# A New Approach for Mission Planning of Satellite Constellations

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## ABSTRACT

*In recent years, there has been a tendency to use micro and nano-class satellites for applications such as EO (Earth Observation) and AIS (Automatic Identification System) satellite systems. The number of satellites has also increased, to decrease the time resolution of the acquired data (such as revisit time) or to perform continuous services for applications such as IoT (Internet of Things). On-board automation is required for the constellations with hundreds of satellites to provide the desired common task in applications such as IoT; however, mission planning on-ground is still essential for high-resolution imaging or SAR (Synthetic Aperture*

*Radar) satellite systems because of the task complexity and reliability requirements. As a solution to this problem, there are a few generalized or semi-generalized mission planning softwares in use today. On the other hand, developing a generalized, mission planning tool that fits all kinds of satellite system missions is a challenging study or maybe it is not possible to attain 100% generalization. Different types of tasks performed or even handicaps of satellites bring changes in mission planning requirements and consequently modification of the software. In this study, a new mission planning software and the methods used in this software are introduced. The proposed software is designed to reduce the need for modifications by using configuration parameters and to reduce the cost and time of modifications in case of any modifications needed.*

## *KEYWORDS*

*Image guidance; Mission planning; Optimization algorithms, Software; Specialists' meeting.*

## 1.0   INTRODUCTION

Satellite Mission Planning (MP) software is a tool that plans the missions of satellites or satellites according to satellite/mission constraints and resources, calculates the necessary parameters for the execution of the mission with high accuracy, and aims to get the maximum benefit from the satellite system.

With the increasing demands from various sectors for satellite capabilities and images obtained through remote sensing, automation has been adopted, which improves the speed and reliability of MP processes. The generalization of MP software is also an important issue due to the high cost of development for satellite systems with different missions or features.

There are multiple nonlinear optimization problems to be solved in MP. Academic studies have solved these problems. In these studies, besides the solution methods, cost functions may also be different. The constraints and search algorithms used in these studies are summarized in Qamar et al. [1].

The general approach in MP of satellite systems is the development of system-specific (custom) MP software. The MP software of TerraSAR-X can be given as an example. The architecture of the software developed for the MP of the TerraSAR-X satellite and the experiences gained during the operation are described in Maurer et al. [2]. The MP software of the DEIMOS-2 satellite is also a custom MP software, but it was also the base of Sentinel-2 satellite's MP software [3] and it is available in the market today. The architecture of the software developed for the MP of the DEIMOS-2 is described in Tonetti et al.[4].

In addition, there are also studies on MP of non-homogeneous systems such as SAR and optical satellites together. The studies of Wang et al. [5] and Vongsantivanich, et al. [6] can be given as examples for MP of non-homogeneous systems. However, different types of payloads may have different types of inputs (such as the incidence angle in a SAR satellite). Therefore, in our software, only satellites of the same (or similar) type should be defined in the same system.

Today, studies on on-board MP are also carried out. The advantage of on-board MP is that the satellite knows its position much more accurately than the position calculated by the orbit determination process on-ground. Liu and Yang [7] present their results for on-board optimization algorithms comparatively. The reference attitude data that the satellite should follow during image acquisition should also be calculated in MP. In on-board planning, this data will also need to be calculated on the satellite. Ekinci and Gulmammadov [8], present an algorithm that can be used for on-board reference attitude calculation. On-board MP is still the subject of research. There are also question marks about how much ground independence can be achieved (such as obtaining cloud cover percentages from weather data for optical satellites).

There are commercial software available in the market. For generalized MP software, CPAW (Collection Planning and Analysis Workstation) from Orbit Logic, FlexPlan from GMV and Plan4EO from Elecnor-Deimos can be given as examples being used today. The approach to solving planning problems used in CPAW software is given in Herz [9].

It was observed that two different approaches were used in the reviewed software. One of the approaches for the developers of commercial off-the-shelf software is to develop the core of the software which has the modules such as optimization algorithms and develop or regenerate specific software modules to answer the needs of the customer. The main disadvantage of this approach is that additional enhancements are costly. The other approach is to use a scripting language inside the software to define user's rules and tasks for the satellite operations. The main disadvantage of this approach is the necessity for the users to know the scripting language and make all the effort to customize the software according to their system.

STM is working on a new generation MP software that will be used for the planning of STM's LAGARI EO Satellite System mission (the expected launch date of the satellite is the second quarter of 2022). The software will be a crucial part of STM's space product family that will serve for new constellation projects. The software is a web-based application and the first version is ready to be used.

STM's MP software has been developed to be suitable for as many missions as possible, being able to be used in systems with multiple satellites and ground stations and enabling rapid development and updating. It is also intended to create a mission plan automatically without the need for user intervention. In this paper, the approach in STM's MP software and the flow of plan generation are presented.

