Planetary and Space Science 231 (2023) 105697

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Targeting and image acquisition of Martian surface features with TGO/CaSSIS

M. Almeida [a,*], M. Read [a], N. Thomas [a], G. Cremonese [b], P. Becerra [a], G. Borrini [a], S. Byrne [c], M. Gruber [a], R. Heyd [c], C.M. Marriner [d], G. McArthur [c], A.S. McEwen [c], A. Pommerol [a], J. Perry [c], C. Schaller [c]

[a] *Physicalisches Institute, University of Bern, Sidlestrasse 5, 3012, Bern, Switzerland*
[b] *Osservatorio Astronomico di Padova, INAF, Padova, Italy*
[c] *Lunar and Planetary Laboratory, Tucson, AZ, USA*
[d] *Open University, Milton Keynes, UK*

A R T I C L E I N F O

Keywords:
CaSSIS
Mars
ExoMars
Planning
Image targeting

A B S T R A C T

CaSSIS is a high-resolution visual telescope onboard the ExoMars Trace Gas Orbiter. The mission started the primary science phase in April 2018. The relatively small single image footprint (typically 40 km × 9.5 km) when compared to the total surface area of Mars demands that images should be targeted and target selection is key for the science return. This paper describes the science planning concept set around the target selection, and the process followed in order to generate the CaSSIS commands.

The tools used are described as well as all the iterations and teams involved. Finally, special cases and the handling of contingencies are discussed. The procedures may serve as a guideline for future high-resolution instruments on missions to planetary objects.

1. Introduction

ExoMars (Vago et al., 2015) is a Mars exploration program consisting of two missions, an orbiter launched in 2016 and a rover mission planned to be launched in 2028. The 2016 mission, also known as the Trace Gas Orbiter (TGO), was launched in March 2016 and, after orbit insertion in October 2016 and a period of aerobraking, entered in its primary science phase in April 2018. The payload of TGO is designed to perform observations of the atmosphere of Mars using two high resolution spectrometers, ACS (Korablev et al., 2018) and NOMAD (Vandaele et al., 2018), along with imaging of potential trace gas source regions at moderately high resolution. Additional objectives include the study of transient, dynamic phenomena on the surface (Vago et al., 2015) and the mapping of hydrogen in the sub-surface down to a depth of approximately 1 m (Mitrofanov et al., 2018).

The Colour and Stereo Surface Imaging System (CaSSIS) is the imager on board TGO and has been designed to characterise sites which have been identified as potential sources of trace gases, to investigate dynamic surface processes, and characterise potential future landing sites (Thomas et al., 2017). Typically, images are around 9.5 km × 40 km in size at a pixel scale of about 4.5 m/px from the nominal orbit altitude and in 3 or 4 colours. Stereo images can also be acquired using a rotation mechanism. The data rates from the spacecraft limit the number of image acquisitions to between 1 and 4 per orbit (12–50 per day) depending upon the Earth-Mars distance and the ground station coverage. The spacecraft orbit is not Sun-synchronous, and the ground-track varies through the full range of local times. Furthermore, the spacecraft acts as a communications relay orbit for landed missions on Mars and this leads to interruption of image acquisition and exclusion zones for imaging. The spacecraft can roll to point CaSSIS to specific targets but there are significant restrictions on this capability arising from the spacecraft design. The control of the spacecraft attitude is maintained using momentum wheels which have to be off-loaded at regular intervals. The other instruments on TGO also have pointing requirements which affect the times at which CaSSIS can image the surface. The constraints and requirements implied by the above leads to a complex planning process for CaSSIS that is needed to optimize the data acquisition and target the most interesting places on Mars under good illumination conditions. This paper describes the operational planning procedure and is intended to support future imaging instrument operations by indicating how the scientific return

* Corresponding author.
E-mail address: miguel.almeida@unibe.ch (M. Almeida).

https://doi.org/10.1016/j.pss.2023.105697
Received 13 December 2021; Received in revised form 12 April 2023; Accepted 21 April 2023
Available online 22 April 2023

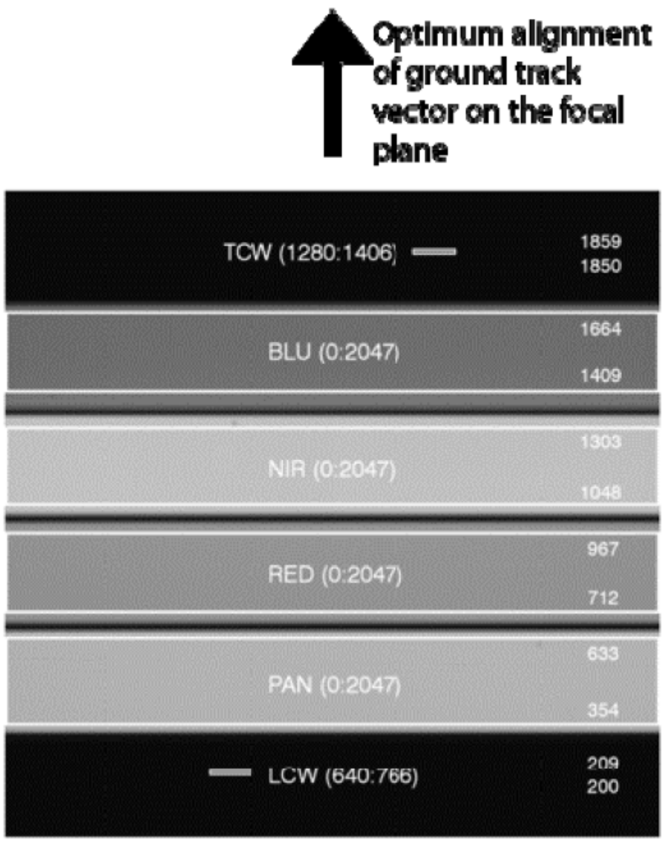

Fig. 1. - CaSSIS filter setup on top of the 2048 x 2048 CMOS sensor (Thomas et al., 2017): This filter mask combined with the push-frame image acquisition setup – allows for up to four colour CaSSIS images. The numbers in between parenthesis are the horizontal pixel coordinates starting on the left, and the numbers on the right are the limits on vertical pixel coordinates for each filter. Areas outside the boxes are discarded during image assembly. PAN (Panchromatic, 676.5 nm), RED (Red, 838.5 nm), NIR (Near Infrared, 1000 nm), BLU (Blue, 480.5 nm), LCW and TCW are below the opaque mask, providing bias and dark current control windows. Shading represents the grey scale interpretation of the different filters.

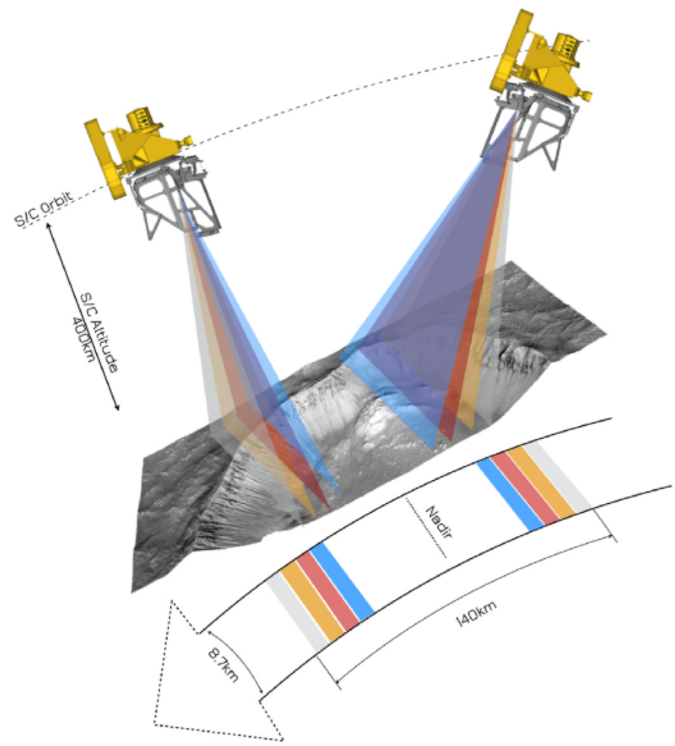

Fig. 2. - Orbit alignment and stereo strategy of CaSSIS (Thomas et al., 2017): The spacecraft is moving from right to left in the image. The CaSSIS motor allows for optimal alignment of the frame with the ground track as well as Stereo image acquisition.

has been optimized using multiple tools. This information also helps users of the science data to understand the dataset.

In the next three sections, we shall recall the important aspects of the instrument and the spacecraft that lead to the planning requirements including the targeting methodology. In the following section, we shall outline the planning methodology used by ESA that was required to be supported. In section 6 we shall describe our planning tools and their capabilities. In sections 7, 8, we shall describe the deliverables and the verification of the execution. We conclude with a summary emphasizing the benefits of the system used but also identifying some of the aspects that could be improved upon for future missions.

