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The Colour and Stereo Surface Imaging System: Science data handling and archiving

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Abstract

The Colour and Stereo Surface Imaging System (CaSSIS) is the Mars surface imager on board the European Space Agency's ExoMars Trace Gas Orbiter. CaSSIS has one of the most advanced capabilities for colour and stereo imaging on any spacecraft currently orbiting Mars. In order to fully utilize this capability, robust data handling and archiving is vital. This publication outlines the various stages of this data handling process, including the data validation steps performed. A description of the final archive products from CaSSIS is also given. The CaSSIS team have designed the data handling process within an underlying framework for all CaSSIS operations, where all steps, from the planning of observations, through to the processing and archiving are intrinsically linked in a continuously evolving feedback loop. While individual steps in the data handling described in this publication might be specific to CaSSIS, the underlying framework implemented by the CaSSIS team defines a generic procedure that could be followed by other teams in future missions.

Keywords: Mars, Remote Sensing, CaSSIS

Acronyms/Abbreviations

CaSSIS – Colour and Stereo Imaging System.
ESA – European Space Agency.
TGO – Trace Gas Orbiter.
EDDS – Electronic Data Dissemination System.
HiRISE – High Resolution Imaging Science Experiment.
ISIS3 - Integrated Software for Imagers and Spectrometers.
NAIF – Navigation and Ancillary Information Facility.
MOLA - Mars Orbiter Laser Altimeter.
CRISM - Compact Reconnaissance Imaging Spectrometer for Mars.
CTX – Context Camera.
PSA – Planetary Science Archive.

1. Introduction

The Colour and Stereo Surface Imaging System (CaSSIS) is the Mars surface imager on the European Space Agency's (ESA) ExoMars Trace Gas Orbiter (TGO). CaSSIS currently offers one of the most advanced remote sensing colour imaging capabilities on any spacecraft currently orbiting Mars. Launched in 2016, CaSSIS began nominal science operations in April 2018, imaging the Martian surface quasi-simultaneously in four separate colour bands. A typical image acquired with CaSSIS covers 9km x 40km on the surface with a resolution of roughly 4.5m/pixel at the nominal altitude of the TGO of 400km (Thomas et al. 2017 [1]). Each of the four colour filters used for observation with CaSSIS are referred to respectively as BLU, NIR, RED and PAN. The BLU and PAN filters are centred at 497nm and 677nm respectively and were designed to closely correspond to the wavelength bands used by the HiRISE instrument on the Mars Reconnaissance Orbiter (McEwen et al. 2007 [2]), for the purpose of cross instrument consistency and studies. The RED and NIR filters are centred at 835nm and 940nm respectively and split the remaining third filter on the HiRISE instrument for improved distinguishing of surface minerals, particularly those containing ferrous iron $Fe^{2+}$and ferric iron Fe^{3+} (e.g. Tornabene et al. 2018, in prep [3,4]).

CaSSIS operates with a push-frame method of imaging, where many individual exposures in each of the four colour bands are acquired at a rate proportional to the ground track velocity of the TGO (roughly 3km/s). Typically, CaSSIS acquires such individual exposures every 350ms, which gives an overlap between subsequent exposures of roughly 5-

10%. On-ground processing then matches the overlap areas between exposures to create the full image swath of 9km x 40km for a typical 40 framelet image. An example CaSSIS image is given in Figure 1.

A novel rotation mechanism on CaSSIS allows the entire telescope system to rotate in a 0-360deg motion about the nadir vector of the TGO, with CaSSIS itself mounted to observe 10deg off the TGO nadir vector for any given rotation mechanism position. CaSSIS is therefore capable of stereo imaging during a single TGO overpass of a target. Here, the instrument is rotated to observe a target in front of the TGO in the direction of the ground track velocity. The entire instrument is then rotated 180deg in time to observe the same target from behind the TGO (~45s later). This allows for on-ground construction of colour stereo images where both halves of the stereo pair were acquired with identical illumination conditions.