## 2.0   THE APPROACH PROPOSED

STM's MP software uses resource constraints such as on-board memory, power, angular momentum, and torque per satellite and has resource optimization features for the whole satellite system in terms of minimum power, memory and roll angle. The parameters of all kinds of optimization algorithms are also configurable parameters by the user. In principle, all types of earth-centered satellite mission types can be supported such as:

- One satellite – Ground station(s) / Multiple satellite – Ground station(s);
- Electro-optical;
- SAR (Synthetic Aperture Radar);
- Non-Imaging satellites such as AIS;
- Agile / non-agile satellites; and
- Imaging parallel to the ground track / inclined.

The approach used in STM's MP software is to support the satellite systems by allowing the user to define satellite system features (space segment and ground segment), operational use strategies, conflict resolution rules, tasks, etc. via the Graphical User Interface (GUI). It currently supports many types of satellite missions with around 200 configuration parameters. Parameters can be entered separately for the satellite system and each satellite and ground station within the system.

The planning modules / algorithms in the MP software are developed in MATLAB and integrated into the software as Dynamic Link Library (DLL) files. The use of this environment enables rapid algorithm development and debugging. If there is a satellite system feature or situation that cannot be covered or handled by the current parameters and rules, a modification must inevitably be made. In such a case, additional modifications can be made quickly, as the software is designed with a modular approach. The flow chart of MP software is given in Figure 1.
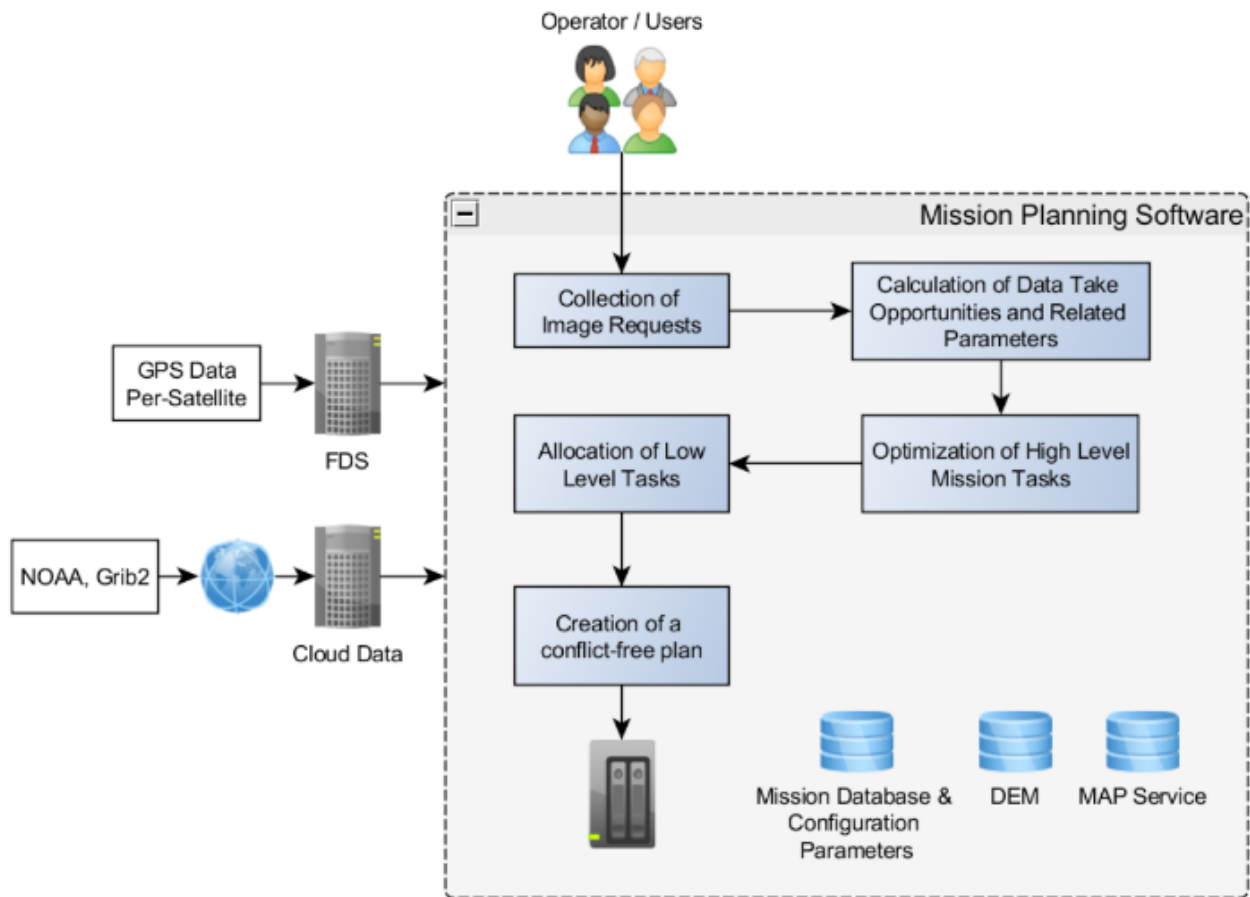
**Figure 1: MP flow**

