ExoMars Trace Gas Orbiter: Evolution of the science operations concept during the nominal and extended mission phases

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Abstract

The ExoMars Trace Gas Orbiter (TGO) spacecraft performs scientific observations from 400km above the Martian surface while also providing relay support to landed assets on the Mars surface. TGO entered its nominal science phase in April 2018 for an initial duration of 1 Martian year with further extensions approved to provide relay capabilities for the European Space Agency (ESA) surface assets scheduled to arrive in the late 2020s within a reconfigured ExoMars programme. The ExoMars TGO Science Operations Centre (SOC) is located at ESA´s European Space Astronomy Centre (ESAC) near Madrid and is responsible for coordinating the science planning activities with the instrument teams and the Mission Operations Centre (MOC). Due to the vast number of solar occultation, nadir measurement, and surface imaging opportunities afforded by a 2-hour 400km science orbit, the planning iterations at long and medium-term planning horizons are made through generic observation types rather than directly at the detailed commanding and pointing timeline level. This operations concept was extended to predefine sets of observation patterns that do not violate very restrictive spacecraft dynamic constraints and allow for interleaving of payload observations with data relay slots for Mars surface assets. The first months of the nominal science operations were used by the TGO ground-segment to confirm the adequacy of the concept through the inclusion of basic observation types. The SOC has subsequently phased in more complete observation types, increased the number and complexity of the observation patterns, and participated in coordinated multi-mission observation campaigns of high-value targets. The enhancement of the traditional ESA planetary mission science operations approach, initially driven by the specific needs of the TGO operational profile, has already proven its worth during the nominal phase of the TGO mission. It has demonstrated a large increase in achieved observations and coverage when compared to previous ESA missions. The number and complexity of observation types has continued to increase throughout the mission extension, and experience gained during the nominal operations phase resulted in the relaxation of the more restrictive operations constraints. The combined result is that TGO continues to execute a science observation timeline populated far beyond the level considered at the start of the mission, while also functioning as a highly effective relay platform currently returning a large fraction of the data relayed from the Mars surface.

Keywords: Planetary, Operations, Concept, Reuse, Evolution

Acronyms/Abbreviations

European Space Agency (ESA)
European Space Astronomy Centre (ESAC)
High Value Observations (HVO)
Mars Express (MEX)
Mars Reconnaissance Orbiter (MRO)
Mission Operations Centre (MOC)
Principal Investigator (PI)
Science Operations Centre (SOC)
Science Working Team (SWT)
Solar Occultation (SO)
Trace Gas Orbiter (TGO)
Ultra-High Frequency (UHF)
Wheel Off-loading (WOL)

1 Introduction

The ExoMars Trace Gas Orbiter (TGO) spacecraft performs scientific observations from 400km above the Martian surface while also providing relay support to landed assets on the Mars surface. The main characteristics of the mission are summarised in Figure 1.

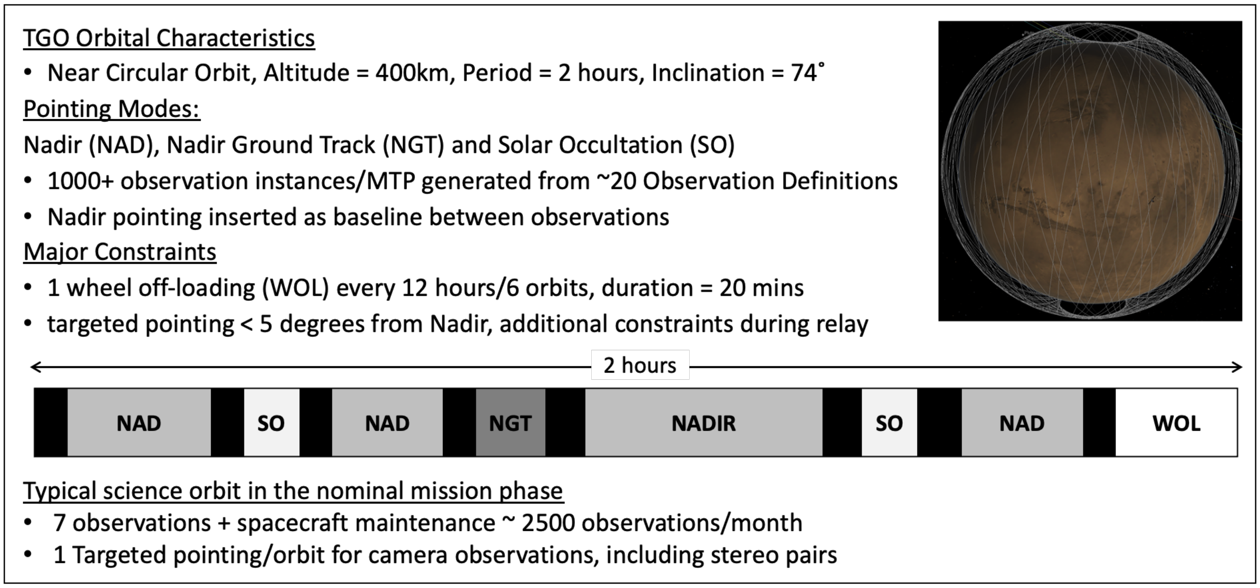


Figure 1: TGO mission overview, typical pattern of science observations for each 2-hour orbit in the nominal mission phase.

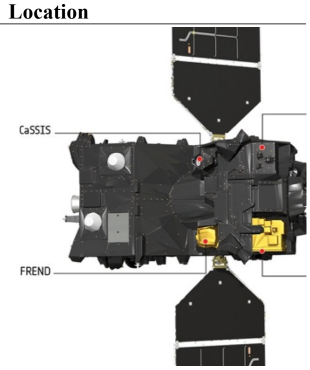
1.1 Nominal and Extended Mission

TGO entered its nominal science phase in April 2018 for an initial duration of 1 Martian year, is currently in a mission extension until June 2023 with further potential extensions under discussion that would see TGO continue as a platform for science measurements and relay support into the 2030s.

1.2 Science Payload

The TGO science payload consists of two spectrometers (NOMAD and ACS), capable of detecting a wide range of atmospheric trace gases with higher sensitivity than previous missions, a high-resolution stereo colour imaging camera (CaSSIS), devoted to imaging surface targets, and a neutron detector (FREND) for subsurface studies. An overview of the scientific payload and pointing types used to execute the science observations are listed in Table 1.

*Table 1: TGO Payload Description and main pointing used to execute science observations (*in extended mission)*

TGO Payload	PI team	Description	Pointing	Location
ACS (Atmospheric Chemistry Suite)	Space Research Institute (IKI), Moscow, Russia	Suite of three infrared instruments will help scientists investigate the chemistry and structure of the Martian atmosphere.	Solar Occultation Nadir Limb	
CaSSIS (Colour and Stereo Surface Imaging System)	University of Bern, Switzerland	A high-resolution camera (5 m/pixel) capable of obtaining colour and stereo images over a wide swathe.	Nadir Targeted Limb*	
FREND (Fine Resolution Epithermal Neutron Detector)	Space Research Institute (IKI), Moscow, Russia	Neutron detector to map hydrogen on the surface down to a metre, revealing deposits of water-ice near the surface.	Nadir	
NOMAD (Nadir and Occultation for MArs Discovery)	Belgian Institute for Space Aeronomy	Combines three spectrometers, two infrared and one ultraviolet, to perform high-sensitivity orbital identification of atmospheric components, including methane and many other species.	Solar Occultation Nadir Limb	

1.3 Science Operations Stakeholders

The ExoMars TGO Science Operations Centre (SOC) is located at ESA´s European Space Astronomy Centre (ESAC) near Madrid and is responsible for coordinating the science planning activities with the Principal Investigator (PI) instrument teams listed in Table 1, and with the Mission Operations Centre (MOC) based at ESA's European Space Operations Centre (ESOC) in Darmstadt.

