An automated, scientifically optimized planning tool for in-orbit imaging of Mars

Matthew Read [ab]*, Miguel Almeida[c], Nicolas Thomas[d]

[a] *University of Bern, Sidlerstr. 5, CH-3012, Switzerland, matthew.read@open.ac.uk*
[b] *The Open University, Walton Hall, Milton Keynes, MK7 6AA, UK*
[c] *University of Bern, Sidlerstr. 5, CH-3012, Switzerland, miguel.almeida@unibe.ch*
[d] *University of Bern, Sidlerstr. 5, CH-3012, Switzerland, nicolas.thomas@unibe.ch*
* Corresponding Author

Abstract

The Colour and Stereo Surface Imaging System (CaSSIS) is the Martian imager on board ESA's flagship ExoMars Trace Gas Orbiter. The nominal science phase of CaSSIS began in 2018, with over 50000 images acquired since, in up to 4 colour bands. CaSSIS offers one of the most advanced platforms for colour imaging of the Martian surface and as such, is a vital resource for Martian science and future exploration. On average CaSSIS acquires ~20 images per day, drawing from a target database of ~25000 targets. Planning this number of images per day is challenging for operators. As such, a planning tool was designed and built to allow for flight ready, fully automatic CaSSIS observation plan generation. The plan is scientifically optimised, fully conflict resolved, considers the full TGO trajectory, all available downlink capacity and more. This paper describes the steps this automatic planner performs and the impact it has had on CaSSIS planning. While initially designed for CaSSIS, the underlying architecture can be adapted for similar missions.

Keywords: Mars, Remote Sensing, CaSSIS, Planning

Acronyms/Abbreviations

CaSSIS – Colour and Stereo Imaging System.
ESA – European Space Agency.
HiRISE – High Resolution Imaging Science Experiment.
MRO – Mars Reconnaissance Orbiter.
NAIF – Navigation and Ancillary Information Facility
TGO – Trace Gas Orbiter.

1. Introduction

The Colour and Stereo Surface Imaging System (CaSSIS) is the surface imager onboard the European Space Agency's (ESA) flagship ExoMars Trace Gas Orbiter (TGO). Launched to Mars in 2016 and beginning nominal science operations in 2018, CaSSIS currently offers one of the most advanced colour imaging capabilities of the Martian surface on any spacecraft in orbit around Mars. It is also represents the highest resolution imager (~4.5m/pixel) Europe currently has in orbit around Mars. CaSSIS images the surface in four colour bands quasi-simultaneously with a swath width of ~9km by 40km with a resolution of ~4.5m/pixel at the nominal 400km TGO orbit altitude (varying from ~380km to 420km) (Thomas et al. 2017 [1]). The four colour bands are referred to as PAN, NIR, RED and BLU. BLU and PAN are centred at 497nm and 677nm respectively to closely align with the filters used by the HiRISE imager on the Mars Reconnaissance Orbiter (McEwen et al. 2007 [2]). The NIR and RED are centred at 835nm and 940nm respectively for improved distinguishing of surface minerals – especially those containing ferrous iron Fe^{2+} and ferric iron Fe^{3+} (e.g. Tornabene et al. 2018 [3]). An example CaSSIS image after nominal on-ground processing and matching of colour bands is shown in Figure 1.

The TGO orbit is inclined at ~74deg and is non-sun synchronous, such that CaSSIS can observe at constantly evolving times of day. While interesting for scientific goals (e.g. diurnal surface frost evolution (Valantinas et al 2024 [4]), dust devil activity etc.), it does make it challenging for quick repeat imaging of sites with similar illumination conditions for stereo image reconstruction. CaSSIS addresses this problem with a novel rotation mechanism that allows the entire telescope to rotate a full 360deg about the TGO nadir vector (CaSSIS itself is mounted 10deg off the nadir vector). This motion can be performed in as little as 30-45 seconds, allowing for CaSSIS to acquire stereo images during a single overflight of a target. Here, the first image is acquired as TGO approaches the target and the second after the overflight has occurred, ensuring near identical illumination conditions for stereo image construction.

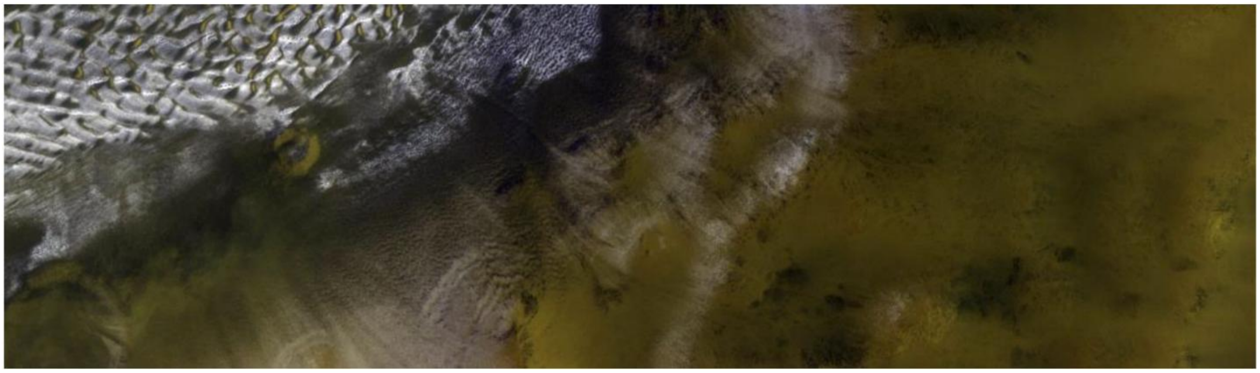

Figure 1: An example CaSSIS image after on ground processing and colour band stitching.