The orbit of the TGO is non-sun synchronous with an inclination of ~74deg, allowing for CaSSIS to image areas on Mars between ±74deg latitude at many local times of day, orbital phase and season.

To date CaSSIS has acquired roughly 35,000 images, including over 2000 stereo observations. CaSSIS operations are primarily conducted from the University of Bern, Switzerland, with support from multiple institutions including, in no particular order: University of Arizona U.S.A, Open University U.K, United States Geological Survey, Flagstaff, U.S.A, Osservatorio Astronomico di Padova, Italy. With such a vast and continuously increasing dataset, it is necessary for robust data handling routines for data collection, calibration and archiving. This paper details this process, from the initial acquisition of CaSSIS image data on the TGO, through the processing and image reconstruction to the final archiving of CaSSIS images for use by the wider community. Section 2 first outlines the underlying philosophy CaSSIS has adopted for data handling and how this is designed to actively feedback into the planning of future CaSSIS images and provide the most up-to-date information on the on-going hardware performance. Section 3.1 then details the specific generation of data by CaSSIS and how this is delivered and checked before on-ground processing. Section 3.2 outlines the processing steps that are then performed on the data. Section 3.3 outlines data validation, with Section 3.4 describing how processed data is then fed back into the planning process to optimize the scientific return of future observations. Lastly, Section 4 describes the final archiving process of the CaSSIS dataset.

Figure 1. An example CaSSIS image with a swath size of roughly 9km x 40km, created through 40 separate exposures of the Martian surface which are subsequently stitched together.

2. Data Handling and Archiving Philosophy

The quality of the data produced by CaSSIS is intrinsically linked to the quality of the targets that are suggested for observation. Moreover, the opposite is also true, for high quality targets to be suggested for observation with CaSSIS, it is necessary to know what data (and of what quality) has already been collected. An obvious example case is where duplicate images are taken of a given target unnecessarily, which may result in other targets not being imaged. However, subtler examples are also possible, such as targets being observed with conditions that in hindsight are not best suited for the associated scientific goal. It was therefore important to the CaSSIS team to develop an underlying philosophy in which data planning, acquisition, processing and archiving were intrinsically linked into a continuously evolving feedback loop. Furthermore, integrating an on-going evaluation of the hardware performance into this feedback loop by default was also deemed to be critical. Such integration allows for the CaSSIS operations team to always have the latest knowledge of the performance of the instrument and be able to

