Advanced LEO observation missions planning

H. Kfir[1] and Y. Arav[2]
MBT-Space, Israel aerospace Industries

MBT-Space, the space division of Israel Aerospace Industries (IAI), is developing a modern Satellite Command & Control (SCC) system. The System is aimed to serve all MBT LEO satellites: OPTSAT 2000 and TECSAR spacecraft, as well as the new generation OPTSAT 3000 and research mission Venus.

The mission-planning post of the SCC is responsible for planning the operational sessions: imaging, downlinking, resources calculation, mission rules verification, and finally - creation of data and timings for the command generation process.

This paper focuses on three key–features of the post: i) The post is generic: it serves all spacecrafts with minor code adaptations - all differences between satellites payload, hardware, software and operational concepts are loaded at run time. This is achieved by a common planning flow, which is initialized with different "models" of on-board components, according to the specific configuration of each spacecraft. ii) Reliability of planning: a session titled "valid" by the post is guaranteed to pass the command generation stage, and smoothly executed, not at the expense of exaggerated margins over the physical abilities of the spacecraft. For this goal, critical hardware components (star trackers, AOCS, gimbaled antenna...) are precisely simulated within the mission planning process, and critical commanding and timing issues are checked and resolved at mission planning stage. iii) Operational flexibility: the system may operate as a standalone post: where a human operator plans imaging sessions via a comprehensive graphical interface, or it may lend itself as a "model" to an automatic-scheduling system.

I. Introduction

MBT-Space, the space division of Israel Aerospace Industries (IAI) designs, builds and operates LEO observation satellites with various sensors and mission profiles. Historically, the Mission Planning software in the ground segment was developed specifically for each satellite. Hence, each space mission had its own Satellite Command & Control (SCC) software, which considerably increased development, testing and maintenance costs. Moreover, applying cross-projects improvements or even minor bug-fixing, turned to be a difficult task, involving coordination between many stakeholders.

It became clear that a unified SCC post, that serves both in-orbit and future missions, will have great advantages: it will enable central management of requirements from different projects; generic software developing; sharing of algorithms and logical processes; cross-platforms testing and bug-fixing; and will provide a standard "look & feel" of the system for different missions, which will simplify the work of operators at ground stations.

This paper describes the mission planning segment of this unified SCC system; focus is given to the main principals and guidelines that enabled developing a generic system, despite considerable variety in mission profiles, sensors and onboard hardware. This configuration variety is described in the following section. The rest of the paper is organized as follows: section III lists the design guidelines of the generic SCC. Section IV – the main flow of the mission planning process, sections V and VI describe the logical flow of a single operation: an image acquisition, and an image downlink, respectively. Section VII describes the validation of an operational session, section VIII describes measures taken in order to ensure the reliability of planning.

II. Variety of configurations, common operational concept

This section outlines the variety in sensors and on-board hardware of MBT LEO satellites on one hand, and their common operational concept on the other hand. This common concept enabled the design of a unified mission planning post.

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[1] System engineer, LEO SCC Post, MBT-Space, IAI, Yahud, Israel.
[2] Algorithms developer, LEO SCC Post, MBT-Space, IAI, Yahud, Israel.

MBT's in-orbit LEO fleet contains five satellites: four "OPTSAT 2000" model - equipped with an Electro-Optic "push broom" Time Delayed Integration (TDI) sensor, and "TECHSAR" – equipped with a SAR sensor. On ground, at different stages of design and integration are two other models: "Venus" – a CNES joint scientific mission with a multi spectral (12 bands) EO sensor (see ref. 1 for more details about the Venus mission planning concept), and "OPTSAT 3000" – with a panchromatic/multispectral EO-sensor intended for high geo-location accuracy imaging missions. Table 1 briefly summarizes these differences:

Table 1: differences among MBT LEO satellites

	OPTSAT 2000	**OPTSAT 3000**	**TECHSAR**	**Venus**
sensor	EO- TDI Panchromatic	EO-TDI panchromatic/ Multispectral	Synthetic aperture radar	EO-TDI multi-spectral (12 bands)
Imaging modes	Spot	Spot Strip	Spot Strip Mosaic	Spot Moon imaging[3]
Imaging options	On-line or Off-line	On-line or Off-line	Off-line	Off-line
Downlink antenna	gimbaled	Gimbaled	Restrained	Restrained
Attitude sensor	IMS/star tracker	Star tracker	Star tracker	Star tracker
Orbit	Inclined or sun-synchronous	Inclined or sun-synchronous	Inclined	sun-synchronous
allocated resources	Mean sun-solar panel angle	Net imaging duration. Net downlink duration	Battery final depth of discharge	Payload permissions (imaging/downlink)

