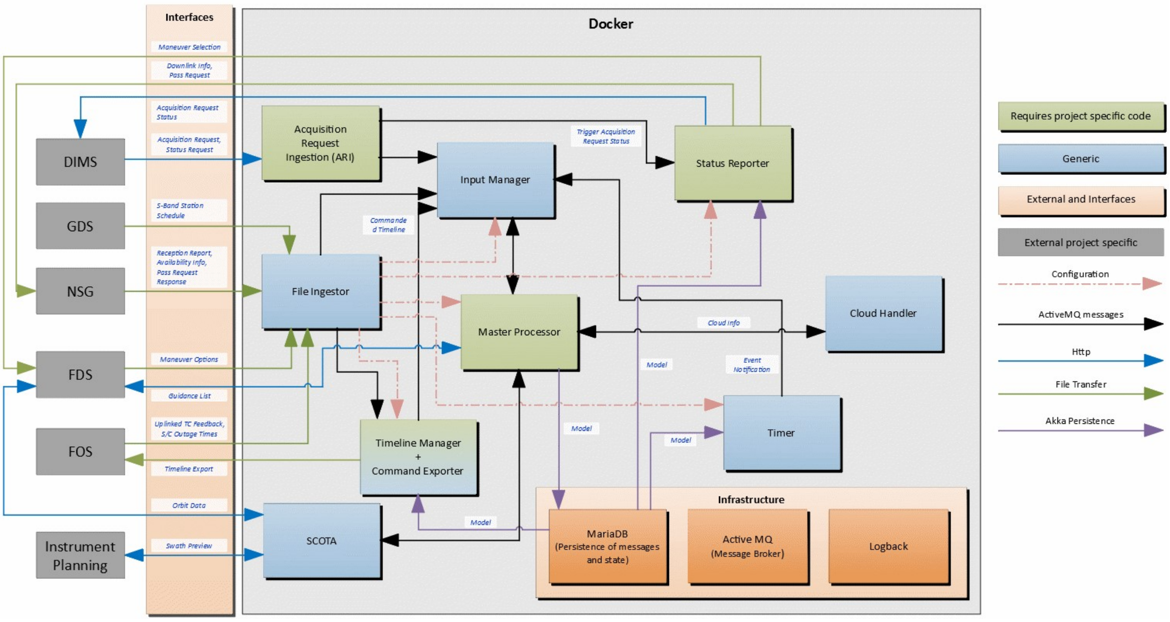

Fig. 3 Overview of the EnMAP MPS and its interfaces

4. Adaptations of the Planning System during the first months of operations

Although the EnMAP mission experienced a decade long delay, some relevant information and new requirements were available only late during the implementation phase. Together with the additional effort of introducing new technologies, it was therefore no surprise that unexpected issues and further novel requirements arose also during the commissioning phase. In this chapter, we describe the most significant ones and how we managed to resolve them, together with other improvements, which solve major issues of the early EnMAP planning system.

4.1 Performance: Memory Consumption

During the first months of operations, we observed a rather unhealthy increase in RAM consumption of our Reactive Planning system. Although we started working on this issue immediately, we failed to avoid an out-of-memory exception within one of the components when activating the sliding window of the thermal model, see 4.3. Fortunately, our IT department was able to increase the RAM of our virtual server by 50% within an hour, allowing us to resume operations without having to roll back our planning system. For a long term solution however, the following topics had and partly still have to be addressed:

a) The most obvious topic is that a planning system needs to clear its history. This has been part of the design of the EnMAP planning system from the beginning, however it depends on our interface partners to signal completion of a request: only when we are told to close a request, we know that no further messages, such as status requests, will be sent for this request and only then are we allowed to actually remove the request and its datatakes from the planning model. During the commissioning phase however, when all systems were still phasing in, loads of 'forgotten' requests have remained in our system. These have to be identified in collaboration with the interface partner and deleted.

