VAMOS – Verification of Autonomous Mission Planning On-board a Spacecraft

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Abstract: For typical ground based mission planning systems for low earth satellite missions one major drawback can be detected: The reaction time to on-board-detected events, which includes at least two ground station contacts. To correct this, the DLR/GSOC invented VAMOS, which is an autonomous concept of minimized on-board complexity which allows on-board reaction to telemetry measurements and event detection. This experiment will be part of the FireBIRD mission and verify the gain when mission planning autonomy is transferred to the spacecraft up to some extent. This paper presents the outcome of the design phase under the given constraints. In order to minimize risks and computational effort on-board, a solution has been chosen that demands relatively simple tasks of the on-board autonomy but nevertheless will lead to maximizing the mission output and on the other hand takes care of all potentially to be considered resource constraints.

Keywords: autonomous mission planning, mission control and operations, onboard autonomy, NRT spacecraft commanding

1. INTRODUCTION

The Verification of Autonomous Mission Planning On-board a Spacecraft (VAMOS) is a GSOC prepared experiment which will take place as a part of the FireBIRD mission. VAMOS will be used to schedule and (re-)command tasks. Its on-board software will be part of the BIROS satellite, but it is necessary to prepare an on-ground component embedded in the FireBIRD mission planning system which will be operated by DLR/GSOC as well.

DLR/GSOC colleagues developed an approach to raise the mission gain by using results of cloud detection and image compression algorithms to enable additional acquisitions (see [Axmann, Wickler, 2006] or [Axmann, 2010]). However, the ideas couldn't be tested then in space for some reasons, whereas VAMOS includes this functionality to prove its applicability in space. VAMOS merges the computation power necessary for complex propagations and calculations that is so far only given on-ground and the quick reaction time to on-board detected events enabling additional acquisitions of areas of interest which could only be provided by an on-board system. Furthermore only an on-board scheduler has the chance to react on real telemetry values and decide whether to activate another image acquisition.

2. THE FIREBIRD MISSION

The FireBIRD mission consists of the two constructed DLR spacecraft TET-1 and BIROS. The main task of this mission is the detection and monitoring of so called high temperature events (HTE), e.g. forest fires or other hot spots.

Both satellites base on the bus of BIRD and carry a camera system with a bi-spectral infrared hot spot recognition sensor system and a three-channel optical sensor as multifunctional camera as their main instrument for this mission. Images with a highly improved resolution compared to other currently orbiting fire monitoring systems will be the result of this combination. The camera system was developed by the Berlin DLR institute for optical information systems and shall also be used for other scientific earth observation tasks. For details see [Ruecker et al.].

TET-1 (an abbreviation for the German expression: "Technologieerprobungsträger 1", which means a carrier for proving new technologies) was successfully launched on July 22nd 2012. Currently its main task is testing of industrial and scientific experimental payloads and spacecraft technologies in the On-Orbit Verification (OOV) program of DLR. The infrared camera system will become main payload beginning with TET-1's second year of operations which will be the start of the FireBIRD mission.

BIROS (Berlin InfraRed Optical System) is planned to be launched in 2014 and belongs to FireBIRD from the beginning. Further experiments will also be carried by BIROS in order to increase the overall mission gain.

VAMOS will be part of the payload processing unit (PPU) of BIROS with its operating system RODOS (see [RODOS links]). RODOS assures real-time execution of VAMOS' processing cycle, provided the software does not exceed its calculation budget. This leads to the restriction that on-board calculation complexity has to be hold at a minimum level, which matches the general desire to reduce code complexity for on-board software. As part of the PPU software VAMOS can only be updated as part of a complete PPU software upload. To avoid this, the software must be well-prepared, integrated and tested on ground. If possible, the BIROS engineering model or even the flight model will be used for testing VAMOS before launch.