1.4 SOC Development Phase

The SOC was established with a relatively short lead-time of 2 years before the start of the in-orbit commissioning and nominal operations phases. For this reason, many aspects of the operations concept, science planning processes and interfaces had to be adapted from previous missions. The starting point for development of the core SOC system modules was reuse from the Mars Express and Rosetta family of missions. File-based interfaces were preserved to conduct plan refinement over the long, medium, and short-term planning cycles that were directly inherited from the previous missions.

1.5 Tailoring the Operations Concept for TGO

The priority for the nominal mission was to establish a workable operations concept through reuse of concepts successfully demonstrated on previous missions. Potential shortcomings of established concepts were addressed through tailoring to the TGO operations concept intended to tackle specific problems presented by the main TGO mission characteristics.

1.5.1 Number of Observations

Compared to previous missions, the 2-hour TGO orbit period resulted in an order of magnitude increase in the number of science observations to be planned by the SOC and further iterated with the PI teams, while remaining within the same turn-around times to conduct the planning activity. The repetitive survey nature of the mission meant that the achievement of mission science goals needed to be evaluated through coverage requirements (spatial, seasonal) rather than execution of individual observations.

1.5.2 High-resolution imaging

The CaSSIS camera provides targeted imaging to a higher-resolution than previous ESA Mars missions needed to consider in their planning processes. The interfaces and processes to refine the targeted imaging plan and to provide the operations requests to the MOC need to consider a higher threshold for pointing and timing accuracy to ensure correct execution of CaSSIS requests, to return the expected quality of science data.

1.5.3 Momentum management

The end-to-end pointing requests that are constructed when assembling individual observations need to remain within very tightly defined momentum management constraints, coming from restrictions imposed by the spacecraft design.

1.5.4 Interleaving relay operations with science observations

The science observation timeline must guarantee compatible spacecraft orientations to support the relay operations for multiple landed assets at Mars. The SOC is responsible for efficiently interleaving relay slots into the timeline of science observations.

2 Overview of the TGO Science Operations Concept

The large increase in observations on TGO meant that planning and refinement of the pointing and commanding at individual observation level was not compatible with the available effort at the TGO SOC or the turnaround times imposed by the agreed planning cycles with the MOC. Instead, the level of interaction with the PI teams was abstracted to higher-level timelines that reference generic observation types and robust repeat patterns.

2.1.1 Observation Types

Observation types allow the instrument teams and the SOC to define a library of templates that couple the pointing request (if needed) and commanding components. These observation types can be parameterised to correctly adapt the commanding and pointing attributes for each individual observation instance placed into the timeline. Observation types are usually only valid under a certain set of desired geometries, used by the SOC to identify when individual instances of the observation could potentially be included in the science plan, such as the altitude for solar occultation measurements or the periods with desired illumination conditions.

2.1.2 SWT strategy

The TGO project scientist and the instrument PIs that comprise the science working team (SWT) define a high-level observing strategy defined to meet the science goals of the mission. The SOC devises a set of robust repeat patterns designed to meet the SWT strategy while remaining within the restrictive spacecraft momentum management constraints. Several iterations may be required to converge on an agreed strategy that is demonstrated to be operationally robust, an activity that falls under the long-term planning process. The NOMAD and ACS spectrometers were found after in-flight calibration to be mis-aligned to an extent that does not permit combined observations (see Figure 2). Instrument-level quotas were therefore introduced as part of the SWT strategy and are represented in SOC planning as observation repeat patterns for solar occultation coverage that alternate the allocation between the 2 instruments definitions to ensure a fair distribution of opportunities.

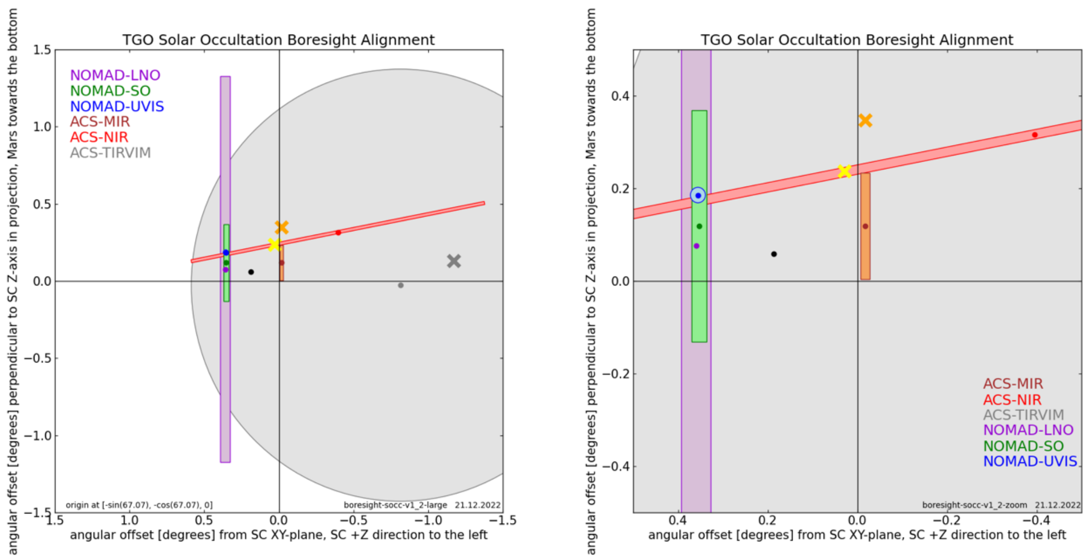


Figure 2: NOMAD/ACS boresight mis-alignment meant that solar occultations had to alternate between the instruments.

2.1.3 Special Observations

Slots for dedicated instrument observations (e.g. for calibration activities or uniquely defined observing geometries) are proposed and planned by SOC, and are isolated from the rest of the observation timeline to assure that the momentum management constraints will not be violated.

2.1.4 Interleaved Spacecraft Maintenance Activities

The SOC includes the spacecraft momentum management wheel off-loading (WOL) slots following rules from the MOC flight dynamics group, allowing a degree of flexibility to interleave them with the science observations. Additional slots for orbit trajectory manoeuvres are included at the boundary of each planning cycle as placeholders for flight dynamics to control the TGO orbit back to the long-term predictions should this be necessary.