2. The CaSSIS instrument

A full description of CaSSIS is given in (Thomas et al., 2017). Here a summary of the instrument is given focusing on elements of CaSSIS that have a direct impact on the planning process of CaSSIS images.CaSSIS is a stereo multi-colour push-frame imager based upon an F/6.5 telescope with a focal length of 880 mm. The detector is a 10 μm pixel pitch CMOS hybrid detector system originally developed for the SIMBIOSYS imager for BepiColombo (Cremonese et al., 2020). CaSSIS has an angular scale of 11.36 μrad/px which, when combined with the nominal orbit altitude (roughly circular 400 km above the surface) leads to a spatial scale on the surface of Mars of approximately 4.5 m/px.

In order to obtain multi-band information of the acquired sites, filters were placed on top of the CMOS detector as shown in Fig. 1. The images are obtained by aligning the line that is orthogonal to all filters with the spacecraft velocity vector over the surface of the planet (i.e. the spacecraft ground track, as it can be seen in Fig. 2). To achieve this, CaSSIS has a motor that can be commanded to a defined position prior to image acquisition. The motor rotates 360° around the CaSSIS mount axis.

CaSSIS does not point directly downwards to the planet but its optical axis is tilted by 10° with respect to the spacecraft nadir vector, where the nadir vector is defined as the vector perpendicular to the spacecraft panel where CaSSIS is mounted. The same motor can therefore be used to look either forward or backward in the spacecraft motion direction, doing a quick approximately 180° rotation, which allows acquisition of stereo pairs with a convergence angle of 22.4° (taking into account the curvature of Mars; Fig. 2).

The images acquired can cover the full swath (left to right in Fig. 1) or only part thereof. A trade-off is made between swath width and the number of colours acquired. In a push-frame system, images are acquired at a rapid frequency that matches the speed at which the spacecraft flies over the surface. The framelets generated by this rapid imaging must subsequently undergo a mosaicking process to produce the final image. Typically, CaSSIS will acquire 40 framelets in an imaging sequence of a target. Sufficient overlap between the framelets is needed to ensure a high quality final mosaic. For the nominal orbital altitude of TGO, the framelet acquisition frequency is around one framelet every 400 ms. The combination of the framelet width and the number of colours to be acquired, and thus the number of pixels acquired, are constrained by the maximum data transfer rate of about 70 Mbit/s (a SpaceWire connection (Thomas et al., 2017);) from the detector to the instrument storage. The trade-off between swath width, representing spatial coverage, and number of colours, representing spectral coverage, is a science choice made by team members proposing and programming the image acquisition.

The flight software provides image compression capability using two algorithms. A wavelet-based JPEG compressor is the most frequently used. The target compression ratio is selectable, from lossless compression of about 1.75 to around 14 (these are not exact as they depend on the scene content) with a value of 3 providing almost no loss in image fidelity, and a value of 6 providing results of acceptable quality (the mean difference in the DN values across the detector are less than 0.1). Use of higher compression ratios has been rare. Data can also be binned onboard. However, this option provides few advantages and is rarely used.

3. The spacecraft planning constraints

The TGO spacecraft is in an orbit with approximately 74° inclination. Small manoeuvres for phasing of the orbit to accommodate the support for landing of various surface missions (e.g. the ExoMars rover) can lead to small changes in the inclination. The 2 h orbit is slightly elliptical (~365 km × 420 km) with the lowest altitude, and hence largest ground speed, always at high southern latitudes.

Unlike, for example, Mars Reconnaissance Orbiter (Zurek and Smrekar, 2007), the spacecraft orbit is not Sun-synchronous and therefore the illumination conditions can be completely different on two passes over the same target. In general, small solar incidence angle observations are most suitable for accentuating colour diversity whereas larger incidence angles tend to provide better topographic definition(Young, 1975).

TGO was originally conceived as a nadir-pointing spacecraft combined with a resonant orbit to provide repeat coverage. However, the distance between ground-tracks at the equator in this configuration was around a factor of 3 larger than the swath width of CaSSIS implying that areas between ground-tracks could not be imaged by the instrument. This was recognized during the development phase and the possibility for small (±~5°) rolls of the spacecraft about the ground-track vector was incorporated into the planning. The roll is constrained by the load it puts on the spacecraft reaction wheels and the fact that from planning to execution there can be a drift of up to 2 min and the corresponding Mars rotation could lead to an actual roll of about 10°. The timescale for rolling to the correct attitude is, however, long (~20 min in each direction), taking a significant portion of the 1 h the spacecraft flies over the day side of Mars. Hence, it was agreed that TGO would only perform one off-nadir pointing (referred to as a “Targeted” image) every orbit.

There are also a range of TGO maintenance manoeuvres that restrict CaSSIS imaging. CaSSIS cannot image during a weekly 3-h slot reserved for orbital correction manoeuvres in order to keep as close as possible to the predicted orbit. Wheel Off Loading (WOL) manoeuvres also prevent CaSSIS imaging. There are also dedicated communication slots with ground assets (e.g. with rovers). These do not prevent image acquisition but they prevent complete freedom of spacecraft movement, as CaSSIS is only allowed to point in the direction of the ground assets as long as TGO is visible from the rovers and landers. This can limit what CaSSIS can image, for about 2/3 of the orbit. Given the number of rovers on the surface, this can provide a significant constraint especially for targets close to but not at landing sites.

Finally, as the Trace Gas Orbiter name implies, atmospheric measurements of the Martian atmosphere are made by the NOMAD and ACS instruments on board the TGO. These instruments point at the Sun through the Martian atmosphere (solar occultation), which is achieved by pointing the underside of the TGO, where all instruments are mounted, at the Martian limb, thus preventing surface imaging by CaSSIS.

4. Target suggestion

The target suggestion follows a similar process that was developed and refined by the HiRISE team (Chojnacki et al., 2020) and ported to CaSSIS.

The very first step in the process of CaSSIS targets definition and selection is the population of a database of potential targets with information on what particular instrument settings are desired (filters, width, length …) and possibly constraints on the timing and conditions of observation (timing, illumination …). The addition of targets to the database can be performed at any time throughout the mission, from long before the beginning of the science phase to immediately before or even shortly after the actual planning of the observations. Until 2022, populating this database has been the sole responsibility of the CaSSIS science team but we plan to open this possibility to the entire community in the future, following what was done for HiRISE with the HiWish tool (Chojnacki et al., 2020). In this context, the discussion provided here should be useful for future proposers to optimize the suitability of suggested targets.

Ingesting new targets into the database is done using the CaST (CaSSIS Suggestion Targeting) web-GIS software, which allows users to freely draw regions-of-interest (ROIs) over Mars maps with various overlayed layers of information. Details on the software and its usage are provided in Section 6 while we focus here on the rationale for choosing suitable targets for CaSSIS and how they are evaluated and prioritized for imaging.

In order to suggest promising targets, some of the specifics of CaSSIS and the TGO platform must be considered. CaSSIS is a high-resolution (4.5m/px) imager with a narrow field of view (8 km across-track). It is therefore best used to target precise regions of the surface but not to map systematically large areas. CaSSIS is a color imager and provides very useful multispectral data to study areas with variegated colours and mineralogy while panchromatic data at similar resolution might already have been taken by other instruments. Even in this case, CaSSIS might still provide additional information because of its high SNR in the PAN filter when the atmosphere is clear and the illumination conditions are appropriate. Good guides to select rocky regions of the surface and avoid dusty homogenous areas are the thermal inertia map of the surface and night time temperature map from the THEMIS dataset (Edwards et al., 2011), both available in the CaST tool. Because of internal limitations in the data transfer rate from the detector proximity electronics to the mass memory, tradeoffs must be made between the number of filters and the width of the field of view. While it is possible to use the whole width (or almost, depending on the spacecraft altitude) with three filters, the use of all 4 filters requires a reduction of the width by about a third. In case when one filter has to be dropped, the NIR-PAN-BLU configuration is generally used but proposers remain free to suggest other combinations depending on their needs. A NIR-RED-BLU combination can be an interesting choice as the exposure time will be optimized for the colour filters instead of the panchromatic filter (see section 6.2.1 on CaPHot), resulting in a better SNR in the three acquired filters. In some circumstances, it is necessary to keep only two filters to use the full width (2048px) of the field of view. In this case, PAN and BLU are most often chosen.