MP software uses external orbit data files for each of the satellites. Orbit data can be propagated by any FDS (Flight Dynamics Software). The current version of MP software is fully compatible with FreeFlyer software (A.I. Solutions) data format.

Meteorological data downloaded from NOAA (National Oceanic and Atmospheric Administration) in GRIB2 format is used in case of electro-optical payload use. If an internet connection is available, the software can download the total cloud layer in meteorological data automatically in a configurable period (otherwise, it can be uploaded manually). The maximum allowable cloud cover ratio can be defined per image and targets exceeding this limit are removed from the plan by the MP software during the planning phase.

MP software uses GETASSE30 (Global Earth Topography and Sea Surface Elevation) digital elevation model where the satellite is needed to be oriented to a point or track a route on-ground, such as calculations for image acquisition activities.

A map server is also integrated into the software so that the user can easily enter the image requests and visualize the previously entered requests. Different map types are also supported under the Open Geospatial Consortium (OGC) standard.

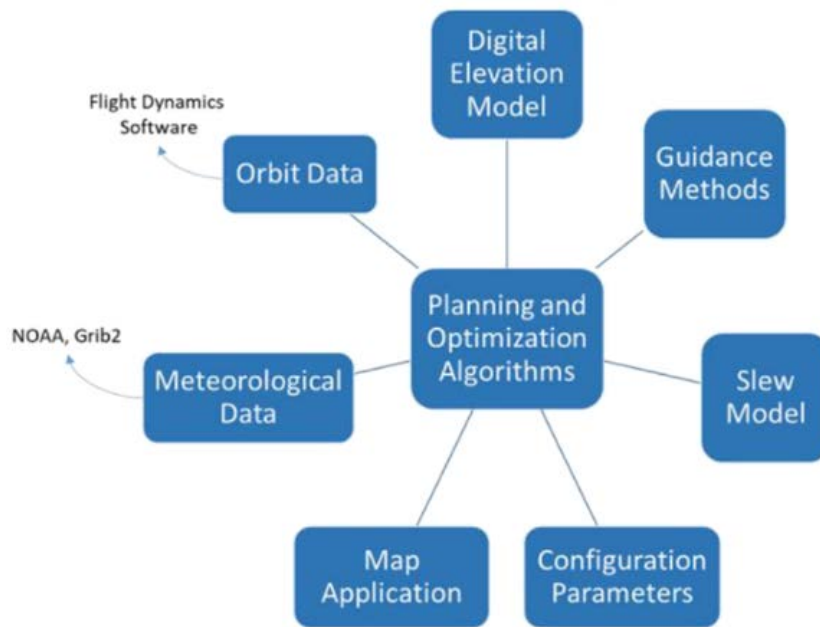The scope of the MP software is given in Figure 2.

**Figure 2: The scope of the MP software**

There are more than ten image guidance algorithms developed for use in MP software. The methods used in guidance algorithms can be found in Topal [10] and Topal et al. [11]. These guidance algorithms can be used for applications / acquisition techniques such as pushbroom, matrix, striped matrix (quasi-pushbroom) sensing with or without yaw steering and applications such as square Ground Sampling Distance (GSD) and other applications such as methods providing very long acquisition time.

Planning of orbital maneuvers (for collision avoidance or orbit maintenance) is not included in the MP software. Orbital maneuvers should be planned separately. The periods in which the mission cannot be performed due to the orbital maneuvers should be defined as the mission unavailability window (see Chapter 0) in the MP software.

## 2.1 Configuration management

With the Configuration Management tool, software option and satellite system parameters can be configured separately. Satellite system (see Figure 3) configuration consists of three parts: System Configuration, Satellite Configuration and Ground Station Configuration. Each of the satellites in the space segment and each of the ground stations in the ground segment is configured separately.
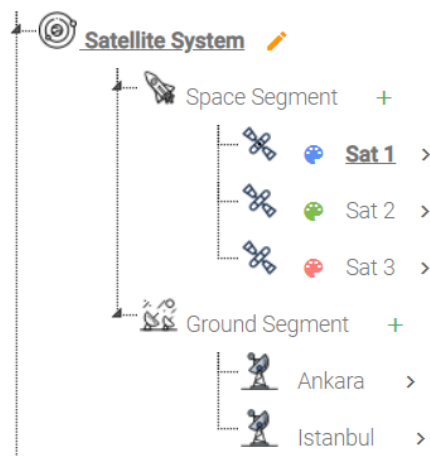
**Figure 3: Sample satellite system tree**

Parameters that concern the system such as planning window properties are defined in satellite system configuration. Satellite parameters such as initial conditions, payload, actuators, communication equipment, power system, download (per image spectral band) and memory properties, etc. are defined in satellite configuration. Lastly, ground station parameters such as coordinates and minimum elevation angle are defined in ground station configuration.