b) The Reactive Planning framework is split into multiple components, which are designed to be able to run independently. This allows separating the vital services from the less important ones by running them in different Docker containers and assigning them a different memory quota. While this approach saved our system from a major contingency during the out-of-memory event, it also caused it in the first place because the current state of the model is stored in four different components. It remains an open question whether we will unify some or all of these components to work on a shared memory or live with a 4-fold memory consumption with the benefit to be warned in time before the core components crash.

c) The planning model is persisted using patches, which describe how the model changes from the state before processing a message to the state thereafter. To reduce the implementation effort, we initially chose a json format to persist such a patch. This however requires a 4-fold memory allocation during the process of persisting and loading data. This would not be an issue if only patches were stored. However, we also have to store complete snapshots, which allow restoring the current state of a component without having to apply all patches since the start of the mission. These snapshots contain the whole model and therefore such a high memory allocation should be avoided. We therefore implemented a binary serialization which reduces this memory allocation drastically to about 1/3 of the json serialization.

d) Currently, we store all information which is required for commanding in the planning model, even if no constraints refer to it. One such information are the GuidanceLists, which contain a time series of quaternions, describing the target orientation of the satellite during image acquisition or X-band downlink. Whenever the algorithm tries to plan an image acquisition or a downlink, it must request the GuidanceList for this operation, because one result might be a rejection due to a potential Sun blinding during the trajectory. On the other hand, the GuidanceList is required for commanding and thus has to be inserted into the export of mission planning, so it is currently stored as a compressed string parameter of the respective activity. It turned out that half of the model consists of such GuidanceLists. Our next step therefore will be to save only a reference to the GuidanceList and store the GuidanceList itself within an external database, from which it can be retrieved when generating the command file.

4.2 Performance: Runtime

One of the benefits of processing each input individually is, that in this case the algorithm usually has only a few calculations to process; however, there exist exceptions. An example for an intrinsically long-running algorithm is the orbit update, due to which each planned acquisition needs to be updated and re-propagated. This has been solved by triggering it preferably at night when no new requests are expected. Other aspects however afforded and afford more effort, such as planning of orbit maneuvers, which usually come as a bunch of about ten alternatives. In the beginning, we used to calculate solutions for all alternatives, where each calculation included the search for alternative opportunities of blocked image and calibration acquisitions, which themselves may have conflicting acquisitions of lower benefit, which therefore need to be replaced or removed. We improved this by sorting these alternatives according to the benefits of conflicting acquisitions and calculating the result only for the best three solutions. Planning of calibration requests, which usually have a significant flexibility in start time, is also much more complex than planning a ground observation, for which only one or a few alternative opportunities with fix start- and end-times exist. This is not directly a problem when receiving a new calibration request, but when repeatedly re-planning multiple existing calibration requests e.g. due to an orbit maneuver request, this can accumulate to a real problem. We have already implemented several improvements, such as delaying the calculation of GuidanceLists; we also implemented a binary search on the number of to-be-unplanned conflicting acquisitions, because un-planning an opponent is much faster than testing whether the calibration can be planned. Nevertheless, there still remains work to do in this area.

4.3 Satellite Thermal Issues

Before powering up the EnMAP instrument, multiple heat pipes should have been activated. One of them however failed, invalidating the thermal analysis which showed that nominal operations would not have exceeded thermal limits of the instrument.

To cope with this situation on short notice, we introduced the concept of semi-automatic planning: Instead of ingesting all input upon reception, we collected acquisition requests within our InputManager. Usually this component withholds new input only as long as a preceding calculation is still ongoing. However, it is also possible to configure it such that all messages of a specified type are blocked until the configuration is adapted, and then all messages are forwarded one after another. We used this feature to block all acquisition requests. Only at pre-defined times, usually twice a week, we re-configured our system temporarily to let pass the collected acquisition requests. After closing our system again, we manually checked the timeline whether only those requests have been planned which were agreed upon previously by the operations team and the ground system manager. If surplus acquisitions were planned, these would have been canceled and removed from the timeline before commanding them to the spacecraft. This way the operations team was able to slowly increase the load on the instrument, allowing to collect sufficient data for a detailed analysis about how much instrument-on time is possible and how much time to cool-down is required.