3. BENEFITS AND DRAWBACKS OF ON-BOARD MISSION PLANNING SYSTEMS

Between two ground station contacts a low earth orbiting satellite cannot be commanded and surveyed. Therefore its tasks are planned in fix timelines whose execution times will start some time after the uplink and whose content will not be modified until a new timeline is uploaded. However actions due to unforeseen events are subject to a short reaction time. If a near-real-time task of the same area shall take place, e.g. in case of fire detection or high cloud coverage, an only ground based planner cannot react quickly enough. Additionally a hot spot detection mission can delete all images without a detected fire, e.g. forest fire, active volcano etc., but no improvement is achieved unless further images are taken which use this ‘unexpected’ free memory. A further drawback of a purely ground based scheduling system results from the prediction of resources: an on-ground scheduler has to calculate with a worst-case scenario for the resource consumption, e.g. the battery state/gain of solar arrays, the level of memory usage, or the thermal state of the spacecraft. Thus tasks of lower priority may remain unplanned although the resources are available, because this is not visible to the scheduling system until the next downlink. For all aforesaid reasons the mission output can be improved with an on-board planner. This system will be able to consider image evaluations, survey telemetry and will decide, based on this information, whether an additional image (of lower priority) can be taken.

On the other hand some characteristics of on-board autonomy can be seen as a drawback to the spacecraft or its environment. In general a fully deterministic and predictable behaviour of the spacecraft is excluded, besides autonomy is subjected to further restrictions. For reasons of functionality, the autonomous system has to assure that a task of lower priority cannot block those of higher priority. So the challenge is to plan new commands for further images, while assuring that they fit into the existing timeline and stay within the given constraints. One further challenge is the limited on-board computation resource, so the autonomy may not become a complex system. Besides, autonomy is often seen as an additional risk for spacecraft health rather than an improvement for the mission output. In contrast to a ground-based system the on-board planner cannot be permanently monitored and the reaction to problems (including their detection) is much more complicated than within a ground-based system where a direct human intervention is possible. To assure a stable on-board system and to keep the risk introduced by the on-board autonomy low VAMOS must comply with the described restrictions.

An example will illustrate a possible use case for on-board planning: Suppose the image of an optical sensor in an area of interest fails. For an only ground-based planner it is impossible to react adequately and quickly and to initiate a new image acquisition in the next orbit. Customary systems only allow the data evaluation on ground so that a new image can be acquired at the earliest after two ground station contacts, but then the spacecraft is no longer in a position to take an image of the area of interest (due to low earth orbit mechanics).

4. VAMOS

Due to the restriction of minimum on-board complexity the VAMOS functionalities have to be split up. The more complex calculations like resource propagation have to stay on-ground and only the results are partly uploaded via tele-commands. Furthermore it is necessary to differentiate between the activation of pre-commanded timeline extensions (OBoTiS) and the generation of new timeline alternatives and their respective telemetry checks from command templates (OBETTE).

4.1 OBoTiS (On-Board Timeline Selection)

The On-Board Timeline Selection (OBoTiS) permits a decision based on comparison of the actual telemetry values with on-ground calculated thresholds. In case all respective telemetry values for a given timeline extension lie within the specified limits, this timeline extension can be activated and executed. This approach allows the maximum use of existing resources such as satellite memory, thermal state or battery capacity/gain of solar array without the need of a perfect on-ground propagation. The following graphs exemplarily show the functionality of OBoTiS:

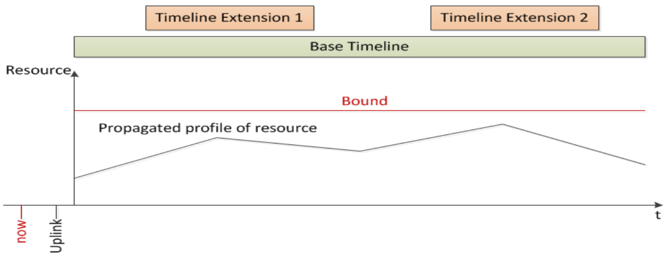

Fig.1: Ground prepared timeline and propagated profile of respective resource

First a base timeline and the corresponding propagated resource states are commanded via uplink to the satellite. Additionally two timeline extensions 1 and 2 are prepared and uplinked, each of which consists of

- a set of tele-commands representing an additional image acquisition
- a time frame when the satellite is affected by this image acquisition, the so-called timeline envelopes
- a set of telemetry checks, and their execution time, which supply the information how much on-board resources shall be available in order to be allowed to activate the timeline extension

These timeline extensions can be identified by their unique timeline ID and are yet deactivated.

