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The CaSSIS approach to Martian automated payload End to End Operations

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Abstract

The Colour and Stereo Surface Imaging System (CaSSIS) launched aboard the European Space Agency's ExoMars Trace Gas Orbiter (TGO) in March 2016. Beginning its primary mission in April 2018 from an orbit approximately 400 kilometers above Mars, CaSSIS has captured over 50 000 multi-color images and more than 2300 stereo image pairs.

CaSSIS utilizes a highly sophisticated and automated operations system designed to minimize manual intervention and maximize operational efficiency for planetary science missions. This system, built around the CaTLIST planning tool and leveraging SPICE kernel data for accurate trajectory information, operates within ESA phased planning (Long-Term, Mid-Term, Short-Term) and set to evolve the planning according to the information made available in each planning cycle. Key features include automated file system preparation, a web-based interface facilitating collaborative planning and data review, and rigorously designed radiometric and geometric calibration pipelines, significantly reducing processing time and minimizing potential for human error. The phased planning approach allows for proactive adjustments to observing schedules and data prioritization, while the automated procedures and web interface streamline data downlink and archiving processes. The Uplink and Downlink systems are integrated so that rapid feedback is possible. A detailed assessment of the automation strategies employed within the system demonstrates a marked reduction in operational workload and a corresponding increase in data throughput, contributing to enhanced mission productivity and resource optimization for operations engineering teams. The system’s modular architecture and comprehensive automation protocols also provide a robust framework for future enhancements and adaptability to evolving operational requirements.

Keywords: Mars, High-Resolution, Images, Automation, CaSSIS

Nomenclature

This section is not numbered. A nomenclature section could be provided when there are mathematical symbols in your paper. Superscripts and subscripts must be listed separately. Nomenclature definitions should not appear again in the text.

Acronyms/Abbreviations

CaSSIS	Colour and Stereo Surface Imaging System
CaST	CaSSIS Sugestion Targeting
CaTLIST	CaTL Imaging Suggestion Tool
CTF	CaSSIS Targetting File
ESA	European Space Agency
ITL	Intrument Timeline
LTP	Long Term Plan
MTP	Medium Term Plan
STP	Short Term Plan
TGO	Trace Gas Orbiter
THEMIS	Thermal Emission Imaging System

1. Introduction

The CaSSIS telescope possesses a unique suite of scientific capabilities [1]. Recognizing that the images acquired are relatively small compared to the scale of a body like Mars, our strategy focuses on selecting high-value targets to acquire highly relevant data that will address key scientific questions. Crucially, CaSSIS has a remarkable ability to discern minerals based on its unique color capabilities. Combined with the telescope's high-resolution imaging, this capability is not only enabling the mapping of specific regions to advance our understanding of the target body, but is also instrumental in identifying and evaluating potential landing sites.

From the outset, the CaSSIS Science team adopted a science-focused operations concept, leveraging existing infrastructure from HiRISE. These initial operations, while yielding valuable data, were largely manual. Building on this foundation, significant effort has been dedicated to automating the entire operational chain, from planning and target selection to data downlink and archiving. This automation has dramatically streamlined workflows and improved efficiency, enabling closer collaboration between the science team through modern, interconnected web interfaces. Automated target planning cycles can run with minimal human intervention, including the population of the target database using intelligent algorithms to prioritize data acquisition. This frees up valuable time for the Planning Scientist to focus on strategic initiatives like multi-year campaigns and data quality assessments, and allows Instrument Operators to explore novel scientific objectives. The complete automation of the downlink system ensures rapid data availability, including automated radiometric and geometric calibration. This streamlined, closed-loop system, connecting uplink planning and downlink processing, achieves unprecedented meter-scale targeting accuracy and provides immediate feedback for continuous operational improvement, setting a new standard for ESA interplanetary missions.

2. The Operations System

CaSSIS Operations are completely integrated, but for simplification purposes it can be subdivided into the Uplink stage where image acquisition is planned and the Downlink stage where image data is processed and archived.

The CaSSIS uplink planning process is a multi-layered approach integrating automated target selection with manual review and refinement. The workflow can be broadly divided into three phases: target list acquisition, automated CTF generation using the CaTLIST tool, and final CTF review and optimization in PLAN-C [2].

