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The Colour and Stereo Surface Imaging System (CaSSIS): Planning and commanding high resolution imaging at Mars

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Abstract

The Colour and Stereo Surface Imaging System (CaSSIS) was launched onboard the European Space Agency's ExoMars Trace Gas Orbiter (TGO) in March 2016. The payload including CaSSIS started its prime mission from its operational orbit (around 400 km above the surface of Mars) on 21 April 2018 and has subsequently acquired over 30000 images of the surface in up to four broad-band colours with over 2000 sites captured in stereo through use of its rotation mechanism (Thomas et al., 2017). Extension of mission operation to the end of 2025 is currently being planned.

The images are typically 9.5 km x 40 km and are acquired using a push-frame technique providing ~4.5 m/px scale. The targeting of imaging acquisition is a necessary part of the operations because the data rate from the spacecraft is only sufficient to cover <2% of the Mars surface per annum and this low value can be reduced further when repeat observations of (e.g.) seasonal targets are included.

It was recognized during CaSSIS instrument development that two tools developed for the targeting of the High Resolution Imaging Science Experiment (HiRISE), which started its prime mission at Mars in 2006 onboard NASA's Mars Reconnaissance Orbiter, could be adapted for CaSSIS planning. This was considered particularly attractive because it reduced the costs of new development and the two tools had already been shown to be effective in allowing the science team to take ownership of the target definition and acquisition planning.

The CaSSIS Suggestion Targeting tool (CaST) is a database of targets entered by the science team and is based upon the architecture of HiWISH (https://www.uahirise.org/hiwish/) – a public suggestion tool for HiRISE. The second tool is PLAN-C which is a derivative of the HiPLAN tool for HiRISE. PLAN-C is based upon the JMARS Geographical Information System (GIS) tool developed by Arizona State University (Wren et al., 2021). This allows detailed planning of targets before generating an output file that can be entered into an automated command generator. Use of these tools has allowed procedures to be developed that have maximized scientific input into the targeting and significantly improved the scientific return. In particular, periods where individual science team members (referred to as "Targeting Leads") can lead and optimize the development of the data acquisition short-term plan, can be defined.

In addition to these main workhorses, the CaSSIS team has developed a number of other tools and scripts to reduce the time needed to construct an observation plan and command file by automating target selection using the existing database. The automization significantly reduces the effort needed by the Targeting Leads to define the acquisition plan making the task of the science team appreciably easier and less time-consuming. Although the details of the tools are specific to CaSSIS, the overall structure and approach can be thought of as generic for all high resolution remote sensing instruments. The experience gained during CaSSIS operations can now be used to describe/define the requirements for each element of a generic procedure that can be adopted by other teams in future missions.

Keywords: CaSSIS, Mars, Imaging, Science, Planning, Commanding

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1. Introduction

The CaSSIS instrument [1] is a high resolution camera on board the Trace Gas Orbiter (TGO) spacecraft, that started its science phase in April 2018. Mars is being studied from orbit since the 1960s, from the original scouting missions, like Mariner 4 that returned a handful of images [2], to HiRISE that is able to image the Mars landscape from Orbit with centimetre resolution [3]. CaSSIS in this context is able to complement the best Mars datasets from having the capability to obtain images of Mars at four different wavelengths with unique colour capabilityarising from its absolute calibration [4] and photometric calibration [5].

CaSSIS plays a crucial role in improving our understanding of Mars by capturing high-resolution images of the planet's surface. It operates using a push-frame method to acquire many individual exposures with four color filters (BLU, NIR, RED, and PAN) that cover an area of 9km x 40km with a resolution of 4.5m/pixel at TGO's nominal altitude of 400km. The filters used in CaSSIS were carefully selected to ensure consistency with data from other instruments such as the HiRISE (High Resolution Imaging Science Experiment) camera on the Mars Reconnaissance Orbiter (MRO).