2.2 Concept Limitations

With limited time for concept and system development, it was essential to establish the scope of SOC activities and to remain pragmatic to the limitations of SOC capabilities. While the TGO concept calls for interacting with the PI teams at a higher level of abstraction to handle the high number of individual observations, this introduces complexity when populating the instantiated observations with all the detailed parameter settings when tailoring to the unique conditions for each of the 1000s of opportunities in a typical month of the TGO mission. Some of this complexity could be transferred to the SOC, e.g. if the parameter setting can be derived from the observation opportunity geometry, but other settings require decisions to be made by the instrument teams and relies on the expertise of their extended teams. Following an initial round of concept discussions with the PI teams, the following areas were identified as requiring critical PI team intervention to have a practical means of moving from the high-level abstract planning to the detailed operations requests.

2.2.1 Target management

The high-resolution acquisition of targeted imaging involves the management of potential targets of interest, science-driven selection of targets and traceability to coverage goals that were beyond the scope of the SOC. In the TGO operations concept, the SOC provides time-periods where the CaSSIS team may select their desired targets if they remain within the off-nadir angle constraints. The CaSSIS team is responsible for managing their database of targets, providing their list of requested targets and pointing times to SOC over a dedicated interface (by-passing the observation definition mechanism) to be merged into the pointing request sent to the MOC.

2.2.2 Detailed Commanding and Parameter Setting

While the observation definition templates are parameterised to adapt to each of the computed opportunities, e.g. to cover the range of desired altitudes for a solar occultation observation. This approach proved adequate for constructing the pointing request, with the merging of the CaSSIS requests into non-interfering slots, but did not address the necessary instrument knowledge required to tailor the instrument commanding for each opportunity. The SOC permits two scenarios for the instrument teams to update their detailed commanding:

1. The SOC system is configured to generate commanding parameters that can be determined when instantiating observations in the timeline, e.g. if values can be computed from the observing geometries. The SOC provides a set of draft timelines to the PI teams for small further refinements. This approach is followed by the ACS team to set their science parameters
2. The SOC provides the PI teams with SOC planning events for their instantiated observations and geometry information in the form of SPICE kernels. Based on this information the PI teams generate and deliver to SOC instrument timeline files containing their detailed commanding, including the setting of parameters that may rely on science models. This approach was selected by the NOMAD and CaSSIS teams.

2.3 SOC Systems

As previously mentioned, core elements of the SOC system were lacking from the modules inherited from previous missions, namely the means to identify the opportunities to insert the observation types (opportunity analysis module) and a mechanism to down-select from all available opportunities to a compatible set of windows that respected the robust repetition rules coming from the SWT (scheduler module). Both modules were rapidly developed in the final years of development and were made available for the MTPs under SOC control.

2.3.1 Opportunity Analysis

As the TGO planning can be based on the long-term orbit products from flight dynamics, the opportunity analysis module is used to precompute observation conditions and other planning parameters, such as slew times, for the range of conditions defined in the observation definitions covering the 6 month timespan of the LTP.

2.3.2 Scheduler Module

TGO planners interact with the scheduler through a JSON configuration file that allows for the specification of e.g. occultation altitudes, pattern of occultations, ingestion of relay slots. The output of the scheduler is a file containing a set of science planning events that represent the baseline plan of activities in the science observation timeline.

2.3.3 Interface to MAPPS planning tool

The science planning events are an input to a science planning tool inherited from previous missions, MAPPS, that is adapted for TGO to ingest the observation types containing pointing as well as commanding. This allows the SOC to define top-level timelines with a few dozen entries which, when resolving observation types to the science planning events, expands to the thousands of observations that constitute the medium-term plan. These expanded timelines can be simulated in MAPPS to estimate the resource consumption and to check against the operational constraints.

2.4 Stakeholder Interfaces

It was essential to establish an operations concept that was compatible with the MOC mission planning system capabilities and the exchange of products with the MOC, such as the provision of orbit information or the update of ground-station allocations. To simplify the exchange of planning information between the PI teams, SOC and MOC, a single planning interface was established for science operations activities between the PI teams and the SOC. The SOC is responsible for the validation of the final set of pointing and commanding requests and for the delivery of the operations requests to the MOC (see figure).

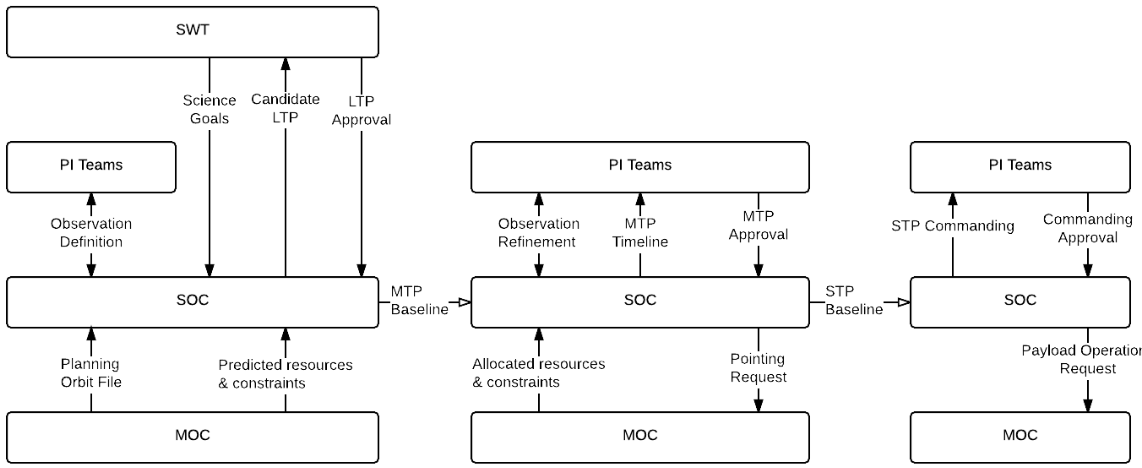


Figure 3: SOC interfaces and interactions with PI teams and MOC in the long-, medium- and short-term planning cycles.

The systems at SOC and MOC were both adapted from previous missions and had inherited overlap in the checks performed on the payload operations resources and constraints. The areas of responsibility were clearly defined to minimise the workload on both teams and to avoid unnecessary iterations.

2.4.1 Resource profiles
The generated payload data, data storage and data return are modelled at SOC to ensure that the mission constraints are met and that no science data are lost. This modelling is not replicated at MOC and is instead provided by SOC as data-rate profiles in the commanding requests.

2.4.2 Mission Operations Constraints
The SOC replicates many of the operations constraints checked by MOC systems to avoid iterations on the delivered requests. Initially it was intended to exchange common definitions as a system configuration file between MOC and SOC systems to synchronise on a common baseline for each planning cycle, however this had to be descoped to capturing constraints definitions in documentation for independent implementation at SOC and MOC.

2.4.3 Flight Dynamics Interfaces
The SOC pointing request interface to flight dynamics was found to be inadequate for high-resolution imaging of targets. The interface was extended to include a dedicated pointing type that meets the target pointing accuracy demands of the CaSSIS camera. Flight dynamics provided a web-service to SOC so that the SOC generated pointing requests are validated prior to delivery. This web service also provides the SOC with periods of high-gain antenna (HGA) outage, when the HGA can no longer track Earth and downlink data due to mechanism articulation restrictions, for the SOC to factor into the data-return calculations.