As mentioned, all satellites share a common concept of operation: each satellite has one Main Ground Control Satiation (MGCS), and one or more User Control Stations (UCS). MGCS is responsible for the operation and well-being of the satellite. It is in charge of maintenance procedures such as orbital maneuvers, periodical calibrations and redundant-units operation. Moreover, the MGCS allocates **Operational Sessions** to its UCS(s). An Operational Session is a time slot (typically 10 minutes long) allocated to a specific UCS for preforming imaging and/or downlinking operations. The MGCS defines "boundary conditions" for each session: start and end time, start and end satellites attitude, and resources allocated for the session. The specific resources differ between satellites: for instance, in "Venus" mission, the resource is in the form of payload activation permissions: sensor, or downlink-unit, defining an imaging or unloading session. Whereas for "OPTSAT 2000" – the session's mean sun-solar panel angle is allocated. Both resources represent restrictions implied by the specific electrical power balance of each mission. The MGCS has a global point of view: it allocates sessions and resources in order to maintain long-term limitations such as thermal and electrical balance per entire revolution.

UCS is in charge of planning image acquisition and unloading operations according to its customer's requirements. UCS's scope is strictly limited to the operational sessions allocated to it by the MGCS, and a session plan will not be considered valid until it meets the allocated boundary conditions and resources. This paper concentrates on the mission planning module at the UCS posts.

Another feature common to all MBT missions is the separation between mission planning and command generation. Mission planning is an interactive task by nature: a human operator plans imaging operation in a trial and error manner, and would use the mission planning post as a "sand-box" for planning different versions of the same mission. Command generation is an automatic process of generating a command file to be uplinked to the spacecraft. Mission planning is a procedure that may be done hours or days prior to execution times, and should be updated along time as new requirements are introduced. Command generation is executed only once, as close as possible to uplink dead-line, a thorough description of command generation sequence may be found in ref. 2.

In order to account for the time gap between planning and command file generation, the concept of "Replan" was introduced: Replan, is an automatic procedure of updating a mission plan to fit an up-to-date orbital ephemeris, and is discussed further in section IV.

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[3] for radiometric calibration.

III. Basic guidelines of design

The design of the common mission planning post is based on several guidelines, which ensure the post will be generic and support future extension:

- **Common planning flow**: The flow of planning a single operational session is a backbone of the mission planning post, a special software entity, named "Planner" governs the flow.
- **Imaging is prior to downlink**: Image acquisition operations have priority over image downlink operations. The operator plans imaging operations, and the system automatically schedules downlink operations that will not affect the planned images (an option of manually inserting a downlink operation does exist, however the operation will be rejected by the system if it conflicts with imaging operation).
- **Modeling and encapsulation of hardware**: On-board hardware components considerably differ between satellites. Components relevant for mission planning are modeled by the software. The models hold data and technical attributes of the hardware component, and perform calculations required for simulating its behavior. Models of components of the same type share common interfaces. For instance: any EO-sensor model must return its FOV; and must be able to calculate its imaging parameters (line rate, TDI level[4]...) for a given image; Any star tracker model must be able to return it's momentary status: "tracking", "blind", or "acquiring".
- **Data accessibility**: Data gathered along the planning session is held by the Planner, and includes the operational plan, satellite's attitude, and timelines of components activation. This data is easily accessed by other software components in a "read only" manner: If an attitude sensor's accuracy depends on the momentary angular rate - its model may find such information in the attitude data. If an On Board Recording (OBR) unit's unload rate depends on the momentarily load rate – the OBR model may access such type of information. This concept, in contrary to the concept of "feeding" each model only with information it requires, simplifies extension of the system to new hardware components as it does not requires new interfaces in case more data is needed. On the other hand, adding or editing data is allowed only to the Planner itself, as it is this component's responsibility to maintain the operational plan updated and synchronized.