Target selection begins with a list of potential imaging targets compiled by the CaSSIS science team and stored within the CaST (CaSSIS Target List) database. These targets are prioritized based on scientific merit and objectives, with specific criteria for observation timing often outlined in the target request. Criteria such as proximity to potential trace gas sources, geological features of interest, or areas requiring stereo coverage are considered.

CaTLIST plays a pivotal role in streamlining the planning workflow by automating the initial CTF generation. This process draws upon the information contained within the CaST database and trajectory data derived from SPICE kernels. While CaTLIST substantially reduces the time required for initial CTF construction, a crucial manual review and optimization phase is integrated within the PLAN-C environment. PLAN-C provides operators with a comprehensive suite of tools for evaluating the generated CTF, including the ability to adjust target priorities, fine-tune imaging parameters (e.g., filter selection, exposure time), and address any issues identified by automated quality checks. This final stage of review ensures scientific integrity and allows for adjustments to accommodate unforeseen conditions, such as updated short notice scientific objectives or past instrument performance deviations, before the CTF is formally approved for command generation and uploaded to TGO.

The Downlink System, encompasses data reception, processing, calibration, geometric correction, and final archival formatting. The entire process uses robust data pipelines, leveraging standardized procedures and data to be archived by ESA for future preservation. The initial phase involves the downlink of raw CaSSIS data from ESA. This is done through the ESA Data Dissemination System (DDS). Raw data is stored as a bit stream, requiring the first processing stage to unpack these streams and reconstruct the initial image data. This stage also performs error correction and validates packet integrity.

The raw image data then undergoes radiometric calibration. This process corrects for instrument detector noise and removes any effects of stray light, as well as providing the absolute calibration of the images that start to be represented in physical units. Simultaneously, initial metadata is generated, including timestamps, instrument configuration parameters (filter selection, exposure time), and relevant engineering data. This metadata provides essential context for subsequent processing steps and is tightly linked to the calibrated image data. A critical stage involves geometric calibration, which corrects for distortions introduced by the spacecraft’s attitude and the instrument’s optics. This process heavily relies on the ESA SPICE kernels, which provide precise geometric information regarding the spacecraft's trajectory, attitude, and the instrument's field of view. The SPICE kernels are used to co-relate individual image frames and establish a consistent coordinate system. This geometric correction culminates in the projection of the data onto a Mars-referenced coordinate system, enabling accurate spatial interpretation and integration with other datasets. This step also generates additional metadata describing the geometric transformation parameters.

The fully processed and geometrically corrected data, including the color images, radiometric calibration parameters, geometric transformation parameters, and all associated metadata, are then formatted according to the ESA archival standard, the PSA. This standard ensures long-term preservation and accessibility of the data. The final, formatted data package is then delivered to the long-term ESA PSA archive, where it becomes publicly available to the scientific community.

3. Uplink Automation

At the start of the primary science phase of the Trace Gas Orbiter (TGO) mission, most plan stages were executed manually. While command generation was automated from the outset—a critical component due to its complexity and potential for error—the planning process itself, outlining which images CaSSIS should acquire and when, was largely driven by human effort. This initial setup presented challenges, particularly as the CaSSIS team scientists volunteered their time to develop these plans. This reliance on voluntary effort proved unsustainable, especially during periods like holiday seasons when obtaining plan development resources was difficult.

To address this, a program of automation was initiated to ensure mission continuity and mitigate the risk of science degradation should the team become unavailable. The goal was to create a system where the operational responsibility could be sustained by the spacecraft operators and the Principal Investigator (PI) team, even in an emergency situation. This automation focused on reducing the burden on the science team while retaining their scientific input.

The CaSSIS uplink planning process begins with the selection of areas of interest by the CaSSIS team scientists. These selections are guided by pre-defined scientific criteria, ensuring that the acquired images contribute meaningfully to the overall mission objectives. This stage remains the least automated aspect of the planning, as the scientists rightly prioritize maintaining control over the scientific direction of the image acquisition.

However, to manage periods of high data volume and the potential depletion of targets in the planning database, automated techniques have been implemented. To supplement the scientist-driven selection of targets, a suite of automated methods has been developed to populate the CaSSIS planning database. These automated methods don't replace the scientist's expertise but serve as a powerful tool to broaden the scope of potential targets and increase operational efficiency. The core principle guiding these automated population techniques is to identify locations on the Martian surface where existing, lower-resolution datasets hint at features of scientific interest that require higher-resolution CaSSIS observations for conclusive study.