3 Summary of the Science Operations Process
To execute this operations concept, the TGO SOC centralised science planning process was defined to interleave a conflict free payload observation timeline with data relay slots.

3.1 Long-Term Planning (LTP)
The main purpose of the LTP process is to support the SWT in converging on a robust observing strategy that meets the science goals of the mission.

3.1.1 LTP Inputs
The process relies on the provision of long-term orbit and ground-station allocation predictions from the MOC which have enough accuracy for the SOC to generate reliable baseline representative plans. The LTP activity also relies on input from the PI teams, including a populated library of observation types and their required conditions.

3.1.2 LTP Process
The SOC generates an agreed set of plots to present to the SWT as input to discussions on observing strategies (see Figure 4).

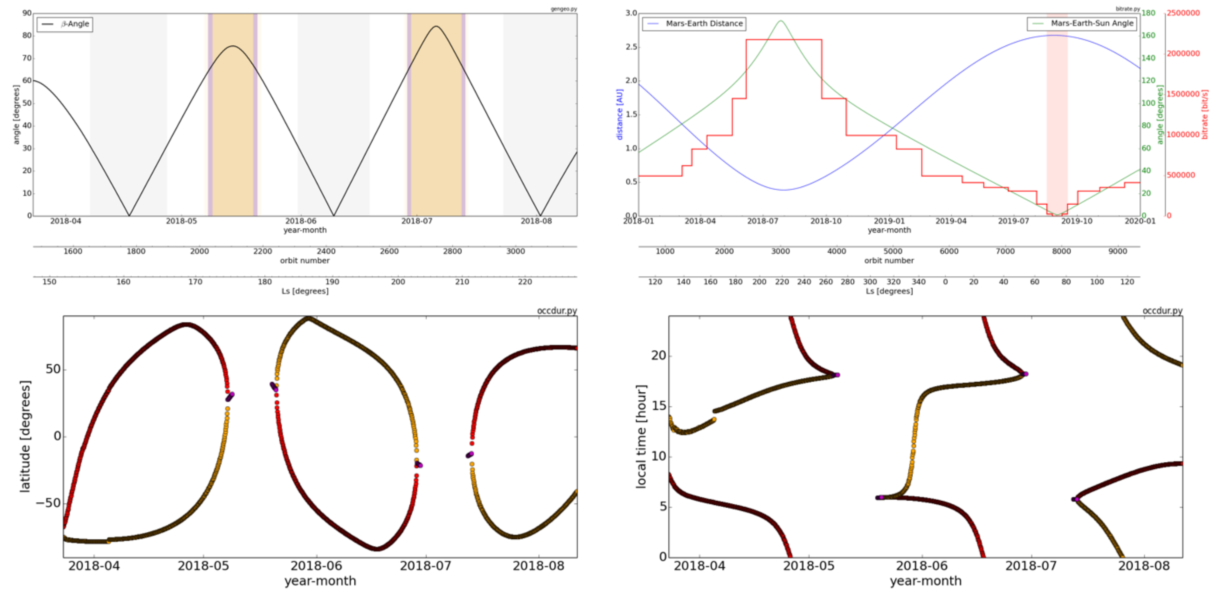


Figure 4: LTP plots provided to SWT to support the evaluation of observing strategies. Top-left: evolution of orbit beta-angle (angle between orbit plane and the sun-vector, grey areas indicate that rate-controlled spacecraft flips are required, orbits inside yellow area are occultation free), top-right: bit-rates throughout the LTP, bottom-left: latitude coverage of solar occultations, bottom-right: local-time of solar occultations.

The long-term planning process make use of the MTP and STP systems and processes described in this paper to validate the strategies under discussion with the SWT remain within the operations constraints.

3.1.3 LTP output

The strategy agreed for the 6-month LTP segment is captured through the configuration of the SOC scheduler, and in the selected observation types called from high-level instrument timelines.

3.2 Medium-Term Planning (MTP)

The start point for plan refinement in the MTP cycle is the baseline set of inputs propagated from the LTP process, as input to an automated scheduling process that regenerates a kick-off plan compatible with the latest inputs from the MOC. The SOC and PI teams then enter a 4-week period of plan refinement to converge on a science operations plan that finalises the pointing request (in the delivered PTR) and allocated resources (Figure 5).

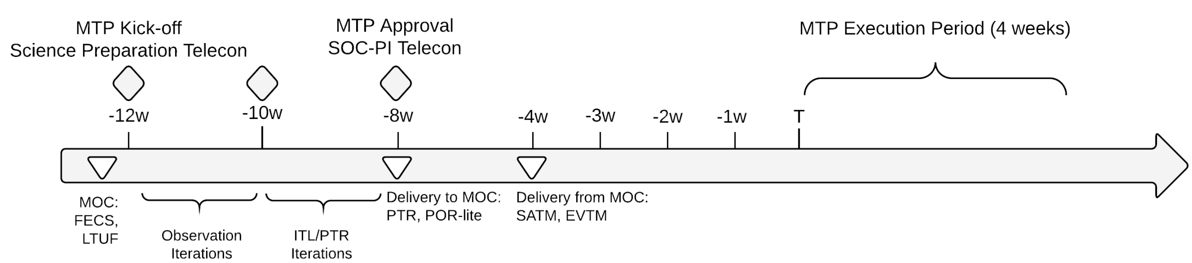


Figure 5: MTP process, file-exchanges and lead-in times prior to execution.

3.2.1 MTP Inputs

The SOC receives the scheduled relay slots from the MOC, then generates a baseline plan applying the strategy agreed with the instrument teams as an output of the long-term planning activity, with careful attention paid to ensuring only compatible observation types are scheduled in parallel to data-relay operations. The SOC manually inserts a small number of special observations as entries in the scheduler configuration file.

3.2.2 MTP Kick-off
A baseline schedule is provided to the instrument teams as a starting point for refinement that proactively avoids conflicts due to relay slots, pointing, resource limitations or spacecraft maintenance activities and covers the 4-week period that corresponds to the TGO medium-term planning (MTP) horizon. The MTP kick-off plan contains the special pointing observations and an assessment of the available data-volume based on the ground-station allocation provided by the MOC. The SOC also provides each of the PI teams with a data-volume budget per STP to avoid over-write of the on-board mass-memory payload data partitions. The timing information for the MTP observations is provided to the PI teams through a SOC generated planning events file in each MTP branch of the SOC GIT repository.

3.2.3 MTP refinement
The MTP is segmented into allocated observation slots and resource budgets per team, any updates made within this segmentation by the PI teams are by construction self-contained, i.e. they will not invalidate updates made by other teams. The MTP planning cycle (summarised in Figure 5**)** envisages two main types of refinement, systematic change to an observation type will update all related instances or the modification of an individual observation instance. In practice the systematic update is used most often in the MTP planning cycle, as the rationale for changing an observation instance is usually valid for all observations of the same type.