A notable particularity of CaSSIS imaging is that orbit of TGO is not sun-synchronous. As a consequence, the surface can be imaged at various local times throughout the season and the illumination will vary considerably. This is both an advantage and a complication for the selection and planning of targets. For this reason, the users of the database are invited to provide constraints on the observation geometry together with each target. For instance, most geomorphologists will favor intermediate phase angles in the range of [20–60°] which provide a good sense of the topography while keeping the length of shadows limited. Scientists who are more interested in the surface composition tend to choose lower phase angles, down to the opposition (0° phase) to limit the influence of topography and reveal the intrinsic color variegations caused by mineralogy. On the contrary, scientists interested in the diurnal and seasonal processes and volatiles might want to plan observations early or late in the day and season and close to the terminator. Such observations often have lower signal-to-noise ratio (SNR) however and the SNR decreases very fast as the incidence angle increases. Good quality color imaging is still possible up to incidence angles of ~75°, while imaging in PAN can still be useful up to incidence angles of almost 90°. This is highly dependent on the brightness of the target and the transparency of the

Table 1
The 18 science themes to which the targets are assigned with the corresponding number of targets proposed and number of images acquired. Numbers of targets and acquired images for each theme valid as of September 2022. Targets can be requested to be imaged multiple times, explaining why more images than targets can exist for a given science theme.

Science theme	Number of targets in the database	Number of images acquired
Atmospheric processes	11	7
Hydrothermal processes	84	25
Diurnal changes	421	350
Eolian processes	900	1047
Fluvial processes	1292	1059
Future exploration/landing sites	429	261
Geologic contacts/ stratigraphy	498	617
Ice and periglacial processes	237	848
Impact processes	1581	2155
Landscape evolution	908	482
Glacial processes	11420	3631
Seasonal processes	319	1762
Sedimentary/layering processes	4389	1169
Slope processes	1592	1231
Rocks and regolith	103	129
Composition and photometry	2476	1690
Tectonic processes	824	752
Volcanic processes	697	699

atmosphere. Note that preferred times of the year and local solar times can be directly provided. This is useful for high-latitudes targets as well as regions that are known to have a clearer atmosphere in specific seasons such as Hellas basin. Repeated imaging at different times of the year as well as stereo imaging are also requested at this stage.

Note that all constraints added at this stage will strongly influence the possibilities for the target to be imaged and therefore the time it will take to actually acquire the image.

Another important aspect to consider when adding targets to the database is their previous coverage by other instruments. CaSSIS color images ideally complement other datasets with different resolution or spectral range. For instance, CaSSIS four-color images are very helpful to map at higher spatial resolution compositional units with an interesting mineralogy identified by CRISM or OMEGA or to add color coverage to an area already imaged at high resolution by HiRISE in its broad red filter. But not all targets should be already heavily studied areas as it is equally important to identify and image other sites of high interest, which might have been neglected as the overall scientific priorities from previous missions were different. Layers are available to identify and quickly access observations from other datasets (MOC, HiRISE, CTX, CRISM).

The users entering the target into the database assign to their targets a self-defined priority, in a range from 0 to 5 and write a short justification (typically a couple of sentences) to explain their choice of this target and choose for it one of the 18 science themes (Table 1). Each science theme has one or two coordinators named Science Theme Lead (STL), whose role is to review all targets in the theme and revise the priorities, on a scale from 6 to 10 based on their expertise and knowledge of the topic, as well as the priorities set by the proposers. This "team prioritization" is the last step of this process and the prioritized targets become the input for the actual planning of observations.

5. Long-, medium-, and short-term plans

The teams involved in the planning cycle are the CaSSIS Operations Team in Bern, the TGO Science Operations Centre (SOC) Team in the European Space Astronomy Centre (ESAC)/Madrid, and the Mission Operations Centre (MOC) Team in the European Space Operations Centre (ESOC)/Darmstadt. For TGO as a whole, the planning cycle is divided into three phases that are named Long Term Plan (LTP), that covers 6 months of commanding, Medium Term Plan (MTP), that are 6 blocks inside the LTP, covering 4 weeks of commanding each, and Short Term Plan (STP), that are 4 blocks inside the MTP that cover 1 week of commanding each (Ashman et al., 2018). The bulk of the planning for the instruments is performed during the MTP and STP parts of the cycle as can be seen in Fig. 3.

The Long Term Plan is used to predict the spacecraft trajectory. The trajectory file usually contains data about one year into the future and is provided about 6 months before the first execution. A basic geometry analysis is performed together with data volume estimates. Typically, downlink occurs between 8 and 16 h per day, depending upon the availability of ground stations. The data allowance for CaSSIS during a Mars year varies from 10 Gbit per week around solar conjunction to 160 Gbit per week when Mars is closest to the Earth. This provides CaSSIS with the opportunity to image only 1–2% of the surface of Mars in one Earth year. This emphasizes the need to carefully select the image acquisition sites so that only the most relevant scientific targets are acquired, thus maximizing the science return.

The LTP provides general trends and allows the operations teams to

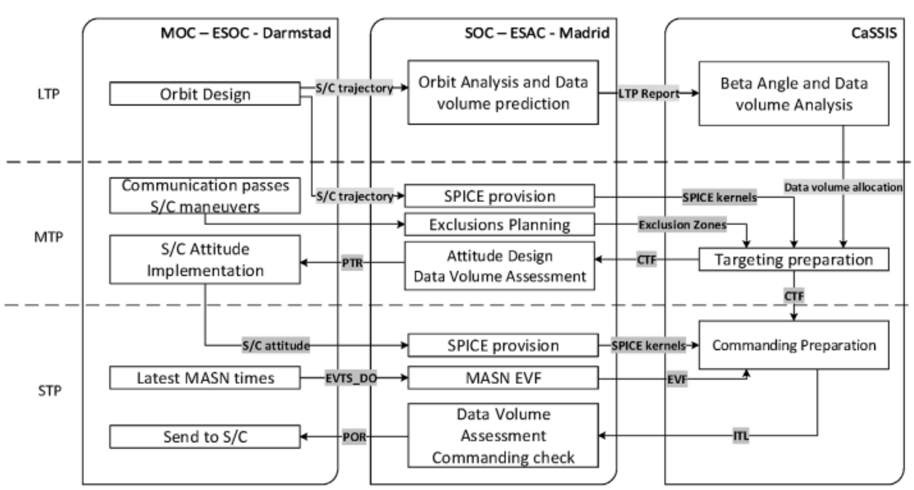

Fig. 3. Planning product exchange during CaSSIS planning cycles: The Long Term Plan (LTP), Medium Term Plan (MTP) and Short Term Plan (STP) grow in level of detail as planning products cascade from level to level. CTF is the CaSSIS Target File, PTR is the SOC Pointing Request File, MASN EVF are the Mars Ascending Node event times, that are transferred from MOC to SOC as the EVTS_DO file. ITL and POR are the CaSSIS commanding files in SOC and MOC formats, respectively.

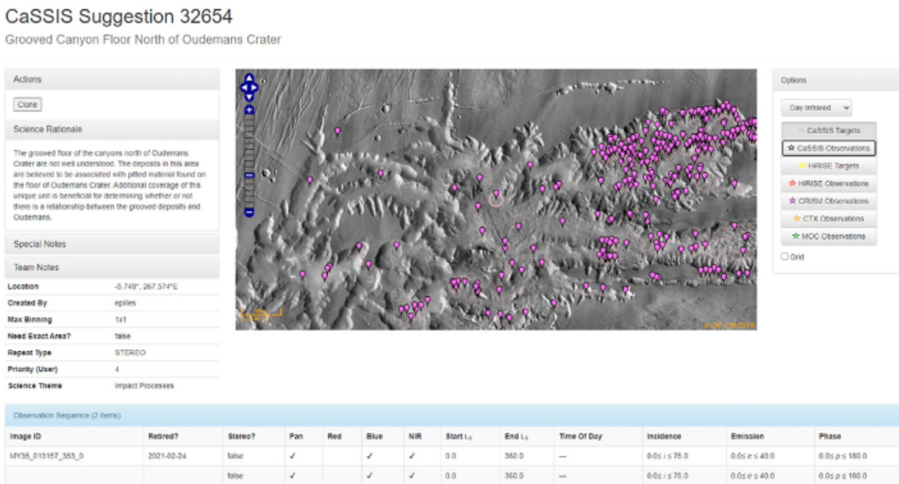

Fig. 4. CaST suggested targets and target data: Through the web interface users can suggest places of interest, and provide a justification for image acquisition.

understand the long-term strategy and limitations. In the case of TGO, and in particularly CaSSIS, the "beta angle" and the available downlink capacity are the main planning drivers. The "beta angle" is the angle between the spacecraft orbital plane and the Sun vector, and it dictates the sub-spacecraft illumination conditions. These two drivers modulate how CaSSIS makes use of its allocation of spacecraft memory. CaSSIS is allocated approximately 400 Gbit data storage on the spacecraft. The memory can be used as a buffer to acquire more scientifically relevant targets when observation conditions are optimal. As an example, the non-Sun synchronous orbit can result in the spacecraft being in a terminator orbit, where the sun vector is perpendicular to the spacecraft orbital plane, during an STP cycle. The large solar illumination angle leads to a low sun elevation over the terrain, diffused by a long atmospheric path length, so lighting of the scene available to CaSSIS is not usually desirable. However, this phase only lasts a few days and hence imaging prior to this period, in better conditions, can be used to fill the spacecraft memory buffer. This data can be downlinked during the terminator period emptying the buffer until better illumination conditions occur. This is fine-tuned during the MTP and STP planning cycles.