## 2.2 Task management

Task Management tool enables the user to define task definitions in detail. Task definitions can be examined under three groups:

- Communication Association
- Task Definition and Placement
- Mission Unavailability Window Definition

### 2.2.1 Communication association

For the management of communication tasks, there are two alternative methods for selecting which passages will be used for the planning of communication tasks. In the first method, communication cone passages of the satellite (per communication band and ground station) are selected manually. Manual selection has to be made for each planning window (for instance every day). In the second method, the selection of the communication cone passages is done automatically by using configurable rules such as ,use only descending passages for X-band communication.

### 2.2.2 Task definition and placement

Task definition and placement inputs have a role in calculating power consumption and generating conflict-free plan outputs.

There are three types of tasks:

- Main tasks
- Sub-tasks
- Independent tasks

The main tasks such as image acquisition, communication (with or without satellite steering), attitude maneuvers, etc. are scheduled in an optimum way via MP software. The sub-tasks such as ,warm up the camera before imaging,' should be defined and the relationship should be established with the main tasks. The independent tasks such as ,turn on GPSR on ascending node passages, are also sub-tasks; however, these tasks can be associated with the orbital events.

Sub-tasks can be linked to a main task using starting and/or ending time of the main task (with time offsets). In addition, starting time and duration of the sub-task can be used for the sub-task placement. On the other hand, independent tasks can be linked to the orbital events such as Ascending Node passage (with time offset). In Figure 4, task placement options are illustrated.
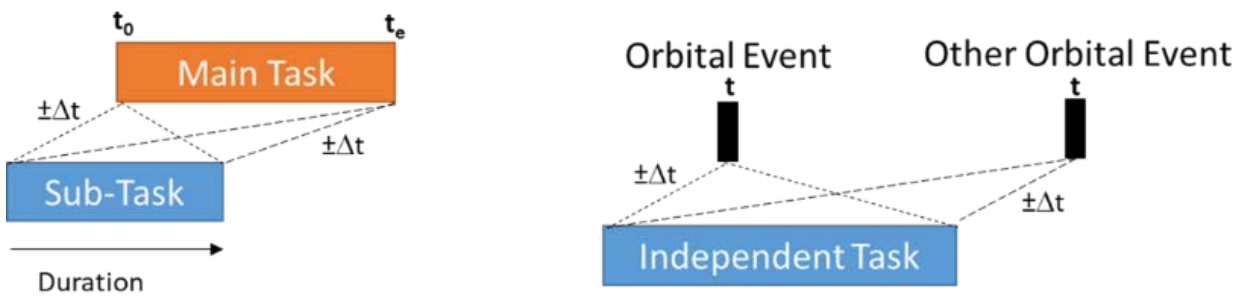


**Figure 4: Task placement**

The main tasks and orbital events of the MP software are given in Table 1 and Table 2, respectively. All events are calculated within MP software. Orbital events within the planning window are calculated immediately after loading of orbital data.

**Table 1: Main tasks of MP software**

| No | Main Tasks |
|---|---|
| 1 | Image Acquisition |
| 2 | Attitude Maneuver |
| 3 | Sun Pointing |
| 4 | Nadir Pointing |
| 5 – number of communication bands given | Other tasks defined by the user related to communication bands such as ,X-Band Communication, |

**Table 1: Orbital events of MP software**

| No | Orbital Events |
|----|----------------|
| 1 | Communication Cone Entry |
| 2 | Communication Cone Exit |
| 3 | Ascending Node Passage |
| 4 | Descending Node Passage |
| 5 | Eclipse Entry |
| 6 | Eclipse Exit |
| 7 | Optically Visible Zone Entry |
| 8 | Optically Visible Zone Exit |
| 9 | Northernmost Passage |
| 10 | Southernmost Passage |
| 11 | Periapsis Passage |
| 12 | Apoapsis Passage |
| 13 | Maximum Altitude Passage |
| 14 | Minimum Altitude Passage |
| 15 | Custom Area |

The 'Custom Area' option given in Table 2 is an option that can be used if a task is required to run on any geographical area on earth. If this option is selected, the entry and exit orbital events of the area will be calculated in the planning flow.