Analysis of thermal emission datasets, like those from the THEMIS instrument on Mars Odissey, can reveal areas with contrasting thermal inertia. These variations are often indicative of differences in surface composition and grain size, potentially exposing bedrock or areas of concentrated material. The automated system searches for these thermal anomalies, flagging them as potential CaSSIS targets. Hyperspectral datasets from instruments like OMEGA on Mars Express provide information about mineralogical composition. Certain spectral signatures may suggest the presence of specific minerals, but the lower resolution restricts definitive identification. The automated system flags locations displaying these spectral features as requiring higher-resolution CaSSIS imagery to confirm mineral presence and spatial distribution.

Increasingly, automated routines are designed to cross-correlate different datasets, combining thermal, spectral, and morphological information to identify locations exhibiting multiple lines of evidence suggestive of scientific interest. Recognizing the potential of machine learning to identify subtle patterns within complex datasets, the CaSSIS team has begun exploring and implementing various machine learning techniques for automated target identification. A particularly successful early example involved the detection of dust devils. Machine learning algorithms were trained on a dataset of MRO HiRISE and CTX as well and Mars Express HRSC images known to contain dust devils. These algorithms were then applied to wider-area MRO data to automatically identify potential dust devil locations, which were subsequently prioritized for CaSSIS observations. This approach allows for the identification of transient features that might otherwise be missed by traditional targeting methods.

This approach helps reduce the scientists' workload while increasing the potential for scientific discovery by ensuring that previously inconclusive data can be revisited with the superior capabilities of CaSSIS.

Following target selection – whether by scientist input or automated population – the CaTLIST tool assumes a central role in the automated planning process. CaTLIST is a dedicated software module that autonomously selects which images will be acquired by CaSSIS, optimizing for scientific priority and spacecraft constraints. It represents the culmination of the automated planning chain, allowing for efficient and resilient image acquisition.

At its core, CaTLIST uses detailed information about the spacecraft's orbit obtained for ESA generated SPICE kernels to determine the optimal imaging strategy for each target in the target database. It prioritizes targets based on a ranking system incorporating scientific importance, observational difficulty (e.g., requiring specific illumination angles or spacecraft attitude), and potential for unique data acquisition.

CaTLIST is utilized across three distinct planning timescales, each with a slightly different focus:

Long-Term Planning: During long-term planning, it identifies exceptionally high-priority targets that are strategically challenging to image due to orbit geometry or lighting conditions.

Medium-Term Planning : During this phase, the CaSSIS team can leverage CaTLIST to assess the feasibility of requesting specific spacecraft rotations, therefore planning all the higher priority targets available.

Short-Term Planning: In the short term, CaTLIST ensures that all available data volume is exploited. It prioritizes imaging areas of opportunity where database targets coincidentally align with the current viewing geometry, maximizing scientific return from each available observation window.

Crucially, the automated process facilitated by CaTLIST does not eliminate scientist involvement. At each step of the planning chain, scientists retain the option to intervene and modify the automated selections.

Recognizing the need for continuous operations even when scientist availability is limited, the CaTLIST system allows for entirely automated planning cycles. In these instances, the planning process runs exclusively based on CaTLIST-selected targets, ensuring that critical imaging opportunities are not missed.

The culmination of the planning process lies in the CTF2ITL software. CTF2ITL acts as the vital bridge, translating the finalized list of images and associated scientific objectives into a detailed command sequence ready for transmission to the spacecraft. This software takes the output of the planning process – the selected targets, desired imaging parameters, and associated observations – and meticulously constructs the precise commands CaSSIS needs to execute the observations.

CTF2ITL incorporates all necessary imaging parameters for each observation, including:

Image Size and Resolution: Defining the spatial dimensions of the acquired images.
Optimal Sensor Windows: Selecting the appropriate portions of the detector for data acquisition.
Exposure Times: Determining the optimal duration for light capture.
Number of Repetitions: That determines the image length.

Furthermore, CTF2ITL calculates the necessary motor movements required for precise camera alignment and stereo image acquisition, ensuring optimal geometric accuracy and 3D reconstruction capabilities.