To date, CaSSIS has acquired over 50000 images, including 2500 dedicated stereo observations and is a critical resource for Martain science and future exploration, with over 65 papers published or being worked on so far. On average CaSSIS takes ~2-3 images per orbit (equivalent to ~20 images per day), however this varies significantly with Earth-Mars distance and associated fluctuations in downlink capacity (~6-7 images are possible per orbit during the maximum downlink capacity season). Off-nadir pointing by the spacecraft for CaSSIS targeting is possible, however this can only be achieved once per orbit due to TGO pointing limitations. These pointings are therefore reserved for high importance targets, with the majority of CaSSIS images being acquired with the spacecraft in nadir power optimised mode. CaSSIS also needs to be mindful of imaging during other regular spacecraft activities (e.g. wheel offloads, non-Mars pointing activities etc.). Non-Mars pointings of TGO to support observations by other payloads are often especially constraining for CaSSIS.

Given that CaSSIS can image the Martian surface at any local time of day, at any season, with/without dedicated stereo and in a variety of colour bands, it raises significant challenges for observation planning. This is further complicated by the large number of images that CaSSIS acquires and constraints placed by spacecraft pointing limitations and activities required for TGO/other TGO payloads. Motivated by the vital resource CaSSIS represents, the CaSSIS operations team have therefore developed an observation planning architecture that primarily focuses on maximising scientific return in the most efficient way possible.

This paper highlights a vital tool in this architecture – *an automated planning tool that creates flight-ready observation plans that are scientifically optimised, fully conflict resolved, fill downlink capacity, consider spacecraft/CaSSIS imaging exclusion zones and more.* The plans created by this tool are fully integrated with an approach that allows for operator validation and customisation if desired. For context, it is necessary to briefly summarise previously existing components of the CaSSIS planning architecture. In Section 2 an overview of the end-to-end CaSSIS operations approach is shown, Section 3 describes the target database used for CaSSIS imaging, Section 4 summaries the ESA/TGO planning approach, and then Section 5 summarises a GUI tool that can be used for plan visualisation and manual planning of CaSSIS images. Section 6 highlights the issues with manual planning of CaSSIS data and Section 7 onwards then describes the automated planning tool that is the main focus of this paper.

2. Overview of end-to-end CaSSIS operations architecture.

The planning of CaSSIS observations is not considered in isolation, but as part of an end-to-end architecture that spans pre-planning target selection, observation planning and acquisition, through to image processing. This architecture is key to the success of CaSSIS operations. For example, to distinguish which targets on Mars should be observed, it must be known if/what CaSSIS data already exists and what the local illumination conditions were. Downlink imaging processing must therefore feed into target selection. Similarly, if certain observations are causing excess wear on the instrument, it must be detected as quickly as possible and folded into observation planning. Figure 2 shows this end-to-end architecture. While this paper focuses on aspects of CaSSIS image planning, many of the decisions made were designed to seamlessly fit with this end-to-end architecture.