IV. Main flow of mission planning

The flow of planning a single operational session is the backbone of the mission planning post. The assumption that all LEO space missions obey the same planning flow is the basis upon which the generic post is established.

The inputs for the planning flow are:

- An operational session, as allocated by the MGCS,
- Predicted orbit for the operational session's time,
- A collection of parameters completely describing the satellite's configuration (e.g. sensor FOV, downlink antenna lobe angle, reaction wheels alignment), commonly referred as Satellite Data Base (SDB).
- A list of mission rules to be checked.
- List of images stored in the OBR from previous sessions (OBR initial state).
- (Optional) A previously planned operational plan of this session (in case the operator opens an existing plan for editing).
- (Optional) A "requirement list" – targets that the customer would like to acquire during this session.

The outputs of a planning session are:

- A Payload Operational Plan (PLOP) containing imaging/downlink operations for the operational session.
- (Optional) Data files for the binary command generation process. These files will be generated only if the PLOP is valid, and the user intends to generate a command file.

The planning flow is described in Figure 1, its main steps are:

- **Open Planning Session (OPS):** this stage initializes the planning process: the planner validates all inputs and infers which satellite this planning session is intended for. It is worth noting that this identification is done at run time, and not hard-coded. The following actions are performed during OPS:

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[4] The number of detector lines that collect light from the image.

  - Initialization of all hardware components models with SDB parameters according to the specific satellite configuration.
  - Determination of start and end attitude according to the data in the operational session.
  - Generation of "background attitude profile": this attitude profile will serve as idle attitude to be applied between imaging operations. The specific attitude per space mission is defined by the mission's system engineer, for instance minimize drag, maximize flux on solar panels, or mimic the non-operational cruise logic.
  - Replan. If a previously planned PLOP (for the same operational session) is given as an input, the system will "Re-Play" the plan and modify the imaging and downlink operations to fit the updated orbit. Modification policy is flexible, currently "maintain images along-track angle" is implemented, however other policies, such as "maintain images cone angle" may be defined in coordination with mission's system engineering team.

  By the end of the OPS stage, the system is ready for planning, and the operator may add, edit or remove imaging and downlink operations to/from the PLOP.

- **Compile**: the user enters inputs for an imaging or manual-downlink operation (e.g. imaging time and target position, or ground station name), and the system preforms all required calculations and presents the results (e.g. imaging resolution or downlink duration). The operator may repeat this stage and modify the inputs until the resulting image meets the requirements.
- **Commit**: at this stage the system adds a compiled operation to the operational plan, and performs the following calculations:
  - Automatic downlink scheduling (if images were not downlinked manually).
  - Calculation of resources usage: OBR free space; execution of Electrical Power Simulation (EPS) – for satellites that require it.
  - Simulation of operation of critical components – such as star trackers.
  - Mission rules verification: a set of mission rules is defined per satellite, and their activation and severity levels are configurable (see section VII). All relevant mission rules are verified at this stage.
  - Determination of the validity status of the PLOP – according to the results of the mission rules check.

  The Operator repeats the "compile" and "commit" steps until the operational plan is completed.

- **Exit planning session**: this step terminates the planning session. The PLOP will be saved to the data base (the system enables saving of non valid PLOPs for further editing), and, if the PLOP status is valid, the operator may trigger the process of command file generation. As atomic commands considerably differ between spacecraft, some parts of this code section are written specifically per each satellite (even of the same model).

It is worth mentioning that planning can be done in a non-sequential order, enabling the operator to start with high priority targets, and then fill the gaps with low priority targets. The user may also modify and remove existing operations. The following sections describe these steps in more detail.

V. Image acquisition flow

The mission planning post supports several imaging modes (e.g. spot, strip, moon imaging.), moreover, the specific implementation of an imaging mode slightly varies among different spacecrafts. Therefore, a basic imaging logical flow was defined, and modifications to this flow were made specifically per each imaging mode. The steps of the basic flow are:

- **Inputs validations** (requested imaging time is within operational session, target is visible at this time…)
- **Calculation of sensor imaging parameters**: this is done by the sensor-model. For EO-TDI sensor, for instance, the line-rate and TDI level will be calculated according to light conditions and ground reflectance. Imaging parameters may also be manually defined as inputs by the operator, in such a case the sensor model will only verify that values are legal.
- **Calculation of scan attitude**: the attitude of satellite during the scan depends on the specific scan. A SAR spot image requires fixed ground point steering; an EO-TDI scan requires a "push broom" motion of the projection of the sensor on the ground; a long EO-strip scan requires a synchronous motion.