3.2.4 Targeted images
The CaSSIS instrument team has a dedicated interface with SOC for requesting their targeted observations. As part of the MTP kick-off data pack the SOC provides windows for the CaSSIS team to plan their observations, as well as some rules for checking if the included targets are valid (e.g. within 5 degrees of the ground track). CaSSIS provides their requested targets and observation types for the full MTP in a dedicated file-type that can be ingested into the SOC planning system for validation as part of the complete pointing request for the MTP.

3.2.5 Product Generation
Once the iterations with the PI teams are complete, the SOC generates a pointing request (PTR) containing requests that are scheduled relative to orbital events (Mars ascending node) spanning the complete 4-weeks of the MTP, validates the PTR using FD web-service then delivers the file to flight dynamics over the established SOC-MOC interface. From this point the pointing request is frozen. Flight dynamics will resolve the event-driven request to the final orbit determination prior to uplink to generate the attitude profile to be followed by the spacecraft.

3.3 Short-Term Planning Process (STP)
The instrument teams use the STP planning cycle to update their detailed payload commanding via instrument timeline files that span the 1-week short-term planning duration.

3.3.1 Command Refinement
The commanding updates are validated to respect the timing of activities provided through the SOC planning event file and the allocated instrument team data-volume budgets. The detailed commanding is checked for consistency with the TGO telecommand database (from MOC) and the modelled instrument operations constraints. SOC systems are then used to generate and validate the set of Payload Operations Request (POR) files that contain the instrument telecommand sequences, before submission to the MOC.

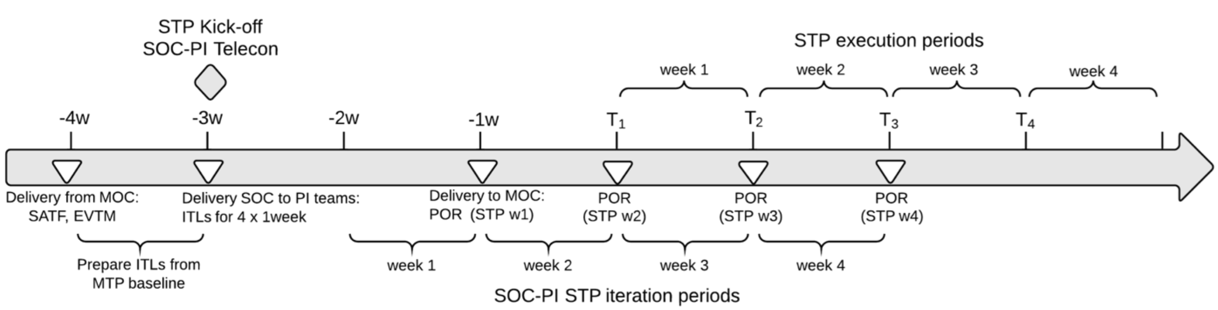


Figure 6: STP process, file-exchanges and lead-in times prior to execution

3.3.2 Fine-tuning of Imaging Parameters

As the TGO orbit is actively controlled, the planning is mostly robust to changes between the long-term orbit prediction and the final orbit determination. Any small offsets in absolute time are normally compensated by generating the operations requests relative to a selected orbital event (the nearest Mars ascending node), for subsequent resolution to absolute time by the MOC based on the final orbit determination before uplink to the spacecraft. The only exception is for high-accuracy imaging which needs to update the timing of images at parameter level based on the STP orbit determination, requiring an extra iteration between the SOC and the PI team once the flight dynamics event file is available.

4 Science Operations in the Nominal Mission Phase

The duration of the TGO nominal mission was one Martian year, spanning the period from 21st April 2018 to 28th February 2020. As the spacecraft employed aerobraking to reach the final science, an orbit prediction with sufficient accuracy for planning the spacecraft pointing was not available for the first months of the nominal mission. The initial strategy was to follow a fixed pointing pattern imposed by the flight dynamics group at the MOC that only made use of a set of observation modes that were relatively conservative from a spacecraft momentum management perspective. The SOC took over responsibility for the pointing requests from MTP005, with the understanding that in-flight operations experience had to be gained before new observing modes could be phased-in to operations.

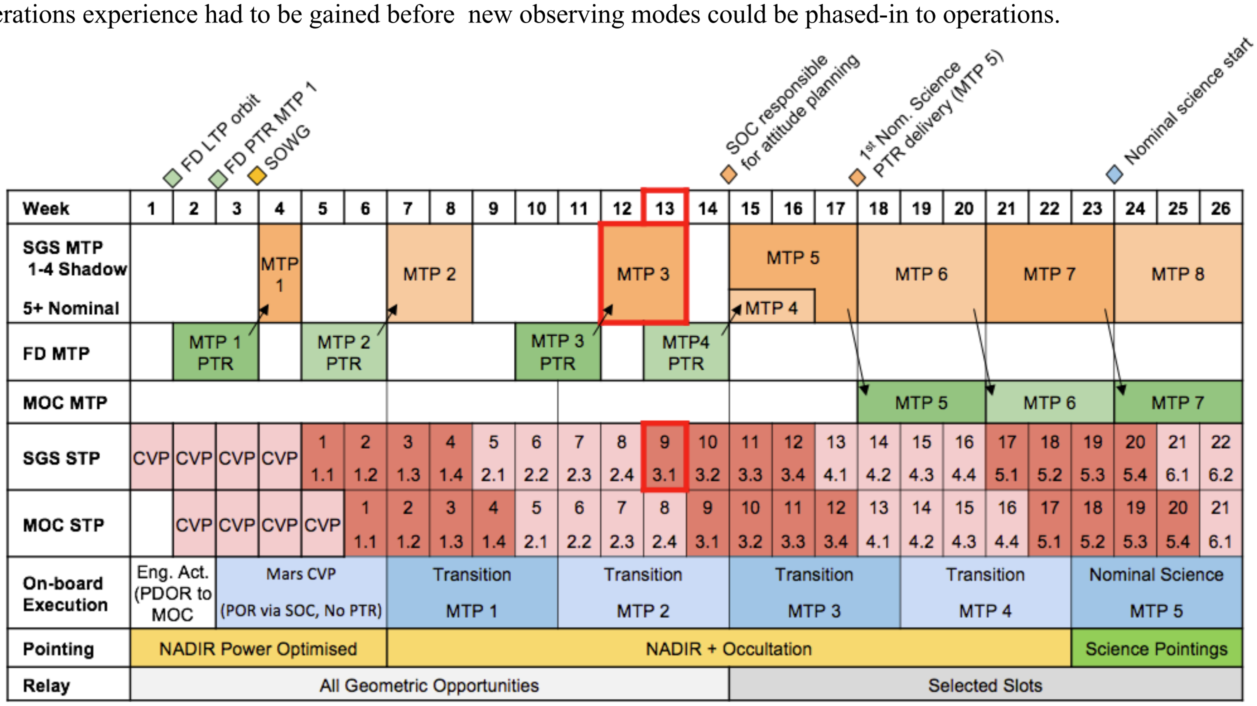


Figure 7: Transition to SOC-coordinated science operations at the start of the nominal science phase. Flight dynamics imposed the spacecraft attitude in the initial MTPs (1-4), SOC attitude planning started from MTP5 with a full-set of science pointings.