The BLUE and PAN filters are centered at 497nm and 677nm, respectively, and were designed to match the wavelength bands used by HiRISE. The RED and NIR filters, centered at 835nm and 940nm, are used to improve the detection of minerals, particularly those containing iron, in the third (IR) filter on the HiRISE instrument. This enhances the overall quality of the Mars data set by providing better information on the composition and mineralogy of the surface.

Moreover, CaSSIS can also be used in conjunction with the CRISM (Compact Reconnaissance Imaging Spectrometer for Mars) instrument to provide even more comprehensive data on Mars. CRISM uses spectroscopy to gather information on the mineral composition of the planet's surface, and when combined with CaSSIS data, provides a more complete picture of Mars's geology and mineralogy.

In conclusion, the images acquired by CaSSIS, and the integration of CaSSIS data with CRISM spectra, significantly improve the quality of the Mars data set as a whole, providing a clearer understanding of the planet's surface and its geological and mineralogical features.

2. The CaSSIS instrument

CaSSIS is a stereo multi-colour camera mounted on an F/6.5 telescope with a focal length of 880mm. It uses a 10µm pixel pitch CMOS hybrid detector and has an angular scale of 11.36µrad/px, resulting in a spatial scale of 4.5m/px on the surface of Mars. The camera uses filters to obtain multi-band information, and images are obtained by aligning the line perpendicular to all filters with the spacecraft velocity vector. The camera's motor rotates 360° around its axis and can be used to look forward or backward, enabling stereo pairs with a 22.4° convergence angle. The images can cover the full swath or only part of it, and are acquired at a rapid frequency that matches the spacecraft's ground-track velocity. Typically, 40 framelets are acquired in an imaging sequence, which are then mosaicked to form the final image. The framelet acquisition frequency is around 1 every 400ms, and the combination of the framelet width, number of colours, and number of pixels is limited by the maximum (SpaceWire) data transfer rate of 70 Mbit/s. The trade-off between swath width and number of colours is a science decision made by the team when planning the specific observations.

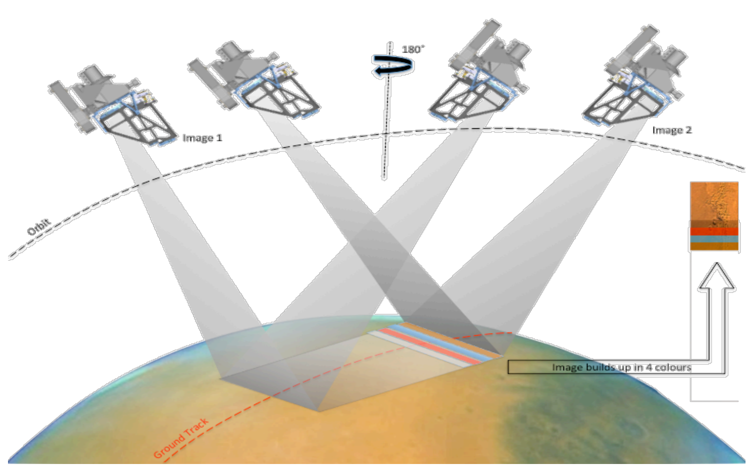

Figure 1 - CaSSIS Colour and Stereo Acquisition Example. The motor in CaSSIS allows the team to align the camera with the orbit track thus permitting colour acquisition as the data for each filter can be matched

at the different acquisitions. Additionally if two images of the same region are acquired, with the motor rotated 180 degrees, a stereo pair can also be obtained.

3. The CaSSIS operations

CaSSIS operations follow the generic ESA planning approach, where the spacecraft attitude is frozen about 3 months in advance of the payload data acquisition sequences. The relatively small footprint when considering the Mars global scale, means that targets have to be selected according to several criteria.Per Mars year CaSSIS is able to image about 3% of the surface. Given that an important objective of CaSSIS is to follow potential geologically active sites, repetition of images also occurs, further decreasing the amount of area covered.