This data has been used to add a new constraint to the planning model: during any time window of size 100 minutes, the detector must not be on for longer than 40 minutes. Such a constraint is called ‘sliding window‘, and is a configurable standard constraint in GSOC’s planning model. Afterwards, we could re-configure the InputManager to let pass all acquisition requests at all times, resuming the fully automated planning.

4.4 Satellite Eclipse End Intervals

When performing a ground observation or an X-band downlink, the satellite needs to switch to the so-called precise mode which allows turning the satellite such that the instrument, resp. the downlink antenna, are pointing in the desired direction. When starting this procedure, a check is performed whether the battery is sufficiently charged to afford such a maneuver. During the first months of operation however, it turned out that this check yields a false negative within the first five minutes after the solar panels had returned to Sun-pointing, e.g. after an eclipse or a preceding precise mode, because the voltage recovered to the expected in-Sun orientation values only with a temporal delay. To solve this issue for the case where we exit an eclipse, we introduced a mechanism which brings forward only the time tag of the procedure to start already during the eclipse. This way, the check is performed during eclipse when a lower voltage is expected and thus the check is passed. In addition to this mechanism, a constraint had to be added which avoids an overlap with a preceding activity that might be planned at this time. We also added constraints which assure that no downlink is planned closer than 360 seconds after a ground observation or another downlink in order to make sure that downlinks succeed in any case. For acquisitions, we did not introduce such a constraint, because there still exists a good chance that the power check succeeds even if a preceding acquisition or downlink turned the solar panels partly out of the Sun, so it was decided to take the risk of losing an expected acquisition. For downlinks in contrast, we would have risked already acquired data together with the orbit data transmitted alongside, which would have been too important.

4.5 Downlink after Orbit Maneuver

For satellite-specific reasons, S-band data are not sufficient for precise orbit propagation. Therefore, the operational concept includes a regular X-band downlink, where extended orbit data are available. Previously, it was assumed that these are sufficient, but with the first operational experiences it was decided to extend this feature by forcing an X-band downlink during the first ground station passage after each orbit maneuver. Only, by implementing this additional feature, we ensured that subsequent collision avoidance can be properly supported in case a maneuver failed.

4.6 Introduction of an additional Ground Station

Initially, the project defined a strict ground station concept: Weilheim for S-Band (TM/TC) and Neustrelitz for X-band downlink (payload data and extended housekeeping). As downlink capacity is a limiting factor for the EnMAP mission, the project requested to add up to two passes per day over Inuvik, where DLR maintains another antenna. Unfortunately, there exist days where all EnMAP-Inuvik passes are blocked by TerraSAR-X/TanDEM-X or Sentinel 5P, we therefore relaxed this constraint to 14 passes per week. As for including Inuvik into the downlink planning, several interfaces are different or have to be served differently in comparison to those with Neustrelitz. We are still in the process of realizing this mission extension.

4.7 Back-to-Back Imaging

The EnMAP satellite requires more than five minutes preparation time for a ground observation. Most of this time is required to acquire the target orientation. Obviously, this restricts the capabilities to acquire data over geographically close areas of interest. In particular, during one pass over Europe usually not more than two observations over areas of interest are possible. To overcome this restriction, it shall be possible to merge the precise mode phases of two ground observations into one, allowing for a significant reduction of the preparation time of the second ground observation. Here again, the GuidanceList generator, which provides the time series of target orientations for the satellite, must remain in the loop of planning, because each GuidanceList must be checked for

Sun blinding events which must be avoided for the sake of instrument safety. A detailed analysis will be required to determine the duration for turning from the end orientation of the preceding image acquisition to the start orientation of the succeeding one. Subsequently, also the propagation of the power consumption will have to be adapted. In summary, this new feature will mean the largest modification of the planning system after launch.