The LTP trajectory cannot be used immediately for image planning because, at this stage, the attitude of the spacecraft is not planned, and some parts of the surface that might appear to be accessible in the LTP planning cycle might be eliminated when non-nadir and maintenance pointings are planned.

The Medium Term Planning cycle (MTP) starts with ESA populating the observation timeline with the limb-pointing activities that ACS and NOMAD require to observe the atmosphere of Mars. With this attitude profile, ESA can produce activity exclusion windows, where the CaSSIS team will know when image planning is not possible.

The MTP planning takes four weeks and is when images that require spacecraft attitude changes from the nominal nadir pointing are requested (Targeted images).

The Short Term Plan (STP), the last stage of planning, takes place from 6 weeks before execution to nine days before execution and covers one week. The STP for CaSSIS is delivered to ESA on a weekly cycle.

It is at this time that nadir-pointing observations can be added to the image acquisition programme. The set-up of the instrument for each image can be confirmed or modified to fit within the data volume allocation. Data compression can be applied to support this if required.

6. The CaSSIS planning tools

CaSSIS Target Leads (CaTL) are members of the Science Team responsible for the target selection of an MTP planning cycle. In order to plan the most relevant scientific images, the CaSSIS team has several tools that provide the CaTL with the geometric conditions, as well as the constraints for the available orbits. They include.

- The target database, CaSSIS Suggestion Targeting (CaST).
- The automated target selection tool, CaTL Image Suggestion Tool (CaTLIST).
- The detailed target identification and image programming tool, Plan-CaSSIS (PLAN-C), which produces CaSSIS target files (CTFs).
- The CTF Checker, which checks the output from PLAN-C prior to command generation.
- The command generator, CTF2ITL, which converts the CTF into the spacecraft Instrument Timeline command file (ITL).
- The retirement tool used to flag execution of a target in the CaST database.

The latter step completes the life cycle of a target suggestion by indicating the completion of execution of that request. We discuss these tools in turn.

6.1. The suggestion interface, CaST

CaST is the CaSSIS target proposal tool. Based on the HiRISE (McEwen et al., 2007) tool HiWish (Chojnacki et al., 2020), it allows users to propose targets for CaSSIS to image through a modern web interface (Fig. 4). The tool allows the user to select a site or a region of interest on one of several maps of Mars, namely Themis IR day and night, MOLA and Viking B&W. The position of already acquired HiRISE images and proposed HiRISE targets can also be superimposed to study context and coordinate with HiRISE acquisitions.

It is important to carefully define the size of the region of interest (ROI). Planning assumes that if an area within the ROI has been imaged, then the requirements for that target have been fulfilled. Hence, if a large ROI is defined, a requestor will get only one image in that region. This may not be enough to reach the science goal. Conversely, if a user "peppers" a region with target suggestions, the suggestions may receive lower priority because the goal is not focussed. Consequently, the strategy of adding targets into the database should be optimized by the user taking into account that the average CaSSIS image is 8 km wide, therefore targets of this dimension or smaller are best.

One of the activities of the CaSSIS team is to maintain the CaST Database. As the targets are acquired, the database is updated and it is a long-term task to keep adding targets and verify that the ones acquired meet the requirements stated by the target requestor.

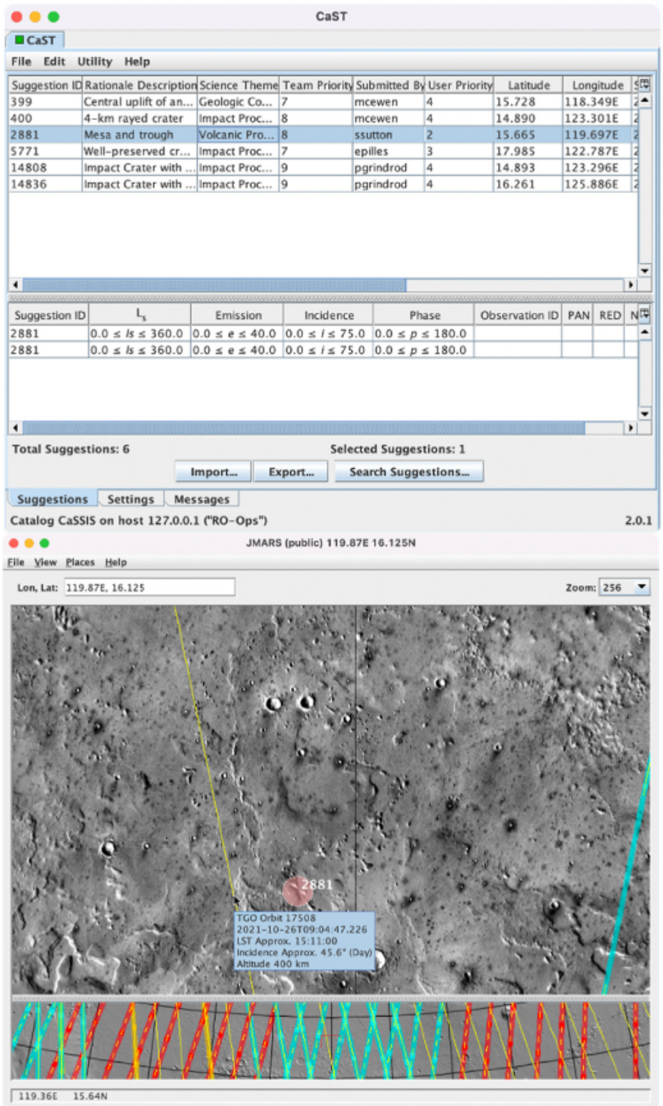

Fig. 5. *Top*: The CaST layer focus panel showing a selected suggestion (ID 2881) in the main table and its required images in the secondary table. *Bottom*: The main JMARS map window showing an orbit from the CaSSIS planning layer as a yellow diagonal line. The tooltip shows the orbit number, UTC time, local solar time (LST), and solar incidence angle as well as the spacecraft altitude. The pink circle to the east of the cursor is the suggestion highlighted in the CaST layer description, ID 2881. The pixel scale of the main view is 256 pixels per degree, with the THEMIS daytime IR map used as the base map.

6.2. PLAN-C

PLAN-C is a geographic information systems (GIS) tool for planning CaSSIS images. It displays maps, GIS shape files, TGO orbit tracks, planning exclusion zones, image footprints, and other information in layers that have individual transparency settings. It is built from the open-source JMARS application (Java Mission-planning and Analysis for Remote Sensing) developed at Arizona State University in Arizona (ASU), USA (Christensen et al., 2009), and provides a similar service to the HiPlan tool used by the HiRISE operations team (McEwen et al., 2007).

Within PLAN-C, two custom data layers are created: a target database layer and an image planning layer.

The target database layer (CaST layer) consists of a modified JMARS GIS shape file layer, displaying information of targets suggested through the CaST interface. Here the unique ID for each of the suggested CaST targets are shown, along with all the conditions requested for imaging. CaST targets can be requested to be imaged multiple times. An associated entry is present in the target database layer for every requested image of the associated target. An example of this target database layer is shown in the top panel of Fig. 6.

The image planning layer geographically displays the TGO predicted orbit tracks and various operations exclusion zones. The layer is interactive with the user, displaying temporal information along the orbit tracks, such as the UTC time at which TGO is at a given position, the local solar time, and the solar incidence angle. The bottom panel of Fig. 5 shows an orbit track in the planning layer with this temporal information displayed. A CaST layer target is shown as the pink circle in this Figure panel, with the associated information of this target from the target database layer being highlighted in the top panel of Fig. 5. Several dozen orbits are shown in the panner view of the image planning layer (the lower map, at a smaller resolution).

To plan an image with PLAN-C, the operator clicks on an orbit track in the image planning layer. Areas where a CaSSIS image is possible, either with a targeted or nadir pointing, are highlighted. To aid in image positioning, a grey outline box denoting a CaSSIS image footprint is shown in this highlighted region at the user curser point. An example is shown in the left panel of Fig. 6. After selecting a location for an image selection (considering a targeted or nadir pointing), the grey outline box is changed to a blue box (shown in the right panel of Fig. 6), to denote a user planned image. Image selection can be made with the CaSSIS rotation mechanism aligned with the ground track of the TGO or at a user fixed position.