4.1 Long-Term Planning Execution

Long-term planning discussions held with the PI teams at the TGO science working team (SWT) meeting at the outset of the mission, supported by simulations and coverage analysis provided by SOC, quickly identified an appropriate segmentation of the solar occultations between the NOMAD and ACS instruments. The SOC was able to demonstrate that outside of occultation share the TGO payloads do not compete for observing time, for example the fraction of time spent nadir pointing was compatible with the coverage requirements of the FREND instrument team and did not constrain the number of excursions from nadir pointing required by the other payloads.

4.1.1 Capturing the LTP Strategy

The analysis provided by the SOC as part of the long-term planning activity included robust observation patterns that were compliant with the constraints imposed by the MOC. These patterns were captured in the scheduler configuration file, observation types and high-level instrument timelines. The SOC proposed strategy was also adopted by flight dynamics when constructing the pointing timeline for the transition MTPs at the start of the mission.

4.1.2 Definition of Observation types

The concept of generic observation types proved successful and made iteration on the TGO operations plan a feasible endeavour. One issue that was faced in the nominal mission was a multiplication of variants, e.g. to fit observations within different data-rate seasons or to capture minor variations in pointing types and parameters, the PI teams started to generate many similar observations that cluttered-up the library of observation types. This issue was largely solved in the extended mission through greater parametrisation of the observation definitions.

4.1.3 LTP output

The SOC generated Long-term planning outputs including representative timelines that met the science goals of the mission and were within the operational constraints. For presentation of the plan to TGO science management the most suitable view of the LTP plan proved to be a set of plots highlighting the advantages of new observing strategies or demonstrating the impact of proposed changes to observation constraints or observing modes.

The critical information to be propagated to the MTP planning process was the configuration of the scheduler tool (the SOC representation of the strategy from the SWT), the updated observations definitions, top-level instrument timelines and the precomputed geometry windows. Disciplined use of the SOC planning repository proved to be essential to maintain a common mission baseline for the MTP planners to reference.

4.2 Execution of Medium- and Short-Term Planning:

For execution of nominal mission operations, a planning lead was allocated to coordinate the medium- and short-term planning activities for each 4-week planning period to ensure the observation context for planning iterations with the PI teams was consistent for pointing and commanding updates.

4.2.1 MTP Kick-off

MTP planning required a re-run of the scheduling tools used for the LTP analysis, applying the configuration files that captured the agreed SWT strategy on the updated inputs from the MOC. The main bottleneck experienced in the nominal mission phase was the provision of the relay files to SOC, sometimes available only days before the kick-off of MTP iterations with the PI teams. The limited lead-in time reduced the capability of the SOC to optimise the placement of the special pointings and efficiently schedule the spacecraft maintenance slots as the hybrid setup of legacy software with new modules was an iterative, trial and error process.

- The scheduling module configuration file was manually edited to include the special pointing slots
- SOC planning event files from the scheduler module were ingested into a legacy science planning tool (MAPPS) inherited from previous missions, resolved to top-level timelines to generate expanded timelines with 1000s of observations (see Figure 8 for one day of observations).
- The expanded timelines were then run through simulations to estimate the resource consumption and to check against the operational constraints, then exported as a full end-to-end pointing request (PTR file)
- The PTR was validated using the flight dynamics web service, through the web front-end.
- For each constraint violation reported by the FD web-service, the SOC planner had to adjust the timing of the special pointings in the scheduler configuration process and restart the process.

During the nominal mission several delays to the MTP kick-off were experienced due to the inefficiencies of the preparation activities, reducing the time for the SOC and PI teams to refine the science plan. System and process improvements to alleviate this situation were prioritised for the extended mission.

4.2.2 MTP Refinement

The TGO MTP refinement process is completely file-based and calls for the simultaneous update of planning files made by multiple instrument teams. While the development of a bespoke collaboration platform was far beyond the scope of the TGO SOC, the available ESAC infrastructure was adequate for plan interactions. A TGO science planning GIT repository was branched per MTP where the planning refinements between SOC and PI teams were managed using pull-requests.

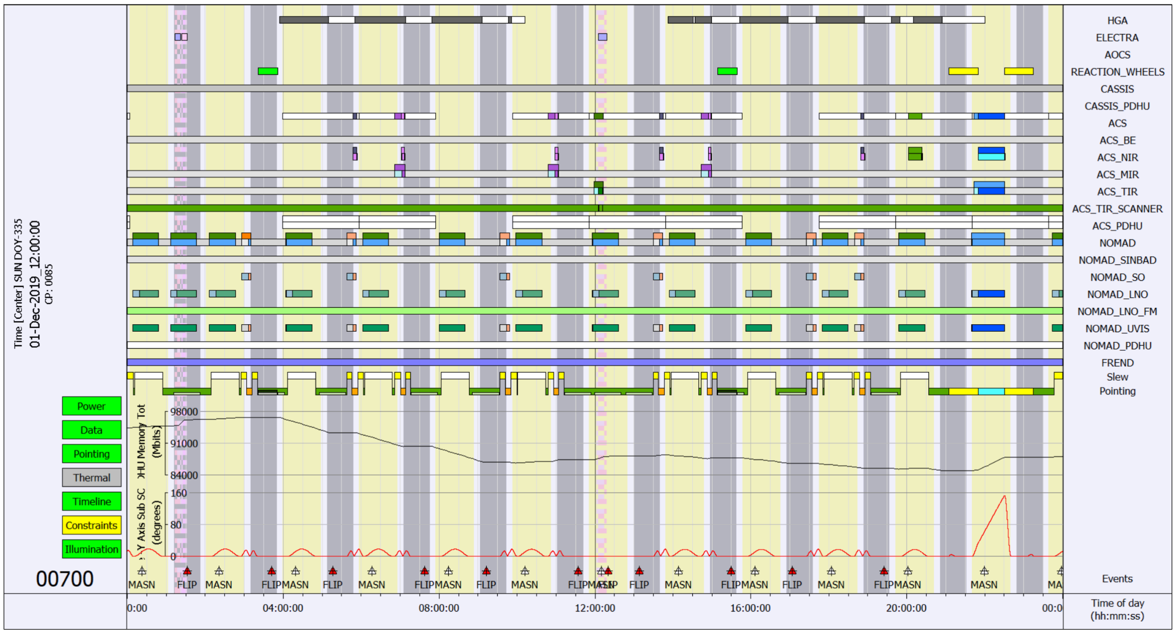


Figure 8: Timeline of science observations instantiated for one-day of TGO operations, including spacecraft maintenance activities (reaction wheels), relay slots (Electra), Communications passes (HGA), Payload operations, mass-memory backlog (PDHU memory), and off-pointing from nadir pointing (-Y axis sub s/c).

4.3 Nominal Mission Constraints

From the start of the nominal mission through to the ongoing mission extension, the SOC and MOC have followed a pragmatic approach to gradually phase-in additional observing modes and allow an increased degree of flexibility in the science observation timeline once validated to be operationally robust based on in-flight experience. Following the transition period (MTPs 1-4), the SOC continued to apply the robust patterns according to rules provided by flight dynamics to remain compliant with the strict momentum management constraints. During the nominal mission the SOC identified several constraints that were causing the largest impact on the science observations coverage and science return of the mission.