Beyond command generation, CTF2ITL plays a critical role in preparing data for subsequent processing. It generates comprehensive planning information, including, the position and orientation of the telescope at the time of each observation, commanding data needed for radiometric and geometric correction during image processing and observation data to facilitate data organization and analysis.

Recognizing the potential for errors to propagate through the complex planning chain, CTF2ITL incorporates a robust set of automated checks. This final layer of safety ensures that any inconsistencies or potential issues arising from previous planning steps are identified and flagged before the command sequence is transmitted. These checks verify:

Parameter Consistency: Ensuring that imaging parameters align with instrument capabilities and mission constraints.
Geometric Feasibility: Confirming that planned observations are geometrically possible given spacecraft constraints and target locations.
Commanding order: Double-checking that all commands are in the correct time order

By acting as a final safeguard, CTF2ITL provides a critical last line of defense, minimizing the risk of errors and maximizing the quality of data acquired by the CaSSIS instrument.

This combination of automated efficiency and human oversight ensures that the CaSSIS instrument consistently delivers the highest-quality scientific data while adapting to the dynamic nature of the Martian environment and operational constraints.

4. Downlink Automation

The downlink process marks the transition from spacecraft operations to scientific exploitation. It's a complex sequence encompassing data retrieval from the ESA Data Dissemination System (DDS), meticulous validation, specialized calibrations, motor analysis, and secure archiving for long-term accessibility. The downlink process commences with querying the DDS to confirm the availability of expected data, followed by identifying and querying the downlinked data based on expected file names, observation IDs, and timestamps. Initial validation is then performed, including rigorous checks like verifying checksums and data completeness to ensure data integrity, before establishing dedicated directories and file structures to organize the incoming data. This also confirms alignment with the anticipated observation schedule.

The downlink process seamlessly transitions into radiometric calibration, which is closely integrated with motor analysis. This begins with updating instrument kernels and performing checks to ensure functionality. Observations with special pointings, any non Mars image like Phobos and Deimos or the Mars limb, are identified and flagged for focused analysis. Simultaneously, 20 images are collected specifically for motor analysis. Following this, analysis code is executed to assess motor performance, a new calibration kernel (CK) is created, and this CK is then copied to be implemented in subsequent processing steps. A full radiometric processing run is then performed, utilizing the new CK. As a parallel effort, the geometric calibration pipeline begins, with data being transferred to the designated geometry directory and the CaSSIS Targeting File (CTF) ingested into the database. Data is queued and processed geometrically, with a parser employed to update labels for data products. NPB and RGB images are collected for a first visual assessment of the geometrically corrected data.

Following radiometric processing, the processed data is validated and copied to the University of Bern Data Server, and a repeat radiometric processing run is then carried out, this time with special pointings, ensuring comprehensive calibration for all observations. Finally, the data archiving process commences by transferring radiometric and geometric data to the University of Bern Mirror Data Server, and prepare the data to transfer to ESA. A final validation check ensures that the data has been successfully processed, archived, and is ready for scientific analysis, marking the successful completion of the downlink and calibration process.