Each selected image is planned with a default set of imaging parameters (image width, number of exposures, which filters to use, compression etc.). These parameters can be manually amended for each image by the user, through a separate user panel within the image planning layer (this separate panel within PLAN-C is referred to as the CaSSIS Observation Generation GUI, or COGG, after the equivalent tool for HiRISE, the HOGG). The exposure time for each planned image is also calculated

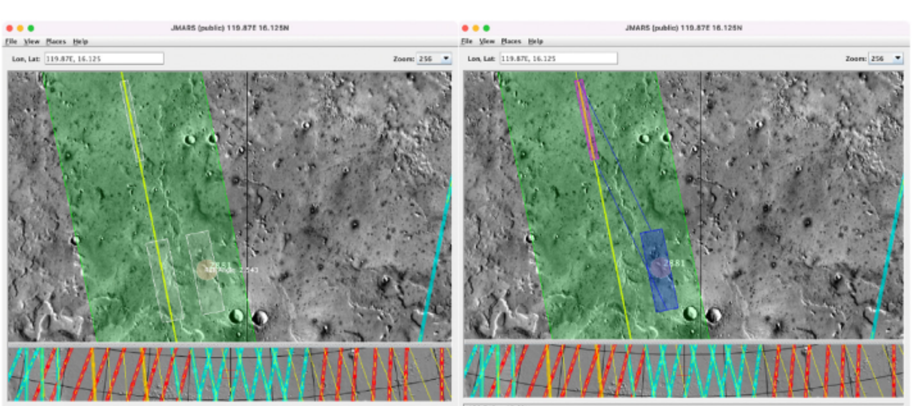

Fig. 6. *Left*: The same view as the top panel of Fig. 5, but with the orbit track selected (yellow line) and the possible imaging area for a targeted observation (green area). The potential CaSSIS image footprint is given by the grey box, considering a targeted or nadir observation (nadir observation follows the orbit track only). *Right:* Same as left panel with image actually selected by user. The image is placed on a CaST target given by the pink circle inside the white box on the left and the blue box on the right with ID number 2881 as in Fig. 5. The pink box refers to the spacecraft position at the time of CaSSIS imaging.

automatically at this point, using a method more fully described in Section 6.2.1.

The image planning layer maintains a table of the images that have been planned up to that point for a given STP planning cycle. In addition to the list of images, the planning layer focus panel includes a data volume management tool, a list of rules violations, a timeline that includes maintenance commands, and additional information about the STP.

The operator may export or import a CaSSIS Target File (CTF) at any point from PLAN-C, which contains all the information pertaining to planned images in a comma-separated format. This file can be read back in by PLAN-C for the purpose of continuing image planning, or be passed on to the CaSSIS operations team, once image planning has been finalized by the user.

The CaSSIS Operations Team includes two Target Specialists (CaTS) that have a set of tools to verify that the programme and images requested are compliant with the flight rules. They also plan maintenance and calibration activities within the CTF. The CaTS work is concluded by preparing the time tagged command files called Instrument Timelines (ITL) by using the CTF2ITL code. The CTF2ITL code compiles the ITLs taking into account the specific timing needed by CaSSIS to execute certain commands and to ensure that the data acquisition and read-out are compliant with bottlenecks in the system affecting data transfer. Periodic re-boots of the instrument, to clean the memory and avoid memory errors, can also be included in the CTF with the CTF2ITL code computing the sequence needed to execute the re-boot in a safe manner.

6.2.1. CapHOT

The exposure time for each image planned in the PLAN-C image planning layer is calculated automatically by a CaSSIS photometry (CaPHOT) tool. The concept philosophy of the CaPHOT tool follows that of the HiRISE Photometry Program (HiPHOP), albeit with updates specifically included for CaSSIS.

The original HiRISE Photometry Program (HiPHOP), upon which CaPHOT is based, used a Hapke photometric function and needed to be manually run for each observation, with input values for surface and atmospheric conditions for each observation (McEwen et al., 2007). This was found to be one of the most time-consuming steps in HiRISE uplink planning. A more automated approach was needed for predicting scene brightness and setting image parameters for CaSSIS, based initially on HiRISE data. With a database of >60,000 HiRISE images, it was determined that scene brightness could be predicted within 10% accuracy (sufficient for setting image parameters) for >95% of the images, by using a simple model:

$$P\ (DN/ms) = (m_1 cosi + b_1)\ x\ (m_2{*}TES + b_2)\ x\ 1.5^2/AU^2$$

Where P is how many DN of signal accumulate in a ms of integration, cosi is cosine of the incidence angle, TES is the Thermal Emission Spectrometer albedo (Christensen et al., 2001), AU is the sun-Mars distance in astronomical units, and m1, b1, m2, and b2 are linear coefficients that fit the average signal levels of acquired HiRISE images. For TES albedo, the most complete Mars Year 26 map at https://sharad.psi.edu/inertia/2007/albedo.html (Putzig and Mellon, 2007) is used. The prediction may be too low when the atmosphere is extra hazy or dusty, especially over low-albedo surfaces, but these conditions do not produce useful images of the surface, so overexposing the image is not a concern. A phase angle correction is needed only when the phase angle is less than 20°, so the global average Mars photometric function of Vincendon et al. (2013) (Vincendon, 2013) is used to model the opposition surge. However, different surface units have different opposition surges, so caution is needed to avoid overexposing low-phase images. The largest errors for unfrosted terrain are due to large image areas of steep sunlit or shadowed slopes or to changes in albedo since the TES data was acquired. When targeting regions with large sunlit slopes or shadows, the CaTL may apply a fudge factor to increase or decrease the exposure time. Based on experience with CaSSIS imaging, a standard fudge factor of 1.05 is used, reducing exposure times by 5% to minimize saturation. For incidence angles greater than about 50° and unfrosted ground, the exposure time is almost always limited by the line time needed to keep smear within 1 pixel, so the CaPHOT calculation is ignored.

Different empirical coefficients (m1, b1, m2, and b2) are needed for frosted versus unfrosted ground. In addition, the frost albedo changes with season (Pommerol et al., 2011), a 1.2x fudge factor to avoid saturation of frost was therefore implemented. To predict when and where frost is present, a lookup table based on past HiRISE images for frost presence as a function of Ls and latitude was created. However, there are local surface anomalies (related to thermal inertia and topography) and season-to-season variability, so automatically predicting scene brightness for these marginal cases when frost may or may not be present is difficult. Optionally, the CaTL may override the default and tell CaPHOT whether or not frost is expected (or if exposure to avoid saturation of the frost is desired). Another good practice is to acquire images all 4 bandpasses, so even if the PAN is saturated there is still unsaturated data in 3 colours.

Once the empirical coefficients were derived for HiRISE bandpasses, a fit was made directly to selected CaSSIS data to derive conversion of P(DN/ms) to the CaSSIS bandpasses. Note however that the exposure time is the same for all CaSSIS bandpass, so typically it is based only on the PAN calculation. If the PAN images are not returned, then the calculation is based on the NIR or RED.

6.3. CaTLIST

Overall, the CaSSIS planning layer combined with the CaST layer and the JMARS core makes PLAN-C a very versatile tool for manual operations planning. However, a more streamlined, automated approach can help assigned CaTL focus on improving target selection for a few targets, taking into account the quality of previous acquired images. The CaSSIS team developed an automated target suggestion tool specifically to aid CaTL in this purpose.

Referred to as the CaTL Image Suggestion Tool (CaTLIST), it is a pipeline that allows for automatic target planning suggestion for CaSSIS imaging prior to ingestion into PLAN-C. It was developed based on a previous concept and tool used for SMART-1 (Almeida et al., 2006). The CaST database of requested targets is used by CaTLIST, such that all targets suggested are those requested by members of the science team. CaTLIST uses suggested targets to produce a full CTF that can be sent to the spacecraft without manual intervention. Parameters pertaining to individual image acquisitions (pixel width of the image, number of filters etc.) are automatically generated to fulfill what was requested for the associated target in the CaST database.

The philosophy of CaTLIST is to map areas of the surface of Mars that are observable with CaSSIS in a given orbit, either with a targeted or nadir pointing. This region is modelled using the predicted trajectory of TGO determined from the SPICE kernels and takes into account imaging exclusion zones. The exact time required for the boresight of CaSSIS to cross any CaST target in this observable region is then calculated, along with the surface illumination conditions (incidence angle, phase angle, emission angle and Ls) of the target at this time. If the illumination conditions satisfy what was requested for a target in CaST, the target is suggested for imaging by CaTLIST. It should be noted here that it is far more critical than other imagers to assess the surface illumination conditions in the TGO case because of the non-Sun synchronous orbit.

In the (very likely) event that several CaST targets are available for imaging roughly at the same time, the target with the highest priority in CaST is always selected and inserted into a CTF, using a default imaging mode selected by the user.

When running CaTLIST in nadir pointing mode at STP planning, the total allowed data volume for that STP is considered. To avoid removing images from the suggested imaging plan, compression of images is first automatically applied where possible. If the data volume of the CTF is still too large after all possible images have been compressed, then images begin to be removed, starting with the lowest priority nadir images.

The result of this process, executed fully by CaTLIST, is a CTF containing automatically planned images of the highest priority CaST targets possible, with both targeted and nadir pointings, where images are sufficiently spaced in time and the CTF is below the allotted data volume. This CTF can be reviewed by a member of the CaSSIS team in PLAN-C and changed, or even be sent directly to the spacecraft.