According to requirements of the AOCS, a short stabilization period will be added to the beginning of the scan.

- **Attitude maneuvers to/from the scan**: attitude maneuvers between the end of previous scan to the beginning of current scan, and from the end of current scan to the beginning of successive scan are calculated. The system supports several algorithms for calculation of the attitude maneuver, which are configured per-satellite.
- **Scan performance calculations**: calculations such as ground coverage polygon, resolution, size of Image in OBR are performed at this stage.

Deviations from this generic flow are easily handled by object-oriented standard techniques such as inheritance and overloading: The implementation of Venus's multi-spectral image acquisition involves running this flow for a single, "virtual" sensor, followed by a calculation of the exact shutter times for each one of the twelve detectors. "Moon imaging" mode required replacing the "ground Point" input by a calculation of the moon position at imaging time, and a calculation of a scan profile with constant velocity in inertial frame, instead of the earth-fixed "push-broom" motion. Both changes required minor code adaptations.

VI. The downlink planning mechanism

IAI satellites considerably differ in their downlink hardware configuration: gimbaled vs. restrained antennas, online vs. offline imaging capabilities, and various OBR systems. Moreover, each Ground Receiving Station (GRS) has its own limits, as signal lock time, obstructed zones, and data rate limits. Designing a common downlink planning module that will serve all satellites seemed like a challenging task.

To meet this challenge, we introduced the concept of "downlink component interface": Every hardware component that is involved in the downlink chain was modeled, implementing the following interface:

- "can start" (to downlink at time t)
- "can proceed" (downlinking at time t)
- "can terminate" (a downlink at time t)
- Downlink rate (at time t)

The calculations required for answering these "questions" must be specifically defined for each hardware component: "can start" implementation for a GRS depends on the required signal-lock time, whereas for the OBR unit it relays on whether the unit's current state is "Idle" or "Load". For a restrained antenna, "Can proceed" is implemented as calculation of the ground pointing error, while for a gimbaled antenna a check is done for body obstructions. The "Can terminate" interface implementation for a gimbaled antenna verifies that after the last downlink in an operational session enough time remains for returning the antenna to its home position. The "Downlink rate" implementation may depend on the range from the ground station, on data unload rate of the OBR, or on the number of active modulators for the antenna.