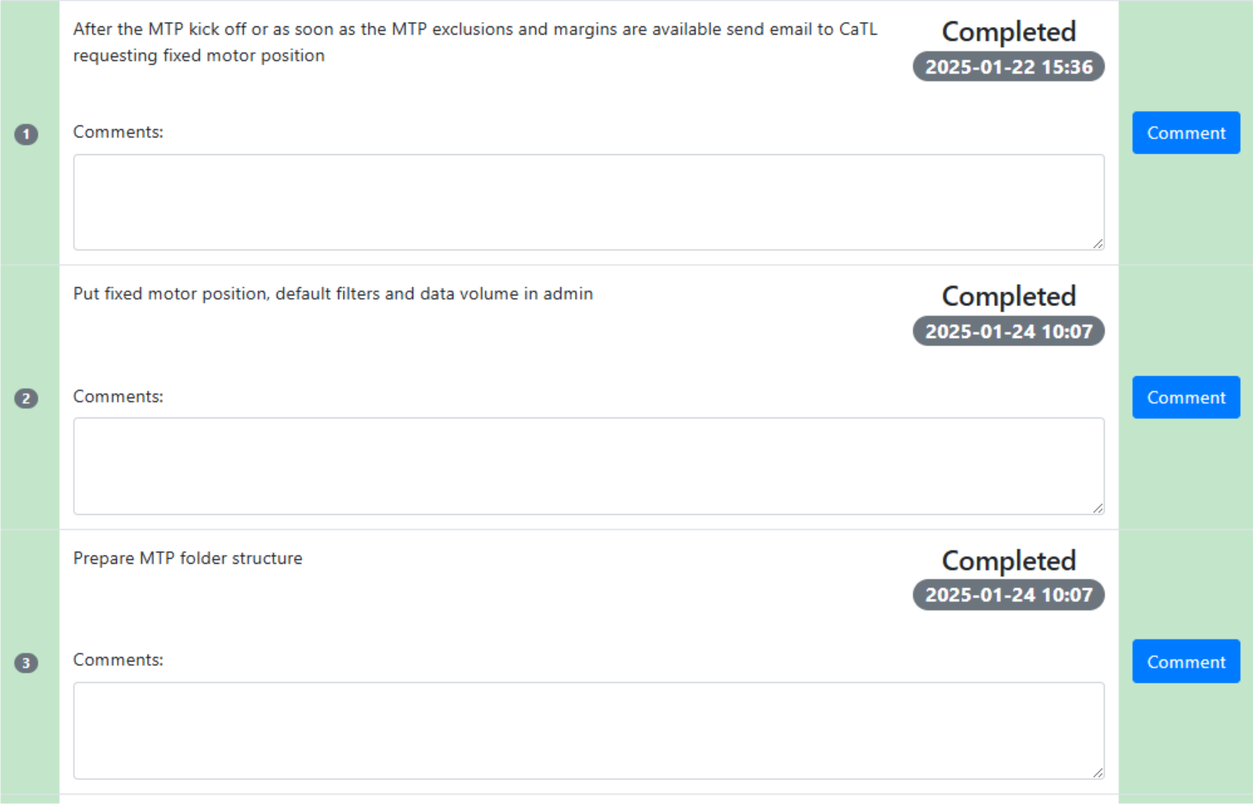
5. The CaSSIS Ops web interface and automated procedures

The Cassis Operations Web Interface serves as a centralised hub for planning and automating the intricate sequence of operations required for optimal data acquisition. It provides a powerful toolset for both operations engineers and scientists, fostering seamless collaboration and ensuring efficient data retrieval. The interface provides a planning location, a crucial interface for CTF (Calibration Table File) exchange, interactive plots displaying Beta Angle, Motor Angle, and Stereo Coverage, and a Planning Data Download function that ensures all data is perpetually up-to-date. Integrated with CaTS (Cassis Automation and Tools System) procedures, the web interface streamlines the entire planning workflow, automating a significant portion of the tasks while providing a simplified front end for scientists to interact with the system.

The interface's functionality is structured around three primary planning phases: Long-Term Planning (LTP), Mid-Term Planning (MTP), and Short-Term Planning (STP), each contributing to the refinement and optimization of the data acquisition schedule. The LTP procedure begins with the crucial integration of the latest spacecraft trajectory information, provided by ESA in the form of SPICE kernels, covering a planning horizon of approximately six months. This automated process incorporates the LTP data volume prediction, automatically generating the necessary file infrastructure for the data set, while proactively preparing for the subsequent planning phases. The entire process relies on automated file ingestion from ESA, minimizing manual intervention.

The MTP procedure further refines the planning process, again leveraging automated data ingestion from ESA. This phase prepares the file system and the operations system in general with the latest information, and crucially, prepares configuration files that allow scientists the flexibility to perform manual image selection should they desire.

The CaTLIST tool is run as part of this procedure, and the planning interface is configured to facilitate an iterative process with the science team, allowing them to directly ingest and modify image planning lists and CTFs within the system. The system generates a detailed report, assessing the quality of the provided list and highlighting any necessary modifications.