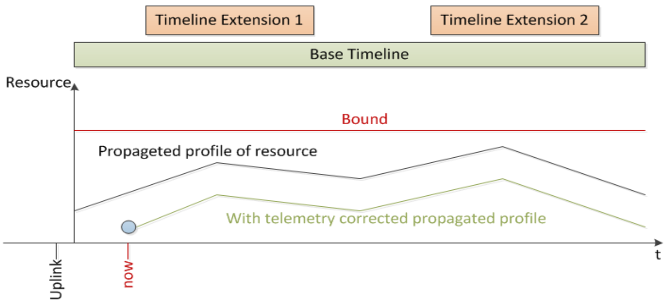

Fig. 2: Comparison of true and propagated value at decision time

At decision time of timeline extension 1 (a predefined time shortly before the first command of timeline extension 1 would be executed) the current state is read from the telemetry values. In this example the current value lies sufficiently far below the propagated profile thus enabling activation of Timeline Extension 1, because the propagation of the on-ground planner would show the following resource profile:

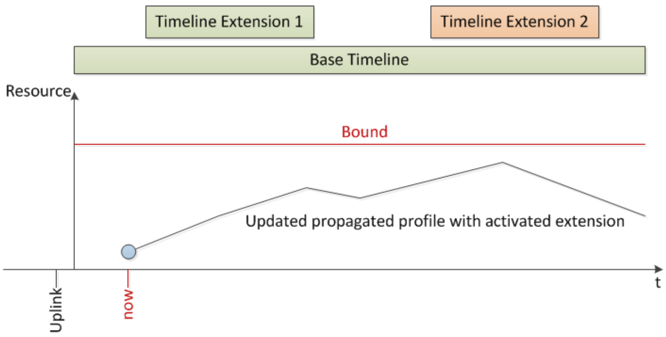

Fig. 3: Activation of first timeline alternative with new propagation of respective resource profile

For OBoTiS there is no need to perform complex profile calculations on-board as long as Timeline Extension 1 is given the correct telemetry threshold, which is the maximum value the resource may have at decision time without causing a conflict in the updated propagated profile. Therefore these calculation steps are performed on-ground and only the thresholds are commanded during ground station contacts (see OBoTiS On-Ground Add-on). Note that the telemetry threshold assures that all activities of the Base Timeline may be executed when activating timeline extension 1.

Priorities

A common heuristic for on-ground schedulers to support priorities is, to consider all planning requests one by one in descending order of their priorities and to try to include them into the timeline. This approach can't be taken over directly by OBoTiS, because the order in which the timeline extensions are considered is determined by their execution time. Considering the on-ground algorithm, we choose this approach because it prevents us from scheduling a planning request, which consumes resources a planning request of greater priority requires. So the point is not to schedule the planning requests in the correct temporal order but always to consider the resource consumptions of the planning requests of greater priority.

Within OBoTiS priorities can therefore be reflected by the base timeline which is used for calculating the telemetry thresholds of a timeline extension. As described in the OBoTiS Add-On section, the on-ground scheduler processes the planning requests in order of their priorities, but it (almost) always keeps the scheduled requests inside the base timeline when considering the next one. This means that the base timeline for a planning request of given priority contains the resource consumptions of all requests of greater priority. Especially all future timeline extensions are included and reflected by the respective propagated profiles. The calculated telemetry thresholds therefore assure that in case this timeline extension is activated, all future timeline extensions of greater priority may be executed with respect to resource consumptions, too.

4.2 OBETTE (On-board Event Triggered Timeline Extension)

The On-board Event Triggered Timeline Extension (OBETTE) reacts to on-board events by creating further Timeline Extensions, whose activation is then within the responsibility of OBoTiS. Such an event could be an evaluated and deleted image of bad quality but high priority and is triggered by another spacecraft component. OBETTE will then derive a Timeline Extension of the same target, e.g. one orbit later with adapted looking angle, and extract the necessary parameters like timestamp for the to be added commands and looking angle from this event. More general, when receiving an event, OBETTE selects a pre-configured template according to the type of the event and derives commands and telemetry thresholds from this template by filling in values which it derives from the event's parameters. This way one can assure that the on-board generated timeline extension follows a safe pattern.

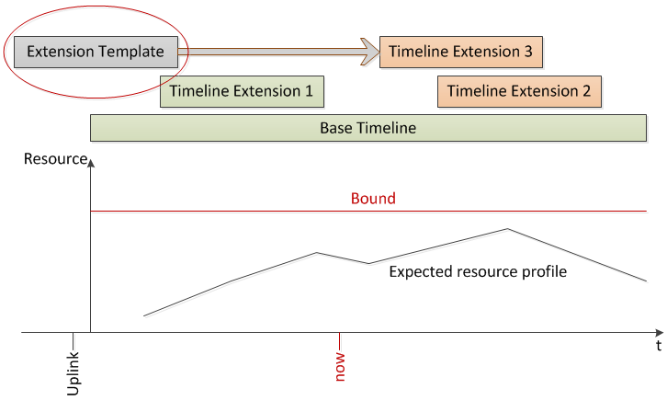

Fig. 4: Creation of a new timeline extension

As shown in Figure 4 OBETTE creates Timeline Extension 3 from the pre-configured extension template. In chapter *4.4 OBETTE On-Ground Add-On* we will see that this step requires no profile calculation on-board other than evaluating a profile at a certain point in time.