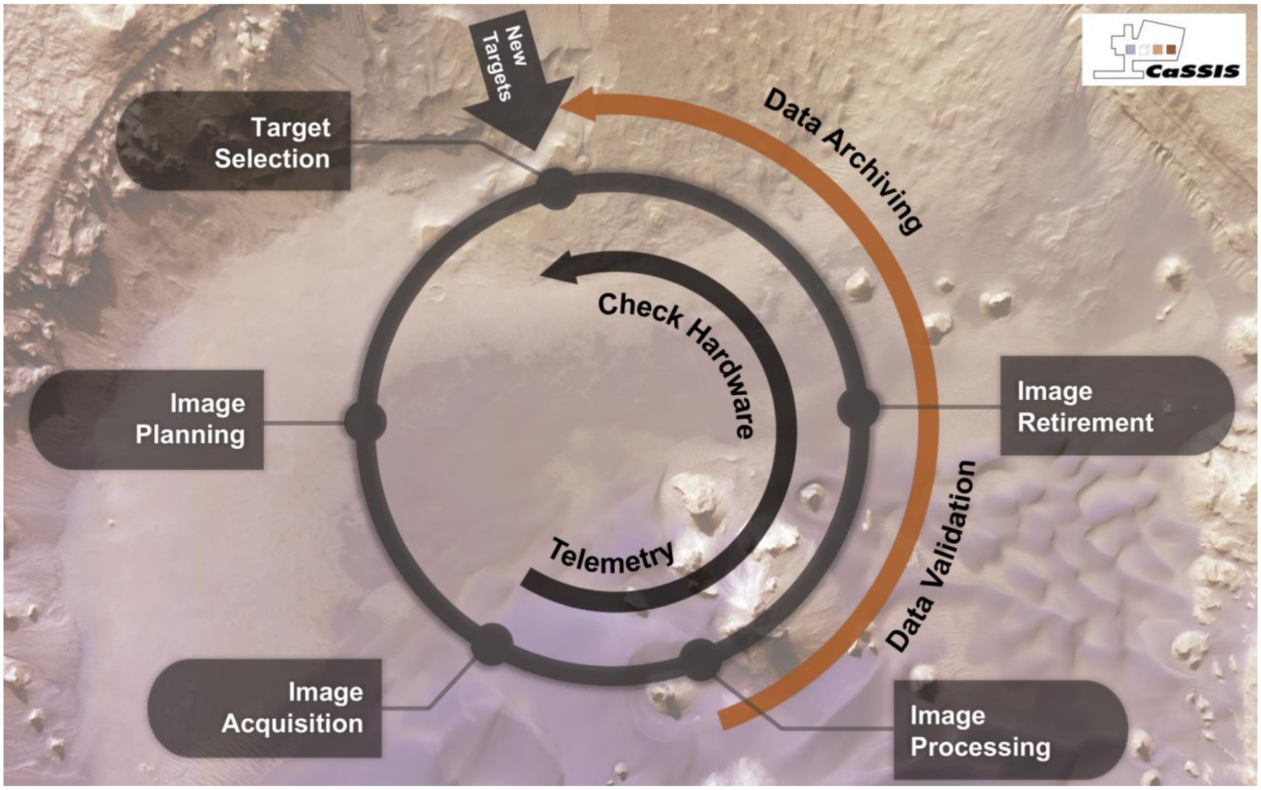

Figure 2: The underlying philosophy for CaSSIS operations. All stages of CaSSIS operations, from image planning to processing are designed to fit into a continuously evolving feedback loop to improve the quality of targets being requested for imaging.

quickly amend the types of targets that are being imaged, should on-going hardware limitations require it. A diagram of the underlying philosophy of CaSSIS operations is shown in Figure 2. For the purpose of this document, how the data acquisition, handling and archiving is constructed within this philosophy is described. For details of how target selection and imaging planning are made, reference can be made to (Almeida et al. 2023 [5]).

3. Data Handling

Data handling of CaSSIS data can be broadly split into the following steps:

- Data acquisition and transmission.
- Processing.
- Validation.
- Feedback into on-going and future CaSSIS observation planning.

This section details each of these steps and how they feed into the CaSSIS operations philosophy.

3.1 Data acquisition and transmission

Data acquisition with CaSSIS can be split into two main categories: instrument telemetry and science image observations. Instrument telemetry (sometimes referred to as housekeeping) contains the information read out by on-board sensors across CaSSIS that log hardware performance at any given period of time. These include, but are in no way limited to: currents/voltages across the instrument, sensor temperatures, number of commands issued, position of the rotation mechanism etc. Telemetry information is stored as single packets of information of ~500bytes for a given moment of time on the spacecraft. Once Earth transmission of this data is complete, it is stored and accessed through the Electronic Data Dissemination System (EDDS) from ESA. Through collaboration with ESA, raw CaSSIS telemetry is queried from the EDDS automatically every 15minutes. This data is then automatically unpacked, converted to human readable format and saved to a database. The visualisation of the telemetry data is subsequently performed by a data panel webtool (Almeida et al. 2023 [6]) for monitoring by the CaSSIS operations team. This process not only allows the most up-to-date status of CaSSIS to be viewed at any time, but also seamlessly allows for telemetry investigations of anomalies through the ability of database queries.