4.3.1 Off-Nadir Pointing during Lander Relay

During the nominal mission only pure nadir pointing was permitted during relay passes. In the extended mission TGO benefitted from experience coming from other Mars missions that use the same ELECTRA communications package, and so could apply similar rules to allow limited excursions from nadir pointing for a subset of relay passes with high elevation as seen from the landed asset. The relaxation of this constraint increased the number of targets available to the CaSSIS camera team, as well as permitting the acquisition of context images near the location of the landers.

4.3.2 Future Changes

Further changes to the mission constraints are foreseen to enhance the capabilities of the mission, but also to adapt to changes in the programmatic baseline that may require SOC and MOC to define operational strategies that proactively preserve the longevity of several life-limited systems present in the scientific payloads and the spacecraft.

4.4 MTP Outputs

The process for generating the main SOC deliverable outputs of the MTP planning cycle worked as expected in the nominal mission. Flight Dynamics reserved a 2-week period for iteration on errors in the pointing requests, but the only problems encountered were to insert additional wheel off-loading slots after a major orbit change manoeuvre. The SOC provided preliminary versions of the payload commanding files (POR-lites) which also contained representative data-rate profiles. The content of these files varied in accuracy by instrument, given the approach to commanding update in the STP cycle. Minor issues with requests were identified at the MTP stage and were addressed through updates to the payload state-models in both MOC and SOC systems or with small adjustments to operations margins in the constraint definition.

5 Science Operations in the Extended Mission Phases

Several improvements were made to the TGO mission capabilities, science operations process and constraint flexibility were made in the extended mission phase (summarised in Table 2).

Table 2. Main improvements made to TGO operations in the nominal and extended mission phases.

Improvements	Nominal Mission Phase	Extended Mission
Observation Types	MTP 1-4 only Nadir and solar occultation. MTP5+ gradual introduction of targeted pointing	Systematic inclusion of targeted pointing
Highly Valuable Observations	Constrained by relay slots	Most opportunities preserved
Special Observation Slots	1 slot per week for calibration 1 slot per week for inertial limb pointing (from MTP014)	4 slots per week Limb tracking from MTP037 MIR Aerosol observations from MTP037 Phobos/Deimos observations
Mission Constraints	30-minute WOL blocks Symmetric occultations only (tranquilisation, pairs) No targeted pointing during relay slots	20-minute WOL blocks, dayside WOLs Asymmetric occultations from MTP041 Targeted pointing during relay slots
Data management	Even split of data volume allocation	Greater use of on-board storage Data-volume split based on previous MTP trends Management of HGA time
Degree of Automation	Early version of scheduler software Extremely manual process, work-arounds using legacy tools including PTR generation Manual PTR validation PI team iterations for parameter updates	Scheduler enhancements and performance improvements Stand-alone PTR generation Scripted PTR validation using FD webservice Automated telecommand parameter updates at SOC

5.1 Preservation of High-Value Observations

In the extended mission phase the LTP process was adapted to proactively reserve the slots for high-value observations as an input to the relay planning activity, preventing the loss of opportunities due to conflicting relay requests at MTP. The quota of slots reserved for special pointings was gradually increased, starting from a single calibration slot per week at the start of the mission, the inclusion of inertial limb pointings from MTP014, through to the current quota of 4 special pointing slots per week driven by access to new pointing types and extended observing capabilities.

5.2 Extended Observation Capabilities

The PI teams requested new observation types at the SWT to improve on shortcomings observed in the results obtained during the nominal mission. The SOC analysed the needs coming from the teams and proposed expanding the pointing request interface with flight dynamics to accommodate additional pointing types, some of which were used on previous planetary missions. In particular, the inertial pointings used for Mars limb observations were greatly improved in the extended mission through the implementation of a dedicated limb-tracking pointing mode (see Figure 9).

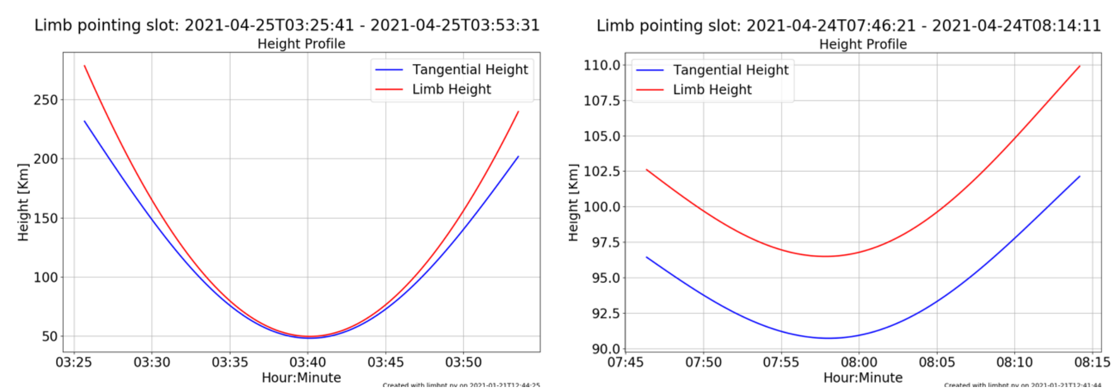


Figure 9: Inertial pointing (left) used in the nominal mission resulted in a large variation in altitude during the limb observation. Introduction of limb-tracking (right) in the extended mission resolved this issue.

5.3 Flight Dynamics Constraint Evolution

A pragmatic approach was taken with the flight dynamics to incrementally phase in new spacecraft dynamics constraints, especially those related to ensuring the momentum management thresholds were respected. The constraints at the start of the nominal mission required a 30-minute wheel offloading (WOL) slot to be allocated in the pointing request every 12 hours. The duration of this WOL slot was very restrictive to science operations as it would typically remove one or both solar occultations every 6 orbits. In-flight experience demonstrated that typical WOLs were less than 5 minutes in duration with very few outliers around 10 minutes long. It was agreed to reduce the WOL duration to 20 minutes, keeping some margin for orbit prediction errors, which allowed the SOC to preserve one of the occultation pair in one out of 6 orbits.

This improvement relied on relaxing another requirement on occultation symmetry, or the need to always have an occultation pair in the pointing request. The SOC provided test PTRs for MTP deliveries that demonstrated keeping only one of the solar occultation pair had no significant impact on the flight dynamics constraints, allowing this restriction to be dropped and more solar occultation observations to be included in the PTR (see Figure 10).

For the first MTPs with relaxed flight dynamics constraints the agreement with SOC was that the 2-week iteration period after request delivery could be used to insert additional WOL slots should this be determined as necessary. This iteration was not required, and the new constraints were applied without disturbing the operations process.