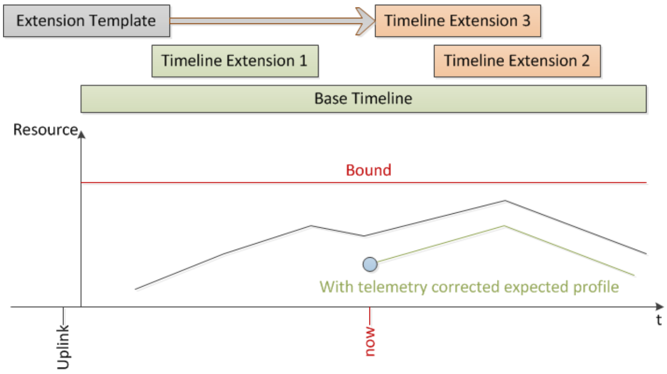

Fig. 5: Creation of a telemetry check for new timeline extension 3

When reaching its decision time, OBoTiS checks whether the generated timeline extension 3 can be activated.

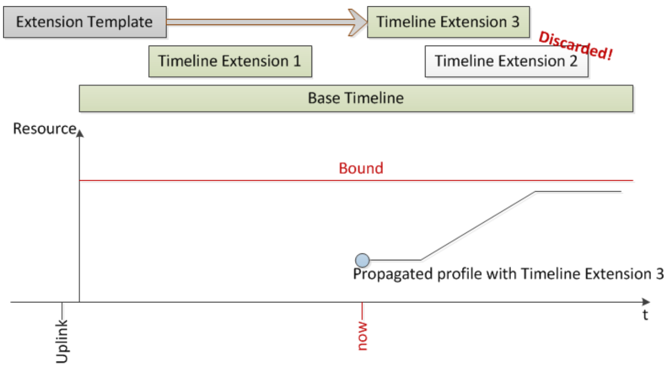

Fig. 6: Activation of OBETTE created timeline extension

In the depicted situation, timeline extension 3 overlaps with timeline extension 2. In order to avoid unexpected interferences of the commands of different timeline extensions, each timeline extension is given a time envelope. Timeline extensions, whose time envelopes overlap, must not be activated simultaneously. Therefore a new timeline extension may only be generated in case all pre-existing, overlapping timeline extensions of higher priority have an earlier decision time than the new timeline extension. This means in the example shown above that if timeline extension 2 had a higher priority than timeline extension 3, it must not be generated at all.

4.3 OBoTiS On-Ground Add-on

For the decision whether to activate or discard a timeline extension, OBoTiS need to know the time envelope reserved for executing this extension as well as the times and thresholds of the respective set of telemetry checks. To generate this information, the on-ground scheduler starts with a timeline consisting only of the downlinks, which is in general assigned highest priority, and then processes the planning requests in descending order of their priorities as follows:

1. Set the decision time T to one second before the first command of this request would start.
2. If an overlapping and not yet discarded planning request with higher priority and later execution time exists, the currently considered planning request has to be discarded.
3. For each related resource the resulting time profile, containing this timeline extension, has to be calculated. The remaining resource availability at a time T, defined as the minimum availability of this resource in the time interval $[T,+\infty)$, can be derived from it. Thus the entire future with propagated development of this resource is considered, but note, that this value can be negative for critical resources, see fig. 7.
4. Telemetry threshold = expected resource profile at decision time + remaining resource availability at decision time. Negative availability means this threshold is below the expected telemetry value.
5. Now replace the propagated profile by a worst case estimation of all considered planning requests of higher priority. In case there exist no overlapping planning requests, this means that this request's consumption remains added to the propagated profile.