5. Evaluation of Reactiveness

One of the main improvements of Reactive Planning [6] is that one can observe modifications to the planning model and the timeline immediately after new information has been ingested. This feature initially was intended for missions like TerraSAR-X, where customers may want to react when their request is blocked, e.g. by requesting an alternative acquisition, or want to request ad-hoc uplink contacts. However, this feature proved equally helpful during the EnMAP commissioning phase, where manually reacting on un-foreseen events was required, because when manually interacting with a complex planning system, one tends to overlook details. In particular in combination with PintaOnWeb ([15]), which displays the planning model and the timeline, we were able to immediately observe the result of a model manipulation therefore provides the possibility to correct mistakes before the succeeding command export, possibly saving a whole passage for ongoing operations.

One example was when we were asked to merge uplink sessions in order to allow for more preparation time for the Flight Operations system: The planning model already contained a parameter which allows merging multiple uplink passages of consecutive orbits to one uplink session. If configured this way, the command export takes place before the first uplink passage, but the first commands included in this export are to be executed only after the last uplink passage, which means that the Flight Operations System has much more time to prepare and uplink the commands of the exported timeline. This update had to be performed during two uplink passages of consecutive orbits, leaving only little time to implement this change. In order not to be disturbed during the re-configuration, we started with blocking all input, except for the model manipulation message, via configuration of our InputManager (see 4.3). We sent the re-configuration message and could immediately verify that the parameter had been modified. For the change to be reflected in the timeline, we also had to re-ingest the message containing the uplink station availabilities. This message however had been blocked with all the other external messages. When realizing why the timeline hadn't been updated as expected, the command export for the upcoming uplink had already been triggered by the Timer component. Usually the command export trigger interrupts any ongoing calculation and `overtakes` all other pending messages. In this case however, it had been blocked and buffered, so we were able to re-configure the InputManager to let pass only the uplink availabilities first, which then updated the timeline correctly, before we let pass all other messages, including the command export trigger, which then correctly caused the timeline to be exported until the end of the succeeding uplink session, which - according to our re-configuration - was the end of the next but one uplink passage.

These benefits however had come at the cost of quite some additional implementation effort. An algorithm which starts planning from scratch, such as the one used for TerraSAR-X/TanDEM-X, usually ingests all input in a proper order, e.g. starting with Flight Dynamics events, such as ground station contact times, thereafter loading the commanded timeline and then trying to plan one acquisition after another in descending order of their benefits. A complex algorithm therefore is only required for planning an acquisition. The reactive approach however requires a timeline update algorithm for each type of input, because, no matter which input is received, the timeline already contains planned acquisitions, which may need to be moved or even removed, and therefore other acquisitions may need to be checked whether they can now be planned. Such incremental planning algorithms may result in cascading effects, which must be avoided for reasons of runtime performance. For EnMAP, we also chose an increase in benefit for already planned acquisitions to avoid a frequently alternating selection of sets of acquisitions, since one goal of Reactive Planning is to provide a reliable preview of the upcoming timeline. Such details may not be very demanding by themselves, however the amount of these details and the complexity introduced by their combination required a lot of work.

6. CloudComponent

In contrast to the radar payloads of the TerraSAR-X/TanDEM-X missions, the instrument used within the EnMAP mission cannot look through clouds. We therefore implemented the new CloudComponent [8], which retrieves the latest forecast data [18] from the German Meteorological Office (DWD). In addition to the latest forecast, the CloudComponent also has access to the statistical cloud coverage [19].

Every six hours, the CloudComponent receives new data from the DWD. When the data has been ingested, it sends a message to the EnMAP Mission Planning System, which in turn invokes the CloudComponent's service functions to update the benefits of all currently planned and not planned image acquisitions within the newly covered time window. This window starts roughly 30h in the future and covers exactly 6h. For acquisitions which are expected to be clouded by more than the fraction specified in the request, the benefit is reduced significantly, which means that the respective acquisition will only be planned if no conflict exists with another acquisition which has a better estimation. For acquisitions which are ingested on short notice and for which the cloud forecast is already available, the cloud prediction will be considered immediately upon ingestion.