The CaTLIST tool has proven to be highly efficient and reduces the time needed for CaSSIS image planning by up to 70%. Consequently, it has now become the first step in the CaSSIS planning process. However, it is still necessary to use PLAN-C for checking and further optimization/improvements of the CTF before moving on to the next stage.

7. The Ground Reference Model (GRM) and the electronic ground support equipment (EGSE)

In order to improve the quality and quantity of data the CaSSIS Operations team uses the Ground Reference Model (GRM) to test new or more demanding commanding sequences, before using them on the spacecraft.

The EGSE software is a set of software applications that helps to prepare flight software updates, provide a complete graphical user interface (GUI) to operate the GRM and some scripts to parse and transform telemetry data into other representations. The most important application is the GUI that interfaces with an electronics box that emulates the physical spacecraft interfaces. Together, they form a tool that basically emulates the functionality of the spacecraft to the CaSSIS GRM. It was key during hardware commissioning and testing of the flight hardware. It has subsequently been used to test commanding sequences and flight software updates and to investigate errors that occurred on the flight hardware on TGO.

A MIL-1553 data-bus is part of that spacecraft interface to send telecommands (TCs) to CaSSIS to control its entire behaviour. The GUI software provides functionality to compose a sequence of TCs with a delay in between each of them. Those sequences can be stored to the file system for later usage or for dissemination to ESOC after successful testing. Furthermore, the software emulates the spacecraft time and periodically synchronizes it to the CaSSIS instrument via the MIL-1553 bus.

The GUI software also reads telemetry data from the MIL-1553 bus and visualizes it to the user as tables and time-series graphs. It also allows for storage of real-time data in persistent database backends. Furthermore, it emulates the spacecraft mass data storage by receiving actual science data over the high-speed SpaceWire link, visualizing those unprocessed CaSSIS images sensor framelets for preview, and saving them to the file system.

8. Monitoring data acquisition

The CaSSIS instrument generates housekeeping (HK) which is transmitted to the spacecraft through a bus linking CaSSIS and the Spacecraft. Additionally, a snapshot of this HK is attached to every image acquired and sent through the SpaceWire interface to the spacecraft memory. The data is returned in near real time, and used on regular basis by the CaSSIS Operations team, when the spacecraft is in contact with Earth and is available for download from the ESA EDDS (European Space Agency Data Distribution Service). This system provides controlled access to mission data which is physically at ESOC. A Linux server periodically requests the most recent telemetry data from the EDDS. The server also has CaSSIS specific software installed to parse and transform all the enclosed housekeeping data into engineering units using a calibration file with linear coefficients. Furthermore, it maps the spacecraft times to UTC timestamps to store all the telemetry data into an InfluxDB time-series database system that contains all telemetry that has been read since the beginning of the mission, in a time tagged tabular format. The same server serves a dashboard that is constructed from an interface tool called Grafana (https://grafana.com). This provides a rapid visual assessment of the current status of CaSSIS and includes displays of the major voltages and currents within the instrument, the temperatures of key components, command counters, the mechanism position, and internal memory usage (see Fig. 7). Command acceptance and failure can also be tracked.

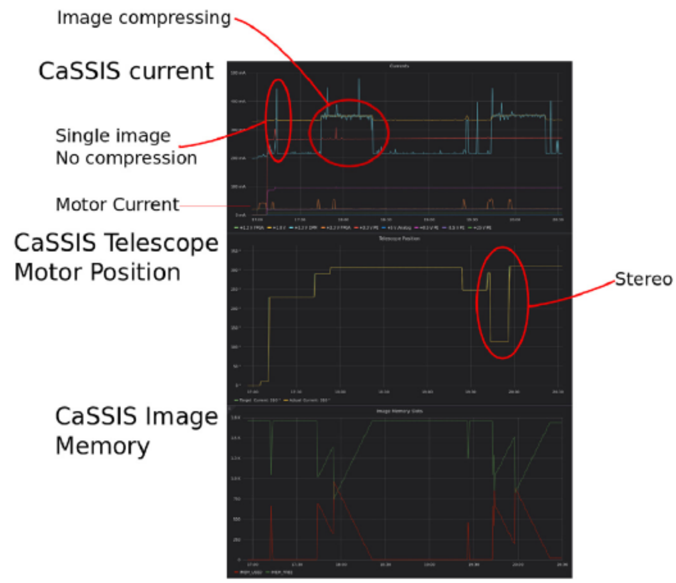

Fig. 7. CaSSIS Grafana panels: The telemetry can be checked live or as fast as it gets to the ground – it's of particular importance to monitor special occasions like a flight software update, but also allows for rapid reaction in case of instrument issues.

9. Evolution of the CaSSIS planning

At the start of the science phase, CaSSIS already had a robust planning system but many aspects of it were manual. Most of the planning was done through PLAN-C, but CTF manual editing was needed for maintenance activities and corrections to items still under development in PLAN-C.

PLAN-C has been updated throughout the duration of the TGO mission. In particular updates were done to CaPHOT as well as the COGG infrastructure in order to make the planning more efficient.

Another important event that triggered software changes at all levels were the motor issues CaSSIS experienced at the start of 2019. Although CaSSIS did recover part of the motor movement, at the time of writing the first 100 degrees of the full 360° rotation are not being used. Also the motor is being moved less frequently, with the end result that more images are acquired with a fixed motor position. In order to minimize the impact on the science, the tools were updated to take into account this fixed motor position. The CaSSIS team then identifies on a weekly basis a motor position that allows acquisition of many targets with a maximum of 20° misalignment with the spacecraft ground track. This provides almost full overlap of the colours in the CaSSIS focal plane so that colour imaging is efficient.

The tools were also updated to allow for stereo images and aligned single images that use the motor on an individual basis. As the CaSSIS teams has gained confidence the number of images allowed with these methods has been slowly increased to the point that is almost indistinguishable from the operations before the motor issues.

Finally, although CaTLIST is shown as an active part of the planning cycle, its introduction is quite recent, and the planning was mostly done for a large part of the mission so far by CaTL adding images in PLAN-C. The introduction of CaTLIST did not change much of the flow of the CaSSIS planning exercise or the general philosophy. It did however make it much more efficient. Reducing the typical planning time of a CaTL from one to two weeks to two to four days, for two STPs (two weeks of

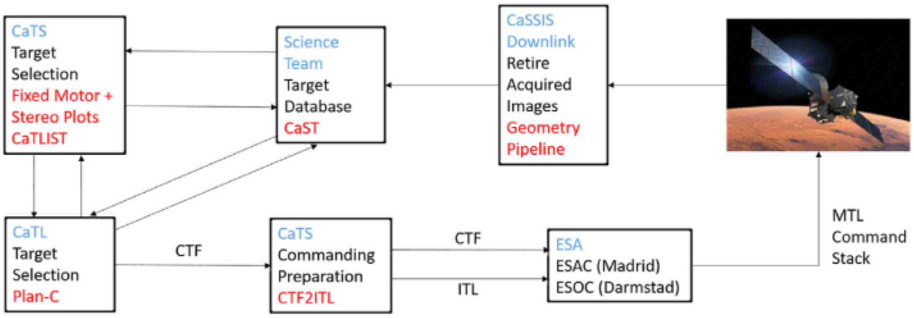

Fig. 8. CaSSIS full planning cycle. Starting with CaTS and CaTL selecting the targets to be planned from the CaST database that was populated by the CaTL beforehand. And the CTF and ITL products being sent to ESA where they are made into attitude and instrument commands that populate the Mission Timeline (MTL) that contains all the commands that are ultimately executed on the spacecraft and produce the planned images at exact locations. These are returned to Earth in a process described in (Perry, 2021) that includes a feedback mechanism that retires acquired targets from the database.

spacecraft imaging). It also allows the CaTL to focus on specific targets, think more "outside the box" and focus the planning on more scientifically relevant issues in contrast to more operational issues.

10. Conclusions and future

CaSSIS is a visual telescope on board TGO unlike any other in the ESA Science and exploration programs, with its high resolution of ~4 m per pixel and relatively small image footprint of 9.5 km by 40 km. These characteristics make clear that the focus of CaSSIS is on the study of specific targets of high science interest, taking advantage of its high resolution colour capability and where possible its stereo capability.

The CaSSIS planning system was developed around the philosophy where the operations are disentangled from the target selection, giving scientists the capability to be able to select desired regions of study without having to know all the details about the CaSSIS trajectory. Having the target database as a starting point, planning tools help the Science Team CaTL optimize the selection of the targets by being able to focus on the science merits of the target planning as opposed to the technical aspects like image feasibility.

CaSSIS has now acquired more than 30000 images, most of very high quality, having retired around 5000 targets. The recently introduced tools will help retire targets much faster. However certain geometries, when the sun elevation is low on the horizon, reduces the signal to noise ratio for many applications, and the targets acquired in those geometries are not retired. Many targets are seasonal and only retired after an image is acquired with the required geometries. These two aspects make sure that there will always be more images than retired targets.