1. After the MTP kick off or as soon as the MTP exclusions and margins are available send email to CaTL requesting fixed motor position

Completed
2025-01-22 15:36

Comments:

2. Put fixed motor position, default filters and data volume in admin

Completed
2025-01-24 10:07

Comments:

3. Prepare MTP folder structure

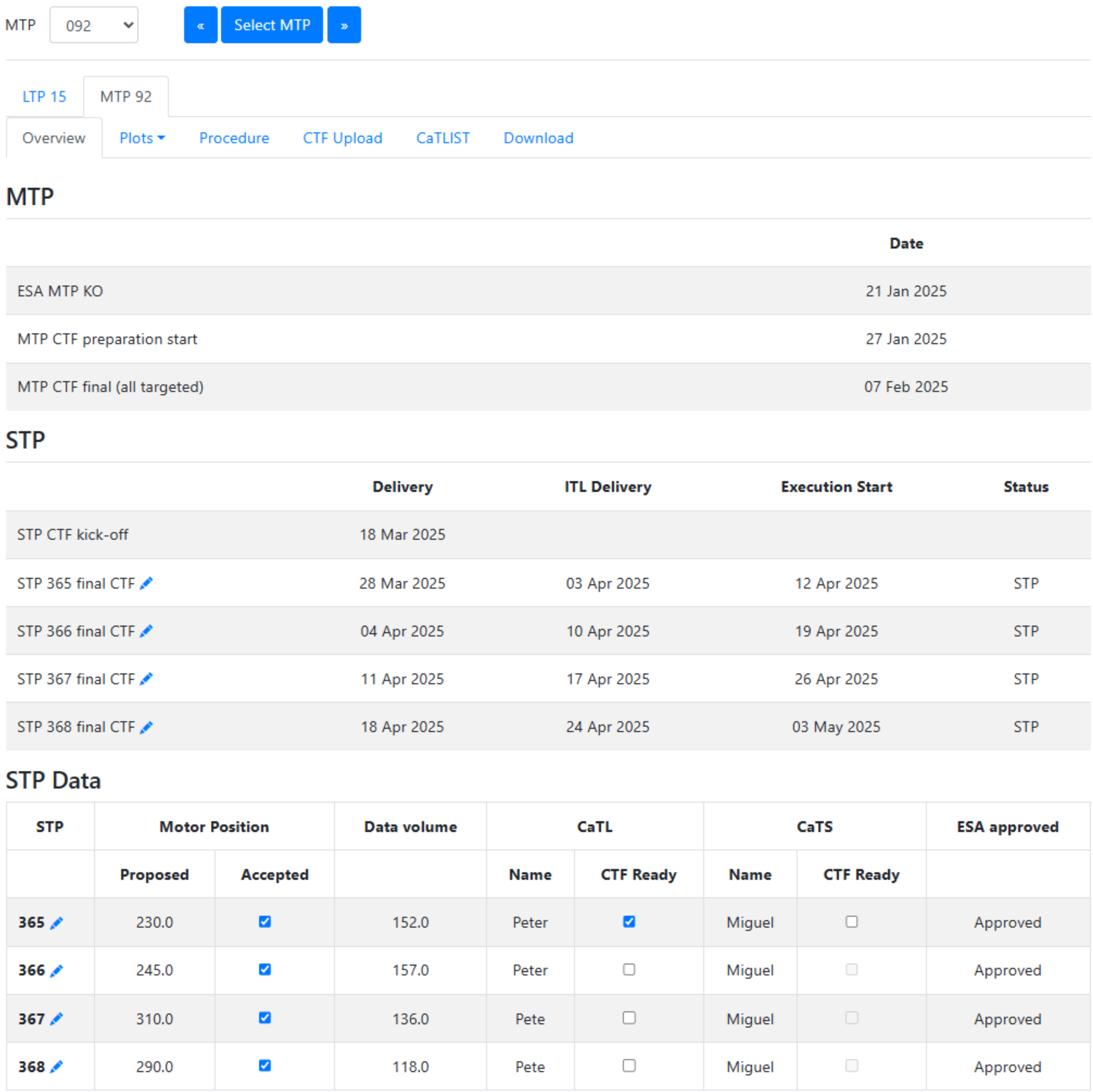
Completed
2025-01-24 10:07

Comments:

Figure 1- Start of the MTP procedure on the CaSSIS Operations Web Interface

The STP procedure's interface mirrors the MTP interface, initiating with a "STP Prep" phase. This phase introduces the latest STP data, runs the CaTLIST tool, and provides a front-end interface specifically designed for image list iteration with scientists, ensuring alignment with their evolving scientific needs. The final, crucial procedure then automatically generates the actual CaSSIS commands. This process automatically ingests the most current information, allowing for the inclusion of last-minute images to meet the data volume requirements. The only manual intervention required at this stage involves the addition of essential maintenance commands, such as detector management, motor management, priority file requests, and occasional reboots, ensuring the overall health and efficiency of the instrument. This combination of automation and targeted manual input ensures a highly effective and collaborative planning workflow for the CaSSIS instrument.