Science image data are stored on the TGO in packets of data, where each packet contains all the information for a specific exposure in a given colour band. Header information is written to each packet containing the flight software parameters used for the exposure acquisition, in addition to the image data itself, with a typical packet size equal to ~700kB. For a given week of imaging, it can be that upwards of 30GB of image packets are created. Similarly to the telemetry, image data are provided through the EDDS from ESA once it has been transmitted to ground. Here, the first stage of data validation is performed through a tool created by the CaSSIS operations team that automatically creates 'pseudo' image data packets, based on the expected packet size and contents from the associated imaging commands issued. An automatic byte by byte comparison is then made as image data are received from the EDDS, to identify any image packets that contain corrupt or missing data, down to the byte level. As the image data itself in a given packet cannot be predicted, a check is only performed on this data to make sure the expected number of bytes of data are present. Any abnormalities in the image data are automatically logged and provided to the CaSSIS operations team for follow up. Image data that passes this initial validation step is then automatically passed to where the image processing itself can begin.

3.2 Data processing

Initially validated raw CaSSIS science data are subsequently considered for on-ground calibration and reconstruction. This processing is split into two main stages: radiometric, followed by geometric calibration.

3.2.1 Radiometric calibration

The radiometric calibration applies both standard and CaSSIS specific calibrations including, but not limited to:

- Bias and flat field calibration.
- Absolute calibration.
- Straylight calibration.
- Rotation mechanism position refinement.

The CaSSIS bias is created from combined in-flight imaging of the night side of Mars, with the flat field being generated from acquired CaSSIS images of sufficiently homogeneous areas on Mars (Pommerol et al. 2022 [7]). Accurate absolute calibration from detector digital number (DN) units to reflectance (I/F), is of particular importance for spectral studies using CaSSIS data (e.g. Tornabene et al. 2018, in prep [3,4]). For CaSSIS, the absolute calibration conversion was measured in-flight, through extended observations of objects with known spectral responses, including Jupiter, Phobos and several standard stars (Thomas et al. 2022 [8]). Current estimates place the accuracy of the absolute calibration conversion at ~3%.

It was discovered in-flight, that in certain orbital geometries, straylight can enter the CaSSIS detector and produce significant parasitic signal. As such, the CaSSIS team created routines to automatically detect and remove the straylight down to an accuracy of ~1% for any given exposure as part of the nominal radiometric calibration (Pommerol et al. 2022 [7]).

Analysis of the status of the rotation mechanism is also performed during radiometric calibration. Knowledge of the exact position of the CaSSIS rotation mechanism is vital for accurately mapping, matching and stitching of individual CaSSIS exposures to create the full image swath. Offsets in the rotation mechanism position can cause mis-registration between the image colour bands, resulting in noticeable colour fringing in the final colour image (Perry et al. 2022 [9]). Knowledge of the exact position of the rotation mechanism from the instrument telemetry is only possible at the 0deg or 360deg position, where 'end switch' Hall sensors are present. The commanded position of the rotation mechanism for all other instances is provided by the instrument telemetry only, using a step counter. To identify any offsets between the commanded and actual rotation mechanism positions, the CaSSIS team have implemented an automated tool as part of the radiometric processing that finds the rotation position that minimises colour fringing when matching neighbouring exposures, hence indicating the actual rotation position that was used for exposure acquisition. The results of this analysis are logged to keep track of the evolution of offsets that occur. This process therefore not only improves the quality of image reconstruction, but is also used by the CaSSIS operations team to monitor the performance of the mechanism and identify operations which cause increased mechanical stress.

Periodic analysis of the detector performance is also performed as part of the radiometric calibration, including searching for additional bad pixels or evaluating the accuracy of the bias and flat calibration. Currently this analysis is performed intermittently by the CaSSIS operations team, due to the observed stability of the detector performance up to this point in the mission (Pommerol et al 2022 [7]).

3.2.2 Geometric calibration

Once radiometric calibration has been performed on each individual exposure, it is then necessary to co-register them for the purpose of creating the full image swath. Map-projection of the individual exposures is also key for accurate mapping onto the surface of Mars. These steps are performed by a geometric calibration of the radiometrically calibrated data (Perry et al. 2022 [9]).

The geometric calibration pipeline incorporates two main software packages: the U.S. Geological Survey's (USGS) Integrated Software for Imagers and Spectrometers (ISIS3) (Backer et al. 2018 [10]) and Nextflow (Di Tommaso et al. 2017 [11]). Routines from the ISIS3 package are primarily used for the co-registration and map-projection of exposures, while Nextflow creates the top level framework for the pipeline in which the ISIS3 routines are run. Nextflow also allows for interaction with a database that tracks which images have been processed.