During the task entry, power consumption values and the solution methods to be applied in case of a conflict should be entered. Users can define all these parameters and selections via user graphical interfaces. There are rules for identifying and resolving conflictions related to sub-tasks and independent tasks, and the user can choose the appropriate one from the interface (see Table 3).

**Table 3: Confliction solution methods for sub-tasks and independent tasks**

| Limit | Solution Methods |
|---|---|
| Minimum Duration Between Co-Tasks | Solution: Combine them |
| Minimum Task Duration | Solution 1: Remove the sub-task<br>Solution 2: Extend the sub-task to the minimum duration, keeping the first date constant<br>Solution 3: Extend the sub-task to the minimum duration, keeping the last date constant |
| Maximum Task Duration | Solution 1: Remove the sub-task<br>Solution 2: Shorten the sub-task to the maximum duration, keeping the first date constant<br>Solution 3: Shorten the sub-task to the maximum duration, keeping the last date constant |
| Operation Time Limit in Sliding Window | Solution 1: Only Rise Flag<br>Solution 2: Remove the sub-task |
| On / Off Number limit in Sliding Window | Solution 1: Only Rise Flag<br>Solution 2: Remove the sub-task |

Note that, all tasks in on/off style are planned to be completed within the MP window. Thus, the satellite is not put at risk by starting for instance an attitude maneuver without an, off, command. Apart from this, another way of use is also possible with code modification. The initial state of nominal attitude modes such as sun pointing and nadir pointing can be changed by the user via GUI as needed.

### 2.2.3  Mission unavailability window definition

For each satellite in the system, time intervals can be defined when the mission payload would not be used or any mission will not be performed due to maintenance work. The MP software plans the mission according to the selected mission unavailability window definition and type.

## 2.3  Image acquisition requests

If the satellite's mission is Image Acquisition (IA), IA requests can be defined by using GUI, which is integrated with a map application. MP software supports the following IA request types:

- Spot
- Strip (parallel to orbit and inclined)
- Periodic image acquisition
- Single Pass Stereo
- Wide Area
- Border Line (it will be integrated on demand)

IA requests can be selected or previewed on the map. There are layers on the map that facilitate request entry such as Field of Regard (FoR) display on the map, display of other image requests in the database and distance and angle measurement tools. For each request, features such as priority, spectral band and tolerable cloud cover and compression rates can be defined.

A pre-feasibility analysis is performed for each IA request using satellite dynamics and image geometry. The user is warned when an IA request is exceeding the capability of the satellite. For instance, an inclined strip image of the desired length may not be acquired with a given azimuth angle due to satellite agility constraints. These kinds of constraints are configurable via lookup tables. The optimum slicing of wide areas and border lines into strips accordingly to the constraints is also done at the request entry. In Figure , sample strips for wide area and border line (can be any polygon) are given.
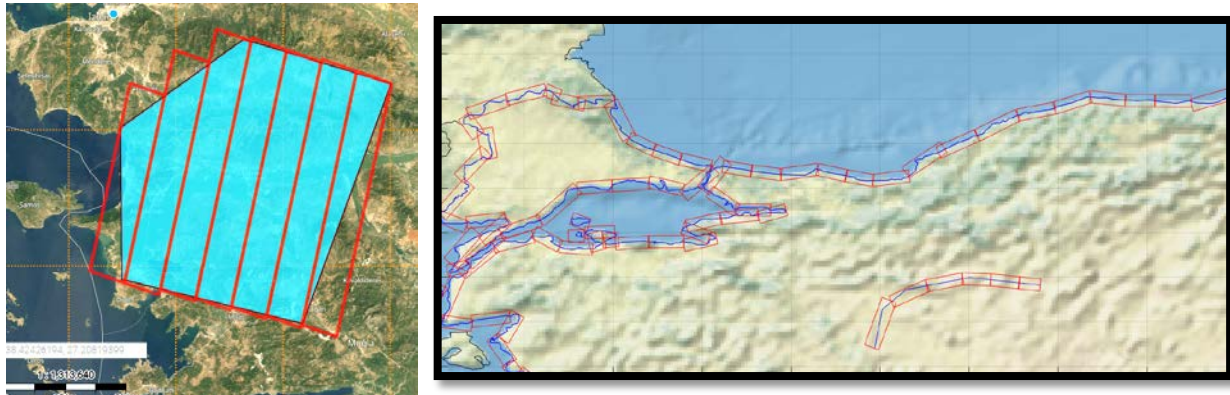


**Figure 5: a) Wide area and b) border line**

## 2.4 Planning flow

In the planning flow, modules that plan the tasks of the satellites (IA and others) optimally according to the satellite/mission constraints and resources take part. There are different types of optimization problems that need to be solved while making the mission plan of the satellite system. During the planning, these problems are solved sequentially and the optimum solution is obtained as much as possible.