Finally the frontend of the CaSSIS operations Web Interface was designed to be a very simple interface where the Scientists can find quickly the most relevant information to help them plan, and with the latest information always available. It includes an Overview with the important dates for deliveries and planning periods as well as the data volume and other important CaSSIS planning parameters, and plots. And it includes the image list ingestion interface, called CTF upload.



MTP

	Date
ESA MTP KO	21 Jan 2025
MTP CTF preparation start	27 Jan 2025
MTP CTF final (all targeted)	07 Feb 2025

STP

	Delivery	ITL Delivery	Execution Start	Status
STP CTF kick-off	18 Mar 2025			
STP 365 final CTF	28 Mar 2025	03 Apr 2025	12 Apr 2025	STP
STP 366 final CTF	04 Apr 2025	10 Apr 2025	19 Apr 2025	STP
STP 367 final CTF	11 Apr 2025	17 Apr 2025	26 Apr 2025	STP
STP 368 final CTF	18 Apr 2025	24 Apr 2025	03 May 2025	STP

STP Data

STP	Motor Position		Data volume	CaTL		CaTS		ESA approved
	Proposed	Accepted		Name	CTF Ready	Name	CTF Ready	
365	230.0	☑	152.0	Peter	☑	Miguel	☐	Approved
366	245.0	☑	157.0	Peter	☐	Miguel	☐	Approved
367	310.0	☑	136.0	Pete	☐	Miguel	☐	Approved
368	290.0	☑	118.0	Pete	☐	Miguel	☐	Approved

Figure 2-The CaSSIS Operations Web page Overview where the scientists interact with the instrument operators

6. Conclusions

The CaSSIS operations system on the Trace Gas Orbiter has demonstrably enhanced data acquisition and processing efficiency through its integrated planning and automated procedures. However, the inherent challenges of planetary exploration, coupled with the vastness of potential targets, have underscored a crucial and often overlooked feedback loop: the rigorous analysis of downlink data directly informs and refines future uplink planning. This iterative process, while initially resource-intensive, has proven invaluable for maximizing scientific return. The limitations revealed through image quality assessments – variations in lighting conditions, unexpected terrain complexities, and the impact of dust accumulation – coupled with unanticipated mission constraints identified during data review, have all shaped subsequent observation strategies and optimized target selection. Observing why a target was not achievable, or yielded suboptimal results, provides crucial context for adjusting approach angles, instrument settings, and overall scheduling priorities in future planning cycles. This continuous refinement demonstrates the inextricable connection between downlink data and uplink execution – a critical understanding for efficient and productive planetary operations.

Looking forward, further automation offers significant potential for enhancement and represents a key area for investment. Specifically, increasing automation within the planning procedure steps, including the integration of robust checking software for validating target selection based on orbital geometry, illumination models, and instrument capabilities, could dramatically reduce planning cycle times and minimize the potential for human error. Beyond this, a comprehensive and ongoing analysis of existing planning data – encompassing target selection rationale, scheduling decisions, instrument configurations, and observed performance metrics – will be essential for identifying recurring patterns, biases, and areas for optimization. This will involve exploring opportunities to incorporate real-time feedback mechanisms into the planning workflow, leveraging machine learning techniques to predict image quality based on orbital parameters and terrain characteristics, and dynamically adjusting observation priorities based on evolving scientific objectives and emerging discoveries. Furthermore, development of automated tools to assess the information content and scientific value of acquired data, facilitating the prioritization of follow-up observations and the efficient allocation of limited resources, represents a particularly promising avenue for future development. Ultimately, a sustained commitment to continuous improvement, driven by this dynamic feedback loop and underpinned by rigorous data analysis, will be paramount to optimizing the capabilities of future planetary imaging systems and ensuring the ongoing success of robotic exploration.

Acknowledgements

This section is not numbered.

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