A full step-by-step description of the ISIS3 routines used during geometric processing is given in (Perry et al. 2022 [9]). A summary of these steps is as follows:

- Exposure ingestion into ISIS3.
- Bundle Adjustment.
- Map Projection.
- Mosaicing.

The initial ingestion step consists of radiometrically calibrated exposures being imported into ISIS3 along with initial geometry information taken from the NAIF SPICE kernels, with exposure orthorectification to large-scale topography subsequently being performed through incorporation of data from the Mars Orbiter Laser Altimeter (MOLA) (Smith et al. 2001 [12], Eliason et al. 2012 [13]).

Bundle adjustment is subsequently performed for improved exposure to exposure matching for the final image swath, to reduce the possibility of mis-registration and colour fringing. While amendment to the rotation mechanism position performed during the radiometric processing significantly reduces colour fringing, the bundle adjustment provides higher level corrections to reduce the chance of colour fringing even further. The bundle adjustment draws a control network of points across exposures and then matches these points in the areas of neighbouring exposures where overlap is present.

For map-projection, an equivalent scheme to that used by the HiRISE instrument was incorporated (McEwen et al. 2007, 2010 [2,14], Eliason et al. 2012 [13]), to improve the compatibility with other Mars image datasets (e.g. HiRISE, CRISM, CTX). For images within ±65deg of the equator, an equirectangular projection is used, with a stereographic projection used for images poleward of ±65deg, where all images are map-projected at a scale of 4m per pixel.

Mosaicing of map-projected exposures is subsequently performed, both in the individual colour band channels and by combining exposures in each of the colour band channels to create the final colour image swath. Several colour image swaths are created using different combinations of the individual exposure colour bands, including: NIR-PAN-BLU, NIR-RED-BLU, NIR-RED-PAN, RED-PAN-BLU and PAN-BLU, with each of these different colour band combinations designed to be sensitive to different surface features (e.g. Thomas et al. 2017 [1], Perry et al. 2022 [9]).

Mosaiced, map-projected images are saved as PNGs, in addition to several other products, for use by the wider community. These include image cubes created during ISIS3 processing and the fully calibrated, map-projected image data as .DAT files for each of the colour bands for a given observation. Processing of stereo observations is subsequently performed externally from the University of Bern at INAF-Padova and the University of Arizona (Fennema et al. 2019 [15], Simioni et al. 2021 [16])

With all these different products created for the science community, the amount of data produced far exceeds the amount of original data acquired on the spacecraft. It is often the case that from the original ~30GB of raw data acquired during a given week, that 40 times this amount of data are actually produced once all steps of data calibration are complete. With such a larger increase in data production, it is vital for robust data validation routines to not only check that all data are accounted for during the data handling process, but to also automatically check for image abnormalities where possible. This validation procedure is discussed below.

3.3 Data validation

Robust data validation is key when evaluating the completeness and quality of the CaSSIS dataset. Calibration of the CaSSIS images is a multi-stage process, with many files and intermediate products being produced by the calibration pipelines. To catch any abnormalities in the dataset, data validation steps were included where possible at each step of CaSSIS data handling process. It should be noted that abnormalities in the dataset could in principal be varied, whether through hardware issues at the point of acquisition, commanded parameters for image acquisition not being suitable for the target of interest, data not correctly being transmitted to Earth, through to more mundane calibration errors or processing server interrupts causing gaps in the final dataset. The CaSSIS team have implemented data validation techniques at each stage of CaSSIS operations to catch such anomalies. Details on the validation steps performed during image planning and commanding can be found in Almeida et al. 2023 [6]. Here, the validation steps performed during the downlink part of CaSSIS operations are described.

As mentioned in Section 3.1, the first stage of data validation is to check the raw image data from the spacecraft has been downlinked successfully. Here the CaSSIS team have a tool that automatically does a byte by byte check of all data that is downlinked to identify at source any initial abnormalities in the data.