For the IA or in cases where the satellite needs to be directed to a target (such as imaging or tracking a ground station), the guidance algorithms calculate the parameters of the attitude of the satellite. These parameters are the quaternion polynomial coefficients.

In the planning flow, data take opportunities are calculated for the IA requests and parameters such as duration and polynomial coefficients are calculated for the imaging activities that are possible to acquire. Cloud cover ratios are also controlled and failed ones are excluded from the plan. Calculations of guided communication activities are then performed and these are evaluated as target (as in IA).

Target-to-target attitude maneuver optimization is performed for all targets. The aim here is to reach as many targets as possible in a way that maneuvers are from target to target. When calculating the attitude maneuver parameters, optionally the reaction wheels zero-crossing and sun avoidance options are also can be activated. In solving the optimization problem, the weighted sums of the priority and length parameters are used when calculating the value of the targets. The optimum feasible combination of the targets is selected at the end of this process.

At the end of this step, all necessary data is ready to calculate the attitude profile of the satellite. The attitude profile of the satellite is defined by the nominal attitude strategy and the events such as target-to-target maneuvers and the targets. The attitude maneuver management module allocates all maneuvers and events by using one of the nominal attitude strategies given below:

- In Daylight Sun Pointing,

- In Eclipse Nadir Pointing

- Only Sun Pointing

- Only Nadir Pointing

For instance, once a group of targets has been acquired by target-to-target maneuvers, the satellite is sent to the sun pointing mode (necessary maneuvers also be calculated) if there is sufficient time before the other group of targets. Upon completion of the orientation profile, download slots and the vectors such as sunbeam on solar panels are also calculated.

After this step, the payload data download and memory management module tries to allocate download slots for the payload data in on-board memory. If the on-board memory limit is exceeded, the imaging tasks that have minimum value are removed from the plan (here and after this stage, in any case where a target is removed from the plan, attitude maneuver management will be run again because of the change in attitude profile). This process will take place until there is no limit violation in on-board memory. The options such as payload data downlink communication band, data acquisition rates for the spectral band of the image, download rates and delete/don't delete after download are all configurable parameters.

After a feasible memory profile is obtained, the power generation and consumption profiles are calculated by the power management module. To calculate the power consumption of the tasks, first, all sub-tasks and individual tasks are allocated in the timeline according to their task description. If the Depth of Discharge (DoD) limit is exceeded, the imaging tasks with the lowest value are removed from the plan. This process will take place until there is no limit violation in DoD.

At the end of this step, all operational events are ready. Finally, the mission plan and all other outputs are prepared for the relevant satellite. If there is more than one satellite in the system, it is checked whether the same imaging task occurs on other satellites. If duplication occurs, the resource optimization module will be activated. In this module, imaging tasks are removed from the mission plan of satellites that are in worse condition in terms of resources and quality of the image. At this stage, while calculating the value of imaging activities, the weights defined for the Ground Sampling Distance (GSD), the power consumption and the memory status of the satellite are used for the relevant image. For instance, increasing the power consumption weight will increase the probability that the image request will stay on the satellite's plan that is in the best condition in power consumption (in terms of DoD).

### 2.4.1  Warning messages and error handling

In the MP process, three types of messages are displayed to the user on the console:

- Status Messages

- Warning Messages

- Error Messages

Status messages give the user detailed information about the status of the planning process. This information is also given graphically.

Warning messages will not cause any errors in terms of MP but indicate situations that the user should be aware of. For instance, a situation may occur if a tolerance threshold defined in the configuration has been exceeded. In such cases, the user can check the numeric value in the message and check whether the warning indicates a problem.

The error message, on the other hand, is an indication of a critical situation that cannot be resolved by the software and causes the planning process to be interrupted. Some of these situations may be caused by a

software problem and some may be caused by incorrect configuration. MP software stores the entries of all modules in files, so that the same scenario can be created and debugged.

## 2.5 Mission planning outputs

At the end of MP, many outputs are produced for each satellite in the system. Some of these data will be converted into commands that the satellite will execute after being uploaded as tele-commands. Others are intended to inform the user about the planned mission. Outputs are presented to the user in four groups. These are:

- Mission Plan Tables
- Gantt Chart View
- Raised Flags and Indicators
- Profiles

The Mission Plan Tables contain the mission plan, guidance parameters (polynomial coefficients), payload data download plan and communication slots to be used for communication bands other than payload data. In the download plan, details of which image data will be downloaded in which slot are also given. Note that, if data download is not performed according to the download plan, the memory status can be updated in the initial conditions of the next day plan.