We activated the CloudComponent after three months. Unfortunately, the effectiveness of the CloudComponent could not yet be analyzed, because insufficient data was available at the time of writing this paper: during the commissioning phase, acquisition requests have been sent in a coordinated way, only very few conflicts between acquisitions existed and therefore adapting the benefit of the acquisitions did not influence the timeline. Even after the nominal end of the commissioning phase, the number of requests unfortunately has not been sufficient yet to provoke conflicts which would have had to be resolved using the benefit concept.

7. Conclusion

Together with the TDP-1 mission, EnMAP has been the first mission to build its Mission Planning System upon the new ReactivePlanning framework. The main benefit for the EnMAP mission is that the timeline is always up-to-date and all changes are immediately visible after ingestion of the respective message. Another benefit is that input may be sent up to 45 minutes before the uplink passage and that even failed uplinks are part of the automated workflows and do not need manual interaction.

The complexity of the required algorithms however increased, compared to a system like the TerraSAR-X/TanDEM-X planning system, which generates each timeline from scratch. Whereas the latter may arrange input in a suitable order and thus may rely on certain scenarios for each input type, with a reactive planning approach, for each input type one has to cover all possible states of the model and timeline. Special effort must therefore be given to identify common sub-algorithms and to implement them in a sufficiently generic way such that they can be applied in all different planning scenarios in order to keep the overall complexity limited. Besides, with planning from scratch, updates of the planning model are no cause of concern, because the model is merely re-generated within each planning run. With a reactive approach however, in addition to adapting the way new model objects are generated, also existing model objects have to updated.

In general, one cannot say that a reactive approach is always the better choice, because it usually requires more implementation effort as soon as prioritization requirments and cross dependencies between different model objects exist, which of course is always to be expected for our missions. For this reason, the refactored TDP-1 MPS still executes its planning from scratch twice a day, instead of continuously reacting on new input, even though it uses the Reactive Planning framework as core planning library. Nevertheless, for both, users and operators, maintaining an up-to-date model provides great benefits, which should be worth the effort for most missions.

Being inspired from its predecessor planning software Pinta and the planning library Plato ([13][20]), the planning model of the Reactive Planning framework was already fully elaborated. Adapting the model to new requirements was therefore never a big deal. In contrast to this, many aspects of the overall planning algorithm have been new. On the one hand, we have mission-specific features, such as including the generation of a GuidanceList into our algorithm or planning X-band downlinks without having payload data, in order to provide extended housekeeping data. Such mission-specific requirements will exist with every new mission. On the other hand, we faced challenges with respect to new technologies (functional programming, multithreading via actor systems, persistence) and the reactiveness of the planning system. Adapting the algorithm therefore required much more effort, but led to many generic improvements to the Reactive Planning framework incl. Plains. Other missions may now benefit from these efforts, the first one being TDP-1, whose migration to the Reactive Planning framework started shortly after the first versions of the EnMAP MPS were finalized. In addition, the experiences with EnMAP will allow better evaluating how an upcoming mission would benefit from the reactive approach and how much implementation effort will be required for such a reactive MPS, when starting with the EnMAP MPS as the blueprint.

Besides EnMAP MPS being GSOC's first reactive MPS, another major challenge we faced even more than with other missions was, that some of the final requirements for EnMAP were only identified late during the implementation phase or even after launch, which made it difficult to maintain a clear overall design for the planning algorithm, in particular when adaptations had to be implemented under time pressure. To maintain the high quality of our service, we relied on thorough code review and on an extensive test suite, which covers all different types of input and all issues which have been encountered during operations. This test suite is automatically run whenever new code is merged into the EnMAP MPS. Finally, the implementation of the feature 'Back to Back Imaging' and several other remaining issues will show whether our system has remained sufficiently maintainable even for major extensions.

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