The following figure illustrates the threshold calculation:

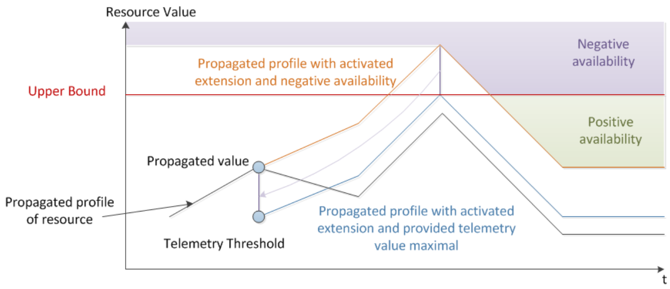

Fig. 7: Calculation of resource condition

In black the expected propagated resource profile is presented without activating the timeline extension. In a first step the propagated profile with activated extension is calculated and branches off at execution time (orange). Because of the additional resource consumption the profile rises temporarily over the bound and thus the remaining resource availability is negative before and during this time frame, in particular at decision time, the resulting telemetry threshold therefore lies below the propagated value. The blue line shows the corrected propagated profile for the case that the telemetry equals the threshold at decision time: it reaches the bound of the resource. If on-board telemetry shows a value less or equal to this threshold the timeline extension can be activated safely. Note that shifting the expected propagated resource profile (black line) beginning at or before the decision time does not modify the resulting telemetry threshold. It is the part after decision time, which reflects the upcoming consumptions of higher priority which matter. Modifications in the past are completely covered by the telemetry check.

4.4 OBETTE On-Ground Add-On

To support the event-triggered timeline extension generation the on-board planner has to generate the same information as OBoTiS' on-ground add on. The challenge is to support this calculation without significant complexity on-board the spacecraft, i.e. without the need of complex profile operations. We therefore need to have the knowledge of the remaining resource availability for each possible decision time (replaces step 3.) and the propagated resource profile (required in step 4.), where both profiles depend on the timeline extensions of greater priority. We therefore need to restrict OBETTE timeline extensions to a dedicated priority, which allows the OBETTE on-ground add-on to supply the following profiles:

1. the propagated profile including all timeline extensions of greater priority than the OBETTE generated timeline extensions (result of OBoTiS on-ground calculation, step 5 after considering all planning requests of greater priority)
2. a profile *RRA(T)* specifying the remaining resource availability (with variable decision time T), considering all timeline extensions of greater priority than the OBETTE generated timeline extensions

Provided with these two profiles, the on-board calculation may easily perform the steps 1 to 4 of the OBoTiS on-ground calculation, with steps 1 and 3 adapted as follows:

1. Set decision time as 1s before execution time or 1s before decision time of overlapping timeline extension with lower priority, depending on whether what occurs first.

3. remaining resource availability at time T = *RRA(T)* – consumption of this timeline extension

Step 5 is omitted, which means that all OBETTE timeline extensions are considered to have equal priority, the execution time will decide which one to consider first.

An example for the threshold calculation and how the relationship between these two profiles would look like is illustrated in the following figure:

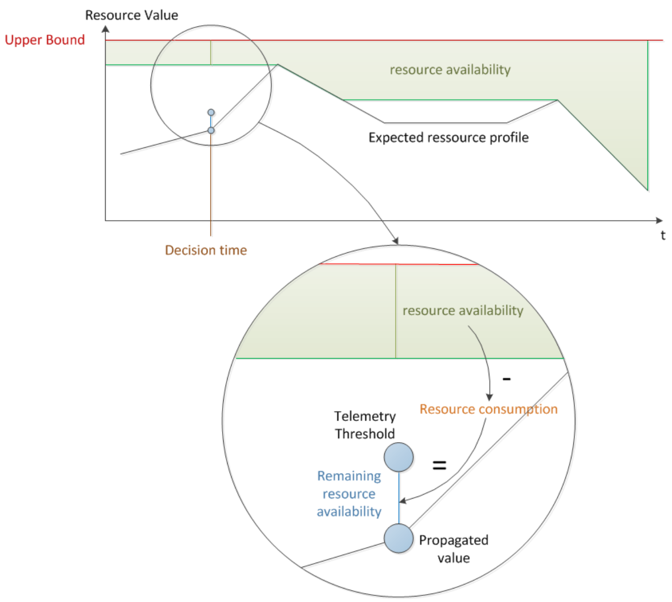

Fig. 8: Example for the threshold calculation

The OBETTE On-Ground Add-On itself consists of the preparation and the upload of the necessary profiles and the respective templates. If necessary, simplified profiles can be uploaded but it has to be ensured that the simplified values lie below the original propagated profiles.