In the future the CaSSIS team plans to further improve the automation and reduce the manual intervention to a minimum. This will both make the process flow faster, but make it more robust and less error prone.

Following the SMART-1, Rosetta and JUICE experience the CaSSIS team is looking to further develop a more strategic plan by building on its CaTLIST tool. This would increase the information available at the point of target insertion, like likelihood of a target being available for imaging, that at present fully relies on the knowledge of the target suggestor, and later filtered by the Science Theme Lead, also based on personal knowledge. The goal here is to produce a tool that is a knowledge database on observation conditions connected to the targets and seasonality to further improve the CaTLIST output.

The operational approach highlights several important aspects of programming high resolution imagers in orbit around Mars (or other Solar System bodies). Firstly, the approach to the spacecraft orbit control is a huge driver. ESA effectively chose to "fly the plan". In other words, it was chosen to make a long-term plan for the spacecraft trajectory and use orbital correction manoeuvres to fly that plan. This allows the planning to be performed well in advance except in the cases when major orbit manoeuvres are required. When a large manoeuvre occurs, the accuracy of the orbit is inadequate for small field of view high resolution imagers meaning that accurate targeting is compromised until the accuracy of the orbit trajectory is recovered. On the other hand, letting the orbit evolve and predicting the trajectory reduces some of these issues but it has the disadvantage of requiring a faster planning closer to the time of execution. Both approaches are possible with NASA taking the second approach with Mars Reconnaissance Orbiter, for example.

Secondly, when wanting to "fly the plan", there is a tendency to want to have resonant orbits, that return to the same place at very short intervals, therefore always covering the same regions. These can be beneficial for planning purposes but only if the field of view of the remote-sensing instrument and/or the roll of the spacecraft can be used to fill in gaps in coverage. Otherwise coverage may be incomplete.

Thirdly, Mars communications with ground assets can significantly complicate operations and can lead to difficult imaging certain areas near landing sites.

Fourthly, with a nominal mission duration, high spatial resolution remote-sensing systems may only be able to target 1–2% of the surface of a planet, large moon, or large asteroid because of the limited data volume available even with large high gain antennas. This necessitates a target selection database that should be science driven and accessible to the operational planning tools. Database entry should of course be simple but the more constraints from the requestor, the more sophisticated any automated selection tool can become.

Fifthly, although we believe that our automated tool (CaTLIST) is very powerful, it is not conceivable that such a tool can be made fully automatic for all objects and all conditions. Hence, a manual review is mandatory. The aim, however, should be to reduce the time needed for this review and/or optimization to a minimum.

Finally, once the target has been acquired, the "retirement" of the target request within the target database is challenging (Perry, 2021). In particular, the non Sun-synchronous orbit, dynamic phenomena (e.g. dust storms on Mars), and instrument anomalies can influence the success or failure of an observation and this can only be judged by the requestor. As a result, science team interaction is a vital part of the process.

The full end to end process is viewed in the schematics of Fig. 8 that includes all the tools and interactions described in the paper.

Author statement

Miguel Almeida, Nicolas Thomas, Matthew Read, Antoine Pommerol and Alfred McEwen contributed to the concept and design of the Study.

All authors contributed to the contents and manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

CaSSIS is a project of the University of Bern and funded through the Swiss Space Office via ESA's PRODEX programme. The instrument hardware development was also supported by the Italian Space Agency (ASI) (ASI-INAF agreement no. 2020-17-HH.0), INAF/Astronomical Observatory of Padova, and the Space Research Center (CBK) in Warsaw. Support from SGF (Budapest), the University of Arizona (Lunar and Planetary Lab.) and NASA are also gratefully acknowledged. Operations support from the UK Space Agency under grant ST/R003025/1 is also acknowledged.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pss.2023.105697.

List of Acronyms

ACS	Atmospheric Chemistry Suite
CaSSIS	Colour and Stereo Surface Imaging System
CaST	CaSSIS Sugestion Targeting
CaTL	CaSSIS Targeting Leads
CaTLIST	CaTL Imaging Suggestion Tool
CaTS	CaSSIS Targetting Specialists
CMOS	Complementary metal–oxide–semiconductor
CTF	CaSSIS Targetting File
ESA	European Space Agency
ESAC	European Space Astronomy Centre
ESOC	European Space Operations Centre
EVF	Event file
EVTS_DO	Short Term Event file
ITL	Intrument Timeline
LTP	Long Term Plan
MGS	Mars Global Surveyor
MGS/MOC	Mars Orbter Camera
MGS/MOLA	Mars Orbiter Laser Altimeter
MOC	Mission Operations Centre
MTL	Mission Timeline
MTP	Medium Term Plan
NOMAD	Nadir and Occultation for MArs Discovery
OMEGA	Mars Express Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité
SOC	Science Operations Centre
STP	Short Term Plan
TGO	Trace Gas Orbiter
THEMIS	Thermal Emission Imaging System
UTC	Coordinated Universal Time

References

Almeida, M., Frew, D., Sarkarati, M., Volp, J., Bloem, F., Koschny, D., Foing, B., Schwehm, G., 2006. ESA's SMART-1 science planning concept and its evolution throughout the mission. SpaceOps 2006 Conf 1–12. https://doi.org/10.2514/6.2006-5962.

Ashman, M., Vega, M.A., Moinelo, A.C., Sitjà, M.C., Frew, D., Beteta, J.J.G., Geiger, B., Metcalfe, L., Crego, C.M., Fernández, M.M., Nespoli, F., 2018. Science planning implementation and challenges for the ExoMars trace gas orbiter. 15th Int. Conf. Sp. Oper. 2018, 1–15. https://doi.org/10.2514/6.2018-2580.

Chojnacki, M., McEwen, A.S., Byrne, S., Hansen, C.J., Daubar, I.J., Beyer, R.A., McArthur, G., 2020. HiWISH: the high resolution imaging science experiment (HiRISE) suggestion tool. LPSC 51. Abs. 2095.

Christensen, P.R., Bandfield, J.L., Hamilton, V.E., Ruff, S.W., Kieffer, H.H., Titus, T.N., Malin, M.C., Morris, R.V., Lane, M.D., Clark, R.L., Jakosky, B.M., Mellon, M.T., Pearl, J.C., Conrath, B.J., Smith, M.D., Clancy, R.T., Kuzmin, R.O., Roush, T., Mehall, G.L., Gorelick, N., Bender, K., Murray, K., Dason, S., Greene, E., Silverman, S., Greenfield, M., 2001. Mars global surveyor thermal emission spectrometer experiment: investigation description and surface science results. J. Geophys. Res. Planets. 106, 23823–23871. https://doi.org/10.1029/2000JE001370.

Christensen, P.~R., Engle, E., Anwar, S., Dickenshied, S., Noss, D., Gorelick, N., Weiss-Malik, M., 2009. JMARS - a planetary GIS. In: AGU Fall Meet. Abstr.. IN22A-06.

Cremonese, G., Capaccioni, F., Capria, M.T., Doressoundiram, A., Palumbo, P., Vincendon, M., Massironi, M., Debei, S., Zusi, M., Altieri, F., Amoroso, M., Aroldi, G., Baroni, M., Barucci, A., Bellucci, G., Benkhoff, J., Besse, S., Bettanini, C., Blecka, M., Borrelli, D., Brucato, J.R., Carli, C., Carlier, V., Cerroni, P., Cicchetti, A., Colangeli, L., Dami, M., Da Deppo, V., Della Corte, V., De Sanctis, M.C., Erard, S., Esposito, F., Fantinel, D., Ferranti, L., Ferri, F., Ficai Veltroni, I., Filacchione, G., Flamini, E., Forlani, G., Fornasier, S., Forni, O., Fulchignoni, M., Galluzzi, V., Gwinner, K., Ip, W., Jorda, L., Langevin, Y., Lara, L., Leblanc, F., Leyrat, C., Li, Y., Marchi, S., Marinangeli, L., Marzari, F., Mazzotta Epifani, E., Mendillo, M., Mennella, V., Mugnuolo, R., Muinonen, K., Naletto, G., Noschese, R., Palomba, E., Paolinetti, R., Perna, D., Piccioni, G., Politi, R., Poulet, F., Ragazzoni, R., Re, C., Rossi, M., Rotundi, A., Salemi, G., Sgavetti, M., Simioni, E., Thomas, N., Tommasi, L., Turella, A., Van Hoolst, T., Wilson, L., Zambon, F., Aboudan, A., Barraud, O., Bott, N., Borin, P., Colombatti, G., El Yazidi, M., Ferrari, S., Flahaut, J., Giacomini, L., Guzzetta, L., Lucchetti, A., Martellato, E., Pajola, M., Slemer, A., Tognon, G., Turrini, D., 2020. SIMBIO-SYS: scientific cameras and spectrometer for the BepiColombo mission. Space Sci. Rev. 216. https://doi.org/10.1007/s11214-020-00704-8.