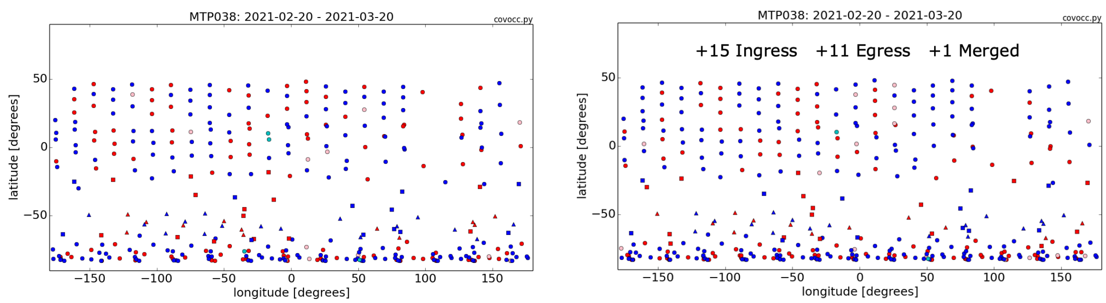


Figure 10: Relaxation of symmetry requirements for limb pointing, (left) requiring ingress and egress pairs and (right) single ingress of egress are allowed resulting in additional occultations.

5.4 MOC-SOC Operations Constraint Evolution

Based on operational experience of the Electra UHF communications package on the NASA Mars Reconnaissance Orbiter (MRO) mission, the strict constraint on pure-nadir pointing during relay overflights was relaxed to permit limited off-nadir pointing for high-elevation overflights. This modification to the constraint allowed the CaSSIS team to schedule targeted pointing in many of the dayside passes that also contained relay slots and allowed for more context images of the landing-site regions.

During the nominal mission the SOC took a cautious approach to providing data-volume budgets to the teams, by trying to minimise the backlog of data accumulated on board in the spacecraft mass-memory. The strategy was adapted in the extended mission to allow the instrument teams to acquire more data in preferable observing conditions (e.g. at low and medium beta-angle ranges) and recover the backlog elsewhere in the MTP (Figure 11). This approach was extended to bridge through the superior solar conjunction and allowed the teams to operate right up until the point where the payloads had to switch-off due to safety concerns.

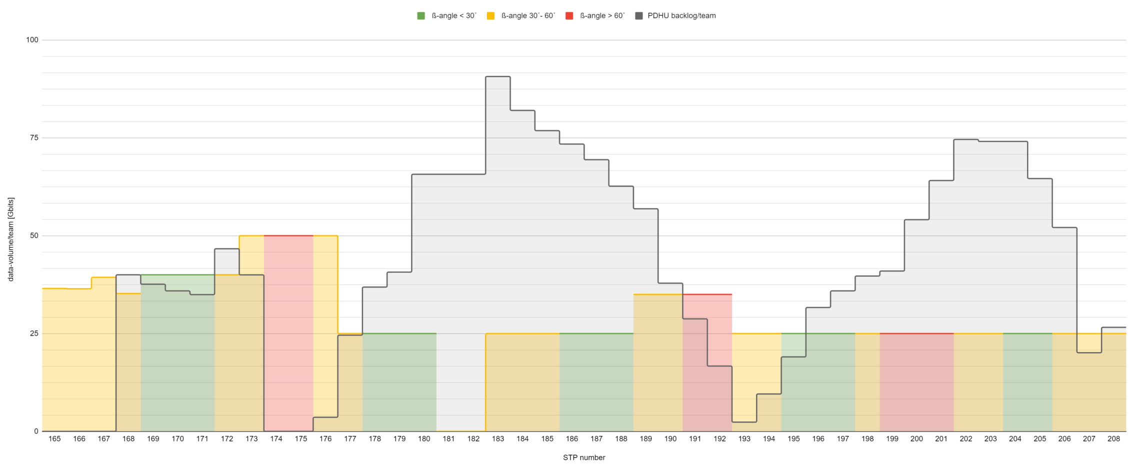


Figure 11: Management of on-board science data in the extended mission. On-board mass memory used to buffer backlog during favourable observation periods (green and yellow shaded areas) and maintain a reasonable allocation of data-volume either side of the superior conjunction (payloads off/standby for the conjunction in STPs 181 & 182)

Analyses of the data-volume trends in the nominal mission were used to determine a realistic upper limit for data-volume acquisition and could be used to limit the number of hours the high-gain antenna needed to operate in the extended mission during the high data-rate seasons to preserve the lifetime of the antenna pointing mechanism. The mass-memory was split into even partitions for the 3 main data-producers (ACS, CaSSIS and NOMAD), this distribution was adjusted based on observed data acquisition statistics, e.g. CaSSIS with 50% of data generated in past MTPs now has around 50% of the mass-memory area devoted to science data.

6 Further Enhancements to the TGO Science Operations Concept

The TGO mission is likely to continue to schedule science observations until the arrival of the ExoMars rover in the early 2030s, providing an opportunity to make further enhancements to the SOC operations concept and processes as well and requiring careful management of life-limited items to preserve the longevity of the payloads and spacecraft sub-systems.

6.1 Management of Life-Limited Items

The SOC and MOC will continue to analyse the data-volume acquisition trends from the mission so far to improve the allocation of ground-station passes tailored to the expected data-return requirements of the mission while avoiding excess usage of the High-Gain Antenna pointing mechanism to extend its lifetime. The SOC will also collaborate with the MOC and PI teams to devise TGO science operations strategies for a spacecraft configuration where the HGA remains fixed requiring a trade-off between science pointings and communications passes while maintaining relay support.

6.2 Future Evolution of SOC Operations Concept

Placement of special observations occupies a large fraction of the time taken by the SOC to prepare each MTP, while the remaining nominal observation types are mechanically filled around these observations by the SOC planning system. With greater emphasis on decision-making in the LTP planning process, the allocation of special observations can be made further upstream, and the opportunity analysis extended to the dedicated calibration and special science observations.

6.2.1 Increased Automation

It is intended to generate candidate slots for some categories of special pointing, to allow the MTP planner to quickly identify the most suitable candidate at MTP kick-off based on the latest available inputs. Remaining special pointings, that do not need any manual optimisation when placed into the timeline, will be treated in the same way as nominal observations and be part automatically included in the scheduled observations by the SOC planning system. This approach will shift the SOC workload away from manual MTP preparation, instead focussing the SOC planning activities on the more strategic science planning discussions at LTP.

7 Conclusion

TGO science operations successfully built on the concepts demonstrated on previous missions, adopting legacy software and established plan iteration cycles due to the short development time before the start of nominal operations. Despite the strong incentive towards reuse, it proved essential to identify the key driving characteristics of the mission to extend the concept and systems to be adequate for conducting science operations. In the case of TGO this was clearly the need to abstract to observation types to have manageable refinement cycles with the PI teams. During the nominal mission the drawback of this approach was a proliferation of types, now successfully tackled in the extended mission with the parametrisation of observations. The concept evolution has consistently been in the direction of moving science planning decision further up-stream towards the long-term planning, and process bottlenecks were mostly eliminated through improvements to lead-in times and system performance. The planning complexity reduced in the extended mission, with the relaxation of operational constraints based on inflight experience, even though number of new observing modes substantially increased to greatly improve the science return of the mission. In future mission extensions the trend towards shifting the strategic decision making up-stream in the planning process and increasing the automation close to the commanding is expected to continue. Despite being in nominal operations since April 2018, conditions on TGO are continuously evolving, and the operations concept will also need to adapt to extend the lifetime of the spacecraft and payload into the 2030s.