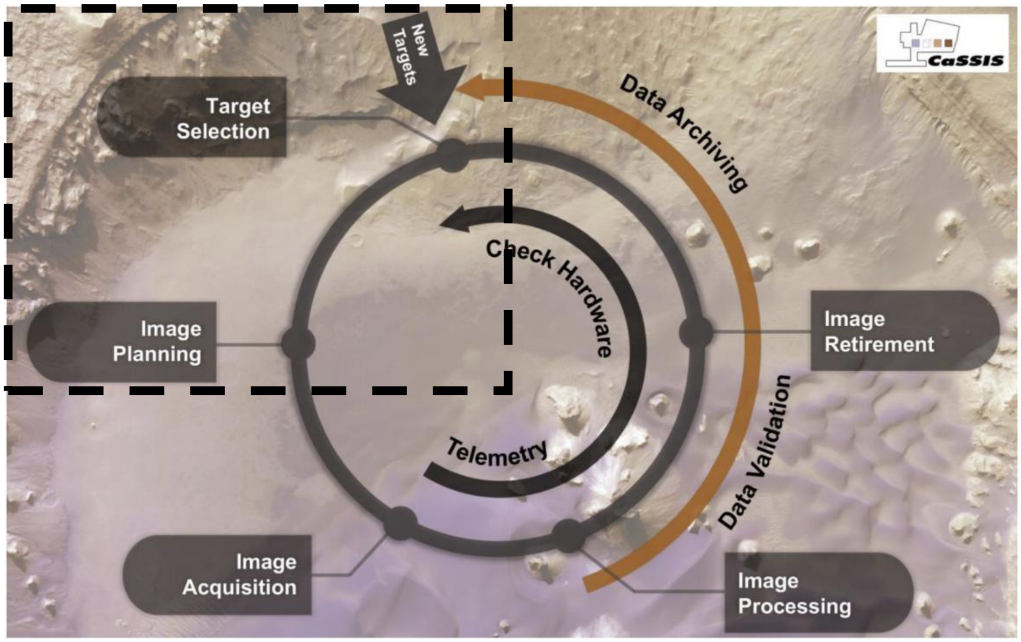

Figure 2: The underlying philosophy of CaSSIS operations. All aspects of CaSSIS operations are designed to feed back into each other to improve the quality of acquired data. The dashed box represents aspects covered in this paper.

3. The CaSSIS target database - CaST.

The CaSSIS Suggestion Tool (CaST) is an interactive database for suggesting and interacting with targets to be observed with CaSSIS. It was created and is maintained by the University of Arizona, with a detailed description given in Almeida et al. 2023 [5], but is summarised here for clarity. CaST contains a web GUI where basemaps of Mars can be loaded along with existing CaSSIS image coverage. Data coverage maps from other missions (e.g. HiRISE) can also be loaded. Users then have the option to create a region of interest (ROI) to image with CaSSIS. Along with the ROI, users need to specify additional parameters describing how the image should be acquired. These include:

- Incidence angle range.
- Emission angle range.
- Phase angle range.
- Local time of day range.
- Season range.
- Requirement for stereo imaging.
- Requested target priority.
- Number of images to acquire of target.
- Which CaSSIS filters to use for imaging.
- Whether a mosaic of CaSSIS images should be acquired.

New targets are then passed to science team members, where an official target priority is assigned. This last step forms the bedrock of all CaSSIS planning – *every target is assigned a scientific priority, decided by leading world experts in the field*. Currently CaST is only open to the wider CaSSIS team, but is planned to be made public at a future date (for enquires about specific access to CaST, please contact the paper authors). An example of the CaST interface is shown in Figure 3.

4. ESA planning cycles.

TGO planning follows an approach commonly used for ESA missions: long term plan (LTP), medium term plan (MTP) and short term plan (STP) (see Almeida et al. 2023 [5] for details). LTP refers to the scheduling of observations/TGO activities that will occur anywhere from ~4 months to 1 year in the future. While this may seem

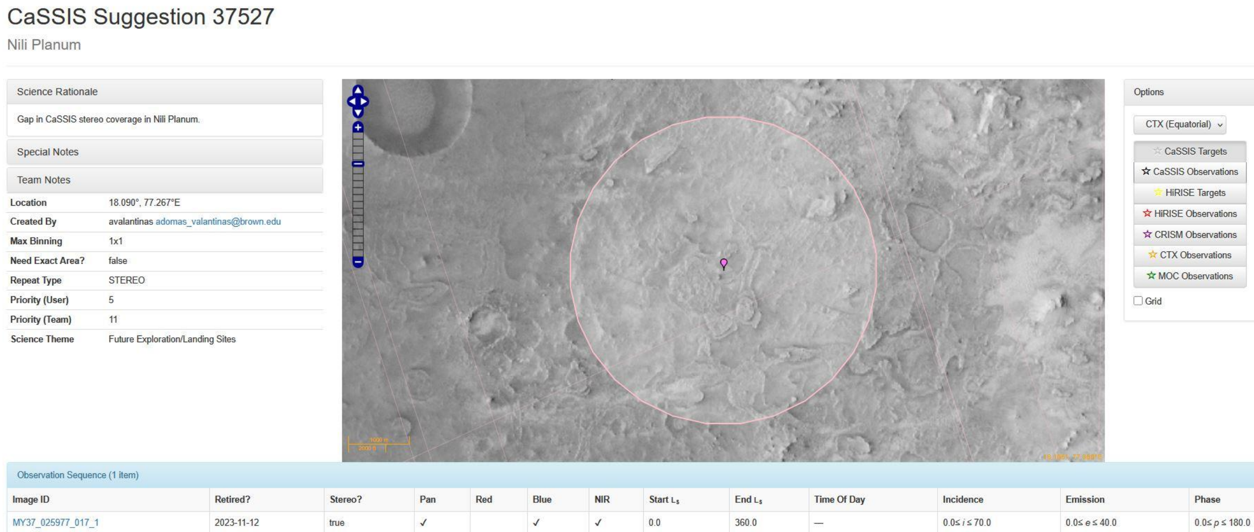

Figure 3: CaST interface. Central pink circle represent CaST target ROI. Bottom table represents illumination parameters target should be acquired with.

premature in regards to the accuracy of possible orbit trajectories, TGO adopts a ‘fly the plan’ strategy, where a baseline orbit is defined far in advance, with later orbital manoeuvres being performed to broadly maintain this trajectory. LTP is mainly used for scheduling TGO activities (wheel offloads, ground asset relays) and non-Mars pointings for payloads. It also allows for CaSSIS to ‘reserve’ a small number of full orbits for very high priority CaSSIS images. Crucially for the CaSSIS operations team, the LTP trajectory allows for a full orbital analysis to determine all imaging opportunities for every CaST target far into the future (see Section 7).