Edwards, C.S., Nowicki, K.J., Christensen, P.R., Hill, J., Gorelick, N., Murray, K., 2011. Mosaicking of global planetary image datasets: 1. Techniques and data processing for Thermal Emission Imaging System (THEMIS) multi-spectral data. J. Geophys. Res. Planets. 116. https://doi.org/10.1029/2010JE003755.

Korablev, O., Montmessin, F., Trokhimovskiy, A., Fedorova, A.A., Shakun, A.V., Grigoriev, A.V., Moshkin, B.E., Ignatiev, N.I., Forget, F., Lefèvre, F., Anufreychik, K., Dzuban, I., Ivanov, Y.S., Kalinnikov, Y.K., Kozlova, T.O., Kungurov, A., Makarov, V., Martynovich, F., Maslov, I., Merzlyakov, D., Moiseev, P.P., Nikolskiy, Y., Patrakeev, A., Patsaev, D., Santos-Skripko, A., Sazonov, O., Semena, N., Semenov, A., Shashkin, V., Sidorov, A., Stepanov, A.V., Stupin, I., Timonin, D., Titov, A.Y., Viktorov, A., Zharkov, A., Altieri, F., Arnold, G., Belyaev, D.A., Bertaux, J.L., Betsis, D.S., Duxbury, N., Encrenaz, T., Fouchet, T., Gérard, J.C., Grassi, D., Guerlet, S., Hartogh, P., Kasaba, Y., Khatuntsev, I., Krasnopolsky, V.A., Kuzmin, R.O., Lellouch, E., Lopez-Valverde, M.A., Luginin, M., Määttänen, A., Marcq, E., Martin Torres, J., Medvedev, A.S., Millour, E., Olsen, K.S., Patel, M.R., Quantin-Nataf, C., Rodin, A.V., Shematovich, V.I., Thomas, I., Thomas, N., Vazquez, L., Vincendon, M., Wilquet, V., Wilson, C.F., Zasova, L.V., Zelenyi, L.M., Zorzano, M.P., 2018. The atmospheric Chemistry suite (ACS) of three spectrometers for the ExoMars 2016 trace gas orbiter. Space Sci. Rev. 214. https://doi.org/10.1007/s11214-017-0437-6.

McEwen, A.S., Eliason, E.M., Bergstrom, J.W., Bridges, N.T., Hansen, C.J., Delamere, W.A., Grant, J.A., Gulick, V.C., Herkenhoff, K.E., Keszthelyi, L., Kirk, R.L., Mellon, M.T., Squyres, S.W., Thomas, N., Weitz, C.M., 2007. Mars reconnaissance orbiter's high resolution imaging science experiment (HiRISE). J. Geophys. Res. E Planets. 112, 1–40. https://doi.org/10.1029/2005JE002605.

Mitrofanov, I., Malakhov, A., Bakhtin, B., Golovin, D., Kozyrev, A., Litvak, M., Mokrousov, M., Sanin, A., Tretyakov, V., Vostrukhin, A., Anikin, A., Zelenyi, L.M., Semkova, J., Malchev, S., Tomov, B., Matviichuk, Y., Dimitrov, P., Koleva, R., Dachev, T., Krastev, K., Shvetsov, V., Timoshenko, G., Bobrovnitsky, Y., Tomilina, T., Benghin, V., Shurshakov, V., 2018. Fine resolution epithermal neutron detector (FREND) onboard the ExoMars trace gas orbiter. Space Sci. Rev. 214. https://doi.org/10.1007/s11214-018-0522-5.

Perry, J., 2021. Geometry Pipeline for TGO CaSSIS Observations. PSS.

Pommerol, A., Portyankina, G., Thomas, N., Aye, K.M., Hansen, C.J., Vincendon, M., Langevin, Y., 2011. Evolution of south seasonal cap during martian spring: insights from high-resolution observations by HiRISE and CRISM on Mars reconnaissance orbiter. J. Geophys. Res. Planets. 116, 1–22. https://doi.org/10.1029/2010JE003790.

Putzig, N.E., Mellon, M.T., 2007. Apparent thermal inertia and the surface heterogeneity of Mars. Icarus 191, 68–94. https://doi.org/10.1016/j.icarus.2007.05.013.

Thomas, N., Cremonese, G., Ziethe, R., Gerber, M., Brändli, M., Bruno, G., Erismann, M., Gambicorti, L., Gerber, T., Ghose, K., Gruber, M., Gubler, P., Mischler, H., Jost, J., Piazza, D., Pommerol, A., Rieder, M., Roloff, V., Servonet, A., Trottmann, W., Uthaicharoenpong, T., Zimmermann, C., Vernani, D., Johnson, M., Pelò, E., Weigel, T., Viertl, J., De Roux, N., Lochmatter, P., Sutter, G., Casciello, A., Hausner, T., Ficai Veltroni, I., Da Deppo, V., Orleanski, P., Nowosielski, W., Zawistowski, T., Szalai, S., Sodor, B., Tulyakov, S., Troznai, G., Banaskiewicz, M., Bridges, J.C., Byrne, S., Debei, S., El-Maarry, M.R., Hauber, E., Hansen, C.J., Ivanov, A., Keszthelyi, L., Kirk, R., Kuzmin, R., Mangold, N., Marinangeli, L., Markiewicz, W.J., Massironi, M., McEwen, A.S., Okubo, C., Tornabene, L.L., Wajer, P., Wray, J.J., 2017. The colour and stereo surface imaging system (CaSSIS) for the ExoMars trace gas orbiter. Space Sci. Rev. 212, 1897–1944. https://doi.org/10.1007/s11214-017-0421-1.

Vago, J., Witasse, O., Svedhem, H., Baglioni, P., Haldemann, A., Gianfiglio, G., Blancquaert, T., McCoy, D., Groot, R., 2015. ESA ExoMars program: the next step in exploring Mars. Sol. Syst. Res. 49, 518–528. https://doi.org/10.1134/S0038094615070199.

Vandaele, A.C., Lopez-Moreno, J.J., Patel, M.R., Bellucci, G., Daerden, F., Ristic, B., Robert, S., Thomas, I.R., Wilquet, V., Allen, M., Alonso-Rodrigo, G., Altieri, F., Aoki, S., Bolsée, D., Clancy, T., Cloutis, E., Depiesse, C., Drummond, R., Fedorova, A., Formisano, V., Funke, B., Gonzalez-Galindo, F., Geminale, A., Gérard, J.C., Giuranna, M., Hetey, L., Ignatiev, N., Kaminski, J., Karatekin, O., Kasaba, Y., Leese, M., Lefèvre, F., Lewis, S.R., López-Puertas, M., López-Valverde, M., Mahieux, A., Mason, J., McConnell, J., Mumma, M., Neary, L., Neefs, E., Renotte, E., Rodriguez-Gomez, J., Sindoni, G., Smith, M., Stiepen, A., Trokhimovsky, A., Vander Auwera, J., Villanueva, G., Viscardy, S., Whiteway, J., Willame, Y., Wolff, M., Patel, M., D'aversa, E., Fussen, D., Garcia-Comas, M., Hewson, W., McConnel, J., Novak, R., Oliva, F., Piccialli, A., Aparicio Del Moral, B., Barzin, P., Benmoussa, A., Berkenbosch, S., Biondi, D., Bonnewijn, S., Candini, G.P., Clairquin, R., Cubas, J., De-Lanoye, S., Giordanengo, B., Gissot, S., Gomez, A., Maes, J., Mazy, E., Mazzoli, A., Meseguer, J., Morales, R., Orban, A., Pastor-Morales, M.D.C., Perez-Grande, I., Queirolo, C., Saggin, B., Samain, V., Sanz Andres, A., Sanz, R., Simar, J.F., Thibert, T., Zafra, J.J., 2018. NOMAD, an Integrated Suite of Three Spectrometers for the ExoMars Trace Gas Mission: Technical Description, Science Objectives and Expected Performance. The Author(s). https://doi.org/10.1007/s11214-018-0517-2.

Vincendon, M., 2013. Mars surface phase function constrained by orbital observations, Planet. Space Sci 76, 87–95. https://doi.org/10.1016/j.pss.2012.12.005.

Young, R.A., 1975. Mare crater size-frequency distributions - implications for relative surface ages and regolith development. Lunar Planet. Sci. Conf. 6th, 2645–2662. http://ads.nao.ac.jp/cgi-bin/nph-bib_query?bibcode=1975LPSC....6.2645Y&db_key=AST&high=3ffd2faa1f05965.

Zurek, R.W., Smrekar, S.E., 2007. An overview of the Mars Reconnaissance Orbiter (MRO) science mission. J. Geophys. Res. E Planets. 112, 1–22. https://doi.org/10.1029/2006JE002701.