In the Gantt Chart View, users can inspect the mission timeline and check if the sub-tasks and independent tasks are allocated correctly. Satellite charge status is given as a percentage and memory usage is given on the same page and linked to the time axis of the Gantt Chart. A sample Gantt Chart view is given in Figure 6.
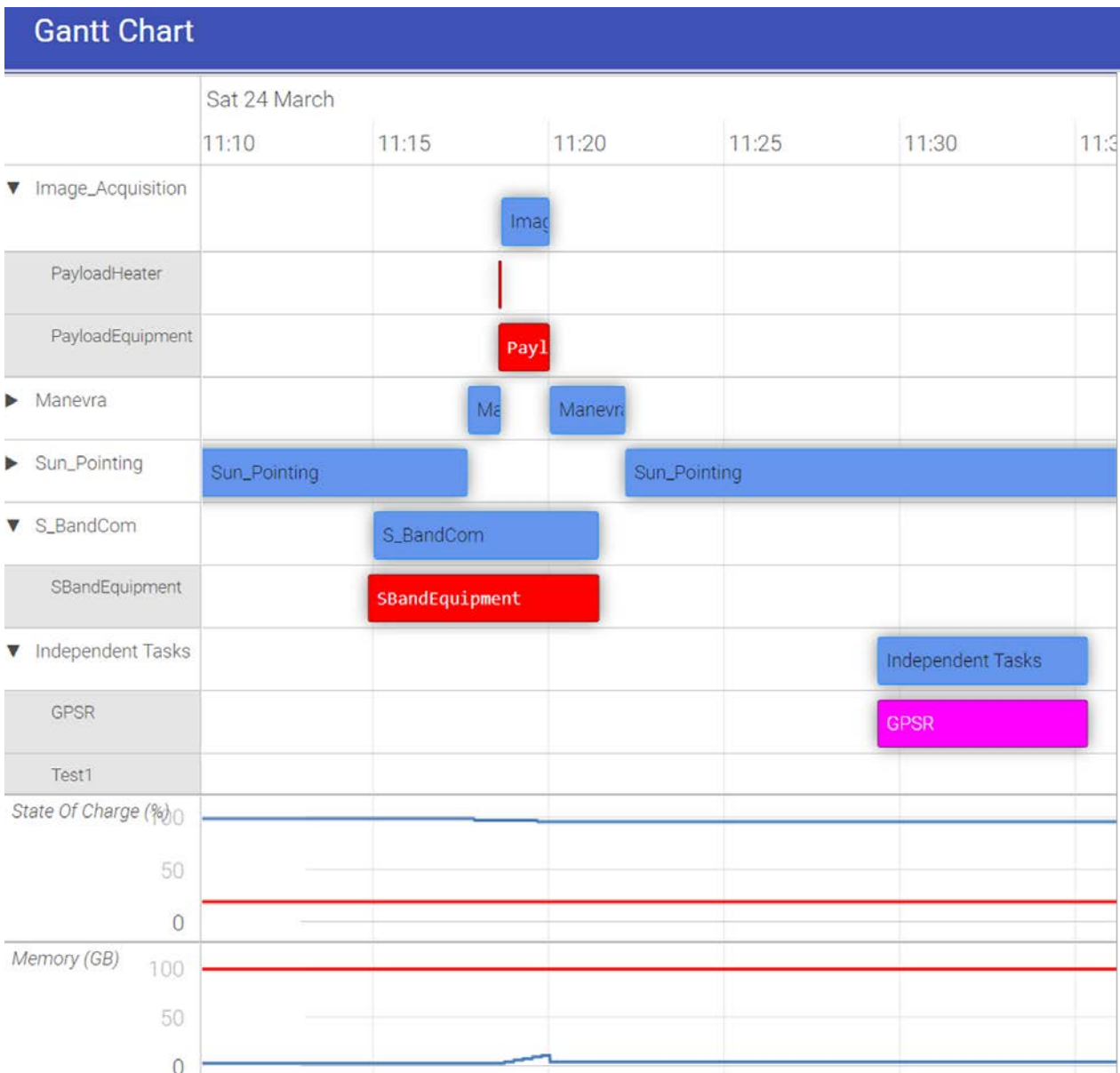
**Figure 6: Gantt chart view**

In the Raised Flags and Indicators page, the maximum number of ON/OFF and usage times within the defined sliding window length are given for all sub-tasks and individual tasks. Apart from this, those who exceed the limit are also indicated. For satellites with an electro-optical camera, the time the camera stays inside the sun exclusion cone is also displayed. Note that, this value is expected to be zero due to the sun avoidance maneuver.