A big part of the planning cycle of CaSSIS is dedicated to carefully selecting the targets that will be imaged, where the CaSSIS team can request the spacecraft to target specific areas, in what is called the targeted planning. Later on and closer to the image acquisition time, the available data is filled with nadir images of areas of interest that are passed by chance.

A set of tools exists that are used by the scientists and engineers on the CaSSIS team. The CaST tool plays a crucial role in the Science planning. Before the actual operational planning starts, the scientists carefully choose the targets they want to capture using this tool. CaST provides a user-friendly and modern web interface, which enables users to suggest targets for the CaSSIS imaging system. This tool is based on the HiRISE tool HiWish [6], which has been extensively used by the scientific community.

One of the key features of CaST is its ability to display several maps of Mars, allowing users to select a region of interest or a specific site. This feature is particularly useful for scientists who are interested in studying a particular area on Mars. The tool also enables users to overlay the positions of already acquired HiRISE images, as well as proposed HiRISE targets. This helps the scientists to study the context and coordinate their acquisitions with HiRISE.

The scientific interest of the region of interest is an important factor that drives the exploration of Mars. A region of interest could contain geological formations, mineral deposits, or other features that could help users understand the history and evolution of the planet. For example, the presence of water on Mars has been a topic of great scientific interest, and scientists have been using various tools and instruments to study this aspect in detail. With the help of the CaST tool, they can select specific regions that contain signs of water or other signs of possible past habitability.

The initial planning step of operations proper is one of the most innovative capabilities of the CaSSIS planning system. An automated tool uses the CaST targets and orbital geometric information together with the ESA provided spacecraft constraints to propose a image acquisition plan.

The CaTL Image Suggestion Tool (CaTLIST) is an important component of the CaSSIS imaging process. It automates the target suggestion phase and prepares the information for ingestion into PLAN-C (see below). CaTLIST was developed based on the previous concept and tool used for the SMART-1 mission [7].

CaTLIST relies on the CaST database of requested targets. All targets suggested by CaTLIST are based on the targets requested in this database. The tool uses this information to produce a full CaSSIS Target File (CTF) - a list of all the images to be acquired during a week of planning., The tool also avoids conflicts in timing and data volume constraints and, after conversion into instrument commands, can be sent to the spacecraft without the need for manual intervention.

In addition, CaTLIST generates parameters for individual image acquisitions such as number of filters, to meet the requirements specified in the CaST database for each target. The tool can be used for both targeted and nadir pointing types, making it a versatile tool for all stages of the CaSSIS image planning process.

Finally, the approach used by CaTLIST to construct an imaging sequence provides valuable insight into the manual process of building a sequence. This tool has the potential to streamline the image planning process and make it more efficient, while ensuring that all targets are acquired to the highest quality.

In order to further improve the quality of the planning, CaSSIS Target Leads (CaTL) can modify the planning provided by CaTLIST and further improve its quality based on their extensive knowledge of Mars science. This is done using the PLAN-C tool.

PLAN-C is a powerful GIS tool designed for CaSSIS image planning. It provides a graphical interface that displays maps, GIS shape files, TGO orbit tracks, exclusion zones for planning, image footprints, and other important information in layers with adjustable transparency. This tool was built using the open-source JMARS application, which was developed at Arizona State University. It offers similar capabilities to the HiPlan tool used by the HiRISE operations team.

PLAN-C creates two custom data layers to aid in image planning. The first layer is the target database layer, also known as the CaST layer. This layer is a modified GIS shape file layer and displays information about targets that have been suggested through the CaST interface. Each suggested target is assigned a unique ID and the requested conditions for imaging are shown. It is important to note that a target can be suggested for imaging multiple times, and each requested image will have an associated entry in the target database layer.

The second layer is the image planning layer, which is used to plan the actual image acquisitions. This layer takes into consideration all of the information from the target database layer, along with other factors such as the TGO orbit tracks and exclusion zones, to create a comprehensive plan for imaging.