MTP refers to observations to be acquired in ~3 months. At this point, spacecraft activities are added to the baseline LTP orbit trajectory, which in some cases prohibit or restrict CaSSIS imaging (wheel offloads, non-Mars pointings etc.) and are referred to as ‘exclusion zones’. During MTP planning, the CaSSIS team have the option to roll the spacecraft to target specific ROIs (known as ‘targeted’ pointings), however this can only be done once per orbit due to spacecraft constraints. At the end of MTP planning, the TGO orbit trajectory is fixed and no further TGO manoeuvres can be requested. In general, CaSSIS observations planned at MTP are of mid-high priority targets, and are where most (if not all) stereo observations are planned.

STP refers to observations to be acquired in ~1 month. CaSSIS images are planned along the nadir track outside of exclusion zones, with the main constraining parameter being available downlink capacity. On average, the bulk of CaSSIS images are planned at this stage, especially during Mars opposition periods.

5. CaSSIS planning interface – PLAN-C.

PLAN-C is GIS based tool for CaSSIS observation planning and was created and maintained by the University of Arizona (Almeida et al. 2023 [5]). It allows for placement of CaSSIS images based on the TGO orbit trajectory, and image acquisition parameters to be specified (stereo images, which filters to use, detector binning etc.). The PLAN-C GUI allows for multiple basemaps of Mars to be loaded, along with the CaST target database and the map of already acquired CaSSIS images. CaSSIS images need not be planned on CaST targets in PLAN-C, any valid part of the orbit trajectory can be used (e.g. areas not in spacecraft exclusion zones). PLAN-C is also fully compatible with the ESA planning approach outlined in Section 4 and allows for TGO off-nadir targeted pointings where appropriate. An example targeted pointing image being planned in PLAN-C is shown in Figure 4.

6. The issues with manual observation planning.

For the first ~3 years of CaSSIS operations, PLAN-C was used as the primary tool for generating CaSSIS observation plans. This tool proved extremely powerful. Planned CaSSIS images could be easily visualised and operators had the choice of creating observation plans exactly to their own specification. However, over time issues with this approach started to arise. As each image needed to be manually planned, it was found to be significantly

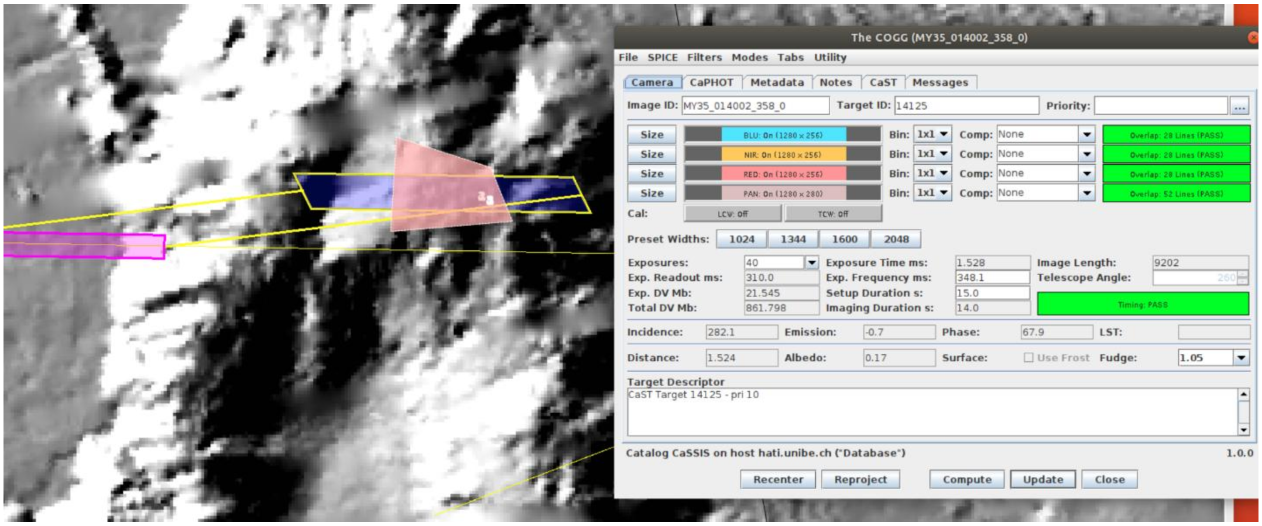

Figure 4: PLAN-C interface. Blue rectangle represents planned CaSSIS image on top of pink CaST target. The GUI on the right shows the parameters the CaSSIS image will be acquired with and is configurable.

labour intensive to generate a full observation plan, especially during periods of high downlink capacity (in some cases, 300+ images needed to be manually planned for a single week of imaging). For example, it could take image planners 1-2 weeks just to create a plan for a single week of imaging at the peak data rate season. Understandably in these situations, it was noted that plans could sometimes suffer from 'planner fatigue', with high priority CaST targets being missed or inadvertent errors being injected. Dealing with the large number of CaST targets in the database (~25,000 open targets as of writing) was difficult, further increasing the chance high priority targets were missed. Each CaST target also needed to have all the parameters described in Section 3 cross referenced with the planned image to make sure an image was acquired with the requested conditions, further compounding planner fatigue. This latter issue was particularly problematic, as repeat imaging would be needed if the illumination conditions were not correct, and sometimes a whole Martian year would need to go by before there was another opportunity.