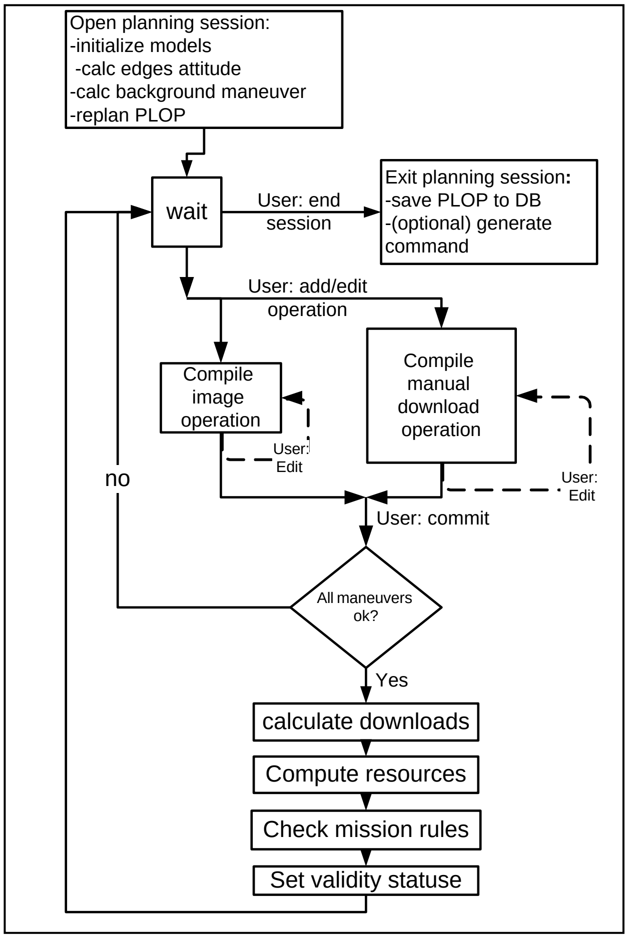

Figure: 1 - mission planning flow

In the "open planning session" stage, downlink components of the specific spacecraft are initialized, according to the configuration data and technical data loaded from the SDB. Compilation of a downlink operation under this design is straightforward: invoke the "can start" method for the downlink components at the desired downlink start time, then, invoke the "can proceed" method, propagate by an arbitrary time step, and accumulate the size of downloaded data according to the minimal downlink rate at each step. When the accumulated downloaded data size meets the size of the image, invoke the "can terminate" method. If "true" was returned in all cases – the downlink operation is legal and may be committed to the PLOP.

This generic design is very flexible, for instance, extending the system to downlink via a geostationary satellite merely requires adding a downlink component that implements the interface for a communication satellite. Furthermore, this concept easily lends itself as a building block to a scheduling algorithm that automatically schedules the downlink operations: the operator creates "downlink missions" that contains priorities and destinations, and the algorithm creates the schedule by calls to the downlink module.

VII. Mission rules verification

The term "mission rules" refer to a set of checks that must be confirmed before an operational plan is tagged "valid", and executed by the satellite. Rules may include: limiting angle between the telescope and the sun; minimal time interval between successive payload operations; avoiding OBR overflows etc. The system engineer of each space mission defines these rules for his project.

In order to maintain the system's common and generic nature, the SCC development team implements rules in the most general interpretation: for instance, the availability of star trackers is defined in terms of minimal-number-of-tracking-heads for one spacecraft, and in terms of maximal-duration-without-tracking-heads for another one. In the SCC, there is a single mission rule that calculates both number tracking heads and duration of obstructions, and the limits are configured to meet each project's definitions.

Since the mission planning post is common, space missions may benefit from mission rules that were developed for a different project, rather than re-implement a similar rule: The activation and severity of each mission rule are governed at run time by external configuration parameters that enables satellite's engineer to update them without requiring code modifications.

VIII. Reliability of planning

A major requirement of the SCC-system is reliability of planning: an operational plane declared "valid" by the mission planning post should pass the command file generation step with no errors, and should be executed smoothly by the satellite, without generating emergency events. This should not be achieved by means of large margins and safety intervals, which will degrade the operational capabilities of the satellite.

This requirement was addressed by modeling any component of the spacecraft that is involved in the operational mission: for instance, modeling all timing and command sequences of the OBR prior to each load and unload operation; simulating the operation of star trackers and gimbaled antenna motors; and modeling the AOCS (Attitude and Orbit Control System).

Prior to command file generation, the post generates the attitude commands, and calculates the dynamic response of the satellite. The system then re-checks that all spatial mission rules (sun-telescope angle, star-tracker-earth angle…), remain valid over the predicted attitude profile.

IX. Conclusion

The common mission planning post plans operational sessions for all MBT satellites, with minor code adaptations, and maximal code reuse. This was achieved by designing a generic planning flow, which operates with strict interfaces, and encapsulating all the differences into models of hardware component, that implement these interfaces. The common code ensures that new features, performance improvements or bug-fixes are available for all satellites.

Switching a post from serving one spacecraft to another doesn't require compilation or installation of new software.

The system's main mode of operation is interactive: a human operator interacts with the post via a graphical interface, and manually plans operational sessions. For "Venus" mission, an autonomous validation mode was created, that receives operational requests (as XML messages) and automatically evaluates operational plans. Valid plans are sent to command files generation. Non-valid requests are rejected and an appropriate XML message is sent as a feedback.

Yet another operational mode is using the algorithmic and logical levels of the post as a model of the satellite in an automatic mission scheduler: the algorithmic layer exposes interface such as "compile image operation", "compile downlink operation", "validate operational plan". The scheduler uses these interfaces for modeling satellite's capabilities and building optimized operational plans.

Future directions for the system include enabling simultaneous multi-session planning, and simultaneous mission planning for different satellites, mainly for data-fusion applications.

References

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