On the profiles page, critical profiles for mission performance are presented. Currently, there are nine profiles. These are:

- Star tracker sun and earth horizon angles;

- Star tracker full loss (due to horizon angles and angular velocity constraints) profile;

- Quaternion and Euler angles; and

- Effective solar array and sun angle.

- Payload ground scanning speed and payload – sun Horizon angle

Attitude History File (AHF) can also be generated and the mission plan can be run in FreeFlyer software.

## 2.6    Processing time performance

Many factors determine the processing time of the MP function. The main factors are listed in Table 4.

**Table 4: Main factors that determine the processing time**

| Processing Time Performance Factor | Comment |
|---|---|
| The size of the mission planning window | e.g., 1 day or 2 days of planning window. |
| Optimization methods selected in the configuration | Some options for the optimization process fasten the solution but it increases the likelihood of falling into local minimum and vice versa. |
| The number of tasks defined for each satellite | Since all events are calculated, it has a lesser effect. |
| The number of IA requests put into the planning session | In some cases, also geographic proximity of the targets may increase the processing time. |
| The number of satellites and ground stations in the satellite system | If the area of FoR of the satellites intersect, there may be duplicated IA activities in some satellites. Resolving this situation also requires additional processing. |
| Application server performance | All calculations are done on the application server. Server performance is also an important factor for processing time performance. |

Although performance comparison of MP software is difficult due to these uncertainties, simulation results can still be given for a given number of IA requests and a reasonable satellite configuration. A satellite system with 3 satellites and 100 IA requests was simulated with MP software and the 1-day MP window lasted approximately 7.3 minutes using a server Intel(R) Xeon(R) CPU E5620 2.40GHz (2 Processors) and 12 GB RAM with 64-bit operating system Windows Server 2012 R2. Since even the location of the targets can affect the processing time, this result is given only to give an opinion.

## 3.0    CONCLUSION

MP Software is being developed to provide optimum planning of satellite or satellite constellation missions. Modular software architecture and structure will also enable MP for satellites with different payload configurations and different configuration requirements. After the completion of the MP software under development, the software will complete verification with its use in the LAGARI mission. However, before the use of MP software in the LAGARI mission, MP outputs will be verified with mission specific-satellite simulator, which is also under development. Continuous improvements will be made through the lessons learned and experience gained during satellite operations.

## 4.0   REFERENCES

[1]   Qamar, A., Salah, E.E., Badran, K.M. and ElNashar, G.A. (2020). Mission planning and scheduling for earth observation space system. Int. J. System of Systems Engineering, 10(1), pp.24-38.

[2]   Maurer, E., Mrowka, F., Braun, A., Geyer, M.P., Lenzen, C., Wasser, Y. and Wickler, M. (2010). TerraSAR-X mission planning system: Automated command generation for spacecraft operations. In IEEE Transactions on Geoscience and Remote Sensing, 48(2), pp. 642-648.

[3]   Monge, A., Cillero, B., Gonzalez, O., Abeytua, J.A.G., Pirondini, F. and Ortiz, A. (2014). DEIMOS-2 advanced mission planning capabilities, SpaceOps Conference.

[4]   Tonetti, S., Cornara, S. and Pirondini, F. (2014). Fully automated mission planning and capacity analysis tool for the DEIMOS-2 agile satellite. 13th International Conference on Space Operations.

[5]   Wang, P., Reinelt, G., Gao, P. and Tan, Y. (2011). A model, a heuristic and a decision support system to solve the scheduling problem of an earth observing satellite constellation. Computers & Industrial Engineering, 61(2), pp. 322-335.

[6]   Vongsantivanich, W., Chaimatanan, S. and P. Tangpattanakul (2016). The development of mission planning tool for Thailand's earth observation mission. AIAA 2016-2542, SpaceOps Conference.

[7]   Liu, S. and Yang, J. (2019). A satellite task planning algorithm based on a symmetric recurrent neural network. Symmetry 11(11), p. 1373.

[8]   Ekinci, M.B. and Gulmammadov, F. (2019). A guidance algorithm for imaging with a LEO Satellite. 9th International Conference on Recent Advances in Space Technologies (RAST), pp. 729-733.

[9]   Herz, E. (2014). EO and SAR constellation imagery collection planning. 13th International Conference on Space Operations, pp. 1-10.

[10]  Topal, E. (2016). Line of Sight Track Guidance Method for Precise Satellite Imagery. Ph.D. thesis, Istanbul Technical University, Istanbul.

[11]  Topal, E., Akyılmaz, O. and Aslan, A.R. (2016). Spaceborne push-broom image guidance, attitude realization errors: A system engineering approach, Arabian Journal for Science and Engineering, 41(11), pp. 4477-4486.