7. The CaSSIS Target Lead Imaging Support Tool - CaTLIST.

The focus of the CaSSIS operations team therefore switched to designing and implementing a fully automated approach for CaSSIS planning. The primary goal with this approach was not to replace human planners, but aid them in generating scientifically optimised observation plans, in as little time as possible. However, in scenarios where human planners were not available, the CaSSIS operations team also wanted the tool to generate observation plans that were fully flight ready and could be immediately uplinked to the spacecraft.

The CaSSIS Target Lead Imaging Support Tool (CaTLIST) was designed and created to fulfil this objective. The tool broadly addresses the following:

- *The plan must be scientifically optimised and be based on the requested CaST target database.*
- The plan must be generated fully autonomously and be flight ready for potential immediate upload to CaSSIS.
- All illumination conditions requested for targets must be considered.
- It must produce LTP, MTP and STP ready observation plans based on the TGO trajectory.
- Multiple pointing modes for CaSSIS must be supported, including stereo and non-stereo observations.
- Full conflict resolution must be performed in the event of imaging clashes.
- A full geometric analysis of the CaST target database must be performed to identify hard to image targets and promote them where necessary.
- Automatic mosaicking of requested targets.
- It must be quick to run, allowing for fast turn arounds for potential last minute commanding.

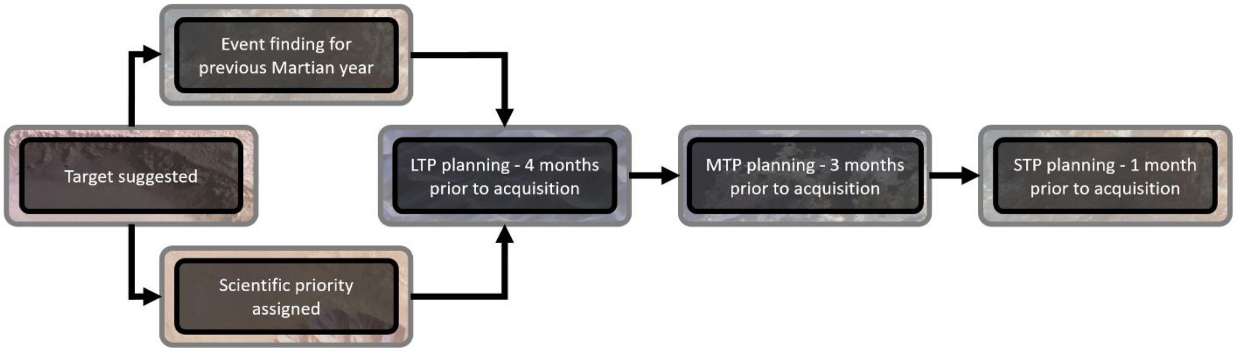

Figure 5: Timeline for how CaST targets are processed as part of nominal CaSSIS planning.

To address this ambitious goal, CaTLIST was broadly split into four different 'modes': geometric event finding, LTP, MTP and STP planning. A summary of the timeline of these modes is shown in Figure 5.

7.1 Geometric event finding of CaST targets

Originally when CaST targets (Section 3) were input into the database, a scientific priority was assigned only. However, this did not necessarily address how easy/difficult a given target might be to observe. For example, a target requested with a narrow seasonal range may only have a small number of imaging opportunities per Martian year and this might not be reflected in the scientific priority. Commonly asked questions to the CaSSIS operations team also reflected this uncertainty. These included questions such as: 'When is the next opportunity to image CaST target X?', 'Why is CaST target X taking a long time to get imaged?', 'Are the illumination conditions requested for CaST target X too constraining for imaging?' etc. Given the number of parameters that affect CaSSIS planning, these questions could often only be fully answered by a dedicated orbital analysis.

It was desired therefore that a full orbital analysis be automatically performed for every newly requested CaST target. This would identify when valid imaging opportunities were possible, both in the past and into the future. An associated 'geometric priority' could then be assigned, which would represent the difficulty in imaging a given target.

The first component of CaTLIST addresses this issue. As soon as a new CaST target is requested, a full orbital analysis is automatically performed. This analysis identifies all valid imaging opportunities of the target a full Martian year (~2 Earth years) into the past (to cover all seasonal ranges), along with all opportunities out until the end of the known TGO trajectory (typically ~6 months to 1 year in the future at any given time). The NAIF SPICE kernels, along with all exclusion zone information are used to identify the exact time of image opportunities, along with all the local illumination conditions. Nadir off pointing, up to the maximum TGO roll allowance of 7deg is considered along with the availability for stereo observations. All failed opportunities and the reason/s for the failure are also identified (e.g. image would not have the requested illumination conditions, it would clash with a specific TGO exclusion zone etc.).