Each selected image in the PLAN-C tool is planned with a set of default imaging parameters such as image width, number of exposures, filters to be used, compression, and others. These parameters can be manually adjusted for each image by the user through the CaSSIS Observation Generation GUI (COGG), which is a separate panel within the image planning layer. The exposure time for each planned image is calculated automatically by the tool, taking into account the imaging parameters and other relevant factors. This allows for precise and efficient image planning, ensuring that the resulting images meet the desired specifications. The COGG interface is similar to the HOGG tool used for the HiRISE mission.

The PLAN-C tool allows for the export or import of a CTF at any stage of image planning. This file contains all the relevant information about the planned images and is stored in a comma-separated (CSV) format for easy processing. The CTF can be read back into PLAN-C for further image planning or can be passed on to the CaSSIS Operations Team once the user has completed the image planning process.

The CaSSIS Operations Team comprises of two Target Specialists (CaTS) who use a set of tools to verify that the program and images requested comply with the flight rules. They also plan maintenance and calibration activities within the CTF. The CaTS then prepare the time-tagged command files called Instrument Timelines (ITL) by using a code called CTF2ITL. This code compiles the ITLs taking into account the specific timing required by CaSSIS to execute commands and ensure that data acquisition and read-out comply with the system's bottlenecks affecting data transfer. Additionally, periodic reboots of the instrument to clean the memory and avoid errors can also be included in the CTF. The CTF2ITL code calculates the sequence needed to execute the reboot in a safe and efficient manner. Other instrument maintenance commands can also be included in the CTF and processed by the code.

4. Conclusions

The CaSSIS telescope aboard TGO has established itself as a unique tool in the ESA program, with its high resolution imaging capabilities of approximately 4 meters per pixel and a small image footprint of 9 km by 40 km. The specific design of CaSSIS has enabled it to focus on studying targets of high scientific interest, taking advantage of its high-resolution colour and stereo imaging capabilities.

The CaSSIS planning system has been designed to separate the target selection process from the operations. This gives scientists the freedom to choose their regions of interest without needing to know all the technical details about the CaSSIS trajectory. With the target database as a starting point, the CaSSIS planning tools help the Science Team CaTL to optimize the target selection based on scientific merits instead of technical feasibility.

To date, CaSSIS has acquired over 30,000 images, many of which are of high quality, and has retired around 5,000 targets. The recently introduced tools aim to improve the speed of target retirement, but certain geometries, when the sun is low on the horizon, can reduce the signal-to-noise ratio for many applications. As a result, these targets are not retired. Additionally, some targets are seasonal and are only retired after an image is acquired with the required geometries. The CaSSIS team plans to further automate the process and minimize manual intervention in the future. This will not only make the process faster, but it will also reduce the risk of human error. Building on the CaTLIST tool, the CaSSIS team plans to develop a more strategic plan, incorporating a knowledge database on observation conditions and seasonality to improve the output of CaTLIST.

There are several important aspects to consider when programming high-resolution imagers in orbit around Mars (or other Solar System bodies). Firstly, the approach to the spacecraft orbit control has a significant impact. In the case of ESA, they chose to "fly the plan," meaning they made a long-term plan for the spacecraft trajectory and used orbital correction manoeuvers to follow that plan. This allows for planning to be done well in advance, except for major orbit manoeuvers. On the other hand, predicting the orbit trajectory, as NASA did with Mars Reconnaissance Orbiter, reduces some of these issues but requires faster planning closer to the time of execution.

When planning to "fly the plan," there is a tendency to have resonant orbits, which return to the same location at short intervals, covering the same regions. This 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.

Mars communications with ground assets can significantly impact operations and make it difficult to image certain areas near landing sites. With a nominal mission duration, high spatial resolution remote-sensing systems can only 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 requires a science-driven target selection database that is accessible to the operational planning tools. The database entry should be simple, but the more constraints from the requestor, the more sophisticated the automated selection tool can become.

Finally, although the automated tool (CaTLIST) is very powerful, it cannot be fully automatic for all objects and conditions. A manual review is mandatory. The goal should be to reduce the time needed for this review and optimization to a minimum.

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