4.5 Commanding Interface

Up to this point the VAMOS functionality and its respective parts have been described, but one drawback has been disregarded until now. On the BIROS spacecraft one cannot simply add extensions into an existing base timeline. To cope with this fact, no base timeline may be uplinked; in particular activities like downlink can't be pre-commanded but must be activated via the timeline extension mechanism, too. Thus the whole timeline is split up into timeline extensions, which can be activated individually following the specified telemetry and envelope checks

4.6 Testing and activation of extensions

As mentioned in chapter 2, on ground tests will include the engineering- or flight model, if available. During mission, VAMOS will be operated during dedicated campaigns. It will be tested in simulation mode first where the system will log all measures and decisions of VAMOS. On ground these log files will be checked and only if these checks are successful during a sufficiently large period, VAMOS will be given permission to activate timeline extensions. When this second stage of testing proves successful and in case the mission decides to use it, VAMOS may be transferred into the nominal operational use of this spacecraft. A similar approach for the stepwise operationalization was applied for the TAFF system (TanDEM-X autonomous formation flight keeping system) (see [Ardaens et al.]).

4.7 Currently Planned VAMOS Use Cases on BIROS

In a first step VAMOS shall be able to decide whether to activate or discard additional or alternative timeline blocks (OBoTiS only). Due to the fire monitoring goal of the FireBIRD mission these timeline extensions will be additional image acquisitions. In the second increment the system will get the ability to react on triggers from the main classificator and the experimental image analyser. If an image of bad quality is detected, e.g. cloud covered, VAMOS has the permission to delete the respective saved data and to fill the new available memory with a new image, perhaps one of the otherwise infeasible timeline extensions of lower priority. The third increment will activate OBETTE: In case of a detected high temperature event the system will create a new timeline extension containing an image request of this area.

5. CONCLUSIONS AND RELATED WORK

The described mechanism allows transferring some mission planning tasks towards autonomy on-board a spacecraft in order to find the best possible solutions for image acquisitions under the given restrictions within the FireBIRD mission. VAMOS combines the NRT-capabilities (events, telemetry) of on-board systems with the processing power of on-ground systems. The result is a relatively simple and low-risk on-board application which complies with all spacecraft given conditions, but nevertheless provides complex mission planning features.

Although VAMOS was invented for a dedicated satellite, its concepts should be transferable to many other earth observing satellites or even "far-distance" missions. In particular the limited complexity of the on-board software makes it both safe and cost-efficient and allows its implementation on most platforms.

An operational challenge is that one can't predict the telemetry received during a ground station contact, because the executed timeline extensions are unknown. This check can only be performed after evaluating the VAMOS logfile.

Related work and developments on likewise ideas but other approaches from outside the DLR can be found in e.g. [Khatib et al. (2003)], which provides an on-board greedy search with a limited number of constraints, or in [Gough et al. (2004)], where decisions are found by probability estimations. A nearly similar problem for on-board mission planning with on-board evaluation and generating new acquisitions when any image can be deleted is solved by the CASPER functionalities in ASE on EO-1described in [Sherwood et al. (2006) or Rabideau (2006) and Rabideau (2009)]. The processing and activation chain of CASPER (see [Chien et al. (2013)]) seems nearly similar to VAMOS, but this approach differs with respect to spacecraft design. While VAMOS has to fit in the given spacecraft and its restrictions, the chosen Cubesat spacecraft for IPEX was planned and built especially for on-board mission planning and usage of the CASPER algorithm. This system uses the same local search algorithm for on-board and on-ground scheduling and (re-)planning of the list of image requests while VAMOS consists of the on-board components and the on-ground add-on.

For the future it is planned to integrate and run VAMOS on the BIROS spacecraft and its on-ground planning system. Its purpose is to verify that the additional output of a mission combining the challenges of earth observation with those of "earth watching" (see [Damiani et al. (2005)]) is worth the effort that is introduced by an extended spacecraft autonomy. After a successful demonstration during dedicated campaigns an operationalization of such features has to be the next step. With future research and improvement of the on-board resources as memory and processing power there will be the chance to transfer the profile propagation itself to the spacecraft. As a consequence we might introduce multiple priorities for OBETTE generated timeline extensions. For this we need to upload one pair of profiles for each priority and update the profiles of lower priority when OBETTE generates a new timeline extension of greater priority.

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