The complexity of this analysis should not be underestimated. It can involve modelling over 13,000 TGO orbits to find the exact time of target imaging opportunities. However, the CaSSIS operations team developed orbit fitting techniques and software that result in this analysis only taking a few minutes per target at most.

A main output from this analysis is the official creation of a target geometric priority, defined as the number of successful imaging opportunities for that target in the last Martian year, with this being fed directly into the next stage of observation plan generation.

7.2 LTP plan generation

As mentioned in Section 4, CaSSIS can request orbits to be reserved for high priority targets. Essentially, this results in all TGO/other payload activities not being scheduled for these orbits where possible. Currently, this is limited to 5 orbits per week (out of the total ~80). These reserved orbits need to be supplied to ESA before the beginning of nominal TGO activity scheduling, and as such must be provided ~4 months before the orbit execution. LTP planning denotes the first stage where an observation plan is generated by CaTLIST. It analyses each orbit for a given week and finds all the CaST targets that can be imaged with the requested parameters. Similarly to the orbit analysis described in Section 7.1, the NAIF SPICE kernels are used to model the TGO trajectory, along with an allowance for an off nadir spacecraft roll of 7deg. Every available CaST target for imaging is ranked, first by scientific and then by geometric priority. The LTP observation plan is then created from the top 5 targets in this ranked list. This observation plan is ‘flight ready’ in that it can (and is) sent directly to ESA without further intervention for inclusion in the later TGO trajectory.

As mentioned in Section 4, TGO only allows for a single CaSSIS off nadir pointing per orbit. In the event two or more of the top five targets share the same orbit, the highest ranked target is always selected, with the next lowest ranked target being considered for the 5th ranked target and so on. Targets that require stereo observations are not inherently treated as more important than non-stereo targets, however it is more difficult to acquire stereos due to CaSSIS timing constraints. This difficulty manifests through the geometric priority from Section 7.1, and as such, it is often the case that a significant fraction of the 5 LTP orbits are of targets requiring stereo observations.

7.3 MTP plan generation

MTP planning allows for CaSSIS to request the TGO operations team to roll the spacecraft either side of the nominal ground track by up to 7deg. These off nadir pointings cannot impact existing pointings in the trajectory (including those requested by CaSSIS during LTP planning) and are limited to once per orbit (out of a total of ~80 per week). Figuring out where the spacecraft should roll to in a given orbit was often a challenging decision for CaSSIS planners. Hundreds (if not thousands) of targets might be observable in a given orbit and as such, selecting which is most suitable required considerable work. CaTLIST run at MTP solves this issue by modelling the TGO trajectory with the SPICE kernels in a very similar way to the LTP mode described in Section 7.2. All available targets that the spacecraft can roll to are identified, checked to see if the illumination conditions are suitable, evaluated to see if stereo observations are possible and then ranked based on scientific priority and then geometry priority. While very similar to the LTP CaTLIST mode, the main difference is now spacecraft exclusion zones (off pointings for other payloads, relay slots, wheel offloads etc.) are considered, such that CaTLIST will not suggest observations if there are clashes. The CaSSIS MTP observation plan is then populated with the highest ranked target for each orbit.

The output plan is flight ready and can be sent directly to ESA for incorporation into the nominal TGO trajectory. However, the operations team can make amendments to the plan at this stage if they choose to. In the event that the highest ranked target for a given orbit is deemed unsuitable, the planner has multiple options. They can first choose to image anywhere possible on the surface, regardless of whether it is of a CaST target or not, using the PLAN-C tool (Section 5). Another option is to choose the next highest priority target from that orbit. CaTLIST saves the top 5 targets for every orbit, allowing for the operator to quickly determine another suitable option. Generally speaking, targets selected for MTP planning are mid-high priority targets, with stereo observations often being selected where possible.

The blending of automated and potentially manual approaches at this stage is a major strength of CaTLIST, allowing for the most scientifically impactful observation plan to be generated in the most efficient way possible.

7.4 STP plan generation

The final mode of CaTLIST is the plan generation at STP. As mentioned in Section 4, CaSSIS cannot request TGO off nadir pointing at this stage and must image along the nadir ground track. The task here is to schedule as many images as possible, mainly considering CaSSIS image timing constraints and downlink capacity. CaTLIST at STP identifies all targets that pass within the CaSSIS field of view with requested illumination, using the TGO trajectory and all spacecraft exclusion zones. Images of these targets are ranked by scientific and then geometric priority. Clashes between images, including those scheduled by CaSSIS at LTP and MTP, are identified and conflict resolved by taking the higher ranked target (LTP and MTP images always have priority). At this stage an observation plan is generated that is flight ready, under the assumption of no constraint on downlink capacity. An iteration of the data volume of the plan is then performed by CaTLIST to match downlink capacity. First, images are compressed and in the (likely) event that the observation plan still exceeds capacity, images are automatically iteratively removed, starting with the lowest priority.

Similarly to the other CaTLIST modes, the plan output is fully conflict resolved and flight ready. Operators have the opportunity to assess the plan and make any changes in a similar way to that possible at the MTP planning stage. This again allows for CaSSIS planning to benefit from automated and manual approaches.

Having a two stage approach for CaTLIST in STP mode, without and with downlink capacity constraints, is intentional. It is often the case that last minute downlink capacity is made available. This is either through other payloads not using their own allowance, or additional ground stations being made available. It was previously

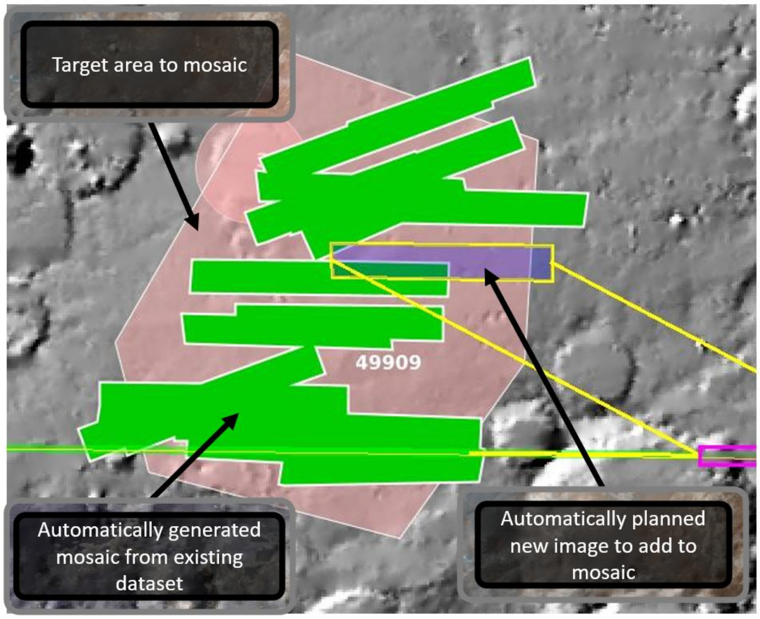

Figure 6: Example of an automatically planned CaSSIS mosaic. Existing CaSSIS dataset is considered and a new image is planned to add the most area to the mosaic.

difficult to take advantage of this additional capacity, as it required a particularly fast turnaround for the scheduling of additional CaSSIS images. However, CaTLIST easily takes advantage of this by inserting images back into the plan that were previously removed due to the old data volume capacity. This process takes a matter of seconds, allowing for CaSSIS to adjust to any additional downlink capacity, no matter how last minute.

7.5 Mosaic generation

Mosaic targets in CaST are specifically requested to have multiple, edge overlapping CaSSIS images for on ground stitching. This represents a challenge for observation planning. The existing coverage must be known at the exact time of image planning, including images that have already been planned but not yet executed. Moreover, for large mosaic ROIs, there is often multiple places where a new image can be planned that would add to the mosaic. Given the large number of already acquired CaSSIS images, generation of mosaics was classed as a priority for extended mission operations.

CaTLIST addresses this issue at all planning stages. It first generates existing mosaic maps based on acquired/ already planned data and calculates the ratio of remaining area that still needs to be imaged to fully cover requested ROIs. It then identifies if the TGO trajectory allows for additional planned images to connect to these maps. In the event that images can be added at multiple locations, the image is chosen that adds the most new unique area to a given mosaic. An example of CaTLIST planned mosaic image is shown in Figure 6.

CaTLIST mosaic image planning fits seamlessly with the planning of other targets. Non-mosaic and mosaic targets are not treated has inherently different for conflict resolution. The target with the highest scientific and then geometric priority is always selected. A notification is sent to the operations team once the imaging coverage (planned or acquired) for a given mosaic ROI reaches a critical threshold, denoting that the reconstruction of the mosaic product can begin.

7.6 Basemaps from other missions

During the high data rate season, finding enough requested targets to image with CaSSIS could prove challenging. Rather than not using available downlink capacity, the CaSSIS team explored using basemaps of Mars from other missions for automatic suggestion of targets. The THEMIS dataset (Christensen et al. 2004 [6]) was found to be complimentary to CaSSIS imaging goals, whilst having wide surface coverage. Areas of potential exposed bedrock (compositionally of interest for CaSSIS) can appear bright in this dataset. As such, these areas were identified and are considered as targets for CaSSIS, in the event of large downlink capacity. CaTLIST automatically considers these targets, treating them with a lower priority to only be used if no other targets are available. An example of an identified target from THEMIS along with the acquired image is shown in Figure 7.

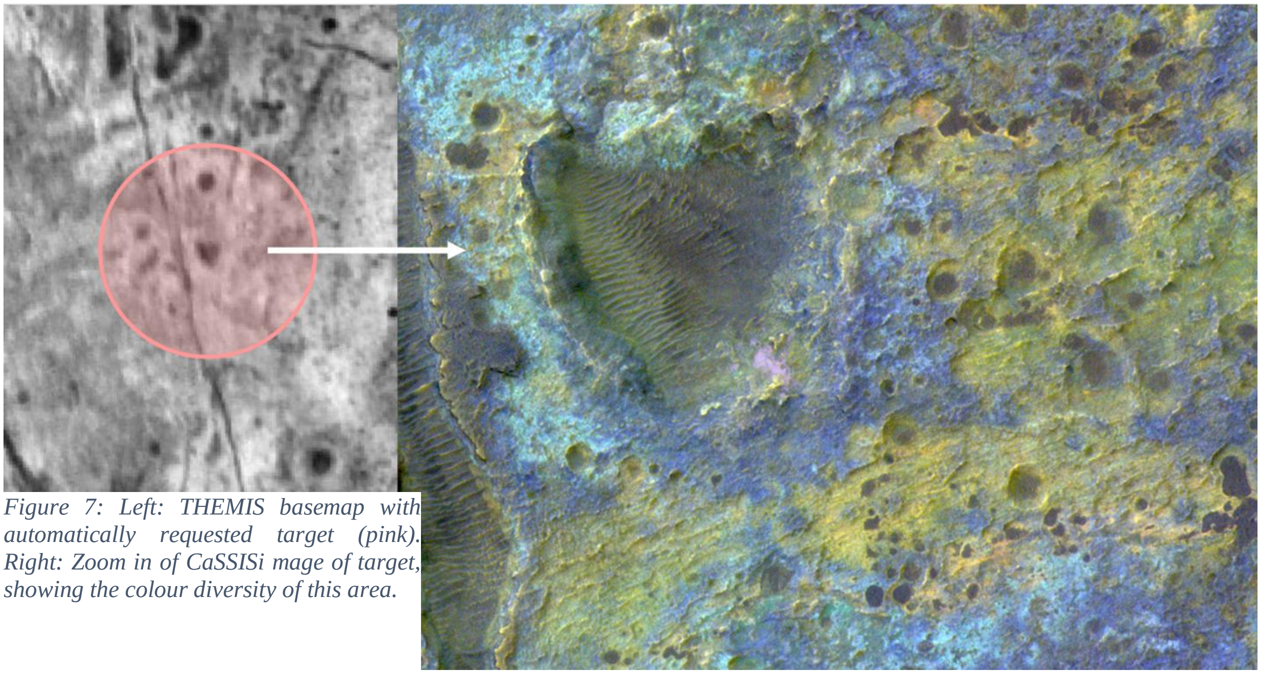

Figure 7: Left: THEMIS basemap with automatically requested target (pink). Right: Zoom in of CaSSISi mage of target, showing the colour diversity of this area.

This strategy has proved to be extremely successful for CaSSIS. Between these targets and CaTLIST, filling downlink capacity is much less of an issue compared with earlier in the mission. Moreover, the quality of the data acquired of these targets has been extremely impressive. As such, many other basemaps are now in the process of being considered by CaTLIST planning.

8. Summary and Impact of CaTLIST.

Creating a high quality CaSSIS observation plan requires numerous constraints to be considered. These include local illumination, TGO pointing constraints, exclusion zones, downlink capacity to name a few. Manual planning therefore required significant time investment, especially during periods of high downlink capacity. An automated planning tool, CaTLIST, was therefore created to produce flight ready CaSSIS observation plans, that are scientifically optimised and take into account all constraints an equivalent human operator would need to consider.

The impact of CaTLIST has been significant. Operators would previously often take more than a week to produce a CaSSIS observation plan that can now be generated, in some cases, in a matter of minutes. The quality of the generated plans means that CaSSIS planners have transitioned more to plan validators and optimisers. There has also not been a single case where a high priority target has been missed for observation since the introduction of CaTLIST and general effects seen from previous planner fatigue have all but been eliminated.

While this tool was generated for CaSSIS, the underlying architecture can be applied to any mission, especially those that follow the commonly used ESA strategy of LTP, MTP and STP planning. The example of CaSSIS has shown just how effective this planning architecture can be.

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 Italien 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 Activites Nationales Complementaires programme of the Swiss confederation under grant REF-1131-6100 and the UK Space Agency under grant ST/R003025/1 is also acknowledged

References

[1] Thomas, N., et al., 2017. The colour and stereo surface imaging system (CaSSIS) for the ExoMars Trace gas orbiter. Space Sci. Rev. 212.

[2] McEwen, A.S., et al., 2007. Mars reconnaissance orbiter's high resolution imaging science experiment (HiRISE). J. Geophys. Res. 112, E05S02.

[3] Tornabene, L.L., et al., 2018. Image simulation and assessment of the colour and spatial capabilities of the colour and stereo surface imaging system (CaSSIS) on the ExoMars Trace gas orbiter. Space Sci. Rev. 214.

[4] Valantinas, A., et al., 2024. Evidence for transient morning water frost deposits on the Tharsis volcanoes of Mars. *Nat. Geosci.* 17, 608–616

[5] Almeida, M., et al., 2023. Targeting and image acquisition of Martian surface features with TGO/CaSSIS. Planetary and Space Science. Volume 231.

[6] Christensen, P.R., et al. 2004. The Thermal Emission Imaging System (THEMIS) for the Mars 2001 Odyssey Mission. *Space Science Reviews* **110**, 85–130.