The next stage of data validation is performed after the radiometric calibration of data. Here a tool is automatically run to check that the number of files generated is as expected. Output JPGs of the data at this stage are also produced for visual inspection, to identify any obvious signs of image corruption. Finally, each image is automatically checked for saturation. Image saturation is rare, but can happen in areas with unexpected levels of reflective material (e.g. varying surface ices). Any exposures found to be saturated at this stage are logged for follow up by the CaSSIS operations team.

Final validation of processed data is then performed after geometric processing. Here, similarly to the radiometric processing, the number of files created are automatically checked to make sure no data is missing. Visual checks on the data are also made at this stage to identify images where significant mis-registration between the different colour bands are present.

3.4 Feedback into on-going and future CaSSIS observation planning

As described in Section 2, it was deemed to be vital that the planning and processing of CaSSIS data form part of an evolving feedback loop to continuously improve the quality of the dataset. The main contribution to this philosophy from the data processing is referred to as 'target retirement'. After the geometric processing of images, where all images have been map-projected, a comparison is made with a database of suggested targets used to inform where images are planned, using a tool developed by the University of Arizona. If an image has been acquired of a given suggested target, with illumination conditions consistent with what was asked for, then this target is removed from consideration for future imaging, with this target classed as being 'retired'. An automatic email is simultaneously sent to the corresponding suggester of the target, with the details of the image that retired their target. Once the target suggester has evaluated the corresponding image, they have the option to request further imaging with different or identical illumination parameters. This process allows for the database of suggested targets to image with CaSSIS to constantly evolve both as a result of new broader science goals that arise in the community, but also as a result of the data that has already been acquired with CaSSIS.

4. Archiving

The archiving of CaSSIS data forms the final part of the data handling process. Data are archived once all stages of data validation have been passed. Currently the CaSSIS team archive data in ESA's Planetary Science Archive (PSA) (Besse et al. 2018 [17]) as well as via a data website hosted at the University of Bern. Both radiometrically and geometrically calibrated data are provided to the PSA in PDS4 format. This includes: the raw exposure data as .DAT files, the radiometrically calibrated exposures as .DAT files, non-map-projected .JPG images of the full radiometrically calibrated image swath in each colour band, map-projected .DAT files for the full image swath in each colour band and .PNG images of map-projected images in the colour band combinations described in Section 3.2. All files are supplied with corresponding .XML PDS4 meta data files to allow for accurate mapping of products. ISIS3 cubes produced during the geometric processing are also available through the CaSSIS data website. Currently this website is available to the CaSSIS science team, but will be open to the general public in the near future.

The final stage of data validation is performed upon delivery of data to the PSA. Here, a list of all files sent across to the archive are logged and sent to the PSA archiving team. A final check if performed at this stage to make sure that all data are PDS4 compatible and that the data present on the archive is consistent with the data that was sent across by the CaSSIS operations team.

5. Summary and Conclusions

The CaSSIS instrument offers state of the art colour and stereo imaging of the Martian surface. To maximise the scientific return of the instrument, the CaSSIS team have set up a framework for operations where planning of images and the data handling process are not stand alone processes, but exist in a continuously evolving feedback loop to improve the science return of acquired data. This publication overviewed how the data handling and archiving routines of CaSSIS data feeds into this framework. Each stage of the data handling was summarized, along with the data validation routines performed at each step.

Acquired and processed data are used to inform which future targets are selected for imaging, through reducing the possibility of unnecessary duplicate imaging and optimisation of the conditions targets should be observed with. Archived CaSSIS data has, and currently is, being used in numerous publications (e.g. Bowen et al. 2022 [18], Fernades et al. 2022 [19], Guimpier et al. 2022 [20]), highlighting the importance of CaSSIS data in the scientific community.

While many of the techniques used in the CaSSIS data handling process have been designed specifically for CaSSIS, we believe the top level philosophy of CaSSIS operations, namely linking observation planning with data handling in a fundamental feedback loop, defines a generic procedure that can be followed by other